Agricultural and Horticultural Engineering

Principles, models, systems and techniques

by

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Preface

A 3,000 year old vision

In the last days
The mountain of the Lord's temple will be established
As chief among the mountains;
It will be raised above the hills, and all nations will stream to it.
Many peoples will come and say,
"Come, let us go up to the mountain of the Lord,
To the house of the God of Jacob.
He will teach us His ways so that we may walk in his paths."
The law will go out from Zion,
The word of the Lord from Jerusalem.
He will judge between the nations
And will settle disputes for many peoples.

They will beat their swords into ploughshares
And their spears into pruning hooks.
Nation will not take up sword against nation,
Nor will they train for war any more.

Come, O house of Jacob, let us walk in the light of the Lord.

Isaiah 2 v 3-5
(circa 740 BC)

In the past sixty years agriculture and horticulture have changed drastically in response to changing demands and technology. Inevitably the engineer has been called in to assist in implementing these changes, and equally inevitably the result is an increasingly sophisticated technology, demanding a greater understanding of the science and equipment which has been brought onto the farm. By nature, the farm is a complex system, demanding adaptability and flexibility in management, combined with a practical and theoretical knowledge of the whole system of plants, animals and machinery.

Farmers and growers, and those who assist them, generally possess all these attributes in varying degrees, and while success does not always match the degree of competence, it is usually related to it.

Agricultural and horticultural engineering is the study of any area of engineering relevant to agriculture or horticulture. It thus may include subjects normally classified as civil, electrical, or mechanical engineering. The agricultural (horticultural) engineer is therefore required to be knowledgable in a wide range of diverse subjects, as well as having a good grasp of the agricultural scene.

This is a demanding role, but one which is of immense value to mankind, providing theory and practice can be merged satisfactorily. This book strives to bridge the gap between the

horticulturalist or agriculturalist, with his or her need to get on with the main function of cultivating crops and handling livestock, and the engineer who finds her or his interests in the science of technology.

The book uses SI units throughout, with conversion tables in an Appendix for those who have yet to come to grips with what to many rural managers remains as a difficult system of measurement. This reflects the book's emphasis on a twentieth century approach to agricultural engineering. The reader may notice that units are referred to in a variety of ways. For example, for power, the symbol "W", or the full name "watt" may be used. Similarly both the m/s and $m\ s^{-1}$ forms of notation are used where there is no ambiguity in the meaning. This is deliberate, and is intended to encourage attention to and awareness of the fact that scientists, agriculturalists, and even engineers must be fully familiar with these various styles of presentation.

Some readers may wish for rather more details on some topics than this volume contains. Inevitably space restrictions must result in some omissions, but the concentration on principles should be sufficient to encourage the reader to dig deeper to satisfy his or her needs, and references for further study have been included at the end of each chapter. This book is thus a resource book, and will serve well as a starting point for the in-depth study of a particular subject. The author will have succeeded in his aim if the reader can either solve the problem immediately, or if this book diverts them towards, and equips them for, the rigours of an in-depth, subject specific, text book.

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I would like to express my appreciation to the staff of Massey University, and especially the staff in the Agricultural Engineering Department, both past and present, for their help and support in the preparation of this book. I am particularly grateful for the many helpful suggestions from those who read chapters in their areas of expertise, including Nevin Amos, Andrew Bruere, Ian McGregor, Gavin Wall, and Colin Wells. I am also most grateful to the Department and Massey University for permission to use extracts from a wide range of teaching materials, and individual's lecture notes, (including the notes of some who have since moved on to new fields of endeavour). I would particularly like to thank Gavin Wall for his support and encouragement for the project. I would also like to thank Keith Fisher and Errol Hewitt (Department of Horticulture), for their comments on the greenhouse and post-harvest sections, and Bob Chaplin (Production Technology) for suggestions on the section on electronics and particularly microprocessors. I must add that while I have almost always happily adopted the suggestions made, in the end the choice of topic, the approach, comments, views and errors reflect my own opinions, and I can hold no one else to blame!

This book includes information and diagrams from a number of sources. I am grateful to those who have supplied this information. Where known the source is acknowledged in the text. In particular the author wishes to thank the following for helpful comments and suggestions, and for enabling information to be included:–

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The Engineering Approach

Chapter 1

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1.1 INTRODUCTION

Engineering is often described as "doing the job with the tools that are available". This is not a bad description really, provided you do not restrict your definition of a tool. The only tools some engineers use are a pencil and a computer. There is a lot of confusion in the English language about the word "engineering". Originally it came from a Latin word "ingenium" which means creative or ingenious, and this is where words like genius came from. Unfortunately when devices were developed which converted thermal and chemical energy into mechanical power, these were considered to be such brilliant innovations that the word "engine" was used to describe them. Worse still, when engines became mobile, and ran on iron rails, the driver became known as "the Engineer" in at least one English speaking country. These different uses of the word have caused so much confusion that it is necessary to explain what we do mean by an Engineer, or more appropriately for this book, what engineering is really all about, and what we mean by an engineering approach to the subject.

So what is engineering, and more to the point, what is Horticultural or Agricultural Engineering? Engineering is really the application of science and knowledge to the real world. Thus an engineer is one who is able to take available scientific knowledge and understanding, and to make use of it to

assist people to carry on and improve their daily living. In order to do this the engineer must first have a reasonably sound understanding of the scientific principles which underlie what she or he is doing (*Figure 1.1*). This requires a knowledge of the models which scientists have developed to describe the real world. The idea of a model is most important and there will be much more on this later. Models must be fed with specific information and data about the particular application to enable them to be applied, and the engineer must be able to obtain this from somewhere. The source is often engineering textbooks, or the Standards Booklets and codes of practice produced by a National Standards Institute. The job of these bodies is to produce the best available data and guidelines for use in design and construction.

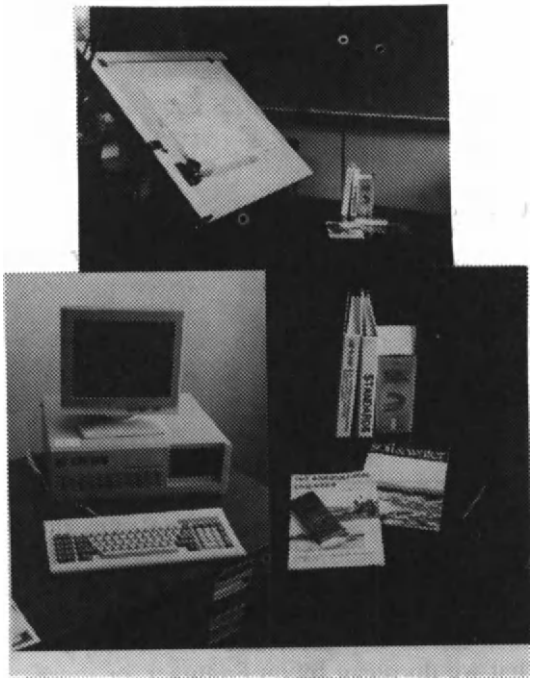


Figure 1.1 The tools of the horticultural or agricultural engineer—drawing board, computer, calculator, reference books and standards.

In order to use the models and the data the engineer must be able to manipulate them and apply them to the problem at hand. This requires a whole tool-kit of mental skills which we call mathematics. I think it is important to think of mathematics as a tool-kit. If your maths is limited, you can still get by, but you will only have a few tools to work with. You can do a lot with just a hammer and a saw, but if you want to make progress faster, or produce better, more elegant and useful items, sooner or later you will have to get (and be able to use) more complex equipment such as a drill, a chisel, or a machine-lathe. In the same way, you can do a lot with addition and subtraction, but using computers, calculus and statistics opens up a whole new world of possibilities.

Having obtained data and suitable models of the system, the engineer now has to design and plan. This is the creative stage of the process, and the one which calls for ingenuity, common sense, experience, judgement, and skill. However it does not finish there. Nowadays the engineer will have to produce a report and a set of drawings containing his or her design and recommendations, and someone else will produce the finished job. The engineer may or may not be involved in this part of the exercise: often he or she will be there in a supervisory role, to ensure that the work is done properly. The engineer will also be keen to evaluate the effectiveness of his or her solution, and to recommend improvements for the future.

This then is a brief overview of the engineering approach. Historically engineering has divided itself up into a number of major sections. These are Mechanical, Electrical, Chemical and Civil Engineering. The first three concentrate on those areas which their name implies, while the Civil Engineer is concerned with structures, buildings and services for human populations. The Horticultural or Agricultural Engineer does not fit well into this sub-division of the subject, since his or her range of interests covers all of these areas. It is better to define Agricultural Engineering as:

> *the application of relevant engineering to agriculture and horticulture.*

This means that we will need to consider any part of engineering which is relevant, be it electrical, mechanical, chemical or civil. We will also need to consider how this can be applied to agriculture and horticulture, and so we need to have some knowledge about agricultural and horticultural systems in order to be able to apply the information.

It is possible to identify key areas in

Horticultural and Agricultural Engineering which have evolved over time. In essence one can identify the areas of soil and water, power and machinery (or mechanisation), and structures. Food engineering can also be classed as another area if off-farm activities are included under the title of agriculture.

1.2 MODELS OR PRACTICALITIES?

In a subject such as horticultural or agricultural engineering, there is always a slight conflict between the need to understand what is going on and the need to get the job done. There is a strong temptation to get on with the job, acquiring the minimum of knowledge necessary to complete the work. If this approach is taken then Engineering can become a series of practical hints about how to achieve an aim, and very little understanding results. The difficulty with this is that it is not easy to develop new ideas or to adapt to change. Once methods and techniques become outdated the individual has to relearn his or her skill from the beginning. A person who can use and understand the theory (ie, the model) behind a phenomenon is able to adapt to change, and can develop new things.

All this is very good, but unfortunately theories also have limitations. For one thing it is hard to get enthusiastic about an equation when one desperately needs water for the maize. It is also not always easy to see the immediate relevance of a model, often because the model is just one step in the path towards a more complex model which does describe the real situation. Theories can also look very good, but implementing them usually requires practical skills and know-how which are outside the limits of the model. It is possible to design a very good water supply, but be quite unable to construct it because one does not know how to join the pipes together in the field.

The result of this is that good engineering is always a slight compromise between the two extremes. Registered Engineers must have undertaken a high standard of theoretical study, and also have had a number of years of practical experience before they are fully recognised. Of course, all this does not mean that the engineer must be able to complete every task required in a project. Rather he or she should be aware of the practical aspects of any problem, and be able to direct craftsmen in what is required. The engineer must be able to ensure that the work is possible in the way that he or she requires it to be done, and should be able to ensure that the work is done to the required standard. All this involves a good practical background and a working knowledge of the system.

1.3 THE MODELLING APPROACH

As we have already said, engineering involves the use of scientific models. It is important to realise why this is so, and why models take the form they usually do.

Our world is amazingly beautiful and complex. A microscopic study of a small section of a lettuce leaf will reveal such a complex structure that a full description would take several pages. An explanation of the photosynthetic processes taking place when light falls on the leaf would occupy several textbooks and would still leave several unanswered questions. Yet we happily eat the product without a care! We can also describe how the leaf grows in very simple terms: light hits the leaf, and the leaf uses this energy to convert water and carbon dioxide into carbohydrates. These allow the plant to grow. An even simpler description says:

(Light and Carbon Dioxide and Water)
= Plant growth **Equation 1.1**

This is quite a useful description or model of the system. It tells us that, if we have the three things on the left, we get the thing on the right. It is not a full description of the system of course. If the levels of the three things are not right then the result may not be as expected. For example if the light is too strong the plant may simply die. Neither does it tell us how much growth we get for a given level of the three inputs. The model also has a number of conditions attached to it. The leaf requires adequate supplies of trace elements, and it requires a delivery system (roots and a plant stem) to be able to take in the carbon dioxide and water. However it helps us because it describes a piece of our complex world in a way which we can understand and use. If you did not know about lettuce plants I could tell you what the leaf does with the aid of this model and you could then set about

growing your own. You would plant the lettuce plant where it could get the three inputs and be delighted when it grew. You would not plant it inside a box because the model has told you that light is needed for growth.

Models therefore, are useful, simplified descriptions of our world. The model can be simple or complex, depending upon what is being described. It need be only as complicated as is necessary to give results which are accurate enough for the job in hand. A model can be in the form of words, or a mathematical equation. We can also use graphs or diagrams which describe all or part of the model (eg, *Figure 1.2*). Note that the model does not actually need to be a true description of what is really happening, as long as it does the job.

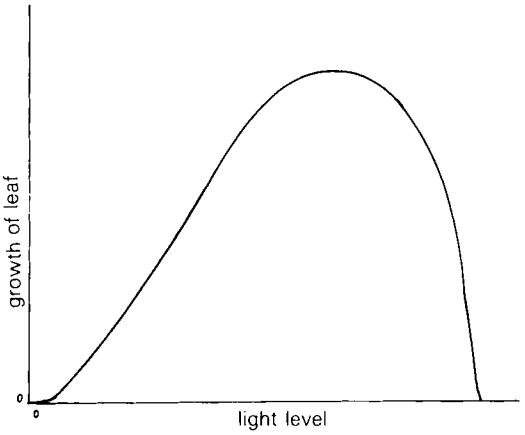


Figure 1.2 Hypothetical model of the growth of a leaf as a function of light levels.

When we look at the physical world, we again observe very complex things happening. If you pick a stone up and drop it, it falls to the ground. So do other objects like apples, eggs and plums. If you looked carefully, you would soon notice that the apples and plums falling from the highest branches get more bruised when they hit the ground because they are travelling faster. The effect of dropping an egg from a great height is somewhat more messy, but the principle remains the same. After a while, we would conclude that all these falling bodies are behaving in the same way. If we want to describe this behaviour, we could try to use models. For example,

Stone + height = Falling **Equation 1.2**

Apple + height = Falling **Equation 1.3**

Apple + Big Height = Falling + bruising **Equation 1.4**

Egg + Big height = Falling + mess **Equation 1.5**

Each one of these lines is a model, but they are fairly limited descriptions of our world. In addition if we wanted to know how much bruising, or how high before the egg breaks, the models are inadequate.

Scientists over the years have studied the world and come up with a number of models which give good descriptions of the physical universe. A model of falling bodies is:

$v.^2 = 19.6 \times s$ **Equation 1.6**

Where v is how fast the body hits the ground (in metres per second), if it is dropped from a height of s metres. Bruising (or cracking) can be described by the model

Bruising if $mv^2 >$ Critical constant, and then

Bruised volume = Constant $\times$ m $\times v^2$ **Equation 1.7**

where m is the mass of the apple.

Here are two models which describe the world. The first, *Equation 1.6*, is a very good description of a falling body. It is based on the observations of scientists over hundreds of years, and works very well indeed for just about anything. Armed with this you can predict how fast an egg, an apple, a rock, a hay bale, or a sky diver without a parachute will hit the ground. The second model (*Equation 1.7*) is less well tested, and is a crude description of the material properties of apples on impact. Experiments indicate that it is not a bad model, ie, it can be used to predict how much bruising you will get.

In these models we have progressed to being able to make predictions and calculations about events which we have not directly observed. The usefulness of a model is often dependent upon its ability to predict such events. Nowadays, some models of the physical world have been so well tested that we have every confidence in them. Every time you get into a car or an aeroplane you are staking your life on the reliability of all the physical models which were used to design it. In fact, some mathematical models are so reliable that we think of them as rules which govern the world we live in. We call

these laws. Thus Newton's Laws of Motion are a set of models which describe the way in which things move in our world in a very reliable fashion. *Equation 1.6* is a simplified version of one of them.

Very often the models involve mathematical equations. These mathematical models are a way of describing the world using a set of symbols which represent physical things. Thus in *Equation 1.7*, m represents the mass of the apple and v the velocity. The symbol v^2 is simply shorthand for writing "how fast the object is travelling in metres per second multiplied by how fast the object is travelling in metres per second". Writing v^2 is quicker.

Some models are of course not mathematical at all. They help us to describe our world without putting sizes to things. For example atoms can be thought of as being just like rigid billiard balls. When we try to describe the structure of crystals this is a very good model. However when we want to explain how light and atoms interact our model is no good at all, and we have to think about another model. This time the model is of a planetary system, with a very small solid nucleus, surrounded by smaller particles called electrons moving around the nucleus. This model has to be replaced in other situations by a model where the electrons are sort of fuzzy clouds around the nucleus, with a probability of being anywhere in the cloud. Quantum theory replaces the billiard ball model altogether with a mathematical wave packet description of an electron, for which there is no simple visual description. None of these models say how the world really is. All they do is give us a simplified description of reality in terms which we can understand, and which allow us to predict the behaviour of our world.

When we look at engineering models, most of them are mathematical models which have stood the test of time and are reliable enough to be called laws. Within their specified range of conditions they are totally reliable.

1.4 ABOUT THIS TEXTBOOK

It follows from the previous discussion that a textbook on agricultural engineering should cover all aspects of engineering relevant to agriculture, and should also discuss not only the theory of how that information should be applied, but should also give numerous practical examples and illustrations, as well as useful tips for the farmer or grower. Naturally this is a rather tall order, and would be quite impossible in a single textbook. However, on the basis of "give a man a fish and you feed him for a day; teach a man to fish and you feed him for life" we will concentrate on a basic structure which will give the reader the basic ideas and principles of the subject, and so provide lead-ins for further study. Each chapter is an introduction to the topic, and although some do go a little deeper than others, the overall aim is to inform the student sufficiently about the topic to inspire her or him to develop their own interest and imagination, and to proceed to more advanced studies of the subject covered. However to pursue the analogy "All fish and no bread" would be a rather dull diet, so we will frequently include some of the more practical aspects, such as how to tie a wire in a fence. Indeed some readers will enjoy the occasional section which is "more bread then fish"!

Initially the book will concentrate on establishing various models which can be used for engineering design. Not all will be mathematical: the second chapter deals with ways of making good working models of a farm or horticultural block, by the process of surveying. There then follows a chapter in which several simple mathematical models are introduced. These are really the laws of physics and mechanics. A short chapter in which some workshop methods are described follows, and then various aspects of horticultural and agricultural engineering are discussed in a series of chapters covering different topics in turn.

1.4.1 Aims of the textbook

At the end of each chapter the aims will be listed. These are a list of the things that you should be able to do when you have read the book. Some aims are quite clearcut: you should be able to calculate this or that given the necessary data, or explain a term, such as "Engineer". Others are open ended in the sense that you should try to form your own opinions using the information in the book together with your own knowledge and experience. Here the aim will be stated in terms of your ability to discuss the subject.

1.4.2 Exercises

Appropriate exercises are given at the end of each chapter. These help you to check how well you have understood the book, and also will improve your understanding greatly as you work through them. By all means look up the answers from the text, or refer to the text in order to work out the answer, but do write out the answer in full in your own words. This is one of the best aids to learning there is.

1.4.3 Examples

Worked numerical examples are provided throughout the book. Rather than just reading them, it is a good idea to write them out in full, as this helps you to realise what is actually going on.

1.5 THE USE OF WORDS IN THIS BOOK

1.5.1 Horticulture and Agriculture

The principles outlined here apply equally well to Agriculture and Horticulture. Therefore throughout this textbook the words Agriculture and Horticulture can usually be used interchangeably. To save lengthy repetition (and therefore increase the price of the book), use of one should be taken to include the other. I have used both, since if I used only Agriculture, students of horticulture would immediately question whether or not the section was for them (and vice versa). Obviously this is not always the case, since the applications sometimes differ a little, but it is unwise to assume that a topic can be easily ignored by either group, since changes in economics can easily thrust horticulture and agriculture together in unexpected ways.

1.5.2 Technology and Engineering

While we are still dealing with words, perhaps one should mention the word "technology". Agricultural Technology sounds better to some and worse to others than Agricultural Engineering. They are really the same thing, at least as far as this book is concerned. If you would rather be studying Agricultural Technology than Horticultural Engineering please feel free to exchange the words wherever you find them!

1.5.3 Trade names

For the sake of clarity, trade names have been used occasionally to refer to types of material or processes, etc. This does not imply commendation or otherwise of that particular brand. Similarly the properties of products can alter as manufacturing techniques change, so data should be considered as a guide only.

1.6 A SPECIAL MESSAGE TO AGRICULTURAL AND HORTICULTURAL STUDENTS

You probably have one of two reasons for studying this book. Either you are doing a course in Horticulture (or Agriculture) and want, must, or need to study some Engineering, or you are a student in Engineering who is selecting Agricultural Engineering as a field of particular interest to specialise in. For many students in the first category, you may be a little fearful of this horrible word engineering. It may conjure up pictures of Physics and Mathematics, welding rods and spanners, which may or may not have been your favourite things at school. Many biologically orientated students have had real difficulties with these subjects, and you may even be a little worried about coping with Engineering. My advice is to forget your fears until you have given it a try. This textbook is written very much with you in mind. It takes a different approach from most by trying to give you a real feel for what engineers and technologists are about. You may not be able to design a greenhouse environmental controller, or a waste disposal system for a farm, after you have studied this book, but you should be able to understand what is involved, what the physical problems are, and be able to talk intelligently to an advisor or designer so that you can get the best job for your farm.

1.7 THE ENGINEERING APPROACH

This section deals with how an engineer approaches a problem. Other professional groups would probably deal with problems in a similar manner. However in farming there is often a tendency to rush into the construction phase of a project before any real thought is given to the work involved. Equipment or systems designed this way are rarely as successful, and take longer to

complete, than they would have been if a little thought had been given and a few calculations completed at the start. If you are doing something just for fun and in your spare time, then it may not matter how you go about it, but if the project is a serious venture, then a sensible approach is recommended. The following steps will help to save you wasting a lot of time on a worthless exercise which could also be very costly. A model of the process is given in *Figure 1.3*.

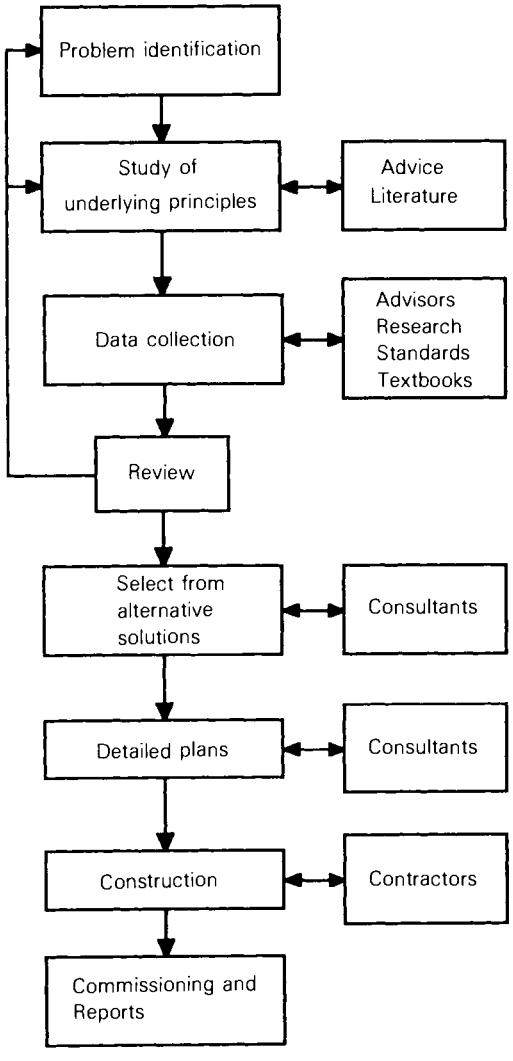


Figure 1.3 The engineering approach to a project.

a. Problem identification

When a project is suggested, it is a very good idea to be sure that the problem has been clearly identified. Often what appears to be a problem is not really the problem at all. A large hot water bill may not be caused because the hot water cylinder needs replacing: it may just be that you have a leaky hot water tap! Similarly it may not be necessary to purchase a larger tractor, if the real problem is that you are using the one you have inefficiently. An automatic feeding system may be an asset, and improve your herd's production by 5%, but if the herd is short of water due to an inadequate water supply, then this is the real problem that should be attended to first.

b. Study of the underlying principles

This may involve reading up a number of textbooks, or calling in a consultant to get professional advice. This is where a broad background knowledge is useful, particularly if it enables you to extend your technical knowledge.

c. Collection of data

Your understanding of the principles involved will help you to sort out what information will be needed, and where to get it from. It may even be necessary to do some serious experiments. For example, if you wish to install an irrigation system you may need to measure the water flow rate from the proposed source, to ensure that it will be sufficient to meet your requirements at the time of year when you need it. Almost all projects involving land will need to be preceded by a survey of the ground, which is why surveying is given a thorough coverage in this book.

After the data has been collected, a study of it may indicate that the problem needs to be redefined. If your survey shows that the main drain is supposed to flow uphill, then your waterlogging problem may not be one of too few mole drains! It may therefore be necessary to return to steps a and b in the process before proceeding further.

d. Consideration of alternative solutions

Usually, there will be more than one way of solving a problem. It is important to consider alternatives and to decide between them using sensible criteria. It is too easy to reject the best alternative for reasons which you later realise were rather silly. Some preliminary design work may be needed at this point in order to evaluate the options.

e. Detailed design and plans

The proposed work should be drawn up and costed. Specifications will be required if someone else will be doing the construction work. You may well employ a designer at this stage or earlier in the exercise. The cost of professional design depends on the source. Some companies offer a free design service. The quality of this is dependent on the company or the individual designer. In many cases the design is sound but the equipment specified is tied to company products. Needless to say, the company must still cover the cost of the designer in the cost of the equipment supplied.

Other companies offer an independent design service, where the specifications are set by consultants and the company supplies the equipment. Design fees are passed on directly to the grower. Growers may also go directly to independent consultants and obtain a design and equipment specification from which they can select components for the minimum cost, similar to competitive tendering. Government advisors may also make recommendations, or act as consultants in some countries.

The use of any professional consultant will involve a design cost. However, the consultant will carry the responsibility of the system operating to the requirements specified by the client.

Finally, the client should be aware of the method of charging. A very low basic design fee could be quoted, but extras for all direct and indirect costs (eg copying, phone, site investigation, automation) could raise costs back to standard levels very quickly. As with all contracts, these points should be made clear in writing before the work is started. The principle of "you get what you pay for" usually applies.

f. Construction

Only after all the other steps have been completed should construction actually begin. This is because it is much easier to make changes by rubbing a line out on a drawing rather than having to remake something. In some projects, particularly where the equipment is a new concept, some reworking may prove necessary. However the aim should always be to reduce this to a minimum. Any construction work should be well supervised to ensure that it is done to the requirements called for. This is particularly true where the finished work is inaccessible or out of view (eg, foundations of buildings or concrete work). Critical dimensions should be checked by someone other than the constructor. Again it may be worthwhile to employ an expert for this purpose.

g. Checking for correct operation

Once a job is commissioned it is worthwhile to ensure that everything is working properly. Some faults can escape unnoticed, and this means the system never works as well as it should. Some faults could have serious consequences later on: for example if a motor is always working in an overloaded condition it will burn out early. A final report may also be required at this point for future reference.

1.8 CONTRACT MANAGEMENT

Once a design has been completed and a project is ready for construction to begin the farmer or grower must now decide how to get the work done. If we consider the construction of a dairy or a greenhouse, the options are:

a. To use contractors,
b. To employ builders on a labour only contract,
c. To do it yourself.

1.8.1 Using contractors

The advantage of this method is that it does not involve time and effort on the grower's or farmer's part. It allows them to carry on doing what they can do best, ie, farm or grow crops. A builder is selected by the tendering process, and may also employ subcontractors. The farmer should not discuss the work with the subcontractors, as they are employed by the builder. The builder is responsible for all work specified and must ensure it is carried out in a workmanlike manner in accordance with the plans and specifications. Unless the farmer has expertise in building, this method of building is usually the best alternative, since experts will do the job.

When employing a builder on contract or when contracting for specific jobs, good contract management is essential.

There are three areas requiring attention. These are:

a. Specification of the job required,
b. Calling for tenders for the job,
c. Analysing the tenders (quotes) and letting the contract.

Specifying what is required is the most important part of contract management and the area where most disputes arise.

When specifying a job there must be detailed plans and specifications to explain the work required. When calling for tenders for building, detailed working drawings are required. These working drawings can be prepared by a draughtsperson, engineer or architect. Next the scope of work must be specified. The scope defines exactly what the contractor is to tender for. Unless the scope of the work is carefully defined disputes will arise later in respect of where one person's job ends and the next person's begins. The standard of work and the quality and type of the materials must be specified. If the building must be completed by a set time (eg, the start of a season), the specifications should set the building completion date. Specifications should also include conditions for payment. For example, 5% of the final payment could be withheld for a 3 month maintenance period. Other factors which may need to be included in the specification are the access to the site, site clearance and removal of topsoil, transportation, working areas and facilities, site water and power, overhead wires, requirements for excavations, drains, plumbing, electrical work, plastering, painting and glazing, and landscaping the site afterwards.

With respect to analysing tenders, it is advisable to get at least three quotes for a job. Quotes can vary according to how much work the contractor has and how much the contractor wants your job. In small districts it may be difficult to get this number of quotes as there is often not the skilled labour available. Having received tenders for the job, it is important to analyse them carefully, item by item, to ensure that everything specified has been included, and compare differences between quotes. The cheapest tender may not necessarily be the best as other factors are important. These include the reputation of the contractor in the area. Ask to see examples of the contractor's work or talk to the local building inspector about it.

A contract does not need to be written but when contracts are verbal they are difficult to contest or prove. Contracts can easily be drawn up by a consultant engineer. In some countries a Master Builders Federation exists which can also supply contract forms and specifications. Builders involved with these organisations will not normally work without a written contract.

With contract management there can be many pitfalls for the amateur. Since a new building can be very expensive, it is generally advisable for farmers to employ a professional engineer to prepare plans and specifications and to help with the analysing of tenders. The engineer can also help by preparing the contract for signing and can do some job supervision during construction. The engineer's fee is usually money well spent. It may save a lot of arguments and possibly court cases later, and will go a long way towards ensuring a satisfactory result.

1.8.2 Labour only

This option will involve a fair bit of work in preparing specifications for the building. The grower must manage each contract himself or employ someone to do this and must also check that the work is of good standard. If there is any shoddy workmanship he must deal directly with the contractor to have this put right.

1.8.3 Doing it yourself

The advantage of this method of building is that the farmer only needs to employ experts in the areas that he or she cannot do unaided through inexperience, eg block laying. However he or she must have a fair amount of expertise in building. It is not a job for the amateur. The farmer will be responsible for the ordering of all materials and any mistakes that arise. It can be a very expensive way of building.

1.9 EXERCISES

1. Describe the steps in the engineering approach to a project.
2. Attempt to write a specification for a simple building you may consider building one day (eg, a garage or a small garden greenhouse).
3. Develop a simple model to describe the flow of water out of a tap. Can you develop a numerical model relating the volume of water to the amount the tap is opened?

1.10 AIMS OF THIS CHAPTER

After reading this chapter you should be able to:

1. Explain the meaning of the term Engineer.
2. Explain what is meant by a model, giving examples of good and bad models.
3. Describe the essential steps in the engineering approach to a project.
4. Discuss what needs to go into a specification for a job.
5. Discuss the options for getting a designed project built.

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Surveying

Chapter 2

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2.1 INTRODUCTION

One of the simplest models we can think of is to make a scale model of a block of farm land. Ideally, a three-dimensional model is best, but these are not easy to produce except on a computer (and even then we will always be looking at a two-dimensional screen image). We normally therefore take measurements in the field and then reproduce these on paper. Our reproductions can represent ground plans or vertical sections, or we can draw a plan and simulate the height of the ground using lines and marks to indicate the height. The model thus becomes a scaled down representation of the real world of the farm. Obtaining the data in the field requires a careful systematic approach and this is known as surveying.

The definition of surveying is "taking a general view of a region by observation and measurement". The region may be small or large. It could be a building site, a paddock, or a whole continent. In agriculture and horticulture there are very many examples where surveying is essential for good management:

a. Definition of boundaries

Obviously, it is a legal necessity that all the boundaries of farmland must be clearly defined. This is done by a cadastral survey which requires a certified surveyor.

b. Determination of areas

On the farm it is essential to know the sizes of paddocks, orchard blocks and other features. Grazing management requires the area of grass available to stock to be known, and frequently contract work will often be based on the area to be treated. In New Zealand, bush is cleared by gangs of strong individuals and it is quite important to ensure that the size of the area to be cleared is agreed beforehand! Unless otherwise specified, areas are always defined as being the area on a plan map (ie, as viewed from an aeroplane), and not the actual surface area. On very steep slopes there could be a small error, but for the majority of farmland there is no appreciable difference. If it is important and the area seems to be much greater than it appears on a map, common sense and a little trigonometry should resolve the problem.

When the land is to be subdivided a good survey is essential so that the land can be split into equal areas. In practice this will save time and money in fencing costs, and make grazing management more efficient in terms of land and pasture utilisation. Orchard block areas must be known so that tree numbers and spacings can be calculated.

If the model is drawn so that 1 mm represents 1000 mm (ie 1 metre), then the scale of the drawing is 1:1000. Thus a line 15 mm long on the model will represent a line 15 metres long in the field. Note the order of the numbers in the ratio: a scale of 200:1 would mean that the model is 200 times larger than reality. This would be truly enormous of course!

When areas are being calculated an area represents two distances multiplied together, so the area on the model must be multiplied by the scale squared to get the true area.

Example

A paddock measures 150 mm by 200 mm on a plan drawn to a scale of 1:100. How big is the paddock?

Solution: Area on plan
$= 150 \times 200 = 30{,}000 \text{ mm}^2$

Hence actual area of paddock
$= 30{,}000 \times (100)^2 = 3 \times 10^8 \text{ mm}^2 = 300 \text{ m}^2$

The same result is obtained if the area is found by finding the distances in the field first, ie, $150 \times 100 = 15{,}000$ mm, and $200 \times 100 = 20{,}000$ mm.

c. Buildings

Before a building can be constructed, the site must be selected, and then prepared by being levelled to give a flat building surface. A flat horizontal starting surface is as essential for a greenhouse or dairy shed as it is for a high rise office block. Surveying is required both for selecting and preparing the site. When a large volume of earth needs to be removed, a survey will ensure that the volume can be calculated, and the removal costs can be determined. Similarly fill volumes can also be found. These calculations will be described below.

d. Drainage and water supplies

Water will not flow uphill without a pump, so a good study of land levels is essential before drainage systems are installed. It is often quite difficult to estimate which way land slopes just by eye, since we can be confused by other features. Pumped water supplies can be designed properly only if heights are determined accurately. A survey is needed to select the best route for a pipeline, so that deep valleys can be avoided, while if land is being prepared for flood irrigation then the levelling process is crucial. Trickle irrigation design also requires a good survey of the land beforehand, and a survey will obviously be essential if a dam is to be built. The survey will allow the best site to be selected, and also ensure that the dam is built level so that it will hold the maximum possible volume of water consistent with the current regulations and design requirements. Once built it will be too late or very costly to add extra fill to increase the height of a bank if it was built too low initially.

e. Roads and tracks

The location of roads and races on the farm can best be selected by the use of a survey. In this and other cases the survey may also require an assessment of the properties and stability of the soil at key places.

To sum up, in almost every case of land development and improvement, the first step will be a survey. Experience shows that the cost of the survey will almost always be recovered from the resulting savings in construction costs, let alone the savings that will be made by having a well planned and correctly located structure.

2.1.1 Plans and levels

There is a clear distinction between the two basic survey directions, ie, horizontal and vertical. All plan distances are horizontal, while "levels" (or relative heights) are measured vertically. When plan distances are being taken the vertical change in height is excluded from the measurement. Only when the ground slopes steeply will it be necessary to take ground slope into account in calculating the horizontal distance. When levels (heights) are being taken no measure of horizontal distance is involved, but it is essential that all points are identified carefully on a plan of the area, as the level of an unknown point is of very little value! Plans without levels can be useful, but levels without plans are quite useless. This means that in levelling two exercises are necessary, the first being to obtain a plan. These two stages are not usually combined, except in the case of stadia surveying, which is described later.

2.1.2 The process of surveying

Surveying takes place in three clearly identifiable stages.

a. Preliminary

What is the purpose of the survey? This is the first question to ask; the answer determines the accuracy required and this establishes the method to be used. There is little point in

using a sophisticated time-consuming technique if the survey is only required for establishing an area for contract spraying. Similarly, it is a waste of time doing a survey of an area if a little thought will show that a more accurate survey will be needed later. *Table 2.1* gives values of typical accuracies for particular jobs. It should be noted that inaccurate work cannot be improved whereas accurate work can always be rounded down to suit the plotting accuracy.

The light is bounced off the points to be measured and detected by a sensor back at the source. Measurement of the delay and phase of the beam leads to accuracies as high as a few mm in 50 km with fairly ordinary laser equipment. With more sophisticated systems continental drift and the distance to the moon can be determined to the same accuracy! Angles can be measured by triangulation, or by using some of the instruments which will be described below.

Table 2.1 Suggested levels of accuracy

Project	Plan Scale	Instruments	Suggested Accuracy (m)
Buildings	1:100 to 1:1000	Level, Theodolite	0.005
Farm water supply	1:4000 to 1:8000	Abney + Aerial, or Aneroid Barometer + Aerial	0.5
Trickle irrigation	1:500 to 1:1000	Level, Theodolite	0.01
Border dyke irrigation	1:1000	Stadia, Level	0.005
Urban water supply	1:100 to 1:500	Level	0.01
Sewers and drains	1:100 to 1:500	Level, Theodolite	0.005
Roading	1:100 to 1:1000	Abney, Tape, Level	0.01
Contouring	–	Abney, Tape, Stadia	0.005
Areas and volumes	–	Tape, Level, Stadia	0.005

b. Field work

Once the required accuracy and the method have been established the field work can proceed. Here it is worth noting that two types of measurements will be needed. These are distances between points, and angles between lines (either horizontally or vertically). Distances can be measured using a tape, by optical tacheometry, or by electronic distance measurement methods. A plastic tape has a maximum accuracy of about 1 in 500, or 0.2%. Temperature, sag, or stretch under tension affect the accuracy, but modern materials have minimised these effects, and made the steel chain of old almost obsolete. Tacheometry means "swift measure". Dumpy levels and theodolites can be used to measure distances, as discussed in the appropriate sections. This method has the additional advantage that all the readings can be taken from the instrument and staff positions without the need to walk along the survey line. This can often be useful if the region is inaccessible. In the third alternative, electronic distance measurement, very high accuracy can be achieved by using light waves or laser beams to determine distances.

It is also essential to include ways of checking that the data is accurate. It is alarmingly easy to make a mistake in recording survey results, and the only way to avoid many of these is to incorporate ways of checking the data in the field and afterwards. Obviously field checks are the best, since errors can often be rectified immediately.

c. Presentation

The final step involves bookwork. The field data will need to be presented in a form which can be understood by others. Maps, plans or diagrams must be made which will be clear to all some time after the survey. Often the surveyor will be preparing the work for consideration by others, and the presentation will have to be good. It should contain the results, with critical dimensions clearly shown. As with all reports the best are clear, neat and concise.

d. Area calculations

Often it is necessary to calculate areas of regular and irregular shapes. Formulae for these calculations are given in Appendix 1.3.

2.1.3 Methods of surveying

The following methods of surveying can be used in agriculture and horticulture.

a. Tape (chain) surveying (for areas)
b. Compass surveying (areas)
c. Aerial surveying (mostly areas)
d. Levelling (height measurement)
e. Theodolite surveying (height measurement)
f. Barometric levelling (height measurement)
g. Plane tabling (mostly for landscaping)

2.2 TAPE SURVEYING

Tape surveying is cheap, fairly accurate, easy to do, and good for small areas. However, it is time-consuming. The only equipment needed is two tape measures, some marking (ranging) poles, a few marker pegs, and a notepad. Originally a steel chain was used, and the method was known as chain surveying: the chain was 22 yards long (subsequently revised to 20 metres), and was divided into 100 links, each 200 mm long. Nowadays plastic tapes are almost as accurate as their steel predecessors, and are much cheaper. A compass is also required if the orientation of the area is needed, and for very careful work an optical square can be used for greater accuracy with offset measurements.

2.2.1 Theory

Tape surveying uses the method of triangulation to determine the shapes of areas. No angles are measured, but instead the area is divided into triangles and all the sides of every triangle are measured with the tape. Trigonometry shows us that this is enough to fix the shape of any triangle, and so the land can be mapped out and areas and angles determined from the map. This is shown in *Figure 2.1*, which represents a paddock ABCDE. In the paddock the points A to E are marked out by ranging poles. The lines AB, BC, CD, DE, and EA are called the *Base Lines* and they form the skeleton upon which the survey will be based. The lines AC and AD are called *Triangulation Lines* and they divide the area into triangles. All the lines shown must be measured in the field.

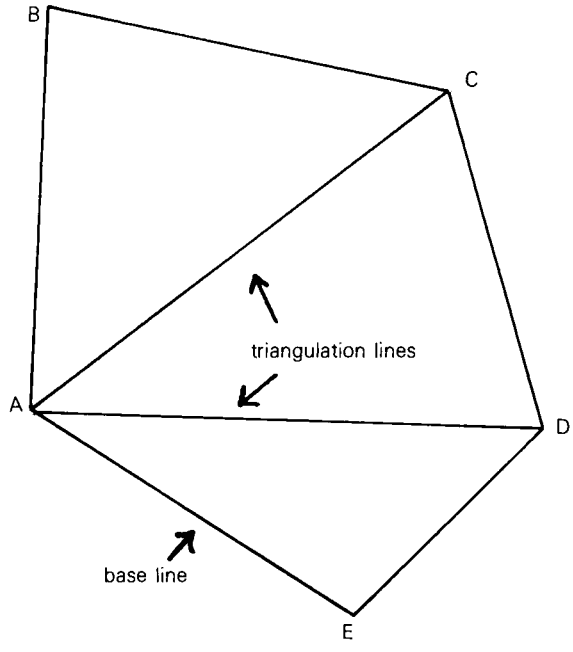


Figure 2.1 Tape survey layout for a paddock.

2.2.2 Conducting the survey in the field

Before readings can be taken for a tape survey some setting up work is needed. On arrival at the site the first step is to make a sketch of the area, indicating the relative positions of any key features, and identifying the positions of the survey reference points (ie labelling the base lines), as in *Figure 2.2*. The location of the base lines of the survey must then be decided. The base lines form the skeleton upon which the survey is to be built, and they should be carefully chosen so that they cover the area adequately, and lie close to important features that will need to be located accurately. Quite often it is convenient to place the base lines along straight fence lines, but this is not essential (an example is given in *Figure 2.2–point* C). The position of triangulation lines should also be determined. The aim here is to give "fat" triangles rather than "thin" ones (see *Figure 2.2*). Check lines should also be chosen (see below).

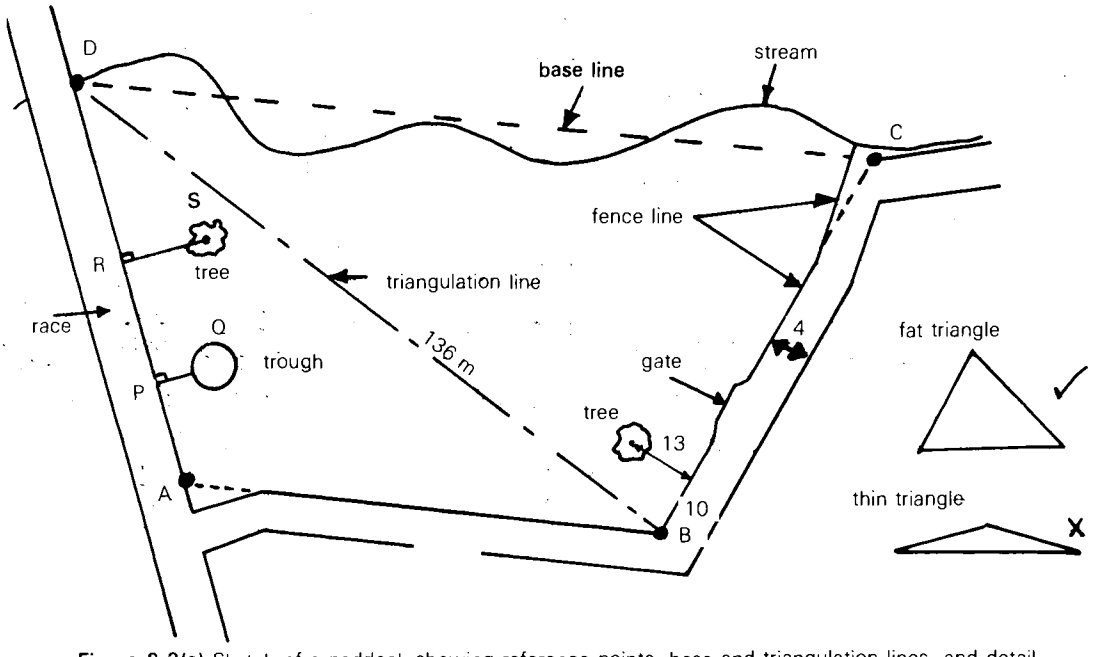


Figure 2.2(a) Sketch of a paddock showing reference points, base and triangulation lines, and detail.

Next the base lines must be marked in the field. Ranging poles should be placed at the ends of each base line. Further poles could also be required if the area is large, or if the ground rises and falls so that the end markers cannot be seen. Aligning these poles is not a trivial exercise, and is really a task for two people. One person sites along the line and directs the other, who must move the new pole into line. A system of hand signals indicating when to move the pole, which way, and when to stop, is essential!

2.2.3 Measurements

Measurements are taken by laying one of the tapes out along the base line, and recording the distance along the line where a feature is to be found. Obviously, the tapes should be kept straight for all measurements. If the base line is longer than the tape then the tape must be moved, and it is vital not to forget how many times this is done. With two people, the leader can place a peg at the end of the tape before moving on, and the follower can pick it up, so that at the end of a line the number of moves can be checked by counting the pegs collected. To avoid confusion the total length along the base line from the start should be recorded for each feature noted.

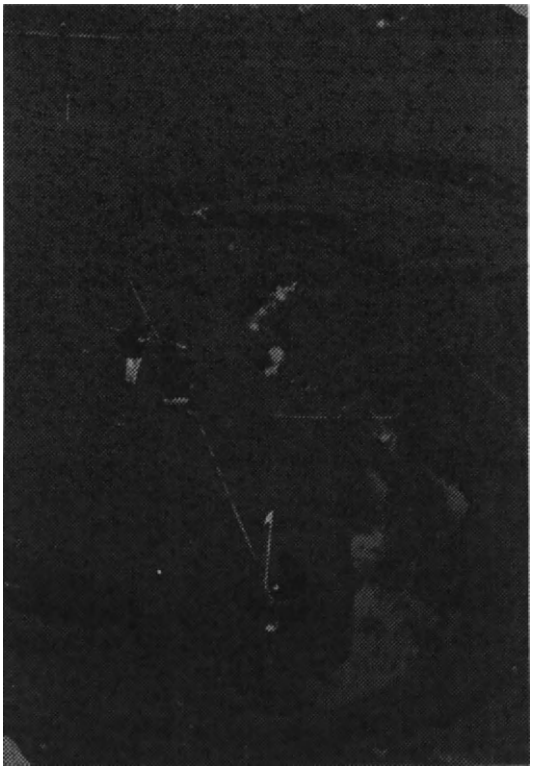


Figure 2.2(b) Tape surveying.

Perpendicular distances from the base line to objects off the line are also recorded. This information is called *Detail*, and the measurements are called *Offsets*. Thus in *Figure 2.2* the base line readings are AP and AR, while the offsets are PQ and RS. It is important that the distances recorded are indeed perpendicular to the base line, and that the base line reading is accurate. An accurate right angle can be found by using an optical square (a device with two mirrors placed at right angles, and which enables the observer to place herself in the right position on the base line). Alternatively, swinging the tape as in *Figure 2.3a* is a quick and easy method which is accurate enough for most purposes. Simply estimating a right angle by eye can give a 3° error at least. This may seem quite small, but it can result in a substantial error in the base line measurement.

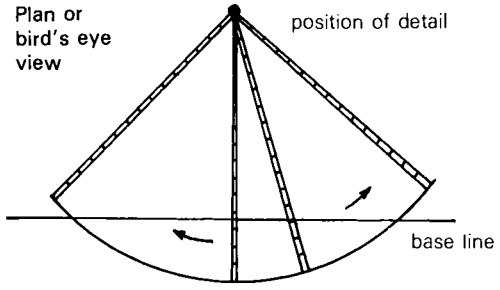


Figure 2.3(a) Swinging the tape from side to side ensures that a right angle can be obtained when the distance reading is a minimum.

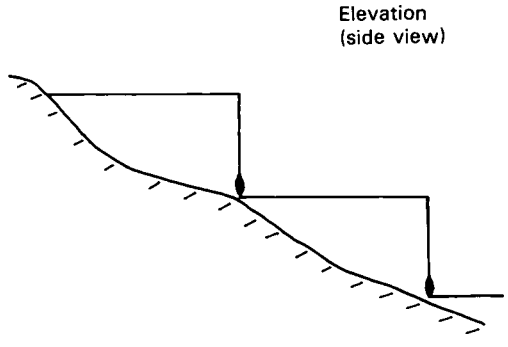


Figure 2.3(b) Stepping the tape.

Measurements need to be made in the horizontal plane. When the ground slopes steeply, it is necessary to "step" the tape. This is done by moving down the slope, holding it out horizontally. At regular intervals the tape is lowered vertically to the ground as shown in *Figure 2.3b*. A plumb bob or ranging pole will help to ensure the tape is moved straight down. In fact the slope needs to be quite steep before the error in ignoring the slope becomes significant. For example, even a 1 in 3 slope only causes a 6% error if the tape is not stepped.

2.2.4 Data recording

In a tape survey a large number of dimensions must be recorded, and conditions may not always be ideal. A clear concise method of writing the data down is essential, and the parallel lines method is a time honoured way of doing just that. It also has the advantage of being a standard method, so that anyone should be able to take the field notes and produce a plan from them. This can be important if you are supplying the data for someone else to draw up the plans.

The technique involves starting with a clean sheet of paper, and drawing two vertical lines about 30 mm apart up the centre. These lines represent the base line, with the ground stretched in the middle so that data can be entered. The surveyor now stands at one end of the base line facing the other end. Looking along the base line, whatever appears on the left will be entered on the left of the page, and whatever is on the right of the base line will appear on the right of the page. Distances along the base line are the only things which go in the middle between the lines. Recording starts at the bottom of the page, so in *Figure 2.4*, the first thing recorded is that the starting point of this part of the survey is point B. Note the convention used to indicate the start of a survey line: the horizontal lines, the identification of the line as Line BC, the clear marking of the start as point B, and the three encircled zeros define this clearly. Now the surveyor can move along the line recording detail and offsets. In this example, which represents part of the survey of the paddock sketched in *Figure 2.2*, the first detail is a tree, 10 m along the base line and 13 m to the left. The race on the right of the base line runs along parallel to the base line and the far side is 4 m away (hence the figure 4 on the right). Next there is a gate, and the offsets to each side of the gate are recorded as 2.6 and 2.3 m. When the end of the base line is reached (point C), this fact is noted, together

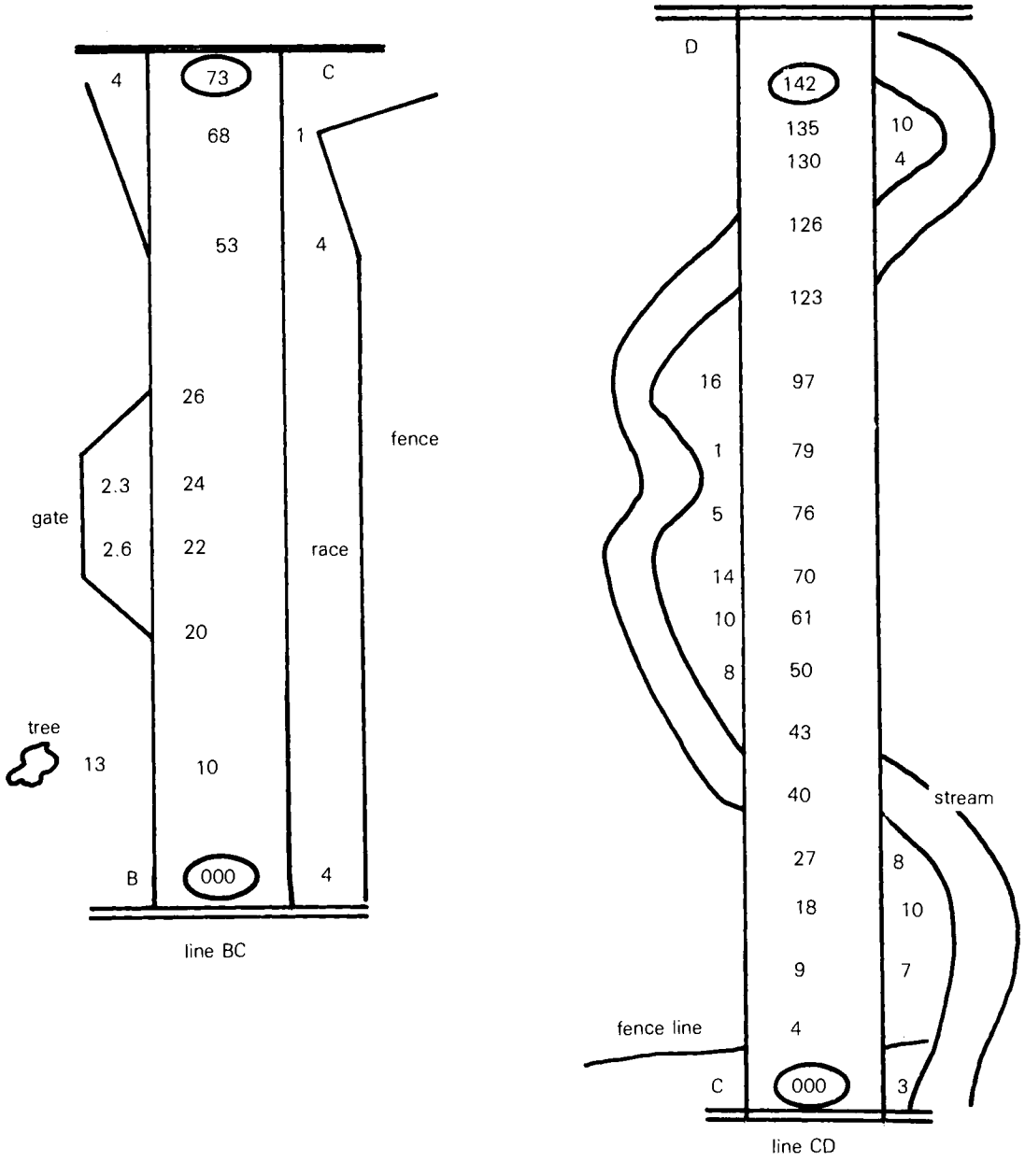
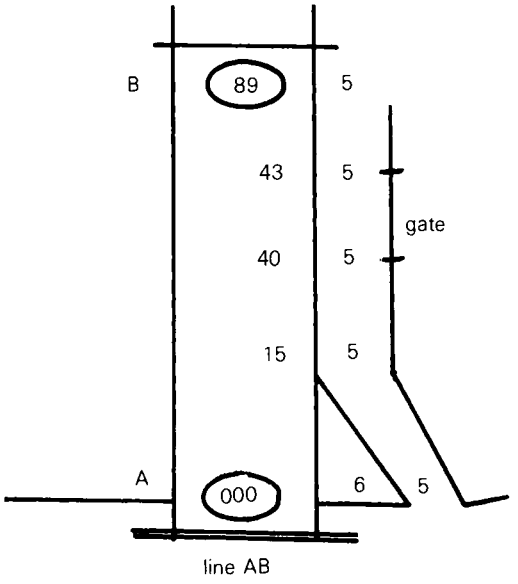
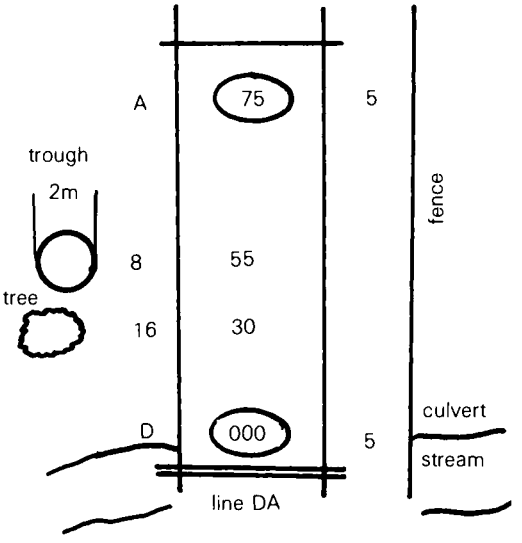


Figure 2.4 Booking data by parallel lines method.

with the distance from B. This is also circled, since it is an important measurement. A new line is then started, and further offsets are recorded. In particular notice how the stream is shown as it crosses the two parallel lines: it must emerge at the same point on the opposite side since the base line is in reality infinitesimally narrow. From this data the actual plan can be plotted.





Triangulation lines

During the survey the triangulation lines must be measured. The lengths can be noted on the sketch as in *Figure 2.2.*

Check lines

Mistakes can arise very easily in this type of work. To ensure that at least serious errors are detected requires that independent checks of the data are made, and check lines go some way to achieving this aim. A check line is an extra measurement of the distance between two points already located with reference to the base lines. An example is shown in *Figure 2.5.* The distance BX is measured, and after the plan has been drawn up, a check is made to ensure that the distance measured in the field corresponds with the distance shown on the plan. If the two agree all is well: if not there is an error and it may be necessary to make another trip to the site to find the error. It is therefore advisable to leave the ranging posts in place until the plan has been drawn and checked.

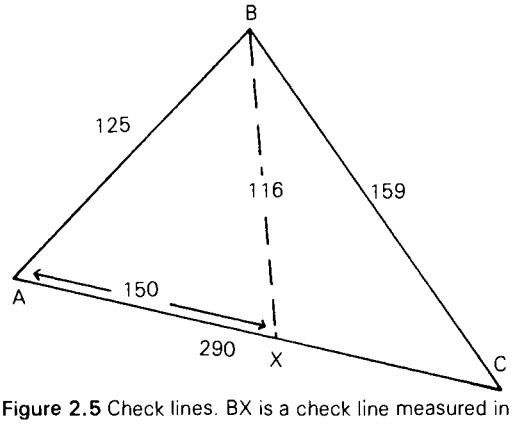


Figure 2.5 Check lines. BX is a check line measured in the field from a known point x. It confirms that triangle ABC has been correctly measured.

2.3 COMPASS SURVEYING

In compass surveying distances are measured with a tape as before, but angles are measured with a compass. The bearing of each base line relative to magnetic north is found, and this determines the angles between the base lines. This method is useful for rapid work where a high level of accuracy is not required. In many cases the method has been superseded by other methods such as aerial surveying. A prismatic compass as in *Figure 2.6* is used. The compass card is rotated by the magnet so that it always points towards the magnetic north and the prism enables the user to view the bearing on the compass card at the same time as the sighting wire is lined up with the base line. Although compass surveying is quick and the equipment is light it is not accurate. It is difficult to see over long distances, and any nearby magnetic materials such as fencing wire or building materials can

upset the readings. It is rarely used nowadays, although in most surveys a compass would be used to find Magnetic North and hence True North.

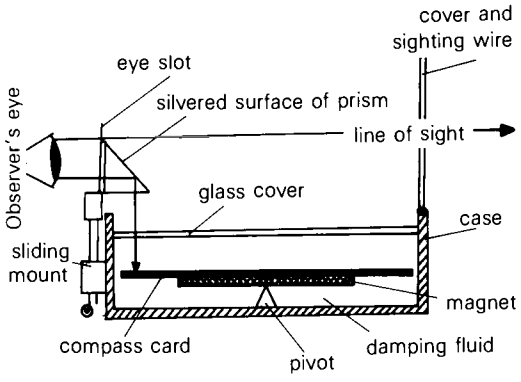


Figure 2.6 Prismatic compass.

2.4 AERIAL SURVEYING

Aerial surveying is one of the most useful forms of surveying available nowadays for the study of large areas. Apart from its obvious value for producing maps for a variety of general uses, it is also of immense value to the farmer and horticulturalist in planning engineering works on the farm or enterprise, particularly water supplies, waste disposal systems, landscaping, and the location of buildings. They are also very valuable for land management purposes, including the calculation of areas for grazing and contract work, and as a means of keeping accurate chronological records of land development, such as the position of fencelines, roads, stream alignments and movements, etc. New techniques including satellite photography also allow for the study of such things as land erosion, resource surveying, determining the spread of crop diseases and pests, and the estimation of land fertility. The advantages include relatively low cost, speed and accuracy.

The earliest occurrence of aerial photograhy seems to have been during the First World War, when the combatants flew their flimsy biplanes over the enemy's trenches in Europe to record troop locations. Aerial surveying started systematically in New Zealand in 1937, when a Tiger Moth aeroplane was used to take farm photographs. Since then the equipment has increased to the extent that there are well over half a million photographs and virtually the whole of the country has been surveyed. Satellite photography has covered the entire world, at resolutions of a few metres, and so the new farmer therefore has a good chance of being able to purchase relatively recent photographs of his farm from one or other of the aerial surveying companies or from Government sources. If a suitable photograph is not available, then it is a very sensible idea to commission such a survey. The cost will be greater of course, but the long term returns will almost inevitably repay the investment. Accurate aerial surveying requires the use of good quality specialised equipment, and amateur attempts with hand held cameras will produce inaccurate results. However, where accuracy is not required a simple aerial snapshot will suffice for recording the positions of tile drains (while the scars are still visible), or planted areas and felled regions on a given date in forestry work, or before and after situations in monitoring erosion. It is possible to transfer points from such photographs onto a map to fill in gaps in the photographic records using the "four point plot" method, but this method is very laborious, and will not be discussed here (refer to the references if required).

2.4.1 Types of aerial photograph

There are two main types of aerial photograph. First there is the oblique type, which covers photographs where the camera is at an angle to the vertical. A low oblique is one which includes the point vertically below the aircraft, while a high oblique includes the horizon. Both have limited value except in military reconnaissance and forestry inventory studies. Second and more relevant to agriculture, is the vertical aerial photograph, defined as one where the axis of the camera is perpendicular to the horizontal, or with an angle of tilt of less than four degrees, and only these will be discussed from here onwards.

2.4.2 Prints from vertical aerial photographs

Several types of print are available as follows. Standard prints are normally 180 mm or 230 mm square, and should be printed midway between being highly contrasting and very flat. For a little more expense, enlargements

of single prints can be supplied at a fixed enlargement. Ratioed prints are a series of prints which are enlarged or reduced to a common average scale. Rectified prints are prints which have been corrected for errors arising from any tilt of the camera away from the vertical.

Mosaics are combinations of several photographs combined and joined in various ways. Index photographs are laid out in strips showing their numbers for ease of reference to individual photographs. Controlled mosaic photographs are laid out with some care, using ground controls for scale. The overlaps are cut and the best fit is made along the contact between prints. The whole lay down is then re-photographed. Large farms can be mapped accurately with this method. The less expensive semi-controlled mosaics involve laying out the photographs and cutting with the best fit, but the ground control is used little except to define the orientation of the mosaic.

Three-dimensional prints can be produced in different forms. There are Anaglyphs, where complimentary colours are used to give three-dimensional information, Vectographs, which use polarised light and which require special viewing glasses, and Trivision prints, where separate images are printed on corrugated emulsion. Three-dimensional prints are not used for map making. They are sometimes used for promotional purposes in displays and articles in periodicals.

Various other types of photographic records can be purchased, depending on the end use. An enlarged half tone negative can be produced, in sizes up to 750×1000 mm. These can be used to produce large numbers of dye-line prints (blueprints) similar to those used by construction engineers. Alternatively the purchaser can buy a suitable transparency, which can be used for printing purposes by the customer. Aerial mapping companies also have facilities to produce large wall mountable mosaic prints of farms which can be 3 m or more wide.

2.4.3 Types of film

Technology has generated a variety of different films which can be put into the survey camera, depending on the purpose of the survey. Panchromatic films (ie black and white) are used most often because they are sensitive to a range of colours, they are fine grained which gives good resolution and clarity in enlarged prints and enables fine detail to be seen, and the image they produce appears normal to the human eye. This is because these films are particularly sensitive over the wavelengths between 0.44 and 0.66 micrometres, while the eye is most sensitive to green light at 0.54 micrometres.

Modern colour films are fine grained and fast and their resolution of detail is adequate for vegetative interpretation. They are usually processed by the manufacturer, and lighting conditions must be good during photography since they lack the tolerance of panchromatic film. Aerial colour photographs of forest areas give contrasts which are helpful in assessing the resource, and they also indicate differences in management practice when used on farm land. The use of colour film is likely to increase as processing costs continue to decrease and the quality and tolerance to light levels increase.

Infra-red film also has an attractive future. The colours recorded by our eyes or by ordinary film are visible because sunlight is reflected and scattered off the surface of the object and detected by the eye. Thus a green leaf appears green in sunlight because more of the red and blue radiation from the sun is absorbed by the leaf, while much of the green component is reflected or scattered (this subject will be discussed elsewhere in this book). On the other hand, most infra-red radiation falling on a surface is absorbed. However, infra-red radiation is also emitted by all surfaces, the intensity and wavelength distribution depending upon the temperature of the surface and its emission characteristics. Infra-red film therefore records not only the scattered light but also these emissions, and the resulting photograph may differ substantially from a conventional photograph. For example, water absorbs all infra-red and is usually cooler than land, so lakes and swamps appear black, which is useful in soil mapping studies. However, shadows also appear substantially darker. Infra-red radiation penetrates haze well, which is an advantage, and different tree species show up on photographs, with conifers appearing darker. Areas with disease problems may also appear due to differences in the intensity of the radiation.

Another form of photography involves the use of false colour images. False colour photographs are produced by taking a set of photographs using different filters, which only allow selected wavelengths of light through to the negative. Several cameras are used to take each set of photographs at the same moment in time and space. The negatives are developed and a print is produced from the negatives using colour sensitive photographic paper, but for each negative a different colour light is used to expose the print. In this way a coloured image is produced with colours which are not related to reality but which represent the intensity of light seen by the camera in specific wavebands. It is thus possible, for example, to produce a false colour image which indicates the infra-red radiation patterns. Such methods have considerable potential for disease and pest control, and for pollution and land resource studies, and satellite pictures are now an established aid to planning studies on a larger scale. Filters remove light at various wavelengths, and their selected use can improve the overall image in many cases. For example, a yellow filter eliminates blue haze, while a green filter removes blue and red which intensifies contrasts in the green band and therefore highlights vegetation differences. On the other hand a red filter eliminates contrasts in vegetation. The many combinations of film and filter available enable special contrasts to be produced, but the cost involved is high and most available photographs show very little contrast between vegetation types.

The production process just outlined sounds very tedious, but it is possible to use computers to perform the tasks just described. If the photographic information is recorded as, or converted into, digital data, then all the pictures can be recorded in a memory store, and the computer can draw the pictures for any given mixture of wavebands very easily. This allows the user to experiment with levels of intensity and choice of false colour very quickly, to obtain the best effect. This method is called *Image Processing*. The digital images can be obtained from aircraft or satellites, and photographs from the latter may well replace conventional aerial photographs in time as the resolution now produced in military applications becomes available for peaceful purposes.

2.4.4 Seasonal effects

Summer is usually the best season of the year for photography in non-tropical countries, because the days are long with high sun and there is a lengthy daily period when differences are consistent. In countries where summer, autumn and winter landscapes differ substantially in colour and tonal contrasts, some advantage can be taken of the season of photography in photographic interpretation.

2.4.5 Scales

Under normal circumstances the surveying aircraft flies in a straight horizontal line, and a series of overlapping photographs are taken, each of which measures 180 mm by 230 mm. If the flying height is constant, the scale on the photographic negatives will be constant. This is called the *Contact Scale*, since it is the scale on a print made by laying the negative on top of a piece of photographic paper, and shining light on it to produce an image the same size as the negative. The scale will depend on the aircraft altitude.

The effect of flying height H can be seen from the ray diagram for a survey camera (*Figure 2.7*). If the camera is focussed on the ground then the distance from the lens to the photographic negative is a constant equal to the focal length of the lens f (since the camera is focussed on a very distant object—the ground). Simple geometry shows that the scale is related to the Representative Fraction (or Magnification) d/D which is equal to the ratio f/H. Thus:

$$\frac{\text{Photo Distance (d)}}{\text{Ground Distance (D)}} = \text{RF} = \frac{f}{H}$$

Equation 2.1

As focal lengths are usually quoted in millimetres and flying heights are given in metres or even feet, care must be taken that the same units are used for both f and H when using *Equation 2.1*. For example a camera with a focal length lens of 150 mm in an aircraft at 5500 m has an RF of 1/36667.

2.4.6 Ground controls

If the flying height is constant the contact scale will be the same in all the photographs. Unfortunately it is not easy to fly exactly

horizontal for long periods and the ground itself rises and falls. In *Figure 2.7* the effect of a change in ground height can be seen: the area on the right of the figure is not as large as the area on the left, but because the ground rises sharply, they both appear to be the same size on the photograph. Surveying firms will rarely guarantee that the accuracy of the flying height is better than ± 50 m, and so variations in scale must be considered for accurate work. It is preferable not to use the contact scale for more than a rough check of scale in farm surveying but instead a *Ground Control* should be established. This is any distance between two clear features which can be measured on the ground, such as the length of a race or fenceline whose ends are well defined and clearly visible. For thorough work two ground controls at right angles will check the photograph for any distortions. In addition, if the ground varies appreciably in height additional ground controls should be taken at different heights.

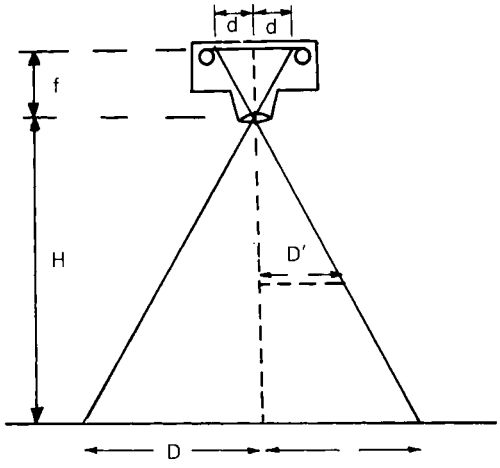


Figure 2.7 Relationship between apparent magnification and flying height in aerial surveying. The camera in the aircraft photographs all ground in the cone. If the ground height changes as on the right, then the magnification increases (D and D' appear to be the same size).

When ordering enlarged photographs, the company should be given a ground control, so that they can adjust the enlargement size to any desired scale (within reason). The most suitable scale for general farm planning and water supply work is approximately 1 : 4000.

2.4.7 Library of photographs

In New Zealand the entire country has been mapped, and photographs are available from the Department of Lands and Survey, or from commercial companies. As land uses change new surveys are being conducted so the records are being updated continually. To identify a particular piece of land a legal description of the land will be required (eg from the rate demand), or alternatively a tracing from a Lands and Survey map or similar plan will be needed. All photographs remain Crown Copyright.

2.4.8 Errors in aerial surveys

Errors in aerial surveys arise from three sources:

a. Aircraft tilt or pitch. This causes distortion of the print, and the scale in different directions may change.

b. Oblique views of hillsides. If the true ground area is needed then the aerial survey of a hillside will be in error if the hill is steep. The same applies to any method which produces a plan of an area.

c. Ground height and altitude fluctuations. As discussed above the distance between the aircraft and the ground affects the magnification of the photograph. This can alter if the aircraft changes height due to air pockets or if the ground itself undulates. The effect is reduced as the aircraft altitude increases, and over the years the standard heights of flying have increased from 3,650 m to 5,500 m and 8,350 m as aircraft performance and equipment has improved.

2.4.9 Three-dimensional data from an aerial photograph

It is possible to obtain an impression of relative land heights by using pairs of overlapping aerial photographs combined with suitable inexpensive stereoscopic optical equipment. Photographs are taken with a 60% overlap so that the same objects on the ground appear on different photographs from two viewpoints. The distance between the viewpoints is the distance between the two positions of the aircraft at the time the exposures were made. If the photographs are later viewed by an observer with one eye seeing the first photograph and the other the second, then the observer is in effect seeing the ground from the two viewpoints at the same time and the brain creates a three

dimensional image. In addition the brain magnifies variations in height and depth because the reference distance it uses normally is the distance between the eyes, and this has been enlarged artificially by a substantial amount.

Although much information can be gleaned by studying a single aerial photograph, this is like looking at the farm from above with only one eye. The brain is perfectly capable of making qualitative assessments of contour changes by observing shadows and the form of the images, but it is not good at estimating vertical distances. The image produced by a stereo-pair of photographs is much more realistic and the brain can make many more judgements about the terrain.

These views can be obtained using an inexpensive stereoscope, but complex equipment is needed if quantitative data such as spot heights or contours are required with any degree of accuracy. Such equipment is of only academic interest to the farmer, but many countries have been mapped by this method.

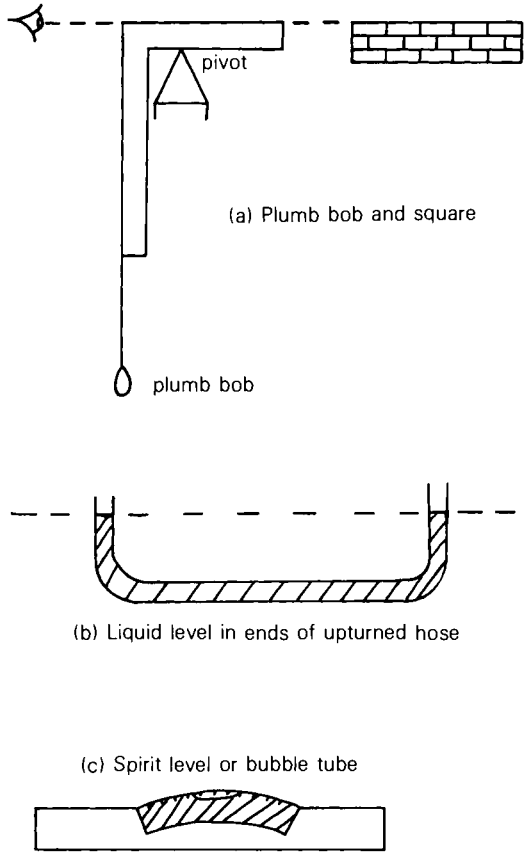


Figure 2.8 Methods of obtaining levels.

2.5 LEVELLING

Levelling may be defined as the process of obtaining relative heights of various points relative to some datum point. This can be done using a variety of instruments, including the aneroid barometer, a clinometer, levels and theodolites or even the water level in a clear plastic tube. Some examples of simple levels are shown in *Figure 2.8*. The plumb bob and square and the water in a tube have been used for centuries (the Romans made good use of the latter), and are still useful for small scale situations such as domestic building work and for rough checks if no other device is available. Some of these early devices appear in modern levelling equipment as we will see below. However for accurate and speedy work the spirit level is much more useful. Spirit levels are available to various standards. The carpenters level is usually relatively crude, since it is only used to test whether a surface is reasonably horizontal. Spirit levels (or bubble tubes) in surveying equipment are considerably more accurate in their construction, and may even be calibrated to measure small inclinations.

2.5.1 Levelling terminology

A number of key terms are used in levelling. These terms are all used in the various levelling methods, which will be described below. They are illustrated in *Figure 2.13*, in the section on the Dumpy level.

a. Datum

This is the "zero" for levelling. Normally mean sea level is taken as the base for national surveys but in farm surveying the datum can be any imaginary level plane chosen to be a convenient number of metres below the bench-mark peg.

b. Reduced Level (RL)

This is the height of any point above the datum.

c. Bench-mark (BM)

This is a real fixed point, which is the practical reference point of the survey. Bench-marks

are set up by the Lands and Survey Department in various locations around the country . They usually consist of a steel cap embedded in concrete, and the height above the datum (reduced level) is measured carefully and marked on the bench-mark. After an earthquake bench-mark reduced levels often need to be remeasured. In farm surveying the bench-mark may be a mark on concrete, or a peg top in some protected spot. The key factor is that the bench-mark will not be disturbed or moved by machinery, stock, humans or water as long as the project is in progress, or until it is of no further use. Often the true reduced level of the bench-mark above sea level is not known. This does not matter since any convenient datum can be assumed for a localised survey.

d. Shot

A shot is the term used to describe taking a measurement.

2.6 BAROMETRIC LEVELLING WITH THE ANEROID

A surveyor's aneroid (*Figure 2.9*) is an extremely useful instrument for measuring large differences in level during the planning of farm engineering projects such as water supplies. Aneroids are frequently used in association with aerial photographs to survey and establish pipeline routes and hydraulic gradients over relatively long distances, both for on-farm distribution of water, and for rural water supply schemes. If sufficient care is taken all readings should be accurate to ± 0.5 metre.

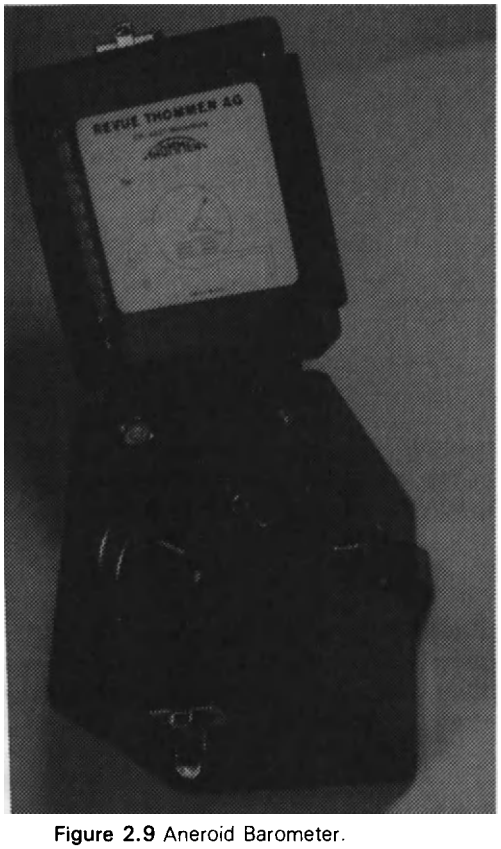


Figure 2.9 Aneroid Barometer.

Aneroids are also often used by surveyors for obtaining levels in remote areas, but their shortcomings, the need to use them in the correct way, and the methods of applying corrections should be understood.

2.6.1 Principle

The fact which makes barometric surveying possible is that atmospheric pressure drops at a known rate as the height increases. The height or reduced level can therefore be calculated from the instantaneous pressure difference between two points. The pressure difference so found is converted into a height difference according to various calibration formulae, all of which, although similar, vary slightly and are non-linear. The calibration formulae are incorporated in the mechanism of the aneroid and the graduation of its dial. Due to the non-linearity of the calibration, it is necessary to set an aneroid to sea level pressure before starting work. This is done by setting the instrument at a point of known height above sea level.

2.6.2 Corrections required

Several factors affect the atmospheric pressure reading, and corrections must be made before accurate estimates of reduced levels can be obtained.

a. Weather patterns

Changes in basic weather patterns give rise to changes in atmospheric pressure. One mb (millibar) equals approximately 10 m and it is not uncommon for the barometer to fall 5 mb per hour in the face of an oncoming cold front. This problem can be overcome by using 2 barometers and by working on calm cloudy days.

b. Temperature

Barometers are constructed to compensate

for temperature changes of the mechanism. The altitude change scale, however, is calibrated for a particular temperature. At temperatures above this the air will be less dense, and for a given difference in elevation, the pressure difference will be smaller. *Figure 2.10* gives the correction data for the Thommen aneroid, a common surveying barometer which is calibrated at 15 °C. In order to calculate the correction, the average of the temperatures and measured heights of the survey point and the reference point are required. The actual height difference is then found by adding the temperature correction factor C to the height difference reading. The figure shows the path to follow for an average altitude of 200 m, at an average temperature of 30 °C, when the apparent height difference is 300 m. The correction is 18 m. On a hot day (eg 25 °C) the correction can be as high as 10 to 15 metres for large differences in altitude.

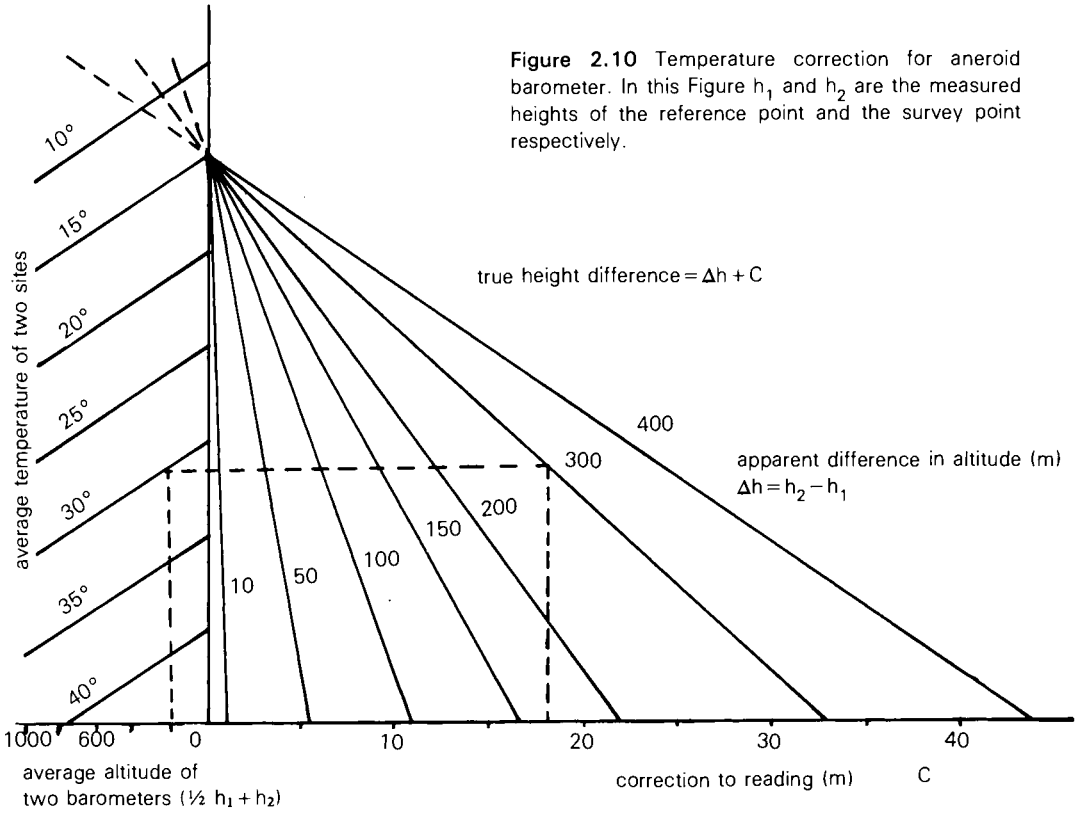


Figure 2.10 Temperature correction for aneroid barometer. In this Figure h_1 and h_2 are the measured heights of the reference point and the survey point respectively.

Humidity

Atmospheric vapour pressure affects the reading of an altimeter. Corrections are small compared to those for temperature (typically 2 to 3 m at most), but if a high degree of accuracy is required, the user's handbook should be consulted.

Wind effects

During windy weather altimeters may suffer error when used on the windward side of a hill, particularly in exposed conditions. Published results indicate that errors of between −5 and −10 m might be expected in gale conditions. Obviously readings should not be taken in strong winds!

Instrument error

Aneroids measure very small changes in pressure, and there is inevitably a limit to their accuracy. The instrument handbook should indicate this.

2.6.3 Field use

Two aneroids are necessary for accurate

work. One is left at the base reference point, and is used to record fluctuations in atmospheric pressure. It should be read every 30 minutes by an assistant (only in extreme cases should spouses be allocated this task). A graph of base pressure as a function of time can then be plotted, and corrections made to the survey reading, providing the time each surveyed reading was taken is noted. The temperature should also be recorded each time, both at the base and on the survey.

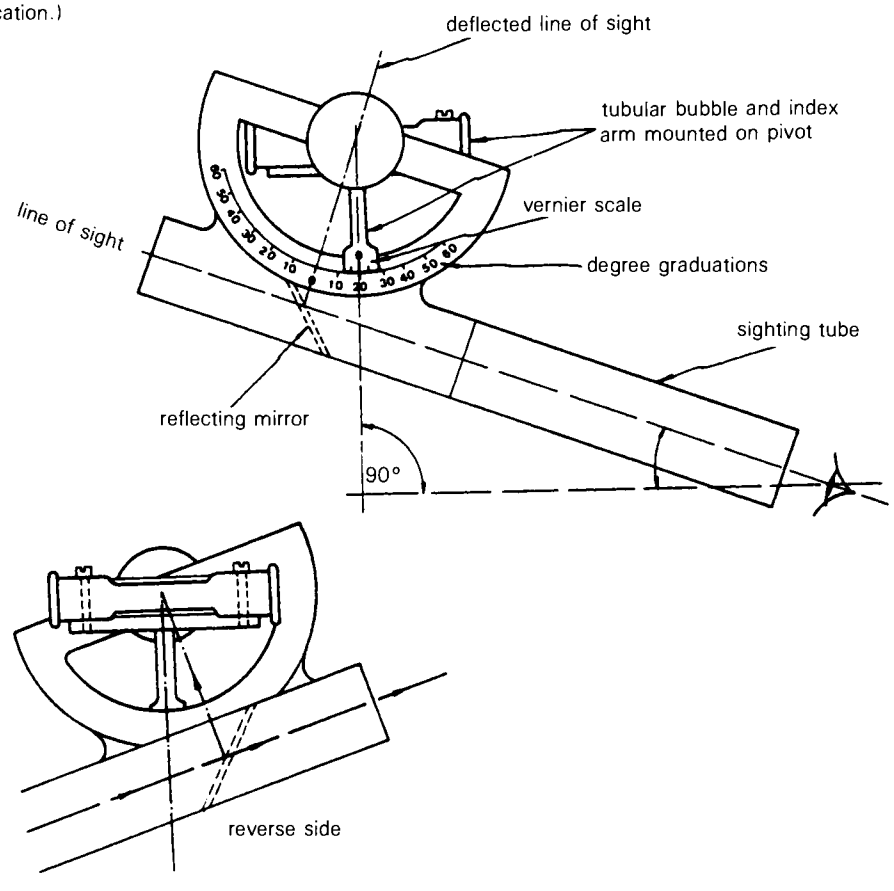
If only one aneroid is available, there is a high possibility of error, due to changes in meteorological conditions. In this case a calm cloudy day should be chosen, and the observations made quickly, closing back to the base. Any variation in atmospheric pressure may be assumed to have occurred linearly and corrections applied accordingly. Repeating the measurements will help to reduce errors.

2.7 ABNEY CLINOMETER

The Abney clinometer is a small hand held instrument used in conjunction with sight rods to obtain the relative heights of various points with respect to other reference points. It can be used, for example, with a tape, to enable roading cross sections to be plotted, or, in conjunction with aerial photographs, to determine the relative elevations of high and low points for pipeline routes.

The Abney Clinometer (*Figure 2.11*) consists of a small tube of rectangular cross-section with a telescopic eyepiece fitted into one end. A smaller rectangular tube is fitted into the other end of the main tube, with a silvered mirror inclined at 45°, and extending halfway across the tube. A sight wire is attached across the other half. A semi-circular scale, graduated in degrees, is attached to the side of the main tube, with a small vernier scale included. The clinometer tube and the vernier are free to rotate about the axis of the scale.

Figure 2.11 Abney Clinometer. (Darling Downs Institute of Advanced Education.)



A miniature spirit level is also attached to a bracket at the pivot of the vernier, but on the opposite side to the semi-circular scale.

The height of a point relative to any reference or datum point is obtained by placing the Abney on top of a sight pole and focussing it onto a sighting pole of similar height held by an assistant. It is important that the distance to the point of each sighting is known, either by using a tape or locating the position accurately using aerial photographs. The angle of inclination and the distance are recorded, and readings are usually taken at each change in gradient. With this data if the angle and the distance along the ground surface are known, then both the vertical change in height and the true horizontal distance can be calculated from simple geometry. For roading, tracks, or races, it is normal to place pegs at regular intervals along the proposed centre line and survey them using a proper level to obtain an accurate section along the line. Then cross-sections at each peg are determined using the Abney.

The advantage of the Abney is that it is fast, but it is less accurate. Its other uses include establishing pipeline routes and to assist in pegging out constant grade lines.

2.8 COWLEY LEVEL

The Cowley level is a device which is mounted on a tripod and uses a pendulum and a system of mirrors to give two half images of the field of view, one erect and the other inverted, such that an object which coincides in both half images is level with the instrument. This enables a set of points to be fixed at a given height. This is a short range instrument only, since there is no telescopic magnification in the optics. The main use of the Cowley level is in foundation work for buildings. The instrument is used with a tee bar sighting rod to give an easily defined image in the eye piece. The tee may be held against a measuring staff, which is read and recorded after adjustment by the staff-person.

2.9 THE DUMPY LEVEL

One of the most useful instruments for serious work, the Dumpy level is in essence a telescope with cross wires on a swivelling mount coupled to a bubble tube (*Figure 2.12*). This means that the telescope can be

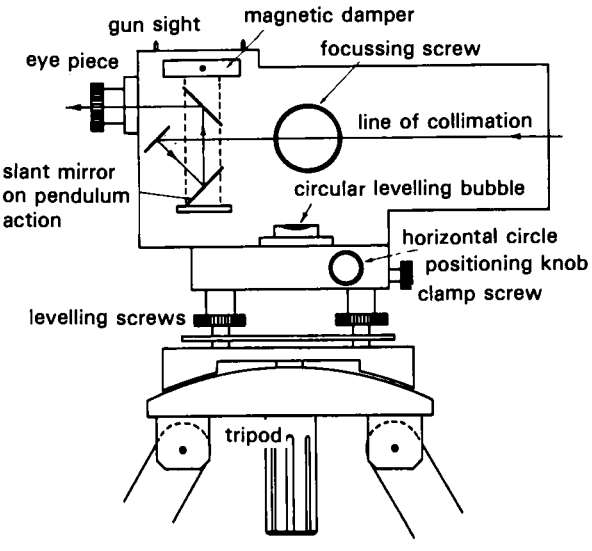


Figure 2.12(a) Dumpy level (schematic).

set up exactly horizontal, and it can be rotated around so that every point seen through it on the cross wires is at exactly the same height. The level effectively generates a horizontal reference plane. If a graduated pole (the Staff) is placed on the ground where the reduced level is required, then the distance between the bottom of the pole and the point at which



Figure 2.12(b) Dumpy level in use.

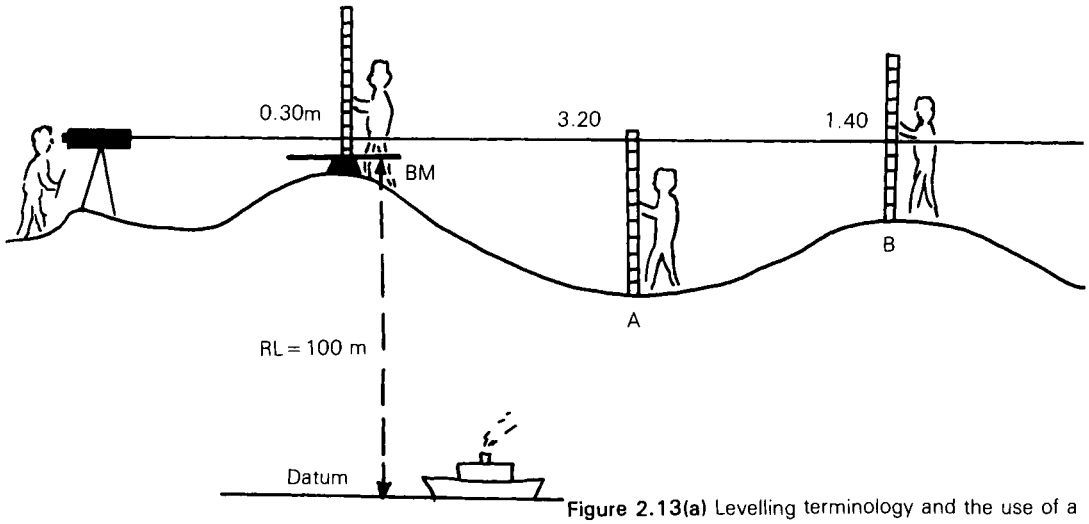


Figure 2.13(a) Levelling terminology and the use of a level.

it cuts the reference plane defined by the line of sight of the telescope is a measure of the reduced level relative to the plane. This can be converted to a true reduced level if the height of the reference plane is also known. This is indicated in *Figure 2.13*. Dumpy levels are capable of working over considerable distances, because of the telescope.

Dumpy levels permit the heights of several points to be taken concurrently without having to shift the instrument. The vertical position and location of the instrument is not important provided that the line of sight is above the highest point to be measured, but not so high that the staff is too short when it is on the lowest point.

When the situation arises where the vertical distance between the lowest and highest points is greater than the length of the staff, or the staff is out of sight of the instrument, it is necessary to shift the instrument by using a "change point", which will be considered below.



Figure 2.13(b) A bench mark.

2.9.1 Types of Dumpy level

There are three main types of Dumpy level: there is the original Dumpy level, in which the telescope and spirit bubble are fixed to the vertical spindle at 90° so that the whole instrument must be set up and adjusted carefully to be truly horizontal right around the circle before any readings are taken. The second type is the tilting level, in which the telescope and spirit bubble are attached to a vertical spindle by a hinge, so that the base of the instrument can be set up and adjusted to be nearly horizontal and a tilting mechanism used to bring the telescope truly level for each reading. The tilting screw must be adjusted for every reading that is made with this instrument. Third, there is the automatic type, where the fine levelling is done automatically by means of a pendulum mechanism inside the instrument.

2.9.2 Setting Up

a. Original Dumpy Level

The original Dumpy levels are equipped with a three-screw base to give the accuracy needed for setting up. The method of setting up is as follows: having selected the position for the level, the tripod is adjusted so that it is at a convenient height for the operator. The tripod feet are then trod down into the ground to ensure they are firm. Then the instrument is secured to the tripod (NEVER sit an instrument on a tripod without clamping it). It is then levelled on the tripod legs using the foot screws for fine adjustments. This procedure involves ensuring that the horizontal bubble is always centralised as the telescope is rotated horizontally, and can be done by lining the bubble tube along the line between two of the foot screws, turning them equally in opposite directions until the tube is horizontal, and then rotating through 90°, and adjusting the third foot screw until the bubble is level again. This process will need to be repeated several times until the bubble stays horizontal whichever way the telescope is turned.

b. Tilting Dumpy Level

Setting up the tilting level is slightly less difficult, in that having set the tripod and clamped the instrument to it, a bullseye bubble is centred by using the three footscrews, or the "quickset" adjustment, and the instrument is then ready to use. There is, however, an additional adjustment which must be made before every reading, and this is levelling the fine spirit bubble with a tilting screw. This bubble may be exposed, and adjusted by watching the bubble in the tube, or it may be covered, and an optical system used to show a split image of the end of the bubble. In this case the bubble is level when the image forms an unbroken line.

The same system of checking the bubble before reading and recording data should be used, as it has even more importance here since the instrument may be considerably off the horizontal when first sighted at the staff. The tilting screw should be used after the telescope has been accurately pointed to the staff, as any rotation after the bubble has been adjusted is likely to cause it to go out of adjustment.

c. Automatic Dumpy Level

The automatic level is set up initially in a similar way to the tilting level in that a bullseye bubble is centred. From then on the instrument adjusts itself to give a truly horizontal reading wherever it is pointed.

2.9.3 Orientation of image

As well as the ease of setting up, the automatic levels have one other major advantage. Most of the other types produce an upside down image of the staff. This means that the surveyor has to be able to interpret the image and take the reading even though it is inverted. This can be very confusing to a newcomer. The automatic levels carry a correcting prism inside them which inverts the image again so that it appears the right way up. For new surveyors this is very helpful, but it can be just as confusing for a person who has grown up reading the old inverted image of the earlier levels!

2.9.4 Parallax correction

Before commencing readings, however, there is one more adjustment to make. This is to adjust the telescope for parallax. When focussing the telescope the real image formed by the object lens must lie in the same plane as the cross hairs. If for some reason the image is not in the same plane, serious errors in reading can occur. This is known as a parallax error. To adjust for parallax the telescope is focussed onto a distant object and the eye piece adjusted to bring the cross hairs into distinct focus, so that if the eye position is moved up and down slightly when viewing the object through the telescope there is no movement between the image of the levelling staff and the cross hairs. This indicates that there are no parallax effects present and that the instrument is correctly adjusted. It should not be necessary to adjust the eye piece again during the exercise, but the focus should be checked by moving the eye position slightly before taking the reading, and adjusting if necessary.

2.9.5 The staff

Normally graduated telescopic staffs are used. Staffs which are 3 or 4 metres long when fully extended are most common. Graduations are placed at 10 mm intervals. With practice it is possible to take readings to the nearest

millimetre. However, if this level of accuracy is to be achieved it is essential that the staff be held exactly vertical by the chain-person. Often staffs incorporate some form of bubble tube.

Depending on the type of level used the staff image may be either inverted or erect. A view of the staff through an erect image instrument is shown in *Figure 2.14*.

The method of reading the staff should be systematic; first the largest division is read, ie the number of metres. This is not always as easy as it may seem, because only a very small part of the staff may be visible. The

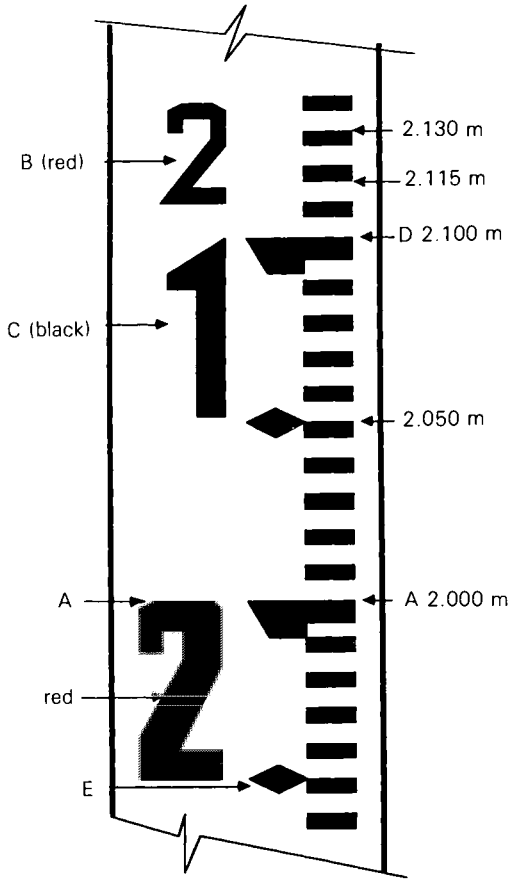


Figure 2.14 Reading the staff.

metre marks are indicated by large red numbers and dots or smaller red numbers on the staff. On most staffs the top of the large red number indicates the position of the point which is the exact number of metres from the bottom of the staff (point A in *Figure 2.14*). The red dots or smaller numbers (B) show the number of metres between the main metre marks. These are essential when the main marks are not visible through the telescope (because only a small section of the staff can be seen through the telescope when they are close together). Next the tenths of metres value is found. This is indicated by large numbers in black (C). Again the top of the number indicates the value (D). Next the hundredths should be noted. These are indicated by black marks. On some staffs the marks are 1 cm wide so that the bottom of a mark represents an odd number of hundredths, while on others the marks are only 5 mm wide, as in the figure. In addition each 5 cm is also indicated by an extended black mark or diamond (E). It is important to check over the staff to ensure that you are familiar with it before the survey. This is especially so if you are using a level with an inverted image! Finally the nearest millimetre can be estimated if required (although this accuracy is not likely to be needed for farm surveys). Examples of readings are given in the figure.

2.9.6 Terminology used in levelling

The following terms are used in levelling to describe particular readings (shots). They are needed so that the data can be recorded in the field book without mistakes.

a. Back-sight

The first shot taken after the level is set up in a new position is always a back-sight. At the start the back-sight will be to the bench-mark. When the level is shifted the first shot will be back to the last measured position of the staff. This establishes a new reference for the next shots.

b. Fore-sight

A fore-sight is the last reading taken before the instrument is moved to a new position. Thus the last reading of all will be a fore-sight (normally it will be a shot back to the bench-mark again), as well as any last readings before shifts are made. Back-sight and fore-sight readings are crucial to the accuracy of the survey, and particular care should be taken with them.

c. Intermediate sight

This is any reading which is taken between a back-sight and a fore-sight from the same

level position, ie any shot which is not a back-sight or a fore-sight.

d. Rises and falls.

In levelling the difference between the current staff reading and the one immediately before it is calculated and this gives the rise or fall between the two points. It is vital to realise that the higher the ground the smaller the staff reading will be (as explained below).

e. Closing the levels

It is good practice for levels to start and finish at a point of known height, ie, to work back to the original bench-mark at the end of the survey. An indication of the accuracy of the field work is obtained by "closing" the levels in this way.

f. Flying levels

Often it is necessary to shift the instrument during a survey and this may mean that the bench-mark is no longer visible from the instrument position at the end when it is desired to close the survey. In this case it is necessary to take flying levels, which means that convenient positions are taken for staff and instrument so that the survey returns for the closing fore-sight on the bench-mark with as few instrument shifts as possible. A set of flying levels will therefore consist of only long fore-sights and back-sights from each position as the instrument is moved back.

2.9.7 Method of reading the levels

To take a reading, the telescope is lined up on the staff by sighting along the top of the barrel, or through the sights provided. A locking screw can be used to secure it on line. The telescope focus is then adjusted until the image of the staff is clear, using the slow motion screw to bring the image to the centre of the field of view. The operator should avoid leaning on the level at all times, as this will alter the readings.

If a tilting Dumpy is used, it is always necessary to check the bubble to ensure that it is still central, before taking the staff readings. To guard against error in the reading it is wise to check the bubble, and adjust if necessary, read the staff, record the reading, check the staff reading, and check the bubble again. If any difference is noted during the checks, the readings must be repeated. This process is unnecessary if an automatic level is used. However, it is worth appreciating that field errors cannot be corrected in the office, and that an unacceptable closing error means repeating the entire job.

After all the readings are taken from a particular position, the instrument is moved to the next position and may be carried still clamped to the tripod.

2.9.8 Recording the data

Data from a survey is normally recorded in a rise and fall level book. This consists of pages with eight columns as shown in *Table 2.2*. Back-sights, intermediate sights and fore-sights are recorded directly in the appropriate columns. From these figures the rise and fall figures are calculated in the field immediately and entered in their columns. Next the reduced level is calculated by adding the rise or subtracting the fall and this is entered in the RL column. The remaining columns are used to indicate distances if a line is being surveyed or to make appropriate comments to identify the survey point otherwise. In the example given in *Table 2.2* some typical entries are given (these refer to *Figures 2.13* and *2.15*, which will be discussed shortly). Each line represents one survey point.

2.9.9 Survey procedure

The method of working in the field is as follows. First of all any initial setting up work should be done. This includes a sketch of the area, the identification of important features, and establishing the bench-mark. Marker poles may be needed in some cases to indicate survey lines (for example if a grid is being measured). Assuming all the preliminary work has been done the next step is to set up the level in a good position. It is worth spending a few moments to select the best place. The main criteria are that the bench-mark must be visible, as many as possible of the points to be surveyed are visible and in range both horizontally and vertically (ie, to minimise the number of instrument shifts), the observer should not have to look directly towards the sun, and preferably the site should be sheltered from the wind. It is important to realise that the position and height of the level do not matter from the point of view of the required results; they just provide a reference from which the

reduced levels of the ground can be calculated.

The level should be set up and levelled as described above before readings can begin. It should be set so that the surveyor can look through the telescope without having to stoop or stretch. It is then worth checking to make sure that the level is high enough so that a reading can be obtained at all the desired survey points. If not it may be prudent to choose a different starting point, which will avoid a shift later.

The first reading will always be a backsight to the bench-mark (refer to section 2.5.1 above). The staffman should place the staff on the bench-mark (*Figure 2.13*) and hold it upright and still while the surveyor takes the reading. The surveyor then reads the staff (ie, the value on the staff which coincides with the horizontal crosswire in the eyepiece) and notes the reading directly in the back-sight column of the rise and fall book. The reduced level of the bench-mark should then be entered in the RL (reduced level) column (if known). If it is not known then a value of say 100.00 metres should be assumed.

The staffman can then move to the first point to be surveyed, where the staff is placed for another reading. This time the value is an intermediate sight and is entered in the IS column. The rise or fall should then be calculated and entered. If the reading goes up then the ground has FALLEN; if the reading is less the ground has RISEN. The change from the previous reading is entered in the appropriate column (*Table 2.2*). The reduced level is then calculated immediately, and written in the column. Any remarks are added (eg, point 1, BM etc). Further points can then be surveyed, and each time the rise or fall is found by finding the change from the previous reading (*Table 2.2*).

This procedure is repeated until all the points have been surveyed, or until it is necessary to shift the instrument in order to obtain further measurements. If an instrument shift cannot be avoided, as will often be the case, then the procedure is as follows (*Figure 2.15*). We start with the last reading before the shift is required (point C). The reading is taken normally, but it will be the last reading before moving the instrument, so it is a fore-sight, and the reading is entered in the FS column accordingly. The rise or fall and the reduced level is calculated exactly as before. However, the point is identified as a *Change*

Table 2.2 Levelling results sheet

BS	IS	FS	Rise	Fall	RL	Distance	Remarks	
0.30					100.00	BM		(Fig 2.13)
	3.20			2.90	97.10	A		(Fig 2.13)
	1.40		1.80		98.90	B		(Fig 2.13)
0.80		1.70		0.30	98.60	C	Change	(Fig 2.15)
	1.80			1.00	97.60	D		(Fig 2.15)
	1.30		0.50		98.10	E		
	3.00			1.70	96.40	F		
1.30		3.50		0.50	95.90	G	Change	
	3.10			1.80	94.10	H		
	3.50			0.40	93.70	I		
3.30		0.30	3.20		96.90	J	Flying level	
		0.20	3.10		100.00	BM	Flying level	

Arithmetic checks (see text)

Sum BS	Sum FS	Sum rises	Sum falls
5.70	5.70	8.60	8.60

Sum BS − Sum FS = 5.70 − 5.70 = 0.00 (A)
Sum Rises − Sum Falls = 8.60 − 8.60 = 0.00 (B)
Last RL − First RL = 100.00 − 100.00 = 0.00 (C)

Conclusion: No Maths errors, no closing error

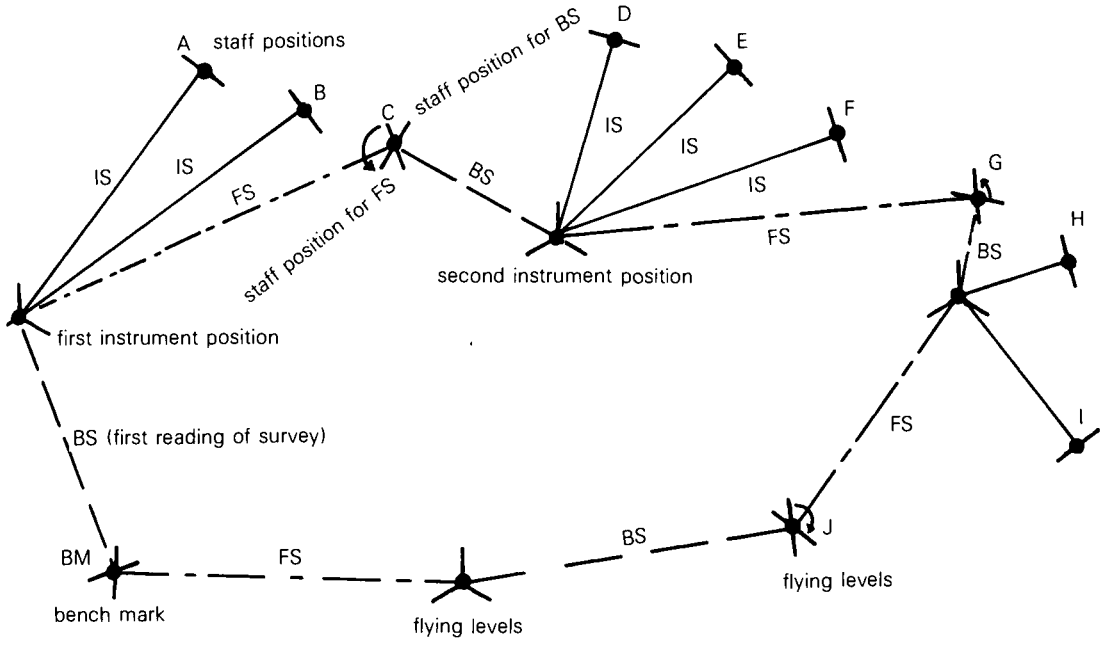


Figure 2.15 Plan of a survey

Point in the remarks column (*Table 2.2*). Now the staffman stays still without moving the staff at all, while the surveyor moves the level to a new position. The new site must be chosen so that not only can the next points to be surveyed be seen, but the last point (the change point) can also be surveyed. As soon as the instrument is set up the surveyor takes a back-sight to the change point. The staffman may rotate the staff to facilitate this reading but it is crucial that the staff is not moved otherwise. The reading is entered in the BS column, on the same line, since it is the same point. The next set of intermediate sights can now be taken (points D to F) and the survey line is carried forward.

The process continues until all the survey points have been completed. Then the final step is to close the survey by returning to the bench-mark. If the survey has covered a long distance it will be necessary to shift the instrument one or more times to do this. This is called taking flying levels; the staff is placed at any convenient point on the way back to the bench-mark (such as point J in *Figure 2.15*), and a fore-sight taken. The instrument is then shifted and a back-sight obtained, and the process is repeated until the bench-mark reading can be taken as the final fore-sight. Providing this procedure is completed the survey is called a closed traverse, because the survey has returned back to the original starting bench-mark (otherwise it would have been an open traverse).

Where a large area is to be levelled, it is usually necessary to use change points to "carry" a line of levels over a long horizontal distance. The effective range of most Dumpy levels is approximately 70 m for an accurate sighting, so that if the horizontal distance between points is greater than 140 m, at least one change point will be required. Where change points are used, it is essential to do a closed traverse to check the accuracy of the work. This is also recommended even when there are no instrument shifts, since it checks against the possibility of the level being moved accidentally during the readings. If the survey is completely accurate, then the first and last RLs must be the same, since they are of the same point. If an instrument shift has been made, it is likely that the final RL will not agree with the initial reading, resulting in a *Closing Error*. This error may or may not be acceptable depending upon the accuracy required for the job. In some cases a 50 mm closing error may be acceptable while in others anything over 5 mm would not be. In the event of an unacceptable closing error, there is no alternative but to do the field work

again. If the survey is an open traverse, an accuracy check is still possible if a series of bench-marks has been established and the traverse is run between two known bench-marks. In this case the final RL is compared to the known RL of the final bench-mark, to establish the accuracy of the traverse.

There remains only the vital requirement of an arithmetic check. This involves three calculations. First the readings in the fore-sight column are added together, and this value is subtracted from the sum of the back-sight readings giving the difference (A) between these totals (*Table 2.2*). Second, the sum of the rise column and the sum of the fall column are subtracted to give the difference (B) between this pair of totals. If the two differences obtained so far do not agree then an error has been made in calculating the rise or fall figures, or in the additions for the totals. This error must be found, and corrected. The final item is to compare the last RL with the first RL, and ensure that the difference here (C) is in agreement with the two previous differences (A and B). Once again, if (C) does not agree with (A) and (B), then there is a mistake in calculating the RLs from the rise and fall figures and this must be corrected. This check is only to verify the arithmetic, and has no connection with the field work. Any error in the field work measurements (especially intermediate sights) can only be corrected if it is noticed before the instrument is moved from the position in which the mistake was made. A second example of an arithmetical check is given in *Table 2.3*. In this case there is a closing error of 0.03 metres, but there are no arithmetical mistakes, as the check shows.

2.9.10 Instrument checking

The above instructions give correct readings so long as the spirit bubble and line of sight of the telescope are parallel. If this is not so, then obviously errors will result. Checking the instrument is a fairly simple task, and should be done regularly. Two pegs are set out about 60 m apart, on reasonably level ground, and the instrument is set up exactly midway between them. Readings are taken on both

Table 2.3 Levelling results sheet with closing error

BS	IS	FS	Rise	Fall	RL	Distance		Remarks
0.08					100.00		Point No.	BM
	0.48			0.40	99.60	0	1	Start of line
	0.68			0.20	99.40	5	2	
	0.38		0.30		99.70	8	3	
	0.84			0.46	99.24	12	4	
0.01		2.81		1.97	97.27	23	5	Change Point
	1.60			1.59	95.68	35	6	
0.87		2.44		0.84	94.84	43	7	Change Point
	1.18			0.31	94.53	48	8	
	2.24			1.06	93.47	52	9	
1.02		2.11	0.13		93.60	57	10	Change Point
	1.75			0.73	92.87	65	11	
	2.53			0.78	92.09	72	12	
	1.63		0.90		92.99	77	13	
	2.37			0.74	92.25	89	14	
	1.42		0.95		93.20	115	15	End of Line
2.90		0.50	0.92		94.12	–		Flying Level
3.16		0.10	2.80		96.92	–		Flying Level
		0.11	3.05		99.97	–		BM
8.04		8.07	9.05	9.08	99.97			MATHS
8.07			9.08		100.00			CHECKS
−0.03 (A)			−0.03 (B)		−0.03 (C)			

(a) NO ARITHMETICAL ERROR
(b) CLOSING ERROR = −0.03 m

pegs and the difference in height between them is calculated. The instrument is then moved to a position on the line of the pegs and behind one of them, as close to it as the focus will allow. Again readings are taken on both pegs and the difference in height calculated. If there is a discrepancy between the two calculations of height difference, the instrument is out of adjustment, and should be corrected before being used again. The instrument manual will give details of the method of adjustment.

2.10 THE THEODOLITE

The theodolite is one of the most widely used instruments in surveying. It is an expensive instrument, but has distinct advantages over the level. It allows the operator the facility to measure both vertical and horizontal angles. This reduces the number of instrument positions needed in undulating country. With a level, once the staff is above or below the line of collimation of the instrument a new instrument position must be established, but it is possible to alter the vertical angle of the telescope on a theodolite so that the staff can be read. By recording the stadia data both the angle of elevation of the staff position and the horizontal distance of the staff relative to the instrument can be calculated.

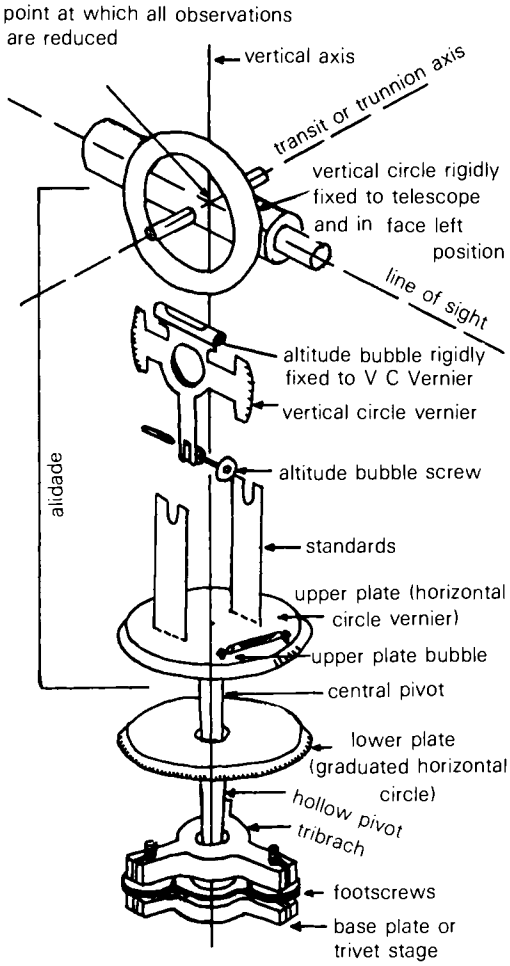


Figure 2.16 Theodolite (schematic).

As with Dumpy levels various designs of theodolite are available (*Figures 2.16* and *2.17*). *Figure 2.16* shows a simplified diagram of the vernier type of theodolite. Although this type has been superseded by the optical reading theodolite, it illustrates the basic features rather well. With reference to the Figure the following should be noted:

a. The vertical movement is measured by a vertical circle indicator which is rigidly fixed to the telescope and rotates with it.

b. The vertical circle vernier remains fixed relative to the vertical circle and is the datum from which vertical angles are measured.

c. The altitude bubble is fixed directly to the vertical circle vernier. Thus when the altitude bubble is set horizontal the vertical circle vernier is also zeroed at the same time. This adjustment must always be done for each new staff position. As with the automatic Dumpy level, this adjustment is done automatically on modern equipment.

d. The upper plate supports the telescope and is fixed so that it rotates with it in a horizontal plane. It can be locked to the bottom plate by the upper motion clamp (*Figure 2.17*) and further fine adjustment can be made using the upper motion fine adjustment screw.

e. The lower plate can also be rotated in a horizontal plane about the centre pivot. It can be locked into place by the lower motion clamp, and the lower motion fine adjustment screw can then be used for fine adjustment of its position.

f. In most instruments the telescope can be rotated through a full 360° in the vertical plane. This allows vertical angles to be read on either the left or right face (ie, on both sides of the vertical circle, as discussed below).

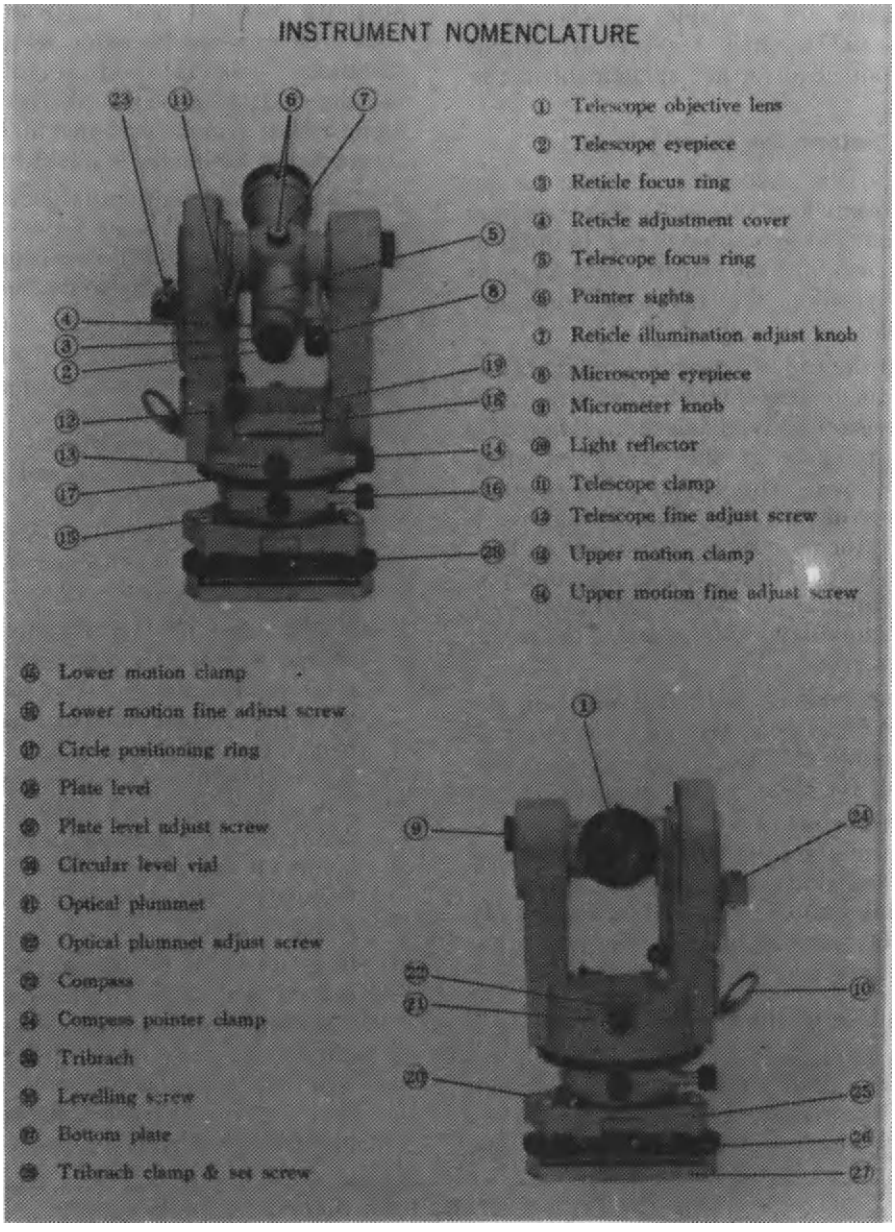


Figure 2.17 Theodolite (Sokkisha Ltd).

2.10.1 Theodolite adjustments

In order to obtain reliable data from a theodolite, there are a number of basic requirements. In particular, the vertical axis should be truly vertical, the line of sight of the telescope should be perpendicular to the horizontal axis, the horizontal axis on which the telescope rotates should indeed be truly horizontal, the cross-hairs should be truly horizontal and vertical, and the vertical circle should be at zero when the line of sight is horizontal. These are referred to as the plate bubble, collimation, trunnion axis, diaphragm, and index error adjustments respectively, and may need to be checked and reset if a theodolite is new or has been roughly handled or tampered with. Details of these

adjustments are available elsewhere (eg, Wilson, 1977). Once set the instrument should not need further adjustment in the field.

2.10.2 Setting the theodolite up

Normally, the theodolite must be set up exactly over a fixed position, which is marked out in the field by a suitable peg. In order to do this, each time the instrument is set up in a new position the following steps are required:

a. First the tripod legs should be extended out to about 100 mm less than their full extension, and the foot screws should be set roughly in the centre of their movement. The tripod is then stood approximately over the ground mark using the plumb bob (plummet) and the legs are trod firmly into the ground. The instrument can then be centralised over the ground mark by adjusting the tripod leg screws.

b. The theodolite is then levelled on the tripod legs using the foot screws for fine adjustments. This procedure is the same as for the Dumpy level (section 2.9.2a).

c. The instrument is then centered over the ground peg exactly, by using a centering device, which allows the instrument and plumb bob to be moved independently of the levelling head. When in position the centering device is clamped.

2.10.3 Use of the theodolite.

The theodolite and Dumpy level telescopes are very similar, both having cross hairs and stadia hairs. However, in addition to the readings which can be obtained from these, accurate vertical and horizontal angle measurements can be taken which enable distances, bearings and heights to be calculated. Data can be recorded on a suitable results sheet such as is shown in *Table 2.4*. In particular it should be noted that:

a. The first reading is onto the bench-mark with the vertical angle set to zero. This gives the height of the instrument's line of collimation relative to the bench-mark.

b. The vertical angle is taken as positive if it is upwards (ie, an elevation), and negative if downwards (a depression). The definition of the starting position of the vertical scale needs to be checked: in some instruments a horizontal line would be read as 0 or 180°, while in others it would be 90 or 270°. This can cause confusion if not checked when the reading is being made.

c. Height difference calculations can be a source of error if the sign convention for positive directions is not adhered to strictly. If calculations are being made by hand there will be no problems providing upward heights are taken as positive, and downward heights are negative. Alternatively, if preferred, a sketch could be drawn and the formula for the height calculation determined. However this is rather tedious.

d. It is essential to fill in the remarks column with clear details which specify the point being measured. It is often difficult to remember what individual sightings were for, the more so as the time interval between fieldwork and plotting the results increases.

Table 2.4 Typical results from theodolite stadia survey

Height of Inst. above BM (h)	Angle Observed Horiz.	Angle Observed Vert. (A) (+ or −)	Stadia Readings	Difference (1)	Reading Axial Wire (V)	Horizontal Distance kl $\cos^2 A$ (D) Note k = 100	Height kl sin A cos A (H)	Difference (H − V) elev. (H + V) dep.	Difference in height h + (H − V) elev. (h − (H + V) dep.	Reduced Level	Remarks
1.35										100.00	BM
	316°22′	+3°30′	3.15 1.73	1.42	2.44	141.47	+8.65	6.21	+7.56	107.56	Point 1
	10°25′	+5°00′	1.72 1.00	0.72	1.36	71.45	+6.25	4.89	+6.24	106.24	Point 2

2.10.4 Micrometer readings

There are many different types of micrometer on the market, and it is vital to be familiar with the one you are using. The reading must always be done with considerable care, since mistakes are easy to make and can be hard to find! Whatever the make, it is good practice to set the micrometer scale to zero before any reading is taken, even though this is done automatically on some modern levels with automatic horizontal collimation. Once the telescope readings of stadia and centre wire measurements on the staff have been recorded, the horizontal and vertical readings are made. Usually the procedure is the same for each. An example of an optical reading theodolite is shown in *Figure 2.18*. As can be seen, the horizontal circle angle in degrees is shown in the bottom of the window marked "H". It has a double line above it, with a scale with six divisions representing 10 minutes of arc just above this. The micrometer knob is adjusted until one of the six divisions is exactly in the middle of the two lines on the degree scale. The micrometer reading (the scale in the centre) is then added to the horizontal circle reading. The reading in the Figure would therefore be 245° + 50′ + 3′ + 18″ (the last figure is an estimate), ie, 245° 53′ 18″.

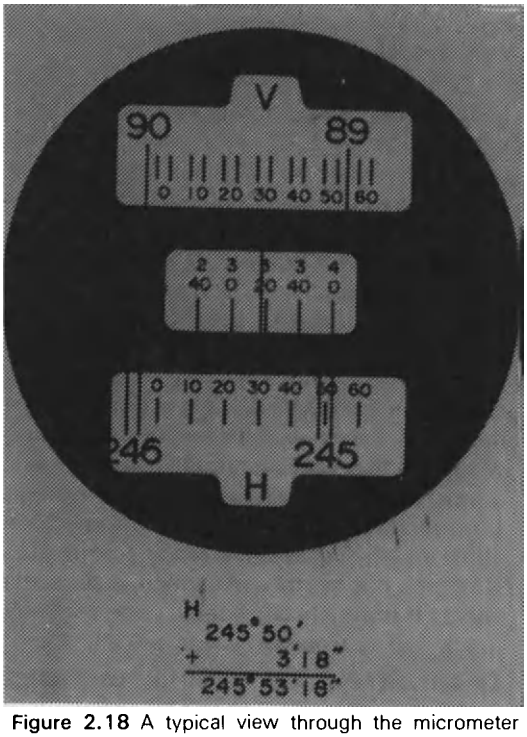


Figure 2.18 A typical view through the micrometer eyepiece with an observed horizontal reading of 245° − 53′ − 18″ (Sokkisha Ltd).

The verticle angle is measured in the same way, this time by centering the marks on the upper scale marked V, and adding the new micrometer scale reading.

2.10.5 Increasing the accuracy of horizontal angle measurement.

It is possible to increase the accuracy of angle measurements by one of two methods, namely reiteration and repetition.

a. Reiteration

With a fully transiting telescope it is possible to rotate the telescope by 180° in a vertical plane. The instrument is "face left" if the protractor circle is on the left hand side of the telescope and is "face right" if the protractor circle is on the right hand side of the instrument. By being able to transit the telescope through 180° it is possible to use both sides of the protractor circle and reduce errors due to variations in the etching of the divisions of the protractor circle. The use of reiteration in the measurement of horizontal angles is described below. It is assumed that a triangular area with corners A, B, and C is to be surveyed.

The instrument is set up over peg C and adjusted. The micrometer must be set on zero. The upper and lower clamps are loosened and the horizontal circle adjusted so that a zero angular reading is obtained. The upper clamp is then tightened. With the lower clamps loose, the telescope is sighted onto peg A using the fine adjustment knob to align it precisely onto the centre of the peg. The micrometer should read zero with the telescope focussed on the peg. The upper clamp is loosened and the telescope is swung clockwise to peg B. The horizontal circle is clamped and the fine adjustment is made. The angle ACB is then read off. The telescope is transited in the vertical plane and swung back anti-clockwise (in the horizontal plane) to B. It is clamped and the fine adjustment is made. The reading is noted and then the measurement of angle BCA is repeated by swinging back to A.

Note that by convention angles are measured clockwise from a zero reading on the preceding station. This means that external angles are measured when traversing anti-clockwise.

b. Repetition

By taking a number of horizontal angle measurements and finding their average, it is possible to reduce the size of any errors. The procedure for measuring an angle from the instrument to two pegs A and B using repetition of sight is as follows:

a. Sight onto A, setting the bearing at zero.
b. Release the upper motion clamp and swing the telescope onto B. Lock the upper motion clamp and make the fine adjustment.
c. Read and record the bearing.
d. Release the lower motion clamp and swing the telescope back to A, locking the lower clamp and making the fine adjustment.
e. Repeat steps (b) to (d) as many times as is required, so that each time the reading is increased by the angle.
f. The final value for the angle can be calculated using the following formula:

$$\text{Angle} = \frac{\text{last reading} + 360 \times M}{N}$$

Equation 2.2

Where M is the number of full protractor circles, and N is the number of times the measurement is repeated.

2.11 TACHEOMETRY OR STADIA SURVEYING

In addition to the sighting cross-hairs, both theodolites and levels often have additional hairs incorporated into the telescope sights, which can be used to measure horizontal as well as vertical distances. Instruments used to give stadia distances have two short horizontal lines called Stadia Lines (*Figure 2.19*). If the staff readings for these two lines are compared, the difference multiplied by an instrument multiplier factor (which will be given in the instruction manual, and is usually 100), equals the distance from the instrument to the staff. The stadia lines are situated equidistant above and below the main horizontal line and this enables a quick check on the staff reading accuracy to be made: the sum of the stadia line readings must be exactly twice the reading of the centre line. This is known as the Stadia Check (see example in section 2.11.2 below).

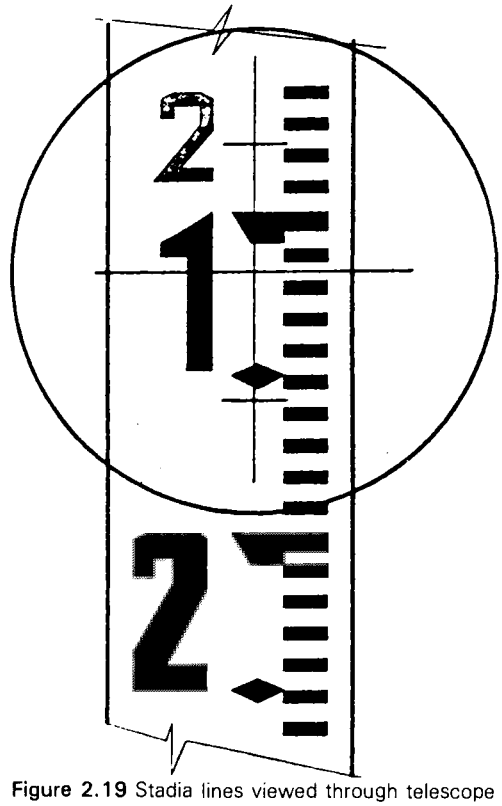


Figure 2.19 Stadia lines viewed through telescope of level. Here the stadia readings are 2.122 and 2.042.

Instruments with stadia capabilities also normally have a 360° circle, mounted so that angles between readings may be measured. This enables the results of field observations to be plotted as each set of readings will give a distance and a bearing. It is important to remember that in surveying a full 360° circle is used and that the numbers always run clockwise. In addition, high accuracy is needed. The divisions of a degree are minutes and seconds, so that sixty minutes makes one degree, and sixty seconds makes one minute. A second is a very small angle, and it takes a very accurate instrument to measure it. Dumpy levels normally have a very basic circle and the accuracy of reading is not high. However, it is often good enough, and a stadia survey is normally considered to be relatively quick and reasonably accurate.

Stadia surveys are used for contouring, locating buildings, trees and fences on plans, and for site surveys for roading and bridging where both plans and relative levels are required.

2.11.1 Field procedures for stadia surveying

In stadia surveying the position of the instrument is important. The normal field procedure for stadia work involves identifying the features to be shown on the plan, selecting the minimum number of instrument stations which will allow all of the features to be seen, and then marking (pegging) these selected stations. Finally, the actual survey work is done. Setting up procedures are the same for levels and theodolites.

The procedure should be as follows:

a Set up the instrument accurately over the selected peg.

b. Sight to the most "backward" peg position (or the bench mark) from the direction in which the instrument will move around the traverse. Using a plumb bob, or a suitable alternative method, ensure the vertical line of the telescope is aligned directly over the centre of the peg. Lock the instrument so it will not move horizontally.

c. Set the horizontal circle to 0°.

d. Level the bubble.

e. Take the staff and stadia readings with the staff now held on the peg. It does not matter which stadia line is called the top one, though it does help to be consistent.

f. Do the stadia check. If the stadia check does not agree, the readings should be repeated. Try to establish what caused the error in the first set of readings (for example, the staff may not be correctly extended).

g. Read the bearing.

h. Wave the staffman to the first feature to be picked up from this particular peg. It is much easier for the staffman to work progressively from the back-sight position, round the features to be measured, to the fore-sight position (the change point). This may not always be possible, but should be attempted.

i. Sight to the staff held at the first feature, taking care in aligning the vertical line exactly on the staff.

The procedure is repeated until it becomes necessary to shift the instrument because the lines of sight have either become too long or are obscured by an obstruction. Before shifting it is necessary to sight onto two known points which can be seen clearly from both the old and the new position and which subtend a wide angle with respect to the new position. These measurements are required to establish the location of the instrument relative to the previous position. The instrument is set up at the new location, levelled, and the sightings made back onto the two known points. Then the process can be repeated.

2.11.2 Theodolite stadia data reduction

The raw readings from the instrument must be converted into information about position and reduced level for each point. The formulae for these conversions are derived as follows:

From the stadia formula and using the nomenclature of *Figure 2.20a*, the distance from the theodolite to the staff is given by:

$$S = k\ x + C \qquad \textbf{Equation 2.3}$$

where k = instrument multiplier (= 100 for most instruments) and C = distance from the lens to the telescope axis of rotation (not shown in the Figure).

In modern instruments the effects of the focal length and distortions caused by the lens not coinciding precisely with the instrument axis have been eliminated. Consequently for most purposes C = 0, which we will assume from now on.

a. Vertical angles less than 10°

For angles of less than 10° the staff is held vertically and the distance between the stadia readings (l) is actually measured. This is the normal situation. In this case,

$$S = kl \cos A \qquad \textbf{Equation 2.4}$$

but $D = S \cos A$

$$\text{therefore } D = kl \cos^2 A \qquad \textbf{Equation 2.5}$$

$$\text{Similarly } H = S \sin A \qquad \textbf{Equation 2.6}$$

$$\text{so } H = kl \cos A \sin A = 1/2\ kl \sin 2A \qquad \textbf{Equation 2.7}$$

b. Angles of greater than 10°

When the telescope is sighted at a vertical angle of greater than 10° the staff should be inclined on the slope so that it is at right angles to the line of sight of the telescope (*Figure 2.20b*).

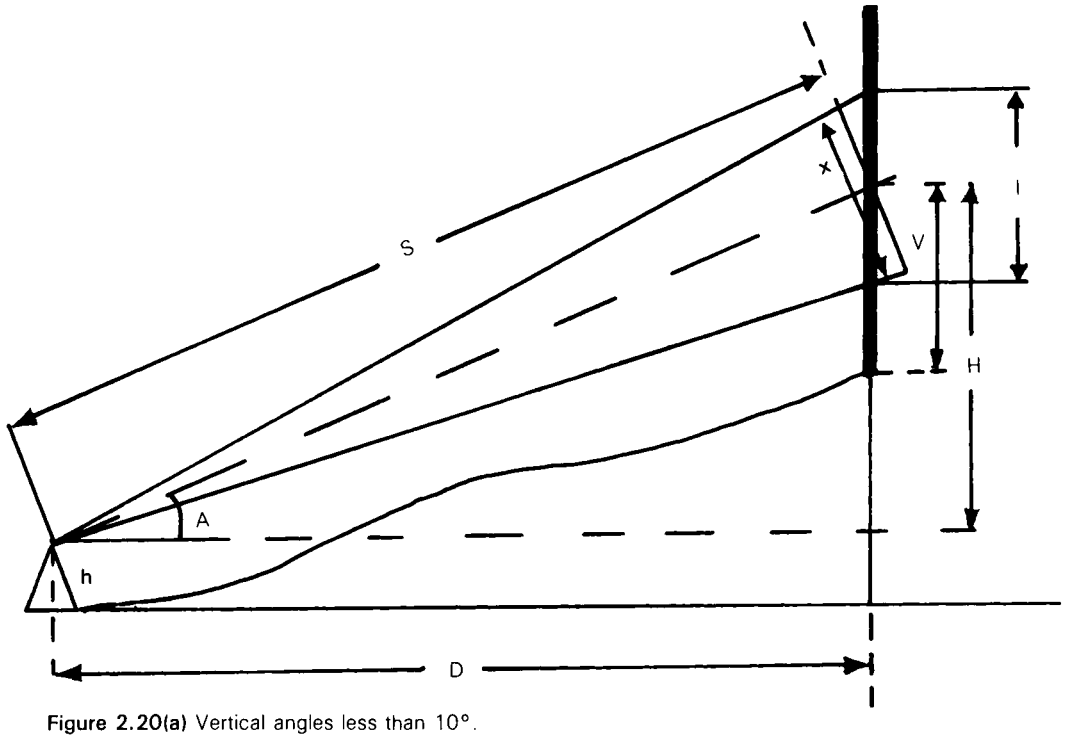


Figure 2.20(a) Vertical angles less than 10°.

The formulae then become:

$S = kl$ **Equation 2.8**

but $D = S \cos A + V_1 \sin A$ **Equation 2.9**

ie $D = kl \cos A + V_1 \sin A$ **Equation 2.10**

Similarly

$H = S \sin A = kl \sin A$ **Equation 2.11**

and $V = V_1 \cos A$ **Equation 2.12**

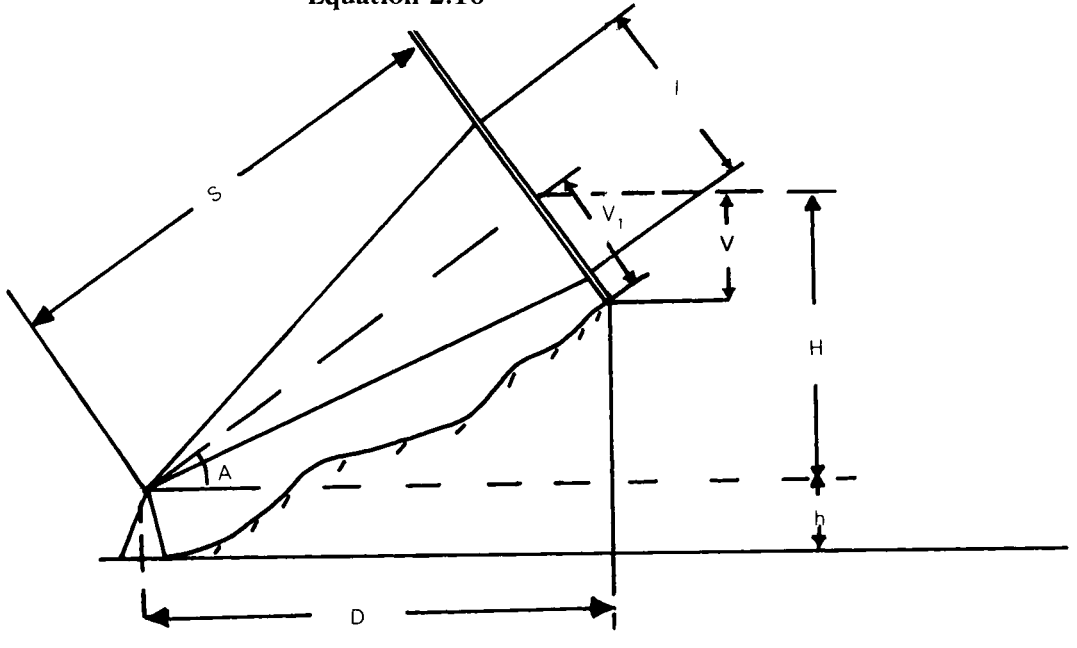


Figure 2.20(b) Calculation of distance and RL (Vertical angles more than 10°).

c. Calculation of reduced level

For any angle the RL is given by:

$$RL = Q + H - V \qquad \textbf{Equation 2.13}$$

where Q is the reduced level of the instrument telescope, and where H is positive for elevated angles, and negative for depressed angles. The actual staff reading V is always subtracted.

Example

a. Calculate the distance and RL of the point in *Figure 2.19*, if Q = 127.403 m and A = + 8° 32′ 45″, and the stadia constant k = 100 for the instrument.

Solution: From *Figure 2.19* the reading on the staff is 2.082 m. The upper stadia reading is 2.122 m and the lower reading is 2.042. The stadia check requires that 2.122 + 2.042 = 2 × 2.082 which it does. Thus the difference in stadia readings l is thus 2.122 − 2.042 = 0.80 m.

From *Equation 2.5*, $D = k\ l \cos^2 A$
$= 80 \times (0.9889)^2 = 78.23$ m

From *Equation 2.7*, $H = 1/2\ k\ l \sin 2A$
$= 40 \times 0.2939 = 11.756$ m

Thus the RL of the point is given by *Equation 2.13* and is:

$RL = 127.403 + 11.756 - 2.082 = 137.077$ m

b. What would the RL be if the angle was negative (ie, the shot was downhill)?

Solution: In this case H would be subtracted from the total, so that:

$RL = 127.403 - 11.756 - 2.082 = 113.565$ m

The distance calculation is unaffected.

2.12 ELECTRONIC DISTANCE MEASUREMENT AND ELECTRONIC TOTAL STATIONS

It is quite clear from the preceeding sections that the use of a theodolite for distance and angle measurement involves several readings and lengthy calculations. Electronic distance measurement systems reduce the effort involved in measuring a distance, while total stations eliminate both the reading and the calculations!

The principle of an EDM system is shown in *Figure 2.21*. The instrument emits a modulated light beam, which is reflected off a suitable reflector placed at the position to be measured. The reflected beam is received and compared with the emitted beam. From this the distance can be calculated very accurately.

The total station comprises an EDM system, combined with a micro-processor and electronic devices to record the horizontal and vertical angles of the telescope. Thus the surveyor need only point the telescope at the

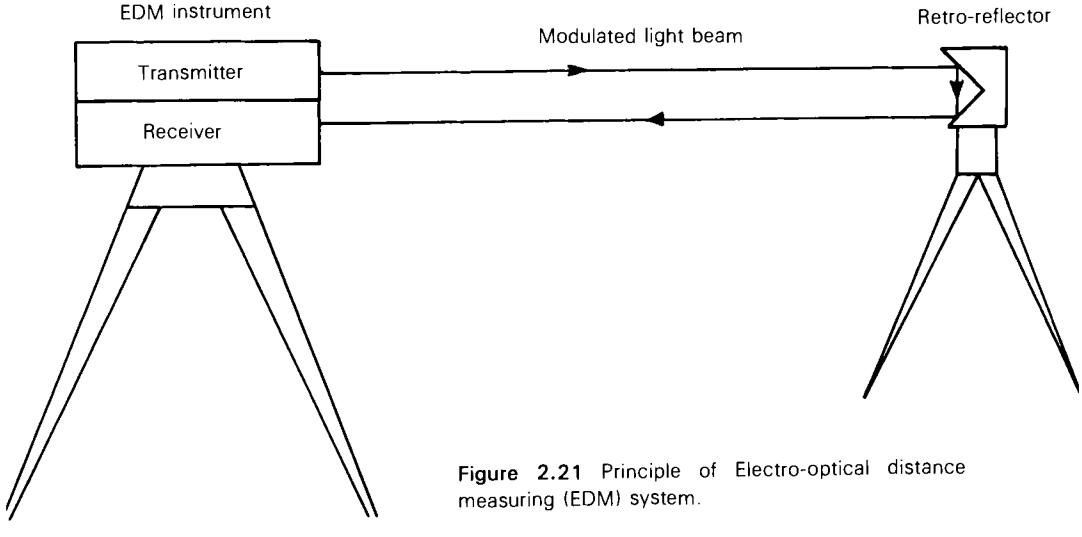


Figure 2.21 Principle of Electro-optical distance measuring (EDM) system.

retro-reflector, push a button, and the location of the point is logged and calculated automatically. This data is also recorded electronically, so that it can be loaded into a computer linked to a plotter. Thus a plan can be drawn without the need of the surveyor's pencil once! It is even possible for the equipment to locate the retro-reflector whenever a button is pushed, so that there is no need to peer down the telescope. This means that the system can be fully automated, and large areas surveyed using a motorcycle with the reflector fitted in place, without the need to stop to take a reading! Unfortunately for the farmer or grower, this type of equipment is rather expensive, and the slower more laborious methods will continue to be used for many years to come.

2.13 PLANE TABLING

Plane tabling is a simple and fast method of producing a detailed drawing of an area. It is also extremely useful for landscapers who can work in reverse. Thus the plan is drawn, and then the plane table is used to set out trees and shrubs from the plan. The apparatus consists of a horizontal drawing board, around 600 mm by 800 mm, mounted on a base, and with a spirit level for levelling. An alidade, or sighting rule, is a length of wood or metal with a straight edge and sighting vanes at each end so that a line can be drawn along the direction of sighting. A compass for aligning the board, a tape measure, a plumb bob, and ranging poles are also required.

The principle of plane tabling is that a plan of the area is drawn to scale directly on paper mounted on the table. The scale of the survey must first be decided and then used thereafter. There are four techniques for producing the drawing. In *Radiation*, the table is set up at a convenient location (P) and rays are drawn from that point in the direction of objects to be located (*Figure 2.22a*). The alidade line of sight must be through the point on the plan which corresponds to the location of the table. The distances to the objects are then measured and scaled off onto the drawing, measuring from the location of the table.

In landscaping the method works in reverse. The location of the table is used as a base point and the adilade is placed along the line to the position of the tree to be planted. The distance is then measured using the alidade to establish the direction by sighting through. The table must be orientated correctly beforehand of course, using the compass, or by sighting to known objects.

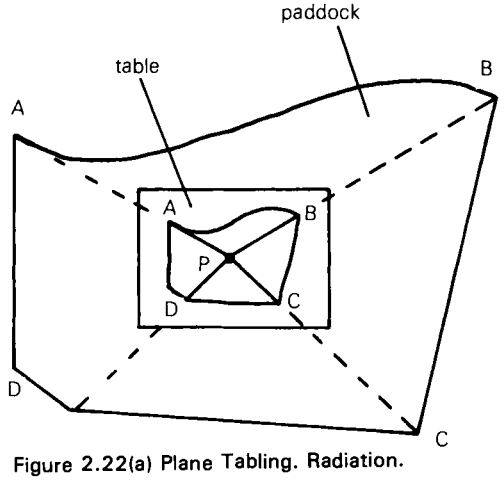


Figure 2.22(a) Plane Tabling. Radiation.

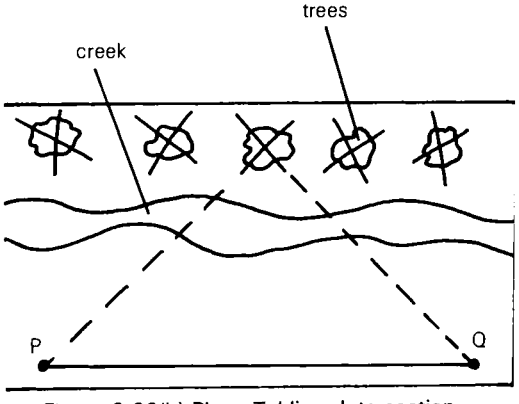


Figure 2.22(b) Plane Tabling. Intersection.

Intersection is a method which enables the position of features to be drawn without measurement of their distance. The table is set up at one point (P) and the rays are drawn to the objects of interest (*Figure 2.22b*). The table is then shifted to another point (Q) a known distance away and the table is realigned by sighting back to the original position. A new set of rays are then drawn. The intersection of the rays defines the location of the objects on the plan.

Progression involves moving the board around a series of base lines to form a closed traverse. The lengths of the baselines are measured, and rays to the other stations are

drawn to fix each new position. Local detail can then be added by radiation. Lastly *Resection* is used to establish the position of the board at a new and unlocated sight. Pins are placed on the board at the locations of three points which have already been marked on the plan, and the real objects are aligned with these to produce a ray. The three rays intersect to locate the position of the table on the plan.

2.14 CALCULATION OF VOLUMES

If an area of ground is to be levelled for a building, the volume of soil to be removed needs to be calculated for costing purposes. In addition if the soil is suitable, it can be used to fill areas which need to be raised. In many cases the best and most economical design is attained if the levels are set so that the volume of soil to be removed equals the volume required for fill. This saves transport costs.

Volume calculations are based on the results from a levelling survey. If the volume to be calculated is a simple shape then the volume will be straight-forward. If the shape is irregular other methods are needed.

2.14.1 Spot height calculations

To calculate the volume of an uneven area, the area can be divided up into a series of rectangles. The more rectangles used the more accurate the result. Spot heights are then taken at the corner of each rectangle, and the average height of each rectangle is calculated by averaging the four corner readings. Alternatively the area can be divided into triangles if this is more convenient.

Example

Calculate the volume of the soil to be excavated to give a uniform depth of 17 m above datum from the data in *Figure 2.23.*

Solution: We calculate the average area of each rectangle. This means that spot height E will be used four times, since it borders four rectangles. We can simplify the calculation by tabling the spot heights, multiplying each by the number of times it is needed, adding the results, and dividing by the total number of times any spot height is used (*Table 2.5*).

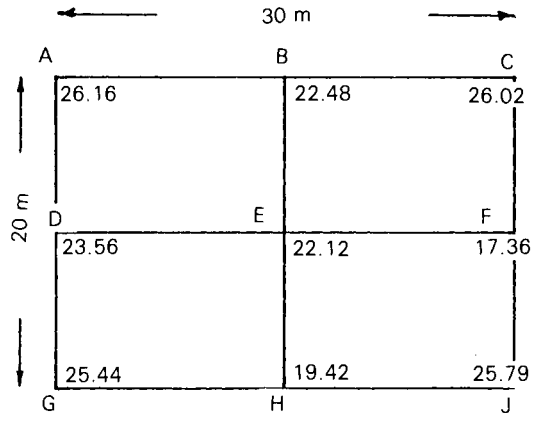


Figure 2.23 Calculation of volumes from spot heights.

Table 2.5 Survey spot heights

Station	RL	No of times used (n)	RL × n
A	26.16	1	26.16
B	22.48	2	44.96
C	26.02	1	26.02
D	23.56	2	47.12
E	22.12	4	88.48
F	17.36	2	34.72
G	25.44	1	25.44
H	19.42	2	38.84
J	25.79	1	25.79
Sum of columns		16	357.53

$$\text{Hence the mean level} = \frac{357.53}{16} = 22.346\text{m}$$

The mean excavation depth is thus $22.346 - 17 = 5.346$ m

The total volume will therefore be the area times the mean excavation depth.

Thus volume $= 20 \times 30 \times 5.346 = 3207\ \text{m}^3$

2.14.2 Volumes using vertical sections

In some cases the volume required may be in the form of an embankment with a regular cross-sectional shape, or the cross-sectional area at regular intervals may be calculable

from the plans. In this case the volume can be calculated by using a modification of the trapezium formula for irregular areas. If cross sectional areas A_1, A_2, A_3, ... A_n, are known at regular intervals h then the volume is given by:

$$V = h\left(\frac{A_1 + A_n}{2} + A_2 + A_3 + A_4 \ldots + A_n^{-1}\right)$$

Equation 2.14

Example

Find the volume of the embankment shown in *Figure 2.24*, where the side slopes (batters) are 1:1, the top is 7 m wide, and the section heights are 8.3, 7.4 and 6.5 metres. The sections are 15 m apart.

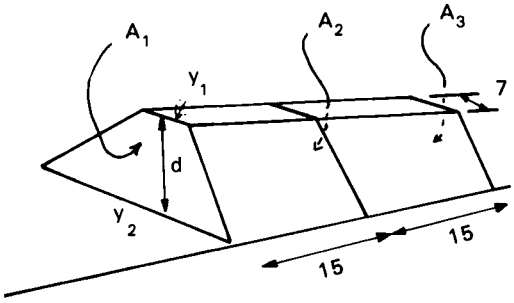


Figure 2.24 Calculation of volumes from vertical sections.

Solution: The area of a trapezium is $0.5 \times (y_1 + y_2) \times d$.

Since the slope is 1:1, therefore

$y_2 = 8.3 + 7 + 8.3 = 23.6$ m.

Thus $A_1 = 0.5 \times 8.3 \times (7 + 23.6) = 127.0$ m^2

Similarly, $A_2 = 106.6$ m^2, and $A_3 = 87.7$ m^2

Thus volume

$$= 15 \times \left(\frac{127.0 + 87.7}{2} + 106.6\right) = 3210 \text{m}^3$$

2.15 SETTING OUT FOR EARTHWORKS

When the plans have been completed and the construction is started, it is necessary to set out guides so that the correct depth of cut, etc, can be made. Profile boards are used to help achieve this. They are temporary wooden frameworks set up in such a way that they establish a centre line or corner position for (for example) a house wall or a ditch. They also establish the level at the required point. It is a waste of time to use anything other than good quality square timber pegs measuring 50 mm by 50 mm and 450 mm long. Angle iron rods 600 mm long can also be used in very hard ground.

In *Figure 2.25* the mark on the centre of the horizontal board (the crosshead) defines the centre of the ditch, and the height of the crosshead is a reference height for the ditch.

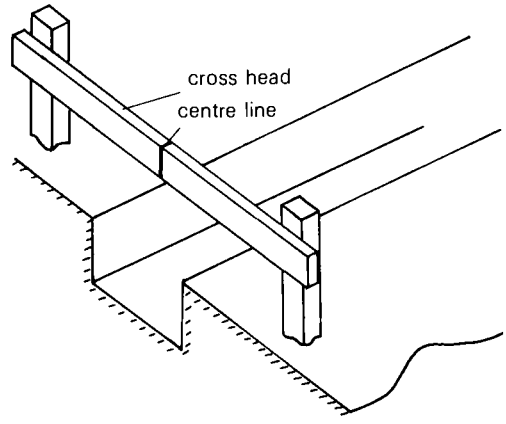
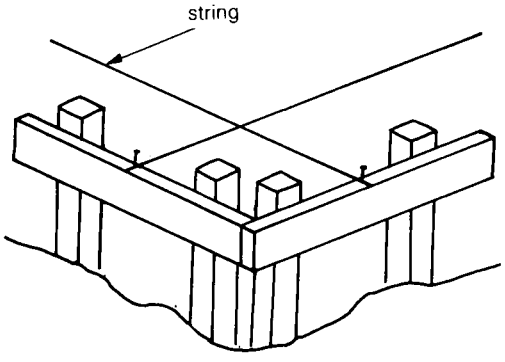


Figure 2.25 Profile board.

The base of the ditch will need to be a fixed a known distance beneath this level. Two profile boards will therefore define the centre line and depth of a ditch. The second board can be set up so that the slope of the ditch can be established. A corner of a building can be marked by two lines defined by two sets of profile boards crossing at a point (*Figure 2.26*). In this case the profile boards will all need to be set up at the same height.

Note that the boards are set up a little distance away from the actual corner. This is so that the work can be done without disturbing the profile boards. In practice profile boards are invariably knocked over by accident, and so it is important to establish secondary reference boards well away from the activities so that the original profile boards can be re-established.

In order to check the depth of a ditch at some point between the profile boards a traveller is required (*Figure 2.27*). The traveller top is sighted between the two boards as indicated, so that the top of the traveller is in line at all positions along the ditch. Batters can be



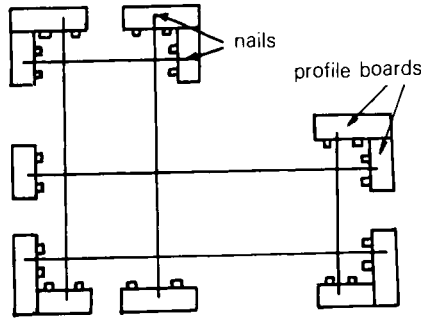
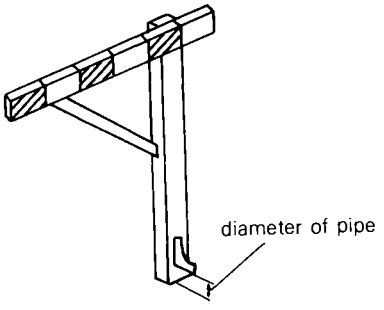


Figure 2.26 Defining corners of buildings during setting out.

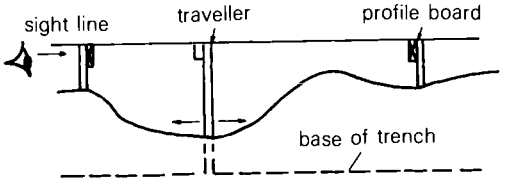
defined with the aid of a slope rail (*Figure 2.28*). The crosshead can be used to check the slope of the embankment as excavation or filling proceeds.

Where excavations are required the centreline peg may be in the way, so offset pegs can be set up around 3 to 6 m from the centreline. Profile boards can also be set up in offset positions so that the contractor has an obstacle free path in which to work.

The procedure for setting out a site involves a few guidelines, but inevitably the precise method will depend upon the particular work. A base line is first set out. This may be the centre of a pipeline, the front line of the building or a line parallel to it, or the centre of a roadway etc. It should be shown on the drawing clearly. Subsidiary lines are then marked out from the base line. If the project is a building the corners need to be defined clearly. Reference marks are then set out so that the baseline and other peg positions can be recovered if the originals are disturbed. The profile boards must all be levelled correctly.



(a) traveller



(b) Traveller and profile boards

Figure 2.27 Traveller.

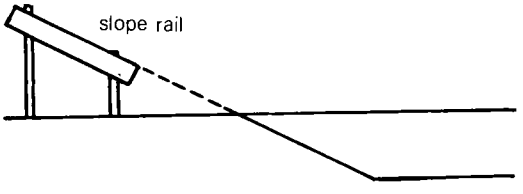


Figure 2.28 Slope rail.

2.16 PROBLEMS

1. Using the field data in *Figure 2.4*, draw the area to a scale of 1:1000. Calculate the area enclosed by the fence and stream, excluding the yards, which lie inside the paddock.
2. Demonstrate how check lines could be used in the survey in problem 1 to avoid errors.
3. The following data was taken from a survey of a line of a proposed pipeline.

a. Complete the level book results.
b. Complete the arithmetical check and state the closing error of the survey.
c. Draw a cross-section along the line using a scale of 1:2,500 horizontally and 1:100 vertically.

BS	IS	FS	Rise	Fall	RL	Distance	Remarks
7.85					50		BM
	3.41					0	Pump house
	2.33					100	
		2.11				200	
	5.02					300	
	4.67					400	
	1.96					500	Pipe outlet
		8.44					Flying level
		8.41					BM

4. Discuss and compare tape surveying, Dumpy levelling, barometric levelling, and aerial surveying. In each case consider the equipment required, the labour input needed, and the accuracy of the results. For each method, give an example of a situation where that method would be most appropriate.
5. Calculate the distance and R.L of a point measured by a theodolite whose telescope is at a RL of 23.28 m and the inclination of the shot is +28°52′35″, if the reading on the staff is 1.460 m. The upper stadia reading is 1.505 m and the lower reading is 1.415. Assume the stadia constant is 100. What would the RL be if the angle was negative (ie, the shot was downhill)?
6. Find the volume of earth to be removed to make a horizontal surface at a RL of 3.2 m from an area as in Figure 2.23, but where the spot height readings in m are: 6.5, 7.6, 9.3, 4.5, 6.7, 8.9, 5.3, 6.8, 8.3, for points A to J respectively, and the grid measures 25 by 15 m intervals between spot points.
7. What would the final RL be if all the soil were used to fill low spots on the site, to produce a level surface?
8. An embankment similar to *Figure 2.24*, but with a top 5 m wide, and with 6 measured sections each 20 m apart and with section heights of 5, 6, 8, 6.5, 6, and 7 m (in that order) above the existing ground level is to be built. Calculate the volume of fill required. The batter is a 1:1 slope.

2.17 AIMS OF THIS CHAPTER

After reading this chapter, and with some practical experience, you should be able to:

1. Explain and define the purposes, principles and steps involved in planning and conducting a survey.
2. Describe and conduct a tape survey, including planning, setting out, recording data, preparing a plan and calculating the areas of any shape.
3. Describe and compare tape surveying, compass surveying, aerial surveying, Dumpy levelling, theodolite surveying, stadia surveying, barometric levelling, and plane tabling.
4. Conduct a survey using a Dumpy level or a theodolite, and book and calculate the results correctly.
5. Explain the terminology used in levelling.
6. Calculate earth volumes from plans.
7. Explain the principles of setting out profile boards for site works.

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Models of our World

Chapter 3

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3.1 INTRODUCTION

In this chapter we will outline some models which describe the things which happen in our world. These models have been developed as a result of the observations of many scientists over hundreds of years, and some are named after the person who first developed the model. When a model becomes sufficiently well tested over a wide range of conditions, to the point where we are confident that it always works, the model is usually called a law. All of the models in this section are in this category: together they form such a good description of our world's behaviour, that we have every confidence in them, and it is safe to say that they will always work.* Many of the terms used in the models will be familiar to you, but it is important for a clear understanding of these models that you are familiar with the way the model uses the term. This is not always quite the same as the average non-scientific person would think, usually because he or she will use the word in a rather ambiguous fashion. One thing models cannot cope with is ambiguity, and so the inventor of the model has the privilege of defining the terms in the way she wants to. This will become clear as we discuss the models. Students with a good background in Physics or Applied Mathematics may wish to skim-read this chapter.

* *Always* is a very dangerous word to use. At the start of this century, Einstein showed that these models are approximations of a more complex model known as the theory of relativity. They are fine until one starts to consider effects close to the speed of light (300,000,000 metres per second), when some of the models start to be inadequate. Similarly some of the models have to be replaced by the Quantum model of the world when one is considering sub-atomic behaviour. For all the situations we shall encounter in agricultural engineering, these can be very safely forgotten about.

3.2 MODELS OF THE ENVIRONMENT—AN OVERVIEW OF PHYSICAL MODELS (LAWS)

3.2.1 Forces

We begin by looking at ways of describing events and occurrences around us. We use the term Force to describe the pushes and

pulls which we experience when (for example) we lean on an object or try to move something. Forces act on objects and make things happen. Thus if you want to hit a ball a long distance you must hit it hard with a bat. The bat strikes the ball producing a large force for a very short time (while the two are in contact), and the ball streaks off to the boundary. The model of a force is as follows:

A force is represented by a straight line drawn on paper (*Figure 3.1a*). The force acts in the direction of the line and the line is called the

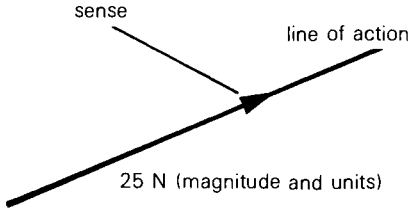


Figure 3.1(a) Model representing a force.

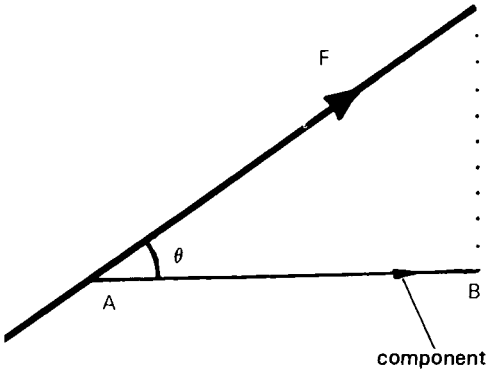


Figure 3.1 (b) Component of force.

Line of Action of the Force. Just a line on its own is not enough, since the force can act in either direction along the line, and so we put an arrow on the line to indicate the direction in which the force acts. This is called the Sense (ie, the direction) of the force. The size of the force is measured in Newtons, the symbol of which is N. In this model the line is labelled with the size of the force, as in *Figure 3.1.*

In the model we have not said at what point along the line the force acts. This is because we do not need to! Forces in nature are completely defined by this model, and the force can be taken to act at any point on the line.

If the force is going to do anything useful it must be applied to an object, such as a spanner as in *Figure 3.2.* The line of action of the force passes through the spanner at point P, and the model says that the spanner is experiencing a push at point P.

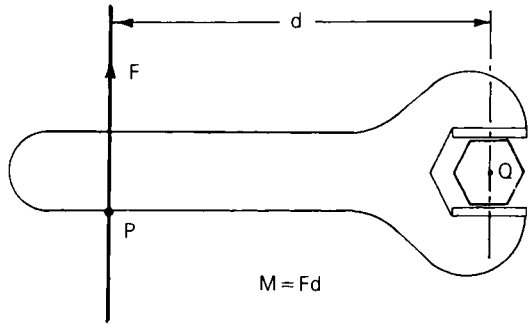


Figure 3.2 Moment of a force about a point.

3.2.2 Component of a force

Any force can be considered to have a component in any direction. The size of the component is given by multiplying by the cosine of the included angle between the line of action of the force and the direction of interest. Thus in *Figure 3.1b* the component in the direction AB is:

Component = F cos θ **Equation 3.1**

The force can have an effect in this direction. The size will be equal to the component. This can be demonstrated by pushing downwards at an angle on a pen or ruler on a smooth table. It is possible to move the ruler providing the horizontal component is big enough. Note that if $\theta = 90°$ then cos $\theta = 0$ and there will be no effect. You cannot move the ruler by pushing vertically downwards because the horizontal component is zero.

3.2.3 Moments

The effect of the force at P on the spanner

in *Figure 3.2* will be to turn the nut. In effect the force is "off-centre" relative to the nut, and this results in a turning effect. We can describe the effect of "off-centre" forces by defining the Moment of the force about a point. This is defined as the product of the force and the perpendicular distance of the line of action of the force to the point. This perpendicular distance is called the *Moment Arm* so:

Moment about point Q (M_Q) = Force (F) × Moment arm (d)

or simply $M_Q = F\ d$ **Equation 3.2**

where F is in Newtons, d is in metres, and M_Q is therefore in Newton metres. It is important to note that the distance d, the moment arm, is the perpendicular distance to the point. The moment of the force will be different for different points off the line of action of the force, even though the force stays the same.

Moments will tend to turn objects either in a clockwise or anti-clockwise direction. Since moments in opposite directions would tend to cancel each other out, we give one direction a positive sense and the other negative. A positive moment is one which has a turning effect in a clockwise direction, as in *Figure 3.2* (if you have a digital watch that means in the order north, east, south, west!).

Example

Calculate the moment of a 30 N force about points A, B and C on the plank of wood in *Figure 3.3.*

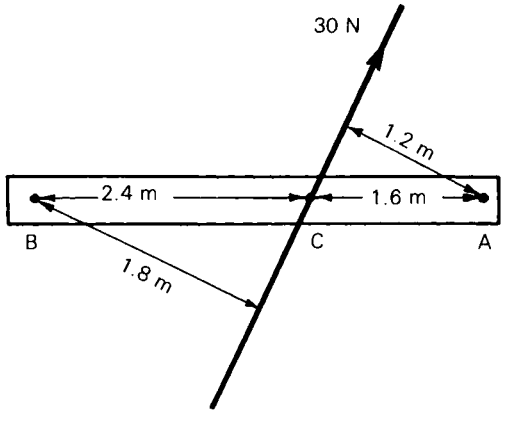


Figure 3.3 Moments about different points.

Solution:

a. For A the moment arm is 1.2 m (the perpendicular distance). Thus the moment of the force about A is:

$M_A = 30 \times 1.2 = 36$ N m

As its effect is to turn about A in a clockwise direction, this moment is positive.

b. About B the force produces an anti-clockwise turning effect and so it is negative.

Thus about B the moment is: $M_B = -30 \times 1.8 = -54$ Nm

c. As C is on the line of action of the force, the moment arm is zero, so $M_C = 0.0$ N m

The moment is often referred to as the Torque produced by the force about the point, particularly when one is considering forces which cause turning about a shaft.

3.2.4 Loads

Of course more than one force may be acting on an object. We can represent each one by a line. We can refer to any system of forces and moments as the Load on the object. There are some types of load which are given particular names.

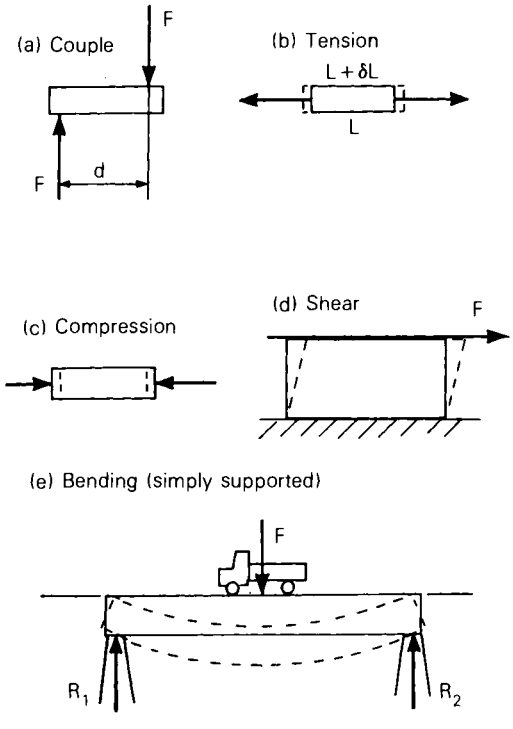


Figure 3.4 Loading configurations.

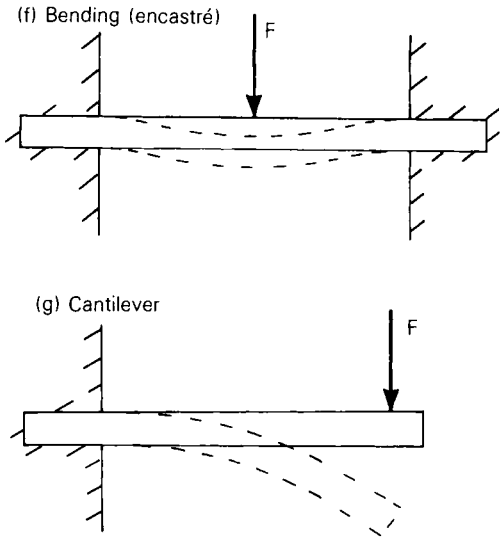


Figure 3.4 Loading configurations continued.

a. Couple

Two equal forces operating in opposite directions are called a couple (*Figure 3.4a*). A couple produces a turning motion. In fact a couple is required before any turning will occur.

The moment of a couple is equal to the product of one of the forces and the perpendicular distance between them, or as in the Figure:

$M_c = F\ d$ **Equation 3.3**

Example

Can you locate a second force which will make up a couple in *Figure 3.2*?

Solution: There must be a force acting at Q through the nut, parallel to the force F but in the opposite sense. This acts on the nut to prevent the nut moving off parallel to the force.

b. Tension (*Figure 3.4b*)

Here there are two equal forces pulling in opposite directions with the same line of action. The effect is to try to stretch the object. The object will usually extend a little, as indicated by the dotted line in *Figure 3.4b*.

c. Compression (*Figure 3.4c*)

This is the opposite of tension. The two forces are now squeezing the object and trying to crush it, and the object may compress a little.

d. Shear (*Figure 3.4d*)

A shear is a sideways force parallel to a surface. If the object is unable to move, it may be deformed slightly as shown. Of course in order for the object to be unable to move other forces must be acting. These are not shown in *Figure 3.4d*, but the shading lines indicate that the object is held firmly along its base.

e. Bending (*Figure 3.4e*)

Bending is a very common form of loading, especially in beams used in buildings. In effect three or more forces must act on a beam or plank, causing it to bend. The forces effectively produce a couple or a bending moment along the beam, and the fibres of the beam must be stretched to prevent the beam from collapsing. The beam bends as shown by the dotted line. We will consider a model for the way in which beams bend later. For now we will discuss different models of ways in which beams are loaded.

The simplest is the Simply Supported beam, as in *Figure 3.4e*. Here the ends of the beam rest on the supports, and are free to move. *Figure 3.4f* shows a Built-in or Encastre beam. Here the ends are rigidly held and cannot deflect at all. The beam will bend as indicated by the dotted line. Clearly the stresses will be somewhat different. We will not consider this type of support in this text. *Figure 3.4g* shows a Cantilever beam. One end only is held rigidly, while the other is free to move. In most real situations one of these models (usually the simply supported model) represents a good description of the real situation.

3.2.5 Combining forces

Suppose there are several forces acting at a single point. An example is given in *Figure 3.5a*, which represents a plan (a bird's-eye view) of a fence post with five fence wires connected to it. It is quite in order to combine these forces together into one force, called the *Resultant*. The resultant has the same effect on the fence post as all the other forces put together, and so in our model of the situation we can reduce the forces to one. This makes the model much simpler and easier to use, and can be done in all cases where forces act at a single point.

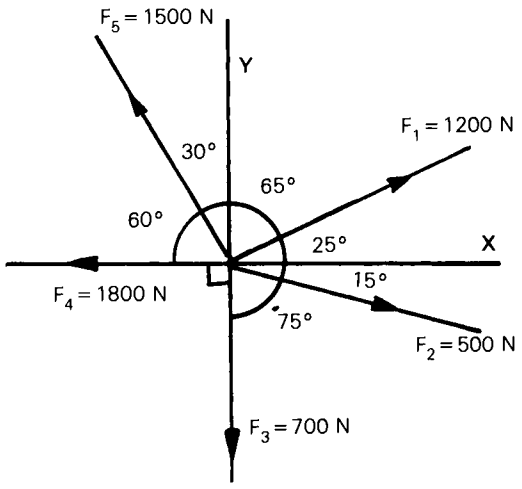


Figure 3.5(a) Plan view of strainer with five fence lines.

The resultant is found by calculating the component of each of the forces in two directions at right angles. Then we add all these components together for each direction separately to give the total resultant force in that direction. Finally we combine these two resultants to give the final answer. Thus suppose we wish to find the sum of all the components of the forces in the direction Y. We must first choose the positive direction or sense: if a component has a sense which is in the direction of the bold arrow in the Figure we shall make this positive.

Thus the net resultant force in the Y direction is given by:

$$R_y = F_1 \cos 65° - F_2 \cos 75° - F_3 \cos 0° + F_4 \cos 90° + F_5 \cos 30°$$

$$= 507.1 - 129.4 - 700.0 + 0.0 + 1299.0$$

$$= 976.7 \text{ N}$$

Note that $\cos 0° = 1.0$ and $\cos 90° = 0.0$ which gives us what we expect in reality for the size of the components parallel and at right angles to the direction Y.

Resolving in the direction X we get:

$$R_x = F_1 \cos 25° + F_2 \cos 15° + 0 - F_4 - F_5 \cos 60 = -979.5 \text{ N}$$

The negative sign merely means that the force is in the negative direction – ie, in the opposite sense to the bold arrow. The five original forces have now been reduced to two forces at right angles. These must now be combined. This requires a so-called Vector diagram. This is a model which says that the force can be represented by a line in the direction of the force, whose length is drawn to scale to represent the size of the force. An arrow is put on the line to indicate the sense. Thus *Figure 3.5b* represents the two forces. The model now claims that the resultant of any set of forces can be found by joining the lines together end to end, so that the arrows follow each other round, as in *Figure 3.5c*. The model then states that the resultant is given by the line which joins the ends of the resulting line (the dotted line in *Figure 3.5c*). Note that the sense is as indicated.

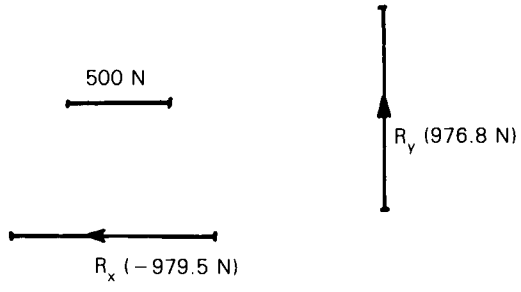


Figure 3.5(b) Vector representation of resultants in X and Y directions.

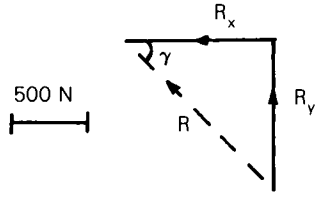


Figure 3.5(c) Combining resultants.

The value of the resultant can now be found by drawing, by Pythagoras, or by trigonometry. Using the latter to solve *Figure 3.5c*, the angle γ is given by:

$$\text{Tan } \gamma = \frac{R_y}{R_x} = \frac{976.8}{979.5} = 0.9972$$

Thus $\gamma = 44°55'$

The Resultant R is thus:

$$R = \frac{R_x}{\cos \gamma} = 1383 \text{ N at } 44°55' \text{ to force } F_4$$

As a check of this last calculation using Pythagoras gives:

$R^2 = R_x^2 + R_y^2 = 1{,}913{,}500$

so $R = 1383$ N as before.

It is worth noting that the Vector model works equally well from the start, so we could have simply done a scale drawing of all the forces as in *Figure 3.5d*, and found the resultant by closing the figure (the dotted line). This method certainly works, but requires the use of trigonometry or accurate drawing, and is more tedious than the method of resolving. However the model has its place in calculating the stresses in frame structures, as we shall see later.

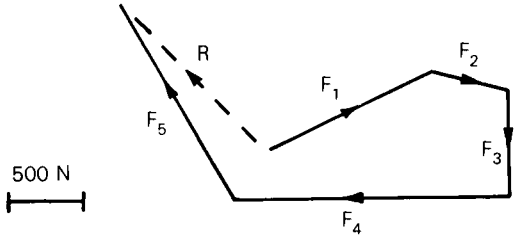


Figure 3.5(d) Complete solution of problem using vector model.

3.2.6 Equilibrium

Solving this set of forces now presents another problem: how do we stop the fence post from moving, since it is under a resultant force? The practical answer is very simple: a stay is placed to stop the post from being pulled over. Put another way the stay counterbalances the load on the post, so that the resultant force on the post is zero. This is the crucial requirement for no movement ie, for equilibrium, there must be no resultant force on the fence post. This sounds simple and almost obvious, but it gives us a very useful tool for working out forces and stresses in all sorts of situations. In fact it is the first step in virtually every case! We will therefore state it (more or less) in the way that Newton did when he first devised the model:

> *A body continues in its state of rest, or uniform motion in a straight line, unless it is acted on by a non-zero resultant external force.*

It immediately follows that if there is any resultant it accelerates away! If there is no movement there is absolutely no resultant force whatsoever in any direction.

This means that if the fence post does not move then the combination of the soil forces and the action of the stay must be such that they balance the forces due to the fence wires exactly. In practice, often the farmer will put a stay in along every fence line so that the post would have five supports. This is an expensive solution! From the calculation here, one stay should be placed along the line of action of the resultant, to produce a force in the opposite direction and so eliminate the resultant force (*Figure 3.5e*). This is a simpler solution.

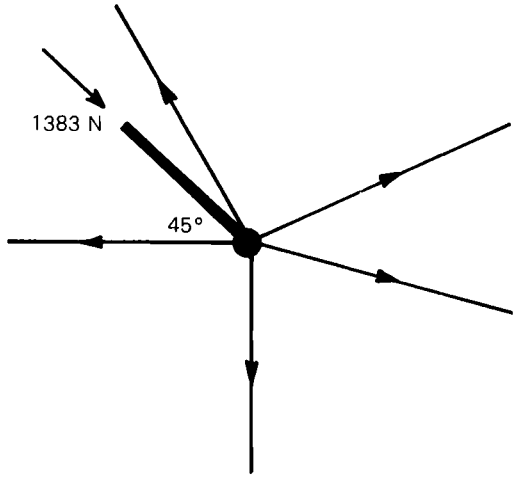


Figure 3.5(e) Position of stay to balance resultant force.

In practice of course, the position of the stay need not be too precise, since we would expect some variation in fence tension with time anyway. Fortunately a fence post is supported by the soil, which counteracts any imbalance of forces, so that there is no noticeable movement. However if the force on the soil is too great the post will gradually tip over and pull out of the ground. In practice the use of two stays at right angles could be a wise precaution, but this type of consideration will be deferred until the chapter on fencing.

To sum up, the key point is that no acceleration implies no resultant force. The condition for equilibrium is that:

> *The sum of all forces in any direction equals zero* or:

$$\Sigma \text{ (All Forces)} = 0 \quad \textbf{Equation 3.4}$$

3.2.7 Stress

Often the load on an object is distributed over an area. A model of this could be a large number of parallel forces acting all over the surface as in *Figure 3.6a*, which shows an

enlargement of a section of fencing wire *under* tension. A simpler model is to describe what is happening as a force per unit area



Figure 3.6(a) Forces are spread over the entire cross-section.

acting on the wire. This is called the stress and is given the Greek symbol σ. Thus:

$$\sigma = \frac{F}{A} \qquad \textbf{Equation 3.5}$$

Where A is the cross-sectional area in m^2 and σ is the stress in Newtons per square metre (Nm^{-2}). Stress is such a useful model of real situations that it is given a special unit: this is the Pascal (Pa). It is equal to 1 N m^{-2}. In practice the Pascal is very small: a smear of water 0.1 mm deep produces a stress of 1 Pa on the surface it rests on, purely due to its weight! Instead we often use MPa (10^6 Pa) or even GPa (10^9 Pa) to record stresses.

Example

Calculate the stress in a rectangular bar whose cross section measures 25 mm by 5 mm, when subjected to a tension force of 20 kN (*Figure 3.6b*).

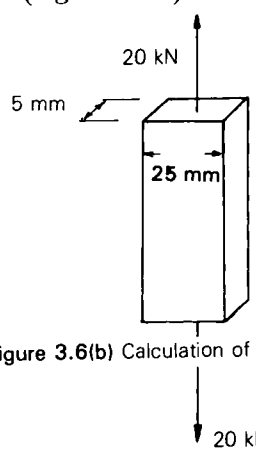


Figure 3.6 Stress.

Figure 3.6(b) Calculation of stress.

Solution: Force = 20 kN = 20,000 N

Cross-sectional area
$= (25 \times 10^{-3}) \times (5 \times 10^{-3}) = 125 \times 10^{-6}$ m^2

Hence the stress is

$$\sigma = \frac{20{,}000}{125 \times 10^{-6}} = 160 \times 10^6 \text{ Pa} = 160 \text{ MPa}$$

3.2.8 Pressure

The term pressure is also used, particularly when we are referring to liquids and gases. Pressure is also defined as the force per unit area and is, in effect, the same as stress. It is also measured in Pascals. The main difference is that we think of a solid as being under stress, and our model uses the idea that the atoms are being squeezed together or pulled apart by the force. The molecules of a gas produce a pressure on the surface of their container by virtue of their movement. Thus the air in our atmosphere produces a pressure on us and everything on the surface of the earth. This pressure is called *Atmospheric Pressure*, and it has a value of around 10^5 Pa or 1 bar. Methods of measuring it and the total pressure in a fluid will be discussed in Chapter 6. The value of atmospheric pressure does not stay constant, but varies with weather conditions. It also changes with altitude, as we have already discussed in the previous chapter under barometric surveying.

3.3 MODELS OF MATERIAL PROPERTIES

The previous section described models of the ways in which forces act on bodies. In this section we will describe models of the materials and substances which make up the real world, and models which describe how they behave. A few key parameters can be used which help to define material properties in a sensible way, and we will discuss these briefly. In particular the common symbol for these quantities, and the units for them, is given.

The materials in our world can be divided into three types, namely solids, liquids and gases. We will deal only with solids to begin with. This is the group of materials whose atoms are more or less held in a fixed position relative to one another. We will consider liquids and gases, ie, materials whose atoms are not held in position relative to each other, but which can move around at random, later in this chapter.

3.3.1 Rigid Bodies

First we need to clarify a common term for a model which is frequently used to describe solids. Often when we apply the sort of loads we have just discussed to things, the deformations are quite small, and we can

make our models much simpler and easier if we assume that the thing being loaded does not deform at all. Although this is undoubtedly an inaccurate model of reality, nevertheless it works very well as a model for many situations. We call something which does not change shape at all under load a Rigid Body. We use this model when we are calculating reactions and resultant forces: the model cannot be used in the analysis of stress and strain in materials.

3.3.2 Mass (Common symbol M)

The mass of an object is a measurement of how much matter there is in the object. The units of mass are kilogrammes (kg). The mass of an object is determined by comparing it against a known mass. Ultimately all masses are measured relative to one standard mass which is a bar of platinum alloy carefully stored in a vault in the Office of Weights and Measures in Paris. Using this as standard, the measures used as standards in countries around the world are calibrated, and these are used to calibrate other masses.

3.3.3 Length, area and volume

Length (L), area (A) and volume (V) are measured in metres (m), square metres (m^2) and cubic metres (m^3). Other sub-units are used such as the hectare (ha) for area, and the litre (l) for volume. One hectare equals 10^4 m^2, while one litre is one thousandth of a m^3. Other units are listed in the Appendices. The area of a circle is given by:

$$\text{Area} = \pi r^2 = \frac{\pi d^2}{4} \qquad \text{Equation 3.6}$$

where $\pi = 3.1416$.

Engineers use diameters rather than the radius, because in practice it is easier to measure the diameter of a pipe or cylinder than the radius. Other formulae are given in Appendix 1.3.

3.3.4 Density (ϱ)

The density of a material is its mass per unit volume. The units are kg m^{-3}.

$$\text{Thus } \varrho = \frac{M}{V} \qquad \text{Equation 3.7}$$

For example the density of water is 1000 kg m^{-3}.

3.3.5 Specific Gravity (SG)

The Specific Gravity is the ratio of the density of the material to that of water.

$$\text{Thus SG} = \frac{\varrho_{\text{substance}}}{\varrho_{\text{water}}} \qquad \text{Equation 3.8}$$

As it is a ratio the SG does not have any units. Values of the SG of a few materials are given in *Table 1*. It is also referred to as the Relative Density.

Table 3.1 Specific Gravity of materials

	SG
Mercury (Hg)	13.5
Steel	7.87
Iron (Fe)	7.87
Aluminium (Al)	2.70
Water (H_2O)	1.00
Diesel fuel	0.80
Air at STP (0°C, 1.013 bar)	0.00129

Example

What is the mass of 200 m^3 of air under standard conditions (this means at 0°C, and 1 atmosphere pressure (1.013×10^5 Pa), as discussed later).

Solution: From the table the SG of the air is 0.00129. Thus, from *Equation 3.8*:

$\varrho_{air} = SG \times \varrho_{water} = 0.00129 \times 1000$
$= 1.29$ kg m^{-3}

Thus 200 m^3 of air will have a mass of $1.29 \times 200 = 258$ kg.

3.4 MODELS OF THE INTERACTIONS BETWEEN MATERIALS AND THEIR ENVIRONMENTS

Now that we have established some material parameters, we shall define some more terms which arise from the interaction between the material and the environment.

3.4.1 Weight (W)

Earlier we defined the mass of a body. It was a measure of how much matter is in the body. Now we will use a model to define a totally different term called Weight.

When we lift a bucket up and hold it off the ground, then we are soon aware that it is

heavy. We have to supply a force to support it. How much force do we need to apply to keep the bucket stationary? In other words our question becomes what is the gravitational force on an object? Lots of measurements have shown that the best model to determine the size of the force we need to hold the bucket up is one which says that there is a force which pulls the bucket downwards towards the earth all the time. This force arises because, in our world, there is always a small but significant force of attraction between objects. The force depends on the size of the objects, and it is only when one is enormous (such as the earth) that we notice it. Only when the force we apply upwards equals the downward force due to gravity will the bucket stay stationary (*Figure 3.7*). The force due to gravity is given by the product of the mass of the body times a constant called the *Gravity* or the *Acceleration due to Gravity* (g). Thus:

Downwards force due to gravity = Mg
Equation 3.9

Stability occurs when:

Upwards force supplied by us = F = Mg
Equation 3.10

We call the downwards force W the Weight of the bucket.

Thus:

Weight $W = M\ g$ **Equation 3.11**

Where W is the force due to gravity. As W is a force its units must be Newtons. The units of M are kilogrammes. The units of g therefore could be N kg^{-1}, but it turns out that g can in fact have units of metres per second squared (m s^{-2})! We shall see why shortly.

On earth the value of g is around 9.80 m s^{-2}. It varies slightly from place to place around the world. At the poles it is 9.83, while at the equator it is 9.78. On the moon the value is much lower at 1.62 m s^{-2} (because the moon is smaller than the earth), so things have only one sixth of the weight even though they still have the same mass.

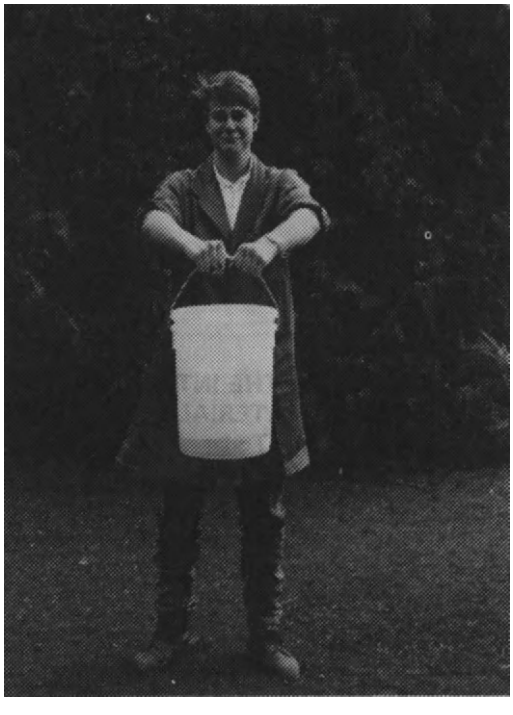


Figure 3.7 Overcoming gravity. The bucket stays in place only if the upwards force provided by my assistant balances the downwards force due to gravity (the weight of the bucket).

Example

A body has a mass of 20 kg. What is its weight on earth? What would its mass and weight be on a small planet if the gravity was only 0.36 m s^{-2}?

Solution: Weight on earth
$= Mg = 20 \times 9.8 = 196$ Newtons

On the planet, the mass would be unchanged (20 kg).

The weight would be $20 \times 0.36 = 7.2$ N. It would therefore be much lighter to carry.

This model of the force on objects in the earth's gravitational field works very well. Unfortunately the term weight is often used by ordinary people to mean mass, so that we often say "an object weighs 25 kg". Although this is not what the scientists would like us to say, I think that they are stuck with it. Accordingly we must watch whether or not the speaker is referring to the mass or the weight. Fortunately this is easy: the units give the game away. If the units are kg, it is the mass, whereas if the units are Newtons, then we have been given the weight. We just need to be a little careful, as the model demands that we make the distinction.

3.4.2 Centre of Gravity (C of G)

The Centre of Gravity of an object is defined as the point through which the line of action of the weight always acts. As we have seen, forces can be combined together into a single resultant force (plus a couple). A good model of the way a rigid object behaves is obtained if we consider all the matter in the object to be concentrated at one point, ie, the centre of gravity. It then becomes important to find out where the centre of gravity is. For symmetrical objects it will be in the middle. For flat plates or objects which are uniform through their depth, the centre of gravity lies along any line which divides the cross sectional area exactly in two. For other objects the position can be calculated or measured by experiment.

For calculation differential calculus can be used: with reference to *Figure 3.8*, the centre of gravity is found by finding the distance Y of the centre from any given line AB where:

$$Y = \frac{\text{Sum of all the thin strips} \times \text{their distance from AB}}{\text{Total area}} = \frac{\int yu\,dy}{\text{Total area}}$$

Equation 3.12

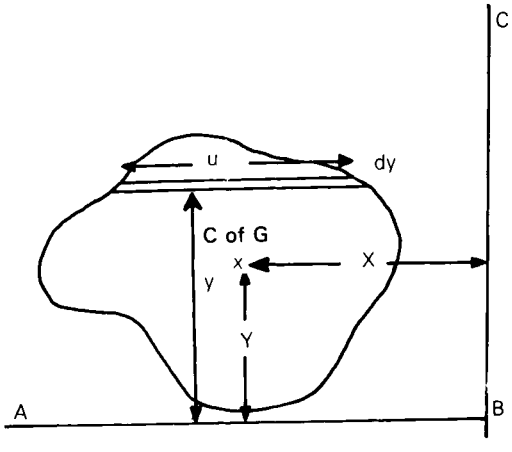


Figure 3.8 Calculation of centre of gravity. X and Y are found by calculation.

Repeating the calculation for another line such as BC will fix the centre of gravity. If the shape of the object is not known mathematically, then the area can be divided into small strips and summed.

The experimental method involves hanging the object from a single point, and marking the position of the vertical line through the point. This is the line of action of the weight. Repeating from another point defines a second line. Where they cross gives the centre of gravity. The last method is a little tricky if the object is a tractor! In this case the centre of gravity can be found by putting the tractor on a ramp which lifts sideways (*Figure 3.9*), and marking the vertical line



Figure 3.9 Determination of centre of gravity using an inclined plane.

when the tractor starts to topple over. At this point the line of action of the weight is just over the side of the tyre. Lifting the other side of the tractor will establish a second line. If the position from the front is required the tractor will have to be lifted a third time, this time from the front, until it topples over. Data of this type is needed to reduce the chance of a newly designed tractor overturning on hilly country, an accident which costs several lives every year. The experiment can be dangerous and expensive if the tractor is not prevented from continuing to topple.

3.4.3 Specific Weight (γ)

The specific weight of a substance is the weight per unit volume. It is used a great deal in fluids and not much elsewhere. Thus:

$$\text{Specific Weight } \gamma = \frac{\text{Weight}}{\text{Volume}}$$

Equation 3.13

The units are clearly N m^{-3}. For water γ is equal to 9.8×10^3 N m^{-3}.

From the previous definitions we can note that:

$$SG = \frac{\varrho}{\varrho_{water}} = \frac{\gamma}{\gamma_{water}}$$

Equation 3.14

3.5 MODELS OF THE RESPONSE TO LOADING OF SOLIDS

As mentioned earlier, real things deform when they are put under a load. In this section we will give models of the different ways in which solids deform. We will describe the behaviour of solids under load with reference to a fencing wire under tension, since this is a good example of the behaviour of most materials. Later, in Chapters 8 and 9, we will discuss material properties in more detail. However, here we must first introduce some more useful terms.

3.5.1 Extension (δL)

If a steel wire is put under tension it stretches. The extension is simply a measure of how much it extends (*Figure 3.4b*). As a practical measure the extension is what we will usually need to know in the end, but it can only be calculated if we determine the strain first. So what is strain?

3.5.2 Strain (ϵ)

The Strain is the fractional extension of a wire or body. It is the ratio of the extension of the wire to its original length before it is loaded. Thus (*Figure 3.4b*):

$$\text{Strain} = \epsilon = \frac{\text{Extension under load}}{\text{Original length}} = \frac{\delta L}{L}$$

Equation 3.15

Strain has no units (it is dimensionless) because it is the ratio of two distances. However be sure that the same units are used for original length and extension. Strains are usually quite small and are quoted as percentages.

Example

A 200 m long wire under tension stretches to a new length of 200.37 m. What is the extension and strain?

Solution: Extension = 200.37 − 200 = 0.37 m

$$\text{Strain} = \frac{0.37}{200} = 0.00185 = 0.185\%$$

3.5.3 Strength and stress at failure

By the word "strength" we are seeking a way of measuring the load at which the material is unable to withstand the applied load, and so fails in some dreadful manner. It is often useful in practice to describe the strength of objects in terms of the failure load of a given component. For example, 4.0 mm diameter mild steel fencing wire fails at a load of around 6.5 kN. However, for design purposes, it is more useful to have measures of strength which are material properties, and so the definitions are usually standardised in terms of the size of the object. Failure stresses (ie, the load per unit cross-sectional area) rather than failure loads are therefore used.

Because loads can be applied in a variety of different ways, we can expect that the strength of materials may differ depending upon the method of loading. This is most definitely the case in reality. This means that we can only specify the strength of a material under a particular set of conditions, such as under tension, and we can expect that the strength of the material under compression or under shearing will be different. In general the tensile strength of a material is most often quoted. However the compressive strength and the shear strength are sometimes more important parameters if the material is always used under compression or in shear (eg, concrete and soil respectively). Again the stresses which cause the material to fail are quoted. In all cases the strengths are measured in Pascals ($N\,m^{-2}$). *Table 3.2* lists the values of the failure stress under tension of some materials.

3.6 THE RELATIONSHIP BETWEEN STRESS AND STRAIN

One of the most useful models in engineering is the one which describes the relationship between stress and strain for solids. The simple linear model works very well indeed for a large number of materials used for horticultural and agricultural buildings and structures, and is widely used by designers. The model only works if the applied stress is small compared to the maximum stress the material can sustain, so that it is insufficient to cause damage. It does not work so well for soft fruit.

Table 3.2 Tensile strength of materials

Material	Tensile strength MPa
Mild steel	460
Cast Iron (grey)	100
Cast Iron (white)	230
Wrought Iron	370
HT Fencing wire	1320
Mild steel fencing wire	500
Steel Piano wire	3000
Copper	150
Aluminium (pure)	80
Aluminium (Strong alloy)	600
Concrete	4
Alumina (Ceramic)	150
Gold	120
Lead	15
Bone	140
Polystyrene	50
Polyvinylchloride soft	15
Polyvinylchloride rigid	60
PTFE	22

Taking as our example a length of fencing wire, if we put it into a testing machine and apply a tension to it, the wire will stretch. The stress can be worked out easily by dividing the load by the cross-sectional area, and the strain is found by dividing the extension by the original length. If the values are plotted as the load is increased, the resulting graph is as shown in *Figure 3.10*. Up to a maximum stress level called the *Elastic Limit* we find that whenever the load is taken off, the material will return to its original length. The relationship between stress and strain remains the same whether one is loading or unloading the wire, and so the strain can be found from the stress directly from the graph. This is known as *Elastic* behaviour. The molecules of the material are being stretched apart very slightly by the load, and they return to their previous position on unloading. No permanent damage is done to the material as a result of this loading, and the loading/unloading cycle will just follow up and down the curve.

More important than this for the designer is that the curve of stress against strain is a straight line over the entire range of stresses up to the elastic limit. It is in the nature of the molecular forces that the strain is proportional to the stress right up to the

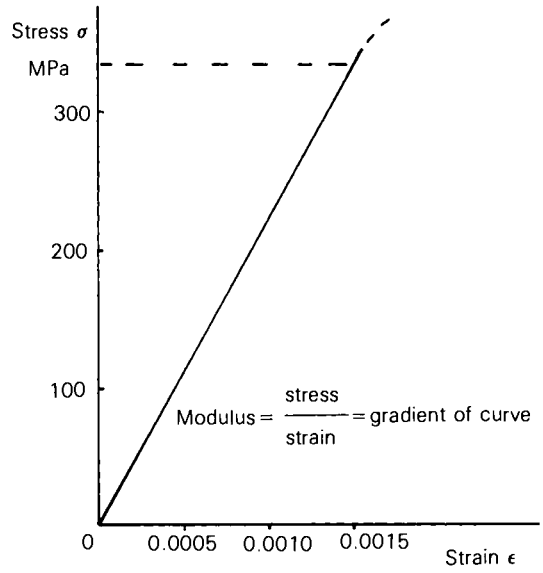


Figure 3.10 Stress strain curve for steel in elastic region.

elastic limit*. Rather than draw a straight line graph every time as our model, it is easier to use the equivalent mathematical model of this behaviour which is simply:

$$\sigma = E\,\epsilon \qquad \textbf{Equation 3.16}$$

where E is a constant.

The constant E is called the *Young's Modulus* (or just the Modulus) of *Elasticity*. It is equal to the slope of the stress/strain curve in the elastic region (*Figure 3.10*). It is one of the most important material properties as far as design is concerned. Its units are the same as those of stress, ie, N m^{-2} or Pascals. Values of E are given in *Table 3.3*.

Example

Find the extension caused by a load of 1500 N on a 200 m length of 2.5 mm diameter fencing wire given E = 210 GPa.

Solution: First we need to find the stress σ. From *Equation 3.5*,

$$\sigma = \frac{\text{Force F}}{\text{Area A}}$$

$$= \frac{1500 \times 4}{\pi(0.0025)^2} = 3.0558 \times 10^8 \text{ Pa}$$

Now Equation 3.16 gives the strain ϵ:

$$\epsilon = \frac{\sigma}{E} = \frac{\sigma}{210 \times 10^9} = 0.001455$$

Hence extension is given from *Equation 3.15*:

$\delta L = \epsilon \times L = \epsilon \times 200 = 0.291$ metres

A similar calculation for 4.00 mm diameter wire gives an extension of 0.114 m, about two and a half times less than for 2.5 mm wire. This has important practical implications for fencing and is discussed in the chapter on fencing.

Table 3.3 Mechanical properties of materials

Material	Modulus of Elasticity GPa
All steels	210
Cast Iron	120
Copper	110
Aluminium	70
Concrete	14
Alumina (Ceramic)	345
Gold	71
Lead	18
Titanium Carbide	345
Wood (with grain)	10–15
Wood (across grain)	0.5
Bone	28
Diamond	1200
Polystyrene	3.1
Polyvinylchloride soft	0.01
Polyvinylchloride rigid	2.8
PTFE	0.34

Before we go on to see what happens when we increase the stress on a material beyond the elastic limit, it is worth emphasising that for nearly all practical situations, all the solid materials we use to make things with are never intentionally loaded beyond the elastic limit. We deliberately design buildings and equipment so that this is so. Structural failures arise when components are loaded beyond the elastic limit through design faults or overloading due to loads in excess of those used in the design calculations. The elastic model of the behaviour of materials therefore enables us to predict very accurately exactly what loads and stresses will be developed in buildings and structures. If the model predicts stresses near to the elastic limit, the designer will usually change the design so that the situation is avoided. For structures the design stresses are usually deliberately kept less than 25% of the elastic limit. This is a factor of safety of four or more. In aircraft the stresses may be designed at 50% of the elastic limit, but the quality control on materials and workmanship is much higher.

* For some materials there is a limit of proportionality which is just a little below the elastic limit. For other materials it is hard to define any linear region at all. Some modern materials exhibit most peculiar behaviour for which the elastic model is quite inadequate. However, for our purposes we can ignore these exceptions to the general rule.

3.6.1 Loading beyond the elastic limit

The testing machine can be made to keep stretching the wire more and more, until eventually the wire breaks. We will now describe the way in which the wire responds. Once the stress goes beyond the elastic limit, the linear elastic model ceases to describe the behaviour of the wire. A full stress strain curve for a soft steel (called mild steel) is shown in *Figure 3.11*. As can be seen there is a deviation from the straight line. On unloading (the dotted line) the wire does not quite return to its original length, but instead retains a small extension even at zero load. This is called the *Permanent Set*. This represents permanent damage which has been done to the wire. Any loading which results in a permanent set is described as *Plastic Deformation*. On reloading the wire traces out a new straight curve which remains straight, following the unloading curve precisely, until it almost crosses the previous curve. It then follows the original curve. Unloading shows that the amount of permanent strain increases as the wire is loaded further along the curve. Thus any loading which exceeds the elastic limit of the wire causes plastic deformation, and so the region of the curve beyond the elastic limit is known as the plastic zone. Note how narrow the elastic zone is in comparison. Even in the figure its width is exaggerated for clarity.

In soft metals the next event is a sudden small apparent drop in the stress. This occurs at the *Yield Point* of the wire, and is a point where the wire stretches rapidly. The molecules in the wire are sliding over one another here.

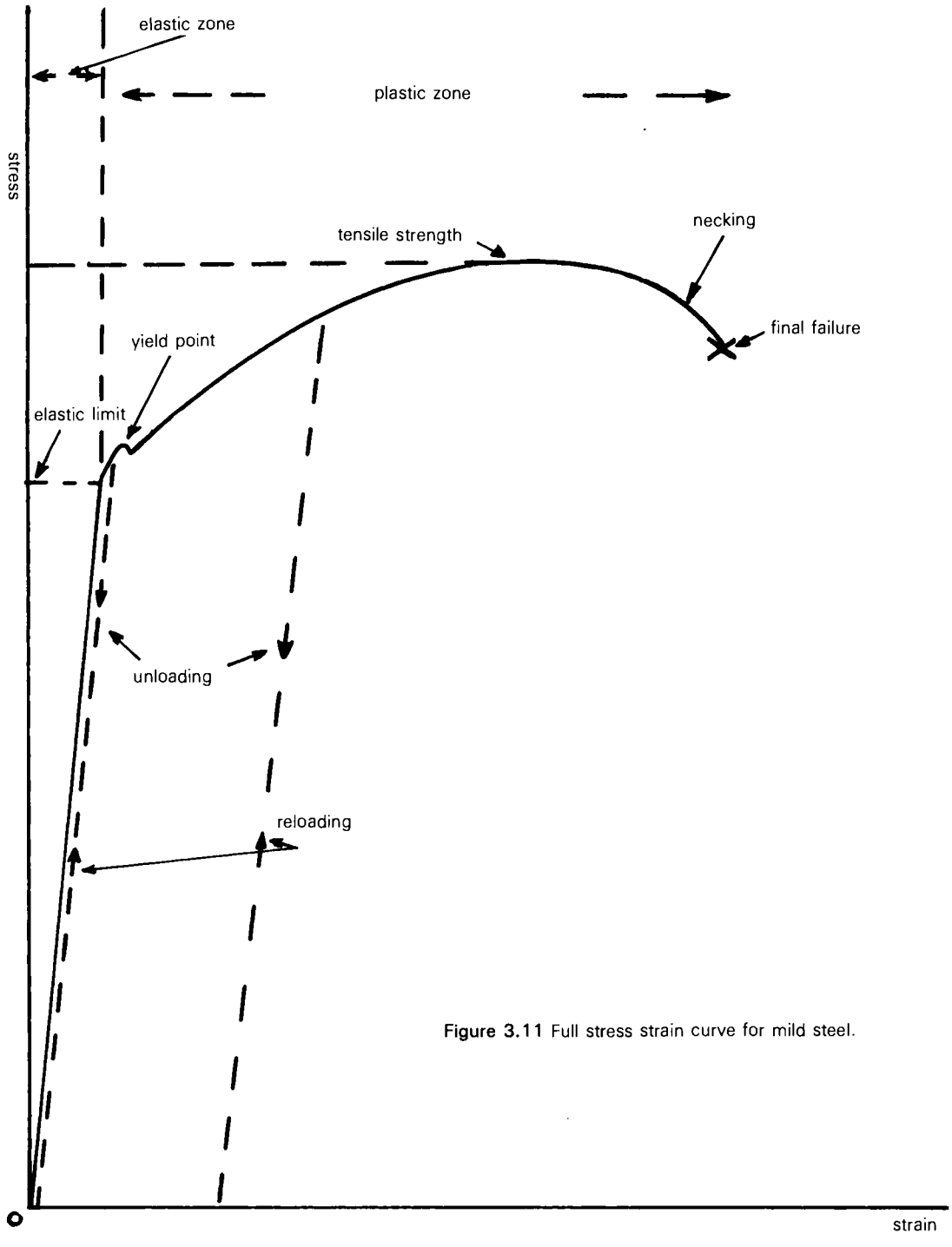


Figure 3.11 Full stress strain curve for mild steel.

Beyond the yield point major damage is being done. In stronger materials it is often hard to identify the yield point as the curve has no detectable dip. In these cases the limit of proportionality, the elastic limit, and the yield point are identified as the same point.

Beyond the yield point the wire recovers, and the stress can be increased further, even though there is considerable strain. Unloading indicates that this is a permanent set. The wire is able to sustain a stress which is greater than the yield point. This is possible due to

a process called *Work-Hardening*, which involves a rearrangement of the atoms of the wire into a stronger pattern. Eventually a peak is reached and the stress will not increase any more. The stress at this point is called the *Tensile Strength* of the wire. Values of the tensile strength of various materials are listed in *Table 3.2*. Beyond this the stress falls off even though the strain is increased further as the testing machine continues to stretch the specimen. Examination of a wire stretched this far will show that at some point on the wire it is "necking", ie, the diameter of the wire is reducing noticeably at one point, forming a narrow neck. Further stretching results in the wire breaking at the neck (*Figure 3.12*).

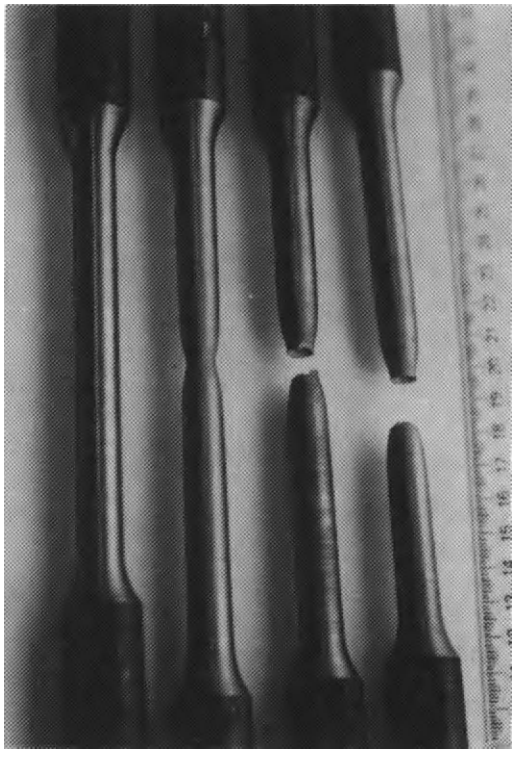


Figure 3.12 Tensile strength—failure under tension.

Because the wire behaves under high stresses in a way which involves plastic deformation, the wire is described as being *Ductile*, and the failure is called a ductile failure. It is usually easy to predict the tensile strength of a component made from a material which fails in a ductile manner, because the material will always start to neck at around the same stress.

3.6.2 Behaviour of other solid materials

Figure 3.11 shows the behaviour of steel under load. Most other metals behave in the same way. As we have already mentioned, some materials behave in slightly different ways, so that the yield point cannot be distinguished from the elastic limit, and the dip in the curve just after the yield point may also be absent. In annealed copper none of these points can be easily distinguished. To get over this problem, the proof stress concept has been introduced: the stress required to give a permanent set of no more than 0.1% is called the *0.1% Proof Stress*. This figure can then be used in design calculations.

There is also another class of materials which fail before the elastic limit is reached. These are the brittle materials, such as glass, cast iron, some hardened steels, and some plastics. A feature of brittle materials is that the failure load varies widely between different samples, and this makes design very difficult. One cannot predict the failure load with any great accuracy, unless the material has been prepared using modern techniques and under extremely high quality control standards.

It is also worth emphasising that many plastics break in a brittle manner—ie, with no apparent plastic deformation. You could demonstrate this with an ordinary plastic ruler, for example.

3.7 HARDNESS

The hardness of a material is measured by pressing a steel ball or a diamond pyramid into the surface, and measuring the size of the resulting indentation. A value is given to the result which is called the Brinell Hardness (for the steel sphere), or the Diamond Pyramid Number (DPN). A DPN of 200 represents a soft steel, while a hard steel would reach up to 700 DPN. Quartz and silica in stony soils are around 1200 DPN. An alternative scale is the Mohs Hardness scale, which relates the hardness of a material to a standard set of materials. The test involves trying to scratch the surface with the standard materials. Thus diamond has a Mohs hardness of 10, corundum is 9, down to talc which is 1. Steels range from 4 to 8 on this scale. Some types of fencing wire are called hard by users because it makes their hands sore very quickly. This is not due to the hardness of the

material, but rather because of the extra hand pressure which is required to bend the wire compared to that for a "softer" wire such as mild steel.

3.8 OTHER TYPES OF MATTER

As described earlier, matter exists either as a solid, a liquid, or as a gas. Solids have been considered above. Liquids are almost incompressible under load. However they shear, which means that they deform by changing shape as shown in *Figure 3.13*. This change in shape is not elastic, and the fluid stays deformed when the load is removed. We will consider this later, in the chapter on water supplies. Here, we will describe the behaviour of gases under load. What distinguishes them from liquids is that while liquids are virtually incompressible, when a gas is put under pressure its volume is reduced measurably.

3.8.1 Model of a gas

Any gas, such as air, or hydrogen, can be modelled as a mixture of molecules rather like billiard balls which are all free to move. The molecules are in constant rapid motion in all directions and if the gas is enclosed in a vessel the molecules continually bombard the surrounding walls. The total force of this bombardment on unit area is called the *Absolute Pressure* of the gas, measured in Pascals ($N\ m^{-2}$). If we had a closed vessel which contained no gas, the absolute pressure inside would be zero.

3.8.2 The ideal gas laws

Over a very wide range of conditions, gases are said to obey certain key laws, called the ideal gas laws, which describe the relationships between the pressure, temperature and volume of the gas. Once again these are models of the way real gases behave. In reality, gases only deviate from these laws if they are compressed to levels such that they approach the liquid state. For practical purposes we can use these models very successfully to describe real gases.

The first model is Boyle's law. This states that, at fixed temperature, the product of pressure and volume is a constant. Thus we can write

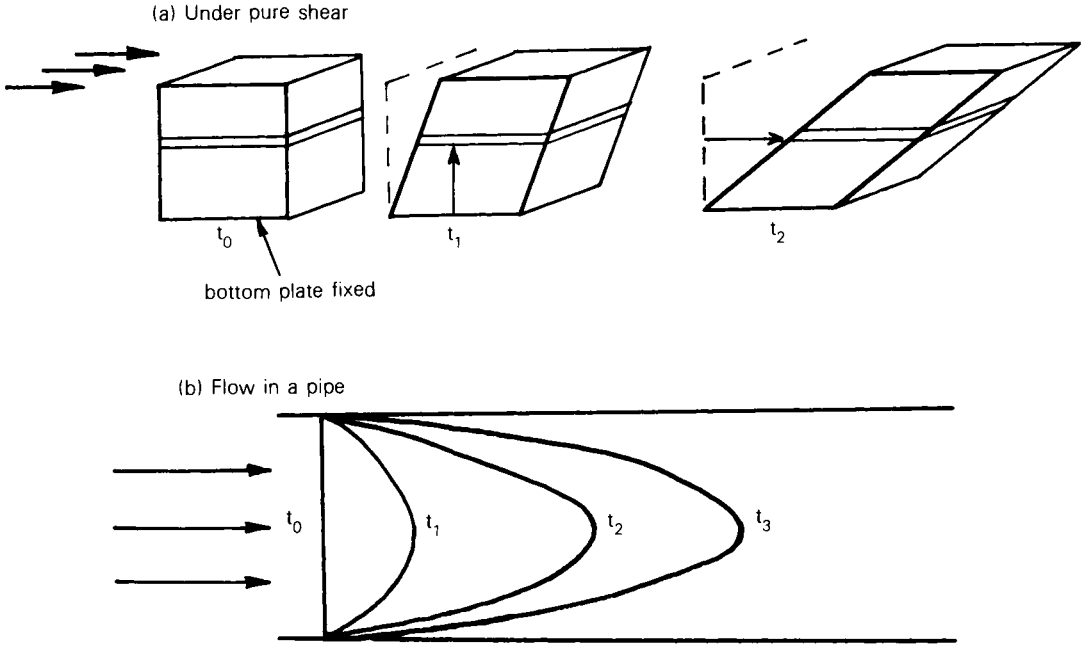


Figure 3.13 Deformation of a fluid under a stress at a series of time intervals t_0, t_1, t_2, t_3 . . . .

$P_1 V_2 = P_2 V_2 = \text{Constant}$

Equation 3.17

where P_1 and P_2 are the absolute pressures in N/m^2 (Pascals) before and after a change, and V_1 and V_2 are the volumes in m^3.

Gases are also affected by temperature. We will discuss exactly what we mean by temperature later on, but for now we will just say that it is a measure of the level of hotness. Gases obey Charles' law, which states that, at constant pressure, the ratio of volume to absolute temperature is a constant. Thus:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \text{Constant}$$

Equation 3.18

where T_1 and T_2 are the absolute temperatures defined by:

Absolute temperature = temperature (°C) + 273°

The units of absolute temperature are °K, which are the same as °C but with a different starting point (strictly −273.15°C).

In 1811, Avogadro suggested that all gases at the same temperature and pressure contain the same number of molecules. At 0°C and 1 atmosphere pressure any ideal gas will have a mass equal to its molecular weight in grammes, contain exactly 6.02×10^{23} molecules, and occupy a volume of 22.414 litres. This amount of gas is called one mole. These conditions are described as Standard Temperature and Pressure (STP).

These laws can be combined to give the relationship:

$PV = nRT$ **Equation 3.19**

where P is the pressure in atmospheres (1 atmosphere = 1.013×10^5 Pa), V is the volume of the gas in m^3, T is the absolute temperature (°K), n is the number of moles of the gas, and R is called the Universal gas constant. It has a value of 82.06×10^{-6} m^3 atm $°K^{-1}$ $mole^{-1}$.

These models apply to all gases with good accuracy, except if the gas is at low temperature or high pressure (ie, where it is very dense, or close to condensation). There are very few cases in horticulture and agriculture where we will need to consider these exceptions and so for most gases such as air the ideal gas laws give us a good way of calculating volumes, pressures, and temperatures.

Example

How many molecules of oxygen are present in 1 m^3 of pure gas at 1 atmosphere and at room temperature (20°C)?

Solution: From Equation 3.19:

$$n = \frac{PV}{RT} = \frac{1}{82.05 \times 10^{-6} \times (273 + 20)}$$

$= 41.60$ moles

But 1 mole contains 6.02×10^{23} molecules, so 1 m^3 contains $41.60 \times 6.02 \times 10^{23} = 2.50 \times 10^{25}$ molecules of oxygen (this is the same as the number of people living on 6,000,000,000,000,000 planets the same as ours!).

3.9 MOVEMENT

3.9.1 Velocity and speed

We describe motion using the term velocity (or speed). It is a measure of how fast an object is moving. Velocity is therefore measured as the distance travelled in a given time, and it is therefore measured in metres per second. When we state the velocity we should also specify the direction. This is because, like force, velocity has magnitude and direction (for the record, these are therefore known as vector quantities).

Speed is the same thing as velocity, except that it does not need the direction to be specified. Such quantities are known as scalar quantities.

Thus the speed of a car could be 25 m/s. Its velocity would be 25 m/s towards the North Pole.

3.9.2 Change in motion (acceleration)

When a force acts on an object it has an immediate effect. If it is the only force acting the object will start to move. It does so at a rate which depends upon the mass of the object, and which can be worked out. Experiments have shown that the best model of this behaviour is *Newton's Second Law of Motion*, which is written as:

$$a = \frac{F}{M}$$

or more commonly:

$$F = M\,a \qquad \textbf{Equation 3.20}$$

where F is the (resultant) force in Newtons, M is the mass of the object in kilogrammes, and a is called the *acceleration*, or rate of change of velocity. Its units are metres per second per second, or m s^{-2}. We all know about acceleration: when a driver puts her foot down in a car or bus, the car accelerates away. If you are a passenger, then you feel a force from the seat pushing your body forward. The size of the force depends on how rapidly the driver accelerates. If the car brakes suddenly you are restrained by your seat belt, or whatever else you hang on to, or hit. The size of the force depends on how fast you are stopped: hitting your head on the car frame could be very painful at best, while the "give" in the seat belt will reduce the rate of deceleration.

The equation tells us either how fast things are changing or alternatively how much force is needed to produce a particular rate of change of velocity.

Example

Calculate the acceleration produced by a force of 30 N (a force that an average person could apply without too much trouble) on an object with a mass of 0.2 kg (a large apple).

Solution: Using *Equation 3.20*:

$$a = \frac{F}{M} = \frac{30}{0.2} = 150 \text{ m s}^{-2} \qquad \textbf{Equation 3.21}$$

Acceleration is obviously an important term which says something about rates of change of velocity. The earth's gravitational field produces an acceleration of 9.80 m s^{-2} on any object which is allowed to fall freely. However this is just a number. In order to make it meaningful, we need to relate it to other terms such as the distance an object travels in a certain time while it is being accelerated by a force, and the velocity after a certain time. There are a set of equations which give these answers for us. They are as follows:

$$v = u + at \qquad \textbf{Equation 3.22}$$

$$v^2 = u^2 + 2as \qquad \textbf{Equation 3.23}$$

$$s = ut + \frac{at^2}{2} \qquad \textbf{Equation 3.24}$$

$$s = \frac{(u+v)t}{2} \qquad \textbf{Equation 3.25}$$

where v is the final velocity of the object in metres per second, (m s^{-1} or m/s), u is its initial velocity in m/s, and s is the distance in metres the object will have moved in the time interval t (seconds). The equations only work if the acceleration (and hence the applied force) is a constant over the time interval t.

These four equations follow on from other models. Again they always work.

Examples

a. A tractor travelling at 10 m/s accelerates at a rate of 0.5 m s^{-2} for 12 seconds. What is the final speed?

Solution: From *Equation 3.22*:

$v = 10 + 0.5 \times 12 = 16$ m/s

b. How far will it have travelled?

Solution: From *Equation 3.25*:

$$s = \frac{(10+16)\times 12}{2} = 156 \text{ metres}$$

c. A hay bale falls from the top of a building 8 m high. What is the speed when it hits the ground, given that the acceleration due to gravity is 9.8 m s^{-2}?

Solution: From *Equation 3.23*:

$v^2 = 0^2 + 2 \times 9.8 \times 8 = 156.8$

Hence $v = 12.52$ m/s on impact with the ground.

d. What force is required from a fence to stop a 40 kg sheep travelling at 12 m/s in a distance of 300 mm?

Solution: First we must find the acceleration (or deceleration since the sheep will be stopped). From *Equation 3.23*:

$$a = \frac{v^2 - u^2}{2s} = \frac{0 - 144}{2 \times 0.3} = -240 \text{ m s}^{-2}$$

Thus, from *Equation 3.20*:

$F = 40 \times (-240) = -9600$ N

The minus sign just means the sheep is stopped by the force which opposes the way it is moving. The breaking load for fencing wire is around 6500 N, so the wire would break under these conditions (which is just as well, as the deceleration would be enough to kill the sheep anyway).

This last problem is an example of a simple calculation which gives unreal answers. This is good because it tells us that the original proposition (ie, that a fence wire can stop a sheep in 300 mm when the sheep is moving at 12 m/s) is unrealistic, or produces unsatisfactory results (a broken fence and sliced sheep). To find a solution to the problem of stopping the sheep without killing it is one which will require more careful thought. Although this problem is perhaps one which is not a great everyday worry for the average sheep farmer, a deer farmer should be concerned about the implications. It is also of considerable concern to the designers of motorway crash barriers, where a rigid barrier would be most unsatisfactory.

3.10 MOMENTUM

The next quantity which needs to be discussed briefly is momentum. This is simply the product of the mass of a body times its velocity. Thus

$$\text{Momentum} = M\ v \ (\text{kg m s}^{-1} \text{ or N s}) \qquad \textbf{Equation 3.26}$$

Note that the units look a little odd. However the key point about momentum is its conservation law:

If no external forces are acting then momentum is conserved.

This can be written as:

$$\Sigma \text{ Momentum before} = \Sigma \text{Momentum after} \qquad \textbf{Equation 3.27}$$

This means that the momentum after an event involving a change in velocity is the same as beforehand. This has applications to the flow of water around bends in pipes, water power turbines, and the impact of a pile driver onto a pile, as well as the behaviour of tractors, cars, and bullets.

Example

A pile driver (mass 100 kg) falling at a speed of 5 m/s strikes a pile weighing 10 kg. Calculate the velocity of the pile and driver immediately after impact if they travel together at the same speed after impact.

Solution: Momentum before
$= Mv = 100 \times 5 + 10 \times 0 = 500$ kg m/s

If the velocity after impact is V, then

after impact, momentum $= (100 + 10)\ V$

By conservation of momentum,

$110\ V = 500$

Thus $V = 500/110 = 4.56$ m/s (initially).

Notice that in the problem we had to specify that the two bodies stayed together after the impact. Some further information is always needed to specify the impact fully, because some energy is normally converted to heat (or sound). Sometimes the *Coefficient of Restitution* (e) is used. This is defined as the ratio of the velocity of separation after the impact to the velocity of approach. Thus:

$$e = \frac{\text{Velocity of Separation}}{\text{Velocity of Approach}}$$

$$= \frac{v_2(\text{after}) - v_1(\text{after})}{v_1(\text{before}) - v_2(\text{before})} \qquad \textbf{Equation 3.28}$$

where v_1 etc refer to the velocities of the first and second object before and after impact. Note that v_1 and v_2 can be positive or negative depending on their sense. Velocities in one direction must be taken as positive, and those in the opposite direction will be negative.

Example

A ripe peach impacts against a large metal plate. If the impact velocity is 3 m/s and $e = 0.25$, calculate the rebound velocity.

Solution: Since the plate is large, this implies that it does not move significantly. Thus the rebound velocity of the fruit will be:

$$v_1 \text{ (after)} = -e\ v_1 \text{ (before)} = 0.25 \times 3 = 0.75 \text{m/s}$$

3.11 GETTING A REACTION

Newton's Third Law of Motion is very simple, but for most people it is also very puzzling. It says that:

For every applied force, there is an equal and opposite reaction force.

Thus if I kick a rock with my toe, in a sense my toe feels as if the rock had kicked me. The bruise on my toe tends to confirm this, so the model seems to be consistent with reality.

The value of this law is that it enables us to make simple models of real situations which are easy to analyse. For example, consider the design of a bridge (*Figure 3.14a*). The bridge

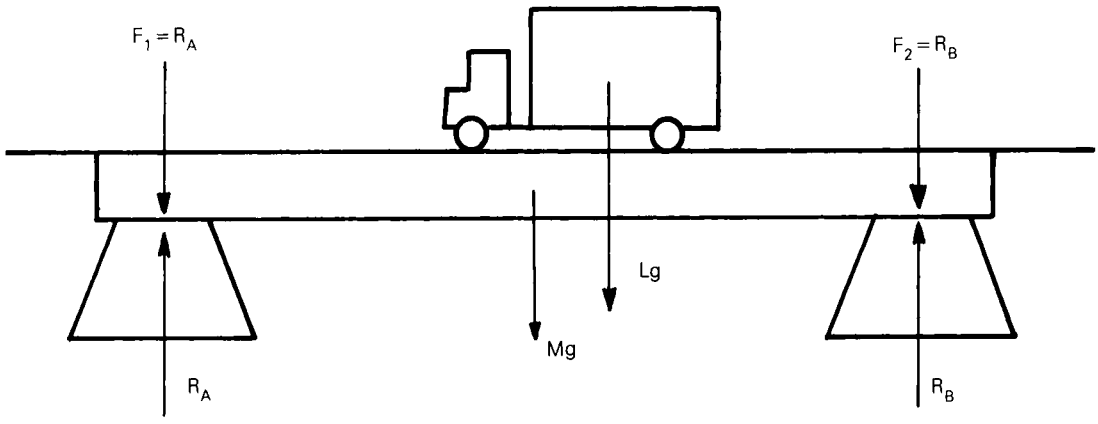


Figure 3.14(a) Bridge and supports showing equal and opposite reactions.

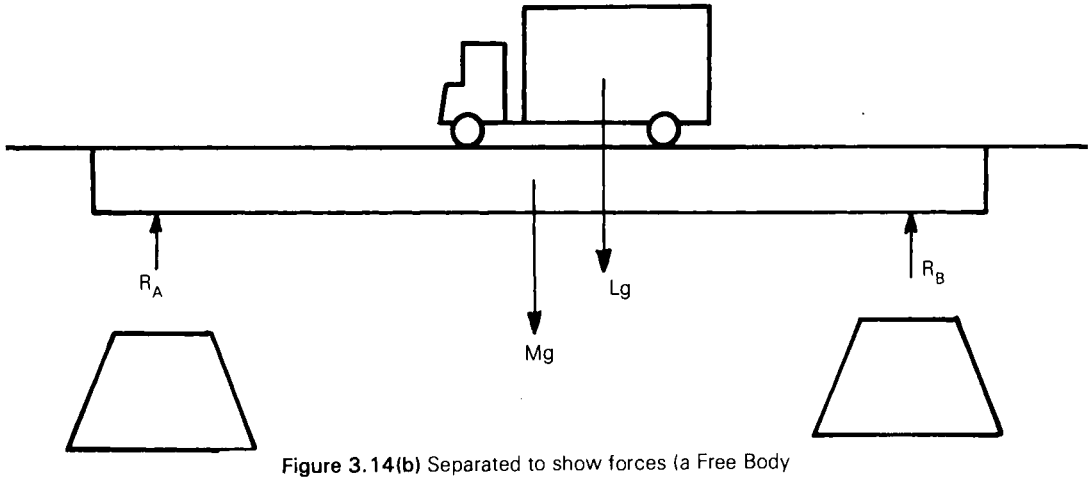


Figure 3.14(b) Separated to show forces (a Free Body diagram).

Figure 3.14 Reaction forces. M and L are the masses of the bridge and the truck respectively.

is supported at the ends. If the supports were not there the bridge would accelerate under gravity until it hit the ground beneath. The supports are therefore providing forces to hold the bridge up. These forces are called the *Reactions*. Thus the bridge pushes down on the supports with forces R_A and R_B, while the bridge experiences these same forces to hold it up.

Interesting but trivial? The answer is yes until we separate the bridge and the supports in our mind or in a model on paper, as in *Figure 3.14b*. Now we can analyse the forces on the bridge alone. We have replaced the entire effect of the supports by the two forces R_A and R_B, so the problem has become a lot clearer to analyse. This is called a Free Body Diagram.

Example

A tree is growing in a container so that the total mass is 40 kg (*Figure 3.15*). The tree is in a wind which is applying a force of 0.3 kN in a horizontal direction through point P. What is the reaction force on the container from the ground?

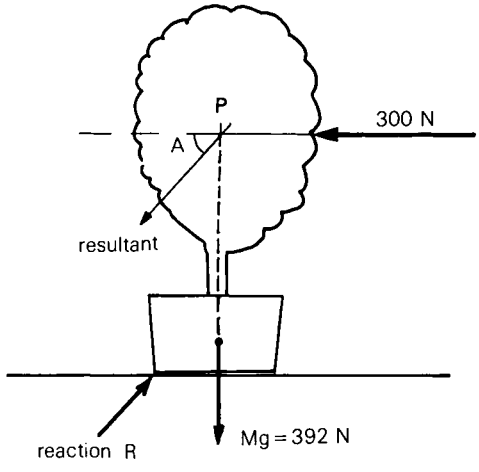


Figure 3.15 Reaction forces: the stability of a pot plant.

Solution: In order for the container to remain stationary, all the forces on the container must add up to zero. The only forces which act are those of gravity, which causes a force of $40 \times 9.8 = 392$ N vertically downwards through the centre of gravity (the weight), the horizontal wind force of 300 N, and the reaction from the ground. Thus the reaction must be equal and opposite to the resultant of the other two forces. Combining these, the resultant R is given by:

$R^2 = 300^2 + 392^2 = 243{,}664$

Thus $R = 494$ N

Note that the line of action of the resultant must be through P.

The direction of the reaction force is at an angle A to the horizontal given by

$$\text{Tan A} = \frac{392}{300} = 1.307$$

ie, $A = 52.6°$

3.11.1 The normal reaction

Whenever two surfaces are in contact there will be a reaction force between them. The component of the reaction force which is at right angles to the surface at the point of contact is called the Normal Reaction. Thus if an object is resting on a horizontal floor, the normal reaction (R_N) will be equal to the weight of the object, and there will be no horizontal component of the reaction. In the case of the tree in *Figure 3.15* the normal reaction will be equal to the weight of the tree and in a vertical direction.

In passing we should note that the tree will fall over if the line of action of the resultant passes outside the base. The wind forces combine with the friction force along the ground (as discussed below) to produce a turning couple. Normally this is balanced because the line of action of the reaction force moves to the left in the figure, producing a couple along with the weight in the opposite direction. In this example as drawn there will be a resultant couple since the couple produced by the wind and friction forces cannot be balanced by the couple generated by the weight and the normal reaction, and the pot will tip over (compare this with the tractor in *Figure 3.9*). The tree is in trouble if the base is too small!

3.12 FRICTION

Consider an object such as a wool bale standing on the floor of a woolshed. There will be a reaction force between the floor and the bale. It will be at right angles to the floor (ie, vertical), and there will be no horizontal component. Suppose we now wish to shift the bale. We try to push it across the floor. At first we simply push and nothing happens. If we increase the effort (push harder or get some help) eventually when the force is enough the bale moves and we are able to slide the bale across the floor. We have just overcome the force due to friction. This behaviour can be described by the following model, using the nomenclature of *Figure 3.16*:

as we increase the sideways force P, up to a limiting (or maximum) value the friction force F equals the force P and so prevents sliding.

The maximum value of the friction force is given by:

$F = \mu R$ **Equation 3.29**

where μ is a constant which depends only on the nature of the two surfaces, and is

independent of the surface area of contact, and R is the normal reaction between the two surfaces. After sliding begins the friction force continues to oppose the motion. Its value is still given by *Equation 3.29.**

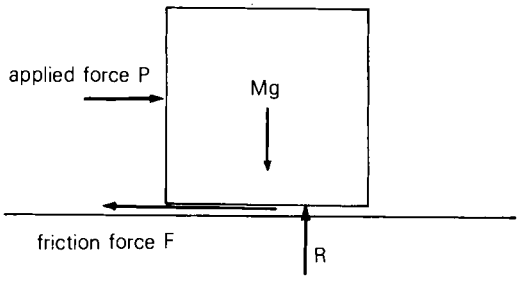


Figure 3.16 Friction: a wool bale being slid across the floor.

Using this model the reaction between any two surfaces in general can be described as having two components: the normal component at right angles to the surface of contact (R), and the frictional component parallel to the surface (F).

It is often useful to simplify the model by assuming μ is very large so that there is no slip regardless of the applied force. In this case the surface is called a rough surface. Alternatively we may wish to say that friction is negligible, so that μ is equal to zero. Now the surfaces are deemed to be smooth.

Example

Calculate the force required to slide a 200 kg wool bale across the floor if $\mu = 0.4$.

Solution: The normal reaction is equal to the weight:

ie, $R = 200 \times 9.8 = 1960$ N

Thus the limiting value of friction is given by:

$F = \mu R = 0.4 \times 1960 = 784$ N

Example

A man can pull with a force of up to 500 N. Calculate the maximum weight of a stack of apple cartons which he will be able to drag up a 30° slope if $\mu = 0.35$.

Solution: The forces are shown in *Figure 3.17*. Let the weight of the cartons be W Newtons.

Then resolving along the slope:

$P = F + W \cos (90 - 30)$

Resolving parallel to the slope gives the normal reaction R:

$R = W \cos 30$

When friction is limiting, $F = \mu R$

Thus combining these three relationships gives:

$P = \mu W \cos 30 + W \cos 60 = 0.8031$ W

$$\text{Thus } W = \frac{P}{0.8031} = 623 \text{ N}$$

This corresponds to a mass of 63.5 kg.

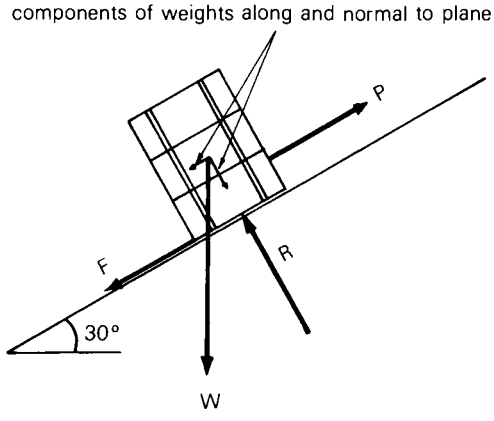


Figure 3.17 Inclined plane and friction.

* In reality, although *Equation 3.29* is still valid, the coefficient of friction during sliding is usually a little lower than the coefficient of friction when the surfaces have not started slipping, which is why objects sometimes slide in a stick slip manner. Thus, some texts will specify the coefficients of static and sliding friction separately. For our purposes the difference is small enough to ignore.

3.12.1 Applications

Friction is a feature of our world. Objects sliding along the ground or down slopes, pistons moving in cylinders, or ladders staying against walls, are all situations where friction has to be considered. Friction also affects the flow of water in pipes and channels. We will describe the way in which friction affects the performance of tractors.

Rolling friction

In order for a tractor (or car) to move forward, it must apply a force to the ground. The

engine applies a torque to the driving wheels which makes them rotate. The tyres generate a frictional force on the soil which pushes the soil backwards. The equal and opposite reaction then propels the tractor forwards. *Figure 3.18* shows the case of a rear-wheel drive tractor. The maximum traction will be equal to the maximum friction force before the wheel slips on the ground. From *Equation 3.29* for good traction the tyre must have a high value of μ and the normal reaction must also be as high as possible. This means that the weight on the tractor driving wheels must be as large as possible. Unfortunately this means that the soil will be highly loaded, which leads to soil compaction, and damage to the soil structure. In Europe soil compaction is a serious problem, and very wide low pressure tyres are often recommended, since they produce a lower soil stress by spreading the area over which the load is applied. The tyre must be designed to increase the friction coefficient. In practice some sliding is inevitable during cultivation work. The tractor needs to be driven so that the wheelslip is just right. It is affected by the soil conditions, the tractor weight and any ballasting, and the gearing. If the tractor is being used for ploughing there is an additional drag force due to the plough which the rolling friction must also overcome.

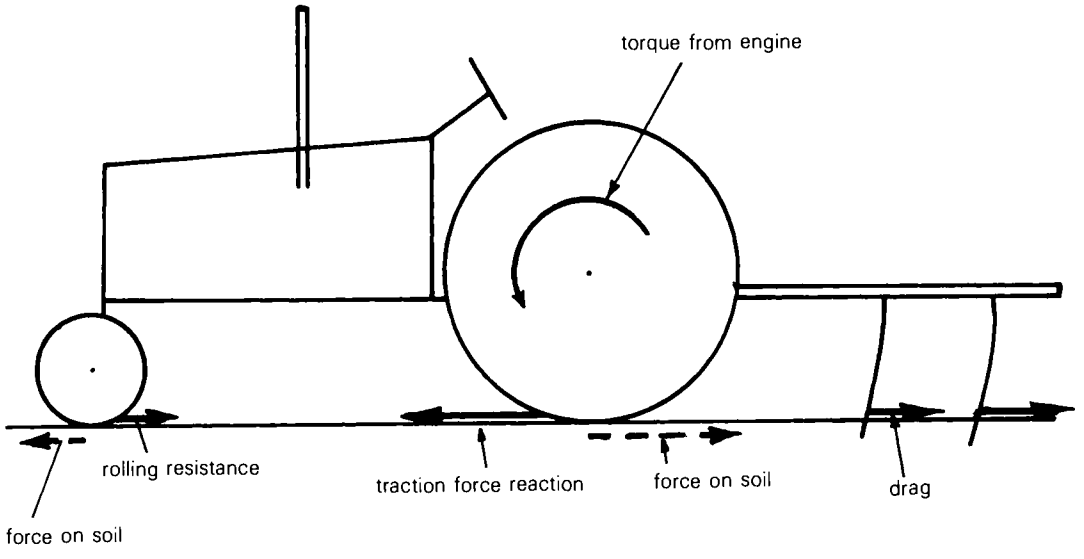


Figure 3.18 Forces on a tractor (rear-wheel drive).

Rolling resistance

Friction also interferes with the progress of the tractor. The front wheels deform the soil, and this causes a resistance to motion (*Figure 3.18*). Other frictional forces also impede the motion and must be overcome. These are called the Rolling Resistance.

3.13 DISTRIBUTED LOADS

Earlier the law for equilibrium was stated for forces acting at a single point. What happens if the forces do not all act through a single point? Is there a similar condition for the equilibrium of an object where the forces act at different points? The answer is yes; the condition is:

> *the sum of all the moments of all forces acting must equal zero.*

Recall that clockwise moments are positive, and anti-clockwise negative.

For example, consider the forces in the support structure for one section of a greenhouse as in *Figure 3.19*. Here we have simplified the model so that the total loads on the structure can be reduced to the forces

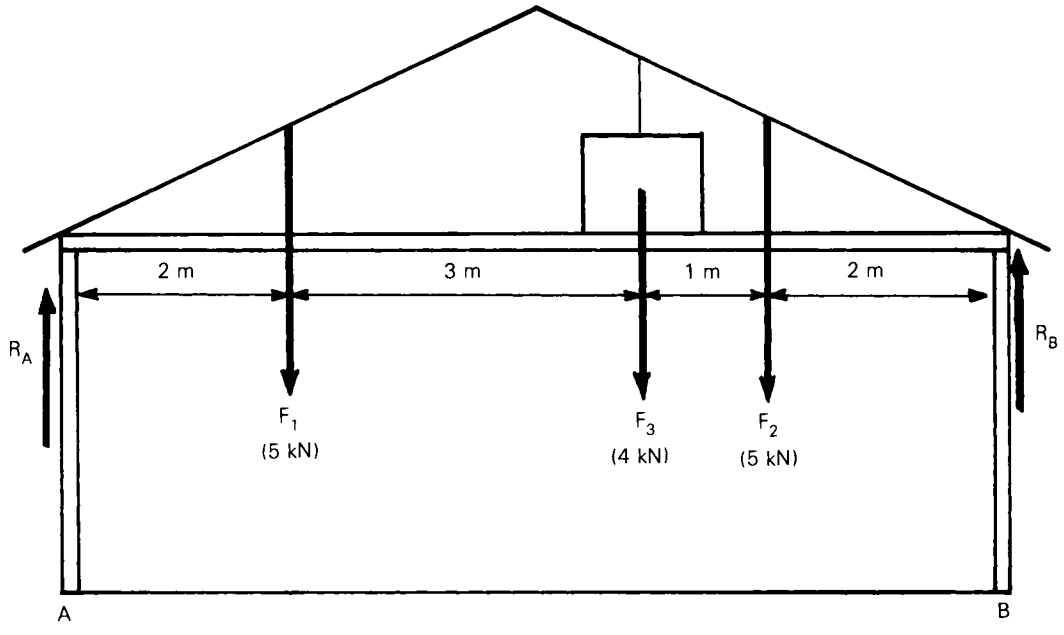


Figure 3.19 Loads on greenhouse support pillars.

shown. F_1 represents the force on the support beam due to the weight of the glass on the left, and F_2 the weight on the right (the position of these forces is fixed by the position of the centre of gravity of each side). In addition the equipment used in the house is supported by the roof structure, and this is represented in the model by force F_3. The first question to answer is what loads will there be on the side walls, since they must be strong enough to hold the beam up? These are represented by the reaction forces R_A and R_B. To solve this problem, we can use our first condition for equilibrium. The sum of all the forces acting on the beam is zero so:

$F_1 + F_2 + F_3 - R_A - R_B = 0$

Substituting the values gives:

$R_A + R_B = 14{,}000$ **Equation 3.30**

This does not solve the problem since both R_A and R_B are unknown. However using this second condition, we can take moments about any point and so obtain another equation.

Taking moments about A:

$0 \times R_A + 2 \times F_1 + 5 \times F_3 + 6 \times F_2 - 8 \times R_B = 0$

Note carefully which distances are involved and the sign of each moment. R_B is negative because it is anti-clockwise. Substituting gives:

$8R_B = 60{,}000$

Thus $R_B = 7{,}500$ N

From *Equation 3.30*:

$R_A = 14{,}000 - 7{,}500 = 6{,}500$ N

This tells us the loads on the walls. As yet we do not know the forces in the members of the beam. We will do this later.

To sum up, this description of the real world claims that any object does not move only if:

a. There is no resultant force in ANY direction;

and

b. There is no resultant moment about ANY point.

If a resultant force acts the object will inevitably move (accelerate) in that direction, while if a resultant moment acts it will rotate the object in the direction of the resultant.

3.14 FRAMEWORKS

A framework is an arrangement of beams assembled to form a rigid structure, eg, *Figure 3.20*. Frameworks are used to support heavy loads such as roofs of buildings, bridges, electricity pylons, and other structures. The

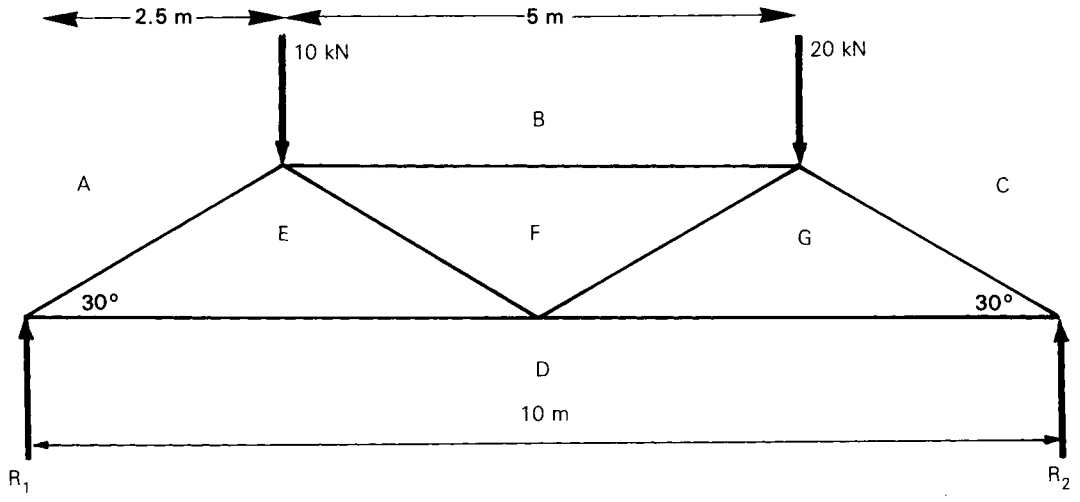


Figure 3.20(a) Calculation of stresses in a framework.

framework is almost always made up of a series of triangles, since three beams form a very rigid structure. Each beam transmits the load it is taking on to another beam, or to the support. The beams are all under different loads, and in order to determine the size of a beam, it is important to be able to calculate the loads and stresses on each beam in turn. In order to do this we make use of a simplified model. We assume that the beams are light compared with the applied loads, and that they are connected together at the ends by frictionless pin-joints (this means that the beams can rotate about the pin: if this condition did not apply then there could be additional stress at the joints). We also need to specify that the loads and supports are applied only at the joints. Under this set of conditions then the beams will all be under tension or compression only, and we can ignore sideways loads on the beams. The method given here works well when this model is close to the real situation.

In order to work out the forces in the beams there are a series of steps which are required. We will demonstrate them with an example using the loading in *Figure 3.20a*. First the reactions at the supports should be calculated. Thus using the laws for equilibrium:

$R_1 + R_2 = 10{,}000 + 20{,}000 = 30{,}000$ N

Taking moments about the left-hand support:

$2.5 \times 10{,}000 + 7.5 \times 20{,}000 - 10 \times R_2 = 0$

$$\text{ie, } R_2 = \frac{175{,}000}{10} = 17{,}500 \text{ N}$$

Thus $R_1 = 30{,}000 - 17{,}500 = 12{,}500$ N

The next step is to letter all the spaces in the diagram (*Figure 3.20a*). First, the spaces between the forces outside the framework are labelled A,B,C, etc, as in the Figure. Next the spaces in the framework are labelled E,F, etc. Each beam, each force and each reaction now lies between two letters and can be identified by those two letters. In order to define the forces precisely, the letters are read in a clockwise direction around any point. Thus R_1 is the force DA, (and not AD) while the uppermost horizontal beam is BF. This is called Bow's Notation (after the inventor).

When this has been done a vector diagram is drawn, which is a model of the forces. The lines representing the external forces are drawn in first, with line lengths which are proportional to the size of the forces (*Figure 3.20b*). These are AB (10 kN vertically downwards with A at the top and B below it), BC (20 kN), CD (ie, R_2, which we have worked out to be 17.5 kN upwards), and DA (12.5 kN). This results in this case in a vertical line with points A,B,D, and C on it in that order.

Next we consider a junction where there are only two unknown forces. The left hand support is just such a junction. We work out

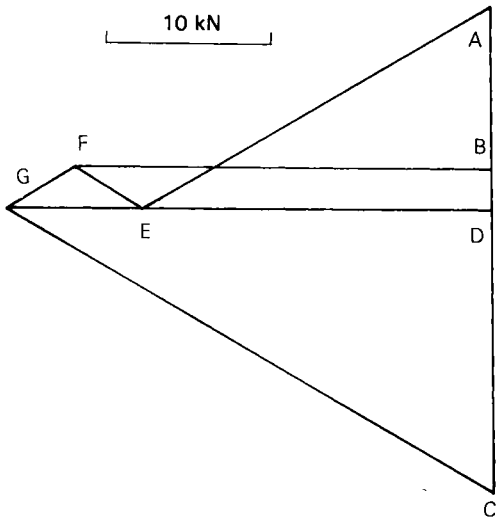


Figure 3.20(b) Force vector diagram (Bow's Notation).

where point E will be on the force diagram, by drawing lines parallel to the directions of the beams DE and EA. Since D and A are already fixed, there is only one point where E can be: at the intersection of these two lines on the force vector diagram. Now the length of line DE gives the magnitude of the force in the beam DE.

Next we can repeat the process to draw in lines representing forces EF and BF to fix point F on the force diagram. Finally point G is found from FG and GC.

The lengths of AE, EF, BF, FG, GC, GD, and DE give the magnitudes of the forces on the junctions. From the figure the forces are 25.0, 5.0, 26.0, 5.0, 35.0, 30.3, and 21.7 kN respectively. The force along each beam will be the same magnitude. We now need to work out whether the beam is under compression or tension, by working out the direction of the forces at the junctions. The direction of the force in the beam will then be in exactly the opposite direction, in accordance with the law of equal and opposite reaction. At the left hand support the force on the junction due to the horizontal beam is ED rather than DE, because we are working in a clockwise direction. The direction of force ED in the force diagram is from left to right, so the force ED must also be from left to right, and we can mark it in at the junction accordingly (*Figure 3.20c*). A similar argument gives the direction of force AE on the junction as downwards. All the forces can be specified by going around the other junctions clockwise. In this way the force on the upper junction of beam EA will be upwards as shown. By inspection beam AE must be in compression, because the forces it is producing on the junction have been calculated and are in the directions marked (*Figure 3.20c*). The beam AE is thus pushing against the junction, and is therefore in compression. The forces on it are shown in *Figure 3.20d*. DE on the other hand is in tension, since it is pulling the junctions together. Beams in compression are called Struts, while beams in tension are called Ties. Thus AE, BF, FG, and CG are all struts, while ED, EF, and GD are ties.

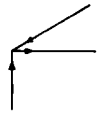


Figure 3.20(c) Forces on junctions.

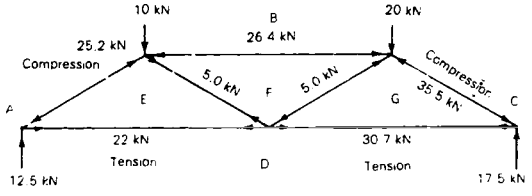


Figure 3.20(d) Loads in members and forces on joints. Arrows indicate direction of force on each joint.

This analysis tells us the forces along the beams, assuming that they are all pin-jointed, so that none of the beams are under a bending load. When beams are subjected to bending stresses, we need to develop another model to determine the stresses it experiences.

3.15 ELASTIC MODEL OF A BENDING BEAM

We will now consider the loads and stresses which develop in a beam which is being subjected to a bending load, as described earlier in section 3.2.4e. *Figure 3.21* shows an example of what happens if the bending moment on a beam is too great! The model which best describes the real behaviour specifies that there is a so-called *Bending*



Figure 3.21 Wooden bridge failure. (MAF Tech)

Moment (BM) and a *Shear Force* which exist at every point in the beam. Together these transfer the load along the beam, so that every part of the beam is in equilibrium. The size of the bending moment and the shear force can be calculated at any point and used to work out the maximum stress in the fibres of the beam. We will describe the model using a simple example.

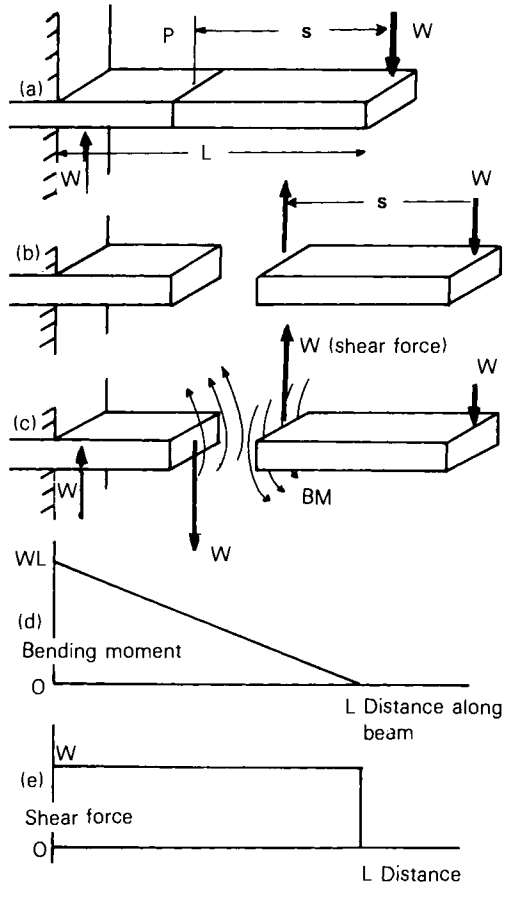


Figure 3.22 Cantilever beam.

Consider the cantilever beam shown in *Figure 3.22a*. Suppose we wish to find the Bending Moment at a point P a distance s from the end. First an imaginary cut is made in the beam at P (*Figure 3.22b*). Now we take moments for one side of the cut. We can choose whichever side of the cut is simplest to do. The bending moment at P is then equal to the total moment about P. Thus in the diagram, taking moments for the right hand end:

$$BM = s\,W \qquad \textbf{Equation 3.31}$$

The same answer would be obtained if moments were taken for the left hand side once a free body diagram is drawn (try it).

The direction of the BM will be such that it balances the moment of the weight. This is shown in *Figure 3.22c*. In addition the shear force W is also shown. The shear force is trying to shear the beam in a vertical plane. The model of one end of the beam shows why this force is needed: the end section must be in equilibrium both for all forces and all moments, so at the place where the section has been taken there must be a shear force to balance the downwards force of the weight on the end. This is needed to keep the right hand section in equilibrium.

The BM and shear force can be calculated and plotted for any point along the cantilever. The result is *Figures 3.22d* and *3.22e* respectively. The BM is a straight line and is a maximum at the support point. The shear force is constant along the entire cantilever. In practice the stresses due to the shear force are often negligible compared with the stresses due to the bending moment, and often it can be ignored safely.

Next let us consider a simply supported beam, as shown in *Figure 3.23a*. We will calculate and sketch the shear force and bending moment diagrams. This could be a beam in a greenhouse with the fans and heaters suspended from it, or a horizontal beam in a woolshed with a water tank and other equipment mounted on it.

In order to use the model to find the BM, all the forces including the reactions at the supports must first be known. This means that the reactions at A and B must first be calculated. This is done by taking moments

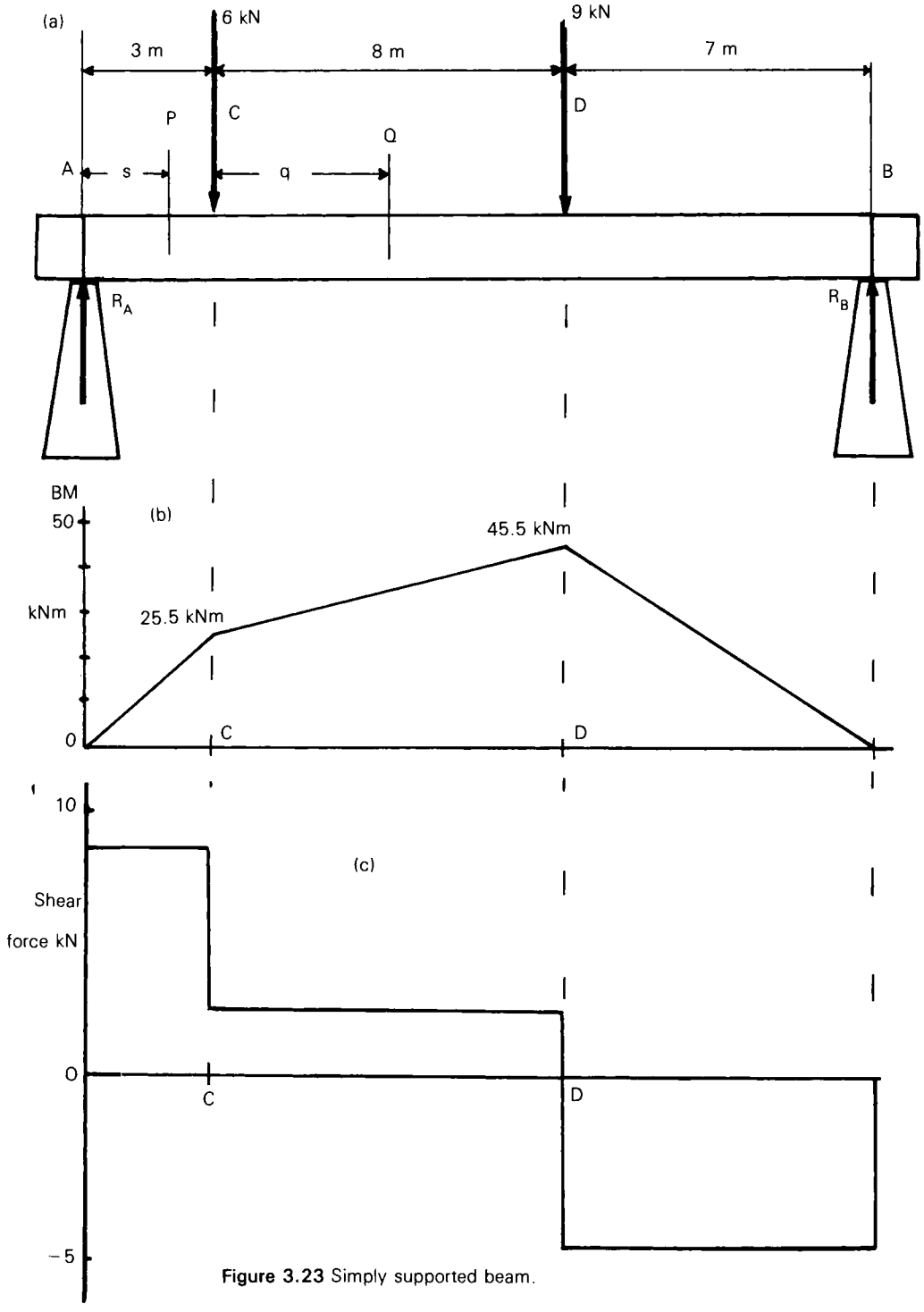


Figure 3.23 Simply supported beam.

for the whole beam and applying the equilibrium laws:

Taking moments about A:

$3 \times 6000 + 11 \times 9000 - 18 \times R_B = 0$

ie, $R_B = 6500$ N

Similarly (or by considering the sum of all the forces):

$R_A = 8500$ N

Now we can find the bending moment at any point by making an imaginary cut at the point of interest and taking moments for either side. Consider the BM at any point P, between A and C. The bending moment at any distance s from A is:

$BM = 8500 \times s$ N m

Between C and D the bending moment for any point Q a distance q from C is given by:

$BM = 8500(3 + q) - 6000q = 25500 + 2500q$

By calculating the bending moment at various points along the beam the resulting bending moment looks like the diagram in *Figure 3.23b*. Here the size of the bending moment is represented by the vertical axis at any point along the beam. Notice that it is zero at the ends, and is a straight line between the points of loading. All simply supported beams with point loads have these two characteristics. The maximum bending moment occurs at point D.

In fact, because we know that the beam is simply supported and has only point loads we only really need to find the BM at the points C and D, since between these points the BM diagram is a straight line.

Thus at A and B the BM is zero. At C the BM is found by taking moments for one side of the beam from C:

$BM = 3 \times 8500 = 25.5$ kN m

At D, $BM = 11 \times 8500 - 8 \times 6000 = 45.5$ kN m

In this way the bending moment diagram will be obtained more easily (*Figure 3.23b*).

The shear force diagram is shown in *Figure 3.23c*. It is produced by starting at one end and drawing vertical lines in the direction of the force wherever an external force is applied. The shear force is greatest between A and C (8.5 kN).

3.15.1 Uniformly distributed loads

Although the point load model is a good way of describing loads placed on beams, in many cases it is also necessary to take into account the actual mass of the beam itself, since in many cases this is greater than the other applied loads. It is also necessary to consider loads which are spread evenly over the entire surface of a beam. Examples of this include wind loads on roofs, or where a flock of sheep can be assumed to be spread evenly over the floor of a woolshed. Such loads can all be modelled adequately by describing them as Uniformly Distributed Loads, or UDLs. UDLs are normally specified in terms of the load per unit length of beam in Newtons per metre. The bending moment and shear force diagrams can be calculated from first principles using integration or by using a model, which states that the UDL can be treated as a point load acting at the centre of whatever moment length is being considered.

Suppose we wish to calculate the maximum bending moment for a simply supported beam of length L with a UDL of w N/m (*Figure 3.24a*). First we take moments to find the reactions at the ends (again a little thought saves doing this because we can see the beam is symmetrical and so the two supports will share the total load equally). The total load is wL, so:

$$R_1 = R_2 = \frac{w\,L}{2} \qquad \textbf{Equation 3.32}$$

The solution by integration is as follows: Consider the BM at a point P a distance p from R_2. Then the BM is found by integrating the contributions from each element ds at a distance s from P. Thus:

$$BM = -\frac{pwL}{2} + \int_0^p s\,w\,ds = \frac{pw(p-L)}{2} \qquad \textbf{Equation 3.33}$$

Plotting this shows that the BM curve is a parabola, with a maximum value at the centre (*Figure 3.24b*).

In some cases, it is possible to avoid this full calculation by using a little insight. We are usually interested only in the largest value of the BM, and if we can decide where it will be, then we only need work out the BM at that point. For example, a little thought shows that the maximum bending moment will lie in the centre (you can always check this by a few calculations).

To find the BM at the centre, we take moments for the loads on one end. The UDL is taken as equivalent to a point load at the centre of the section under consideration (*Figure 3.24c*). Thus:

$$BM_{max} = \frac{L}{2} \times R_1 - \frac{L}{4} \times \frac{wL}{2} \qquad \textbf{Equation 3.34}$$

Substituting for R_1 gives:

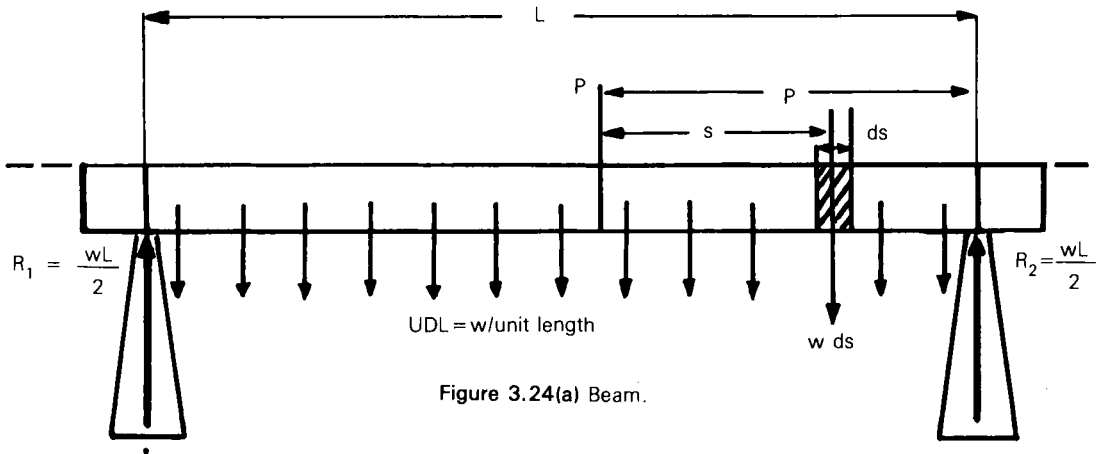


Figure 3.24(a) Beam.

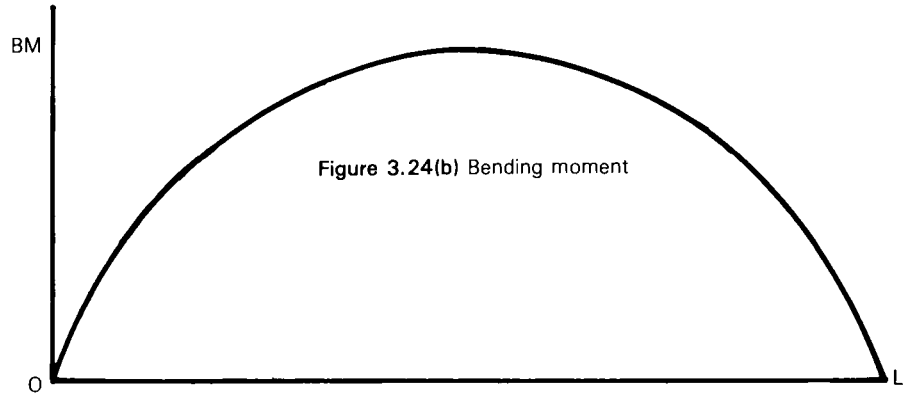


Figure 3.24(b) Bending moment

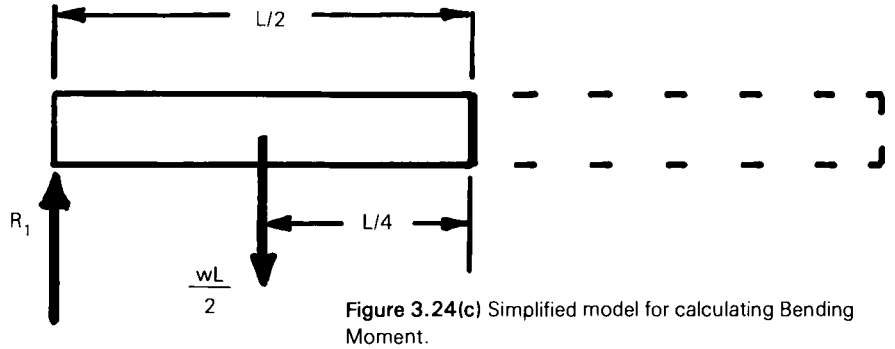


Figure 3.24(c) Simplified model for calculating Bending Moment.

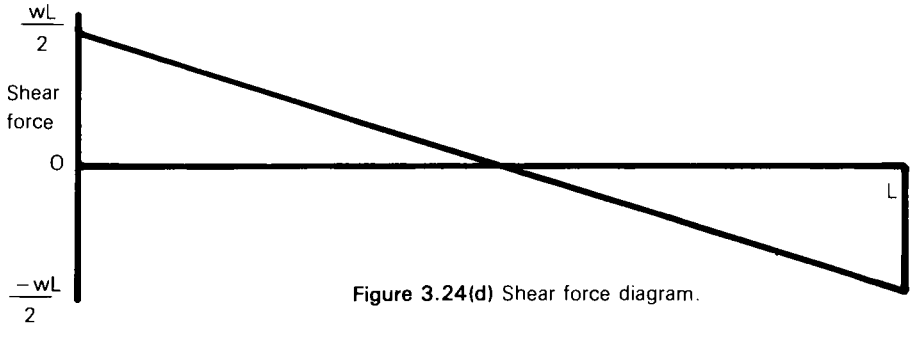


Figure 3.24(d) Shear force diagram.

Figure 3.24 Uniformly distributed load.

$$BM_{max} = \frac{wL^2}{8} \qquad \textbf{Equation 3.35}$$

The shear force diagram is shown in *Figure 3.24d*. Note that the emphasis has been on bending moments. This is because the stresses imposed by the shear force are usually insignificant compared to the stresses imposed by the bending moment.

Example

A farm bridge with a 9 m span between its ends A and B carries a load of 3.6 kN at 2.5 m from end A, and another load of 12.5 kN at 4 m from end B. It carries a UDL of 1.5 kN/m. Calculate the BM under the 12.5 kN load (point X).

Solution: First we find the reactions at the supports A and B. Taking moments about B, we can take the UDL as a single load half way along the beam. Thus, working in kN:

$$9R_a - (3.6 \times 6.5) - (12.5 \times 4) - (9 \times 1.5 \times 4.5) = 0$$

Thus $R_a = 14.9$ kN

and $R_b = 3.6 + 12.5 + (1.5 \times 9) - R_a = 14.7$ kN

To find the BM at X under the 12.5 kN load, we take moments for one side, treating the part of the UDL for that side as a single load half way along the section under consideration. Thus, considering the side between X and B:

$$BM = (14.7 \times 4) - (4 \times 1.5 \times 2) = 46.8 \text{ kN m}$$

This will be the largest BM on the bridge.

3.15.2 Response of beam to a bending moment

The above model requires us to have a bending moment and a shear force of varying size all the way along the beam. The next question is therefore to work out how the beam responds to this type of load. Clearly it bends a little. Let us study the bending of an initially straight beam as in *Figure 3.4e*, which shows the forces on the beam. The beam is under bending in this situation, and the resulting deformation is shown in a greatly exaggerated manner. We will use a model which assumes that the beam behaves elastically, so that the stress is proportional to the strain everywhere. This also means that the load will not cause permanent damage to the beam, providing the stresses calculated do not exceed the yield point of the material.

Consider what is happening at any section along the beam where the BM is known. The beam bends as shown in *Figure 3.25*. As we are assuming the beam is elastic, wherever the beam fibres are stretched or compressed there will be a stress which will be proportional to the amount of extension. The upper surface of the beam AB is compressed to a distance A'B', while the bottom surface CD is stretched. Somewhere near the middle of the beam there will be a place (EF) where the beam is neither compressed nor stretched, so that EF = E'F'. This is called the *Neutral Axis*, which is the line joining all the places along the length of the beam where the strain is zero. The position of the neutral axis is useful as a reference location for analysing the behaviour of the rest of the beam. Since the stress is proportional to the strain, the stresses across the beam vary from

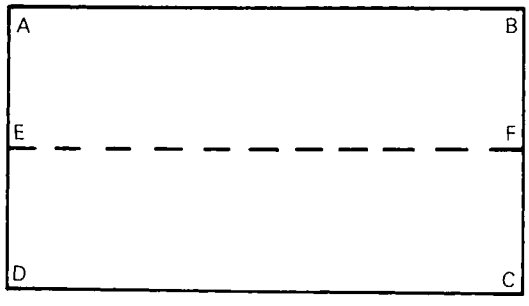


Figure 3.25(a) Original shape of section before loading.

compressive at the top, through zero at the neutral axis to tensile at the bottom as shown. These stresses must match the effect of the bending moment to keep the beam in equilibrium. It is possible to work out their size from geometry: if the beam bends into a curve with the neutral axis at a radius R the strain at a distance s from the neutral axis is given by:

$$\epsilon = \frac{s}{R} \qquad \textbf{Equation 3.36}$$

$$\text{so the stress is } \sigma_s = \frac{E\,s}{R}$$

$$\text{or } \frac{\sigma_s}{s} = \frac{E}{R} \qquad \textbf{Equation 3.37}$$

where E is the modulus of elasticity. If σ is the stress in the outermost fibre, at a distance y from the neutral axis, we can write this as:

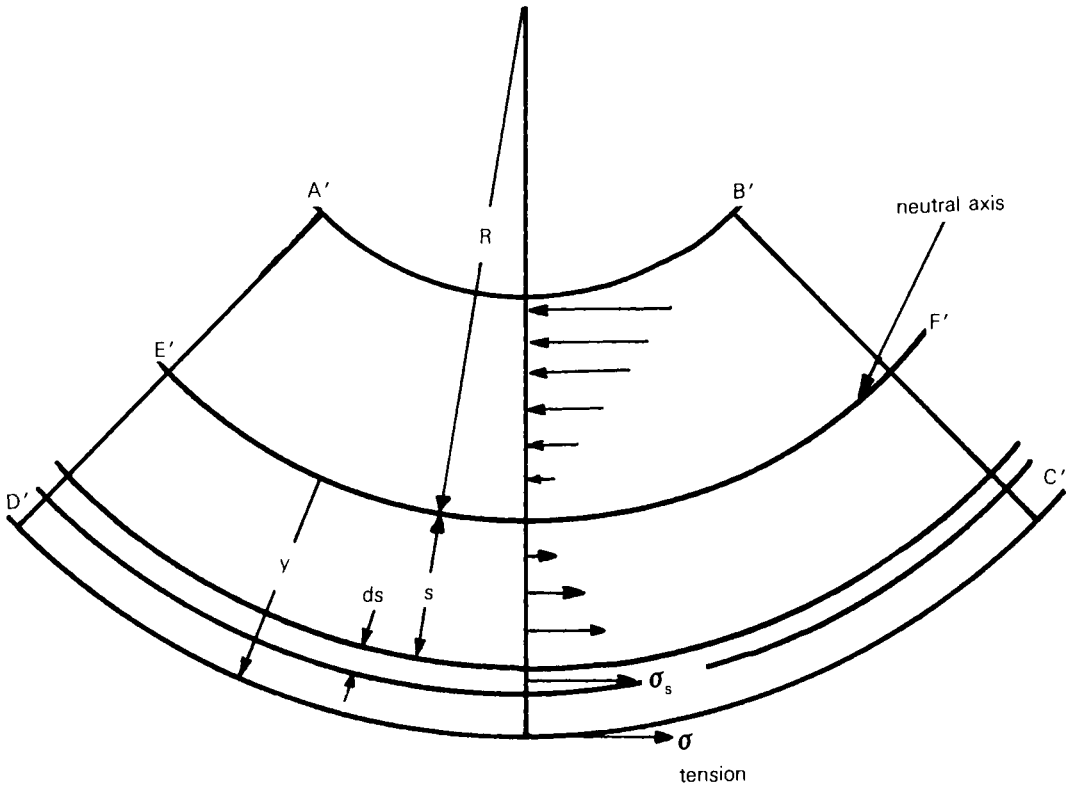


Figure 3.25(b) Beam with load applied (bending is exaggerated) EF = E'F'.

$$\frac{\sigma}{y} = \frac{E}{R}$$ **Equation 3.38**

3.15.3 Position of the neutral axis

The neutral axis is found by ensuring that the sum of the tension forces is equal to the sum of the compression forces on the section (again, this is nothing more than the condition for equilibrium). This requirement shows that the neutral axis must pass through the centroid of the area, which can be calculated using the method described under the section on the centre of gravity. For a simple symmetrical beam the neutral axis will be in the middle.

3.15.4 Relationship between stress and bending moment

If the beam is B thick then for a small strip ds wide the force due to this element is simply:

$$F = \text{stress} \times \text{Area of strip} = \frac{s\ E\ B\ ds}{R}$$ **Equation 3.39**

Thus taking moments about the neutral axis, for the stress at a point s from the neutral axis and integrating gives:

Moment due to stresses = BM at section

$$= \int Fs\ ds = \int \frac{E\ B\ s^2 ds}{R} = \frac{E}{R} \int B\ s^2 ds$$ **Equation 3.40**

Now the integral function is called the second moment of area and is given the symbol I. It is a function of the shape of the cross-section only, and can be calculated without reference to the loading situation. This means that our formula for the bending of the beam becomes:

$$BM = \frac{E\,I}{R}$$ **Equation 3.41**

where $I = \int B\,s^2\,ds$ = Second moment of area

Equation 3.42

In practice the value of I can be calculated for various section shapes using *Equation 3.42*. More often the value is published by the manufacturer, or is available as a standard formula for various section shapes, as listed in *Table 3.4*.

Combining *Equations 3.37, 3.38,* and *3.41* together gives:

$$\frac{\sigma_s}{s} = \frac{E}{R} = \frac{\sigma}{y} = \frac{BM}{I}$$

Equation 3.43

where BM is the calculated bending moment at the section (N m), I is the second moment of area (m^4), σ is the maximum stress (Pa) at the outer edge of the beam a distance y (m) from the neutral axis, E is the Young's Modulus of the material (Pa), R is the radius of curvature of the beam (m), and σ_s is the stress (Pa) in the beam at any distance s (m) from the neutral axis of the beam.

The most crucial and useful part of this equation is:

$$\sigma = \frac{BM \times y}{I}$$ **Equation 3.44**

where σ is the maximum stress in the beam, located at the furthest point from the neutral axis (a distance y from it).

Since the distance to the outermost fibre, y, is fixed for any particular beam shape, it is possible to simplify *Equation 3.44* even further, by defining a material property called the *Section Modulus* z, given by:

$$z = \frac{I}{y}$$ **Equation 3.45**

Values of z are also given in *Table 3.4*. *Equation 3.44* just becomes:

$$BM = \sigma\,z$$ **Equation 3.46**

What does this mean in practice? First we can see that the fibres of the beam are under varying levels of stress. At any section the stress will be greatest at the upper and lower extremities of the section. We can also see that the greatest stress of all will lie where the bending moment is greatest. Thus we can identify the section and the exact point where the load is greatest. If we know the strength of the material the beam is made from, we can calculate the stresses at the worst point and design the beam so that it does not fail.

Example

What is the greatest load which can be supported in the middle of a simply supported wooden beam 6 metres long with a rectangular cross section of 250 × 75 mm, if the maximum safe working stress is 6.9 MPa?

Solution: If the load is W Newtons then the reaction at each support will be just W/2 Newtons, since the load will be equally divided between the two supports.

Table 3.4 Second moments of area and section moduli

Shape of cross section	I (m^4)	z (m^3)
Rectangle (width B, depth D)	$\frac{B\,D^3}{12}$	$\frac{B\,D^2}{6}$
Rod or circle, (diameter d)	$\frac{\pi\,d^4}{64}$	$\frac{\pi\,d^3}{32}$
Pipe (outer diameter d_1, inner diameter d_2)	$\frac{\pi\,(d_1^4 - d_2^4)}{64}$	$\frac{\pi\,(d_1^4 - d_2^4)}{32d_1}$
Triangle	$\frac{bh^3}{36}$	–

The bending moment will be greatest at the centre just under the load, and will be given by:

$$\text{Maximum BM} = \frac{3\,W}{2} = 1.5\,W$$

Equation 3.47

From *Table 3.4* the section modulus is given by:

$$z = \frac{B\,d^2}{6} = \frac{0.075 \times (0.25)^2}{6}$$

$$= 7.813 \times 10^{-4}\ m^3$$

The maximum allowable bending moment will thus be:

$$BM = \sigma\, z = 6.9 \times 10^6 \times 7.81 \times 10^{-4}$$
$$= 5{,}391\ N\ m$$

Hence from *Equation 3.47*, the maximum load is given by:

$$W = \frac{5391}{1.5} = 3590\ N$$

3.16 WORK, ENERGY AND POWER

In ordinary life, the words work, energy and power are used to cover a variety of things. We can talk about work as the job a person does, or we can make a car "work" as it goes up a steep hill, or a broken radio can be made to work by a skilled electrician. Similarly the term energy can refer to a person's enthusiasm, or it is the thing we obtain from fuel, while power can be political, mechanical, cleansing, or even computing in its nature. It can even be a very pleasant shellfish found in New Zealand waters.

In engineering we use these three terms in our models and therefore we are not content to allow them to have vague or ambiguous meanings. Instead they are defined very specifically in ways that may seem a little strange. Again it must be emphasised that we use the terms defined in this fashion because they result in a model of our world which describes what happens successfully.

3.16.1 Work

The definition of work (or work done) is the product of force and distance moved in the direction of the force.

Thus Work done = Force × Distance moved

or $WD = F \times d$ **Equation 3.48**

The units of work are Joules (J) after a famous nineteenth century scientist, who played a crucial role in the development of mechanics. Since the units of force are Newtons and distances are measured in metres, therefore 1 Joule is the work done when 1 Newton acts through 1 metre.

Example

Calculate the work done in raising a 20 kg hay bale through a height of 5 metres.

Solution: Work done = Force × distance moved in direction of force = F × d

Force due to gravity = Mass × g = 20 × 9.8 Newtons

Therefore $W = 20 \times 9.8 \times 5 = 980$ N

Example

A farmer carries a 20 kg hay bale 50 metres across a level floor. How much work has been done?

Solution: The answer is none since the hay bale has not moved in the direction of the applied force. The farmer is only doing "work" when he or she lifts the bale up against the force of gravity. If the farmer were dragging it across the floor then work would be done, since there would be a friction force opposing the movement. If this seems unfair remember that we are not considering a definition of doing work from the point of view of establishing the usefulness or otherwise of labouring activities: the object here is merely to establish the work done according to our engineering model.

It follows that if there is no movement, then no work is done, regardless of how big the force is (ie, how hard we push). This seems odd because if we push against an immovable object, after a time we get tired, and hot, and we feel as if we have been working very hard indeed. Part of the difficulty here lies with the way our bodies operate. In order to apply a force, we must cause the muscles in our body to contract. This requires chemical energy. However in order to maintain the contraction further chemical energy is needed continuously by the muscles, to replenish the chemicals which are being used up all the time. This energy is converted to waste products and heat. Thus when our body

maintains a muscle under compression, it feels as if it is working hard (which it may well be), but this does not mean that it is actually doing any useful work at all.

A final note on work is to say that it is effectively the energy transferred by a force. We will consider this point again later.

3.16.2 Power

Power is simply the rate of doing work. Thus

$$\text{Power} = \frac{\text{Work done (J)}}{\text{Time taken (secs)}}$$

Equation 3.49

The units of power are joules/second, but we have named this the watt (W), after the inventor of the steam engine, Sir Isaac Watt. Thus:

1 Watt = 1 joule/second

Power can therefore be used only to describe how fast something is doing work. Examples of this range from light bulbs which have power ratings (again the rate is important) of around 25 to 200 watts, to electric motors which range from a few watts up to several hundred kiloWatts (kW). This means that when these devices are switched on they will do work at the rates indicated (in the case of a motor the rating is an indication of the maximum rate of power output that the motor is designed to achieve rather than the actual output under all conditions).

Example

A front end loader lifts a stack of hay bales weighing 200 kg through a height of five metres in two seconds. Calculate the power required.

Solution: The work done is

$$WD = 200 \times 9.8 \times 5 = 9800 \text{ J}$$

$$\text{Hence} \quad \text{Power} = \frac{9800}{2} = 4900 \text{ W}$$

Note that the power required will be less if the time taken is much longer. Thus in the design of power equipment there is often a compromise between size of equipment (and hence the cost) and speed of doing the job.

Before leaving the subject we must also mention the old fashioned horse-power which is an old imperial unit for sizing power equipment. It is still a very common term, but it is no more nor less than 746 watts. A one hp motor therefore has a design rating of 746 watts of power output.

It is also worth noting that a healthy adult can generate about 650 watts of mechanical power on a bicycle machine, but only for short periods of time. The continuous rating of a human is about 250 watts.

3.16.3 Energy

Energy is the potential a body has to do work. We know precisely what work is, at least in an engineering sense, from the previous section, so this definition means that energy also has a very specific meaning. However the potential can be present in a variety of different forms which need to be considered.

a. Kinetic energy

A body can possess energy by virtue of the speed at which it is moving. It has a capacity to do work because, if it hits something, it is likely to do work by causing movement of the object. This is called Kinetic Energy (KE). The KE is always given by the formula:

$$KE = \frac{M v^2}{2} \qquad \textbf{Equation 3.50}$$

where M is the mass in kg and v the velocity in metres per second of the body. The units of kinetic energy are thus kg m/s, but this turns out to be the same as the unit of work, the Joule.

b. Potential energy

The Potential Energy (PE) is the energy possessed by virtue of its position. A hay bale on top of a stack could do work if it were to fall onto an unfortunate farmer below (eg flatten him). The potential energy is given by:

$$PE = M\ g\ h \qquad \textbf{Equation 3.51}$$

where h is the height above a reference point.

Notice that the value of h and therefore the potential energy depends on the reference point chosen. Fortunately this does not cause any problems, since potential energy analyses inevitably involve a change from one position to another.

c. Pressure energy

This is energy a fluid or gas possesses by virtue of the pressure it is under. We will consider this more in the chapter on fluids.

d. Chemical energy

When chemical reactions take place, the atoms making up the chemicals change places with other atoms to make other compounds. In the process energy can be either released or used up. Energy is released if the reaction results in the atoms forming compounds which are more stable. In many of these reactions the energy is released in the form of heat, and they are called Exothermic reactions. An example of this is the burning of petrol in an engine, which produces heat and causes the gases in the cylinder to expand rapidly, so that the engine does work. In batteries there is a chemical reaction which causes an electrical voltage to be generated, so that the chemical energy is converted to electrical energy.

e. Electrical energy

When electricity flows it does work. The work done is the product of the voltage, the current, and the time for which the current flows. This will be discussed in the chapter on electricity.

f. Nuclear energy

Nature has provided us with two sources of nuclear power. The first and most important is the fusion reaction which is the basic source of energy for the sun and all the other stars in our universe. At enormously high temperatures and pressures hydrogen and helium gases are so compressed and energised that the nuclei can combine together to form other elements. In the process some matter is destroyed and energy is created in the form of high energy electromagnetic radiation (Gamma rays). Einstein's theory of Relativity suggested that the energy created is given by:

$$E = M\ c^2 \qquad \textbf{Equation 3.52}$$

where E is the energy created when a mass M is destroyed, and where c is the velocity of light. For our purposes we will say little more about this model except that it has been proven to work very well in describing the way our universe behaves.

Einstein's law also explains the other form of nuclear power known as Fission. Fission is the reverse process to fusion, in that atoms split apart into smaller atoms rather than combining together. Fission takes place in many of the heavier elements present in rocks which occur naturally on the earth, such as Uranium, Plutonium and Radium. The nuclei of these atoms break apart spontaneously in nature producing energy together with other nuclear particles. Left alone the reaction is quite stable, although the heat generated by these natural reactions drives most of the earth's geothermal activity. However, by mining ore which is rich in radioactive materials, and refining it, it is possible to produce an unstable situation: the nuclear products trigger off the fission reaction in nearby atoms and the reaction can get out of control. All that is needed is for there to be sufficient material in one place. There is thus a critical mass of material which will be enough to cause an unstable reaction, or nuclear explosion (in fact there is evidence that there has been at least one case where a mass went critical without man's intervention: this occurred some time ago in West Africa). Unfortunately fission produces many radioactive by-products which contaminate the environment for very long periods of time. Fusion is much cleaner, and there are several research projects around the world to produce a controlled fusion reaction. To date we have not been successful in harnessing the fusion reaction on earth, other than to destroy people and places with hydrogen bombs.

g. Thermal energy

Things which are hot have the ability to do work. For example a hot gas will expand causing a piston to move. There is therefore some energy associated with the hotness of an object, and we will discuss this next.

3.17 TEMPERATURE AND HEAT

Temperature and heat are very important aspects of our environment. In horticulture the temperature affects the growth rate of most crops. Where the environment is controlled keeping the temperature right is a major problem, affecting the design and operation of the entire structure. In many countries the greenhouse must be kept cool in summer and heated in winter. When crops are harvested the storage life is critically dependent upon the temperature. It is essential to keep the temperature of most crops low in order to reduce losses. This

means that refrigeration systems are required, and most horticultural crops are stored at near zero temperatures in cool stores. Agriculturalists must also consider heat loads and temperatures whenever animals are confined in houses, as stock can suffer and die due to extremes of temperature. Humans are also most comfortable at temperatures of around 20°C, and rapidly become uncomfortable if the temperature moves far away from this level.

The models which describe the sensations we experience as hotness have evolved over a very long period of time. Nowadays the models are fairly reliable, thanks to some very careful rethinking over the last hundred years. The models which have evolved are called the laws of Thermodynamics. As we have seen, words describing terms used in models mean very special things, and this is particularly so with thermodynamics. We will outline some of the principles involved, and begin by discussing the meaning of the more vital terms.

3.17.1 Heat

The word heat has one very specific meaning. Heat is a form of energy in transit. It refers to the energy flow between two objects by virtue of a difference in temperature alone.

3.17.2 Temperature

A body has the ability to do work by virtue of its temperature. Temperature is a measure of the hotness of a body. Temperature is related to how fast the molecules inside the body are vibrating on average and therefore is in a sense a measure of the "internal" kinetic energy possessed by the body. The model states that two bodies are at the same temperature if no heat transfer occurs when they are put in thermal contact. This means they are at the same temperature, which is obvious if you think about it! However it is so fundamental to the model this statement alone is called the Zeroth Law of Thermodynamics (mainly because no one thought of it until after the first and second laws had been worked out!).

There are three main scales of temperature. The metric system uses the Centigrade scale. Temperature is measured in degrees Centigrade (°C). This is an arbitrary scale used to measure temperature, and is defined so that pure water freezes at 0° and boils at 100° (at atmospheric pressure).

Some countries still use the Fahrenheit scale, where water boils at 212°F and freezes at 32°F. The conversion is given by:

$$°C = \frac{5}{9} \times (°F - 32)$$

Equation 3.53

A more scientific scale is the Kelvin scale. It has a zero at -273.15°C. This is called absolute zero. It is the scale which describes the behaviour of gases. On this scale water boils at 373.15°K, at atmospheric pressure.

3.17.3 Specific heat

We will not pursue the atomic explanation of temperature, but instead we will concentrate on the energy which can be tapped or put into the body as a result. Unlike the previous descriptions of energy the best way to specify the energy content due to temperature is to consider putting energy into a body, rather than getting it out. To do this we use the term Specific Heat.

The Specific Heat (S) of a substance is the energy required to raise the temperature of 1 kg of the substance by 1° Centigrade.

The use of the word Heat is perhaps unfortunate since it has a different meaning by itself as already stated. However we must use what we have been given! Values of the specific heat of various substances are given in *Table 3.5*. Note that the units are Joules per kg per °C.

Table 3.5 Specific heats of selected materials (J $kg^{-1}°C^{-1}$)

Water	4200
Steel	420
Copper	385
Cork	2050
Polythene	2300

In fact the specific heat varies slightly with temperature for all substances, but the error is small for changes in temperature in the range between 0 and 100°C.

From this it should not be to hard to see that the energy required to raise the temperature of a body of mass M from T_1 to T_2 is given by

$E = M\ S\ (T_1 - T_2)$ **Equation 3.54**

Example

Find the energy required to raise 60 gallons of water (1 gallon = 4.54 litres) from 10 to 80 °C.

Solution: First we need to find the mass of water in kg. Since 1 litre has a mass of 1 kg,

$M = 60 \times 4.54 \times 1 = 272.4$ kg

Hence the energy is:

$E = 272.4 \times 4200 \times (80 - 10) = 80{,}100{,}000$
$= 80.1$ MJ

Confusion starts to arise in considering thermal energy when we start to confuse the term heat with the term specific heat. It is important to realise that the term heat applies only to energy in transit. We can never talk about the heat of a body. Sometimes even scientists will refer to the heat content or even the "sensible heat" but they are really referring to the specific heat, ie the energy required to alter the temperature. Thus the Sensible heat describes the heat which is absorbed by or released from a body and which causes a change in temperature only.

3.17.4 Latent heat

When substances undergo a change of phase (ie, changing from gas to liquid (condensation), or liquid to solid (fusion), or vice versa), extra heat is given off or absorbed. Thus heat is required to change a solid into a liquid (melting), or a liquid into a gas (vaporisation). Heat is given off if the change is in the reverse direction. For water at atmospheric pressure the latent heat of vaporisation is 2260 kJ per kg, and the latent heat of fusion is 333.5 kJ per kg. This explains why water boils for a long time on a cooker before it all evaporates, and why ice cream takes a fairly long time to melt: in both cases there is a considerable amount of latent heat which must flow before the change can be completed. This will be discussed further in section 7.8.2.

3.17.5 Enthalpy

Enthalpy is the sum of all the heat which must be input into a substance to bring it to that condition from an arbitrary starting point such as the freezing point of water. It is measured in J/kg. Thus if the substance passes through a change of phase, then the latent heat will be included in the enthalpy. The enthalpy of moist air is an important factor in environmental control and in cool store design. Values can be found from a Psychrometric chart (Chapter 11).

3.17.6 Thermal expansion

Almost everything expands as it gets hotter.* This explains why summer days are longer than winter days. For materials an adequate model is given by:

$\delta L = \alpha\ L\ \delta T$ **Equation 3.55**

where δL is the extension, L is the initial length, δT is the change in temperature, and α is a constant called the coefficient of linear expansion. The expansion arises because the atoms vibrate more violently as the temperature rises, and this causes them to push a little further apart.

Values of α are given in *Table 3.6.*

Table 3.6 Coefficients of Linear Expansion (0 °C to 100 °C)

Material	$\alpha(°C^{-1})$
Steel	11×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Aluminium	23×10^{-6}
Glass (ordinary)	9×10^{-6}
Glass (Pyrex)	3.2×10^{-6}
Invar	0.7×10^{-6}
Ice (−10 °C to 0 °C)	51×10^{-6}

Example

How much will a steel fencing wire 200 m long contract if the temperature falls from 20 °C to −5 °C?

Solution: $\delta L = 11 \times 10^{-6} \times 200 \times (-5 - 20)$
$= 0.055$ m (55 mm).

This can be important if fencing or crop support wire tensions are to be maintained in summer without overstraining in winter.

In many structures it is necessary to include expansion joints so that the construction materials can expand and contract over the seasons without damage (*Figure 3.26*). They are most noticeable on long road bridges and in older railway tracks.

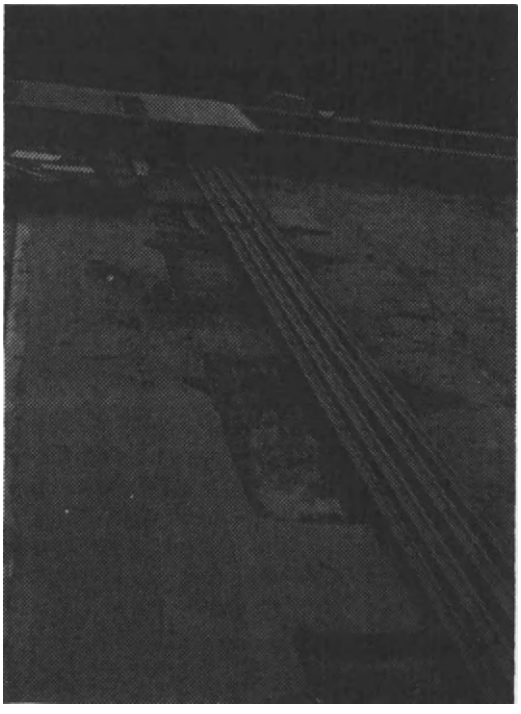


Figure 3.26 Expansion settlement joint placed during construction of a road bridge.

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* One very important exception is water. Upon melting water contracts (becomes denser), and this contraction continues until it reaches its maximum density at 4 °C. This little known fact explains why lakes and rivers freeze at the surface first, since the slightly warmer water sinks, and can remain under the ice in the liquid state. Although the increase in density from 0 °C is only 0.014%, we probably owe our existence to it: this quirk of nature enabled early aquatic life forms to survive the great ice ages on our planet.

3.17.7 Heat transfer

There are three ways in which heat can transfer energy from one body to another. These are Conduction, Convection, and Radiation. We will also mention a fourth "mechanism" called Advection, which is not really a different process, but is a useful model to describe a process which occurs in orchards. Advection is the transfer of energy by the movement of mass out of a region and its replacement by a mass with a different energy content. *Advection* occurs in practice through air movement, and it affects the temperature in orchards and other areas. It is usually associated with convection from a surface.

Conduction is the transfer of heat between molecules without gross molecular movement. In essence, the molecules in the hotter body vibrate close to those in the cooler body, and the kinetic energy is transferred. *Convection* is the transfer of heat by the movement of molecules within a fluid such as water or air. Convection may be free or forced. Free convection occurs because a heated fluid expands and therefore becomes less dense. Forced convection describes the cooling process when the fluid is forced across the hot (or cold) surface by a fan, a pump, or the earth's winds.

Radiation is a process of heat transfer which takes place through a vacuum, without the need for any matter to conduct the heat. The heat is transferred by electromagnetic radiation. Virtually all the energy we receive from the sun is transmitted in this form. Since these waves are a vital part of our environment, we will discuss them next.

3.18 LIGHT AND ELECTROMAGNETIC RADIATION

Electromagnetic radiation affects us in a number of ways. Light is the most apparent form. Objects are only visible because they reflect, refract, absorb, or themselves radiate electromagnetic radiation which stimulates the retina of the eye. The rate at which this radiation is received by the eye from a body (light intensity) and the quality of the radiation received (its colour) are the means by which objects of the same shape but made of different materials appear different to us.

We are all aware of light. But exactly what is it? Scientists have long argued about the reality of what makes up light, and have failed to come to any agreement. When we try to describe how light behaves, more than in any other study we have to rely on our understanding of what we mean by a model. Remember a model is a way of describing our world. Models are good if they describe what is happening successfully, and can predict the outcome of an experiment correctly. When we try to model light, we find that two models are needed. One describes light as a wave motion, spreading out rather like ripples on a pond. This model describes what happens

when light passes through objects, such as the lens of a telescope or a pair of spectacles, and also explains many other phenomena such as the interference between two rays of light, which remain the delight of Physicists and pure scientists (see any good Physics textbook for more details!). It fails totally when it comes to describing what happens when light strikes an object in its path and is absorbed. Instead we discover that a very good model for this is to think of the light as a beam of particles like billiard balls, each striking the target and being absorbed completely. We will discuss these two models in turn.

Before doing so let us just say that neither model describes the true nature of light. Light is not a simple wave, and it is not a stream of particles. Light is ... light. In some situations one model works, and in others a different model is needed. There is no problem providing we know the range of situations over which a model works.

a. The wave model of electromagnetic radiation

In our first model, electromagnetic radiation is considered to be propagated in the form of a wave. Such waves can be of different wavelengths but they all traverse a vacuum at the same speed. Therefore a simple relationship exists between the wavelength, frequency and speed of electromagnetic waves and may be expressed as:

$$c = f\lambda \qquad \textbf{Equation 3.56}$$

Where c is the wave velocity (3×10^8 m/s in a vacuum), f is the wave frequency in cycles per second or Hertz (Hz), and λ is the wavelength in m. Thus long waves have a low frequency and short waves have a high frequency.

b. The particle model of electromagnetic radiation

In our alternative model, electromagnetic radiation can also be considered as a stream of discrete particles, termed *Photons*. This model is useful in describing the energy in the radiation. It can be shown that:

$$E = h\,f \qquad \textbf{Equation 3.57}$$

Where f is the frequency in Hertz, E is the energy of one photon in Joules, and h is a constant called Planck's constant. Its value is 6.6×10^{-34} J sec. From *Equations 3.56* and *3.57*:

$$E = \frac{h\,c}{\lambda} \qquad \textbf{Equation 3.58}$$

When a photon hits its target, eg, an atom, all the energy is transferred and the photon is absorbed. It is an "all or nothing" effort. The energy the photon has is called a *Quantum* of energy. It is evident from *Equation 3.58* that the total amount of energy in a quantum is inversely proportional to the wavelength of the radiation. Therefore, short wave radiation contains photons with more energy than long wave radiation. When a photon is absorbed by a leaf, its effect depends upon the energy. If the energy is too great the photon will actually destroy the molecular structure of the leaf. Since the energy depends upon the wavelength, short wavelength radiation will be more harmful than long wavelength radiation.

Example

Calculate the energy of a photon of blue light (wavelength 0.3 μm).

Solution: From *Equation 3.58*:

$$E = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{0.3 \times 10^{-6}} = 6.6 \times 10^{-19}\ \text{J}$$

3.18.1 The electromagnetic spectrum

One of the most exciting advances in understanding our world came when it was realised that a whole range of types of radiation were in fact all the same thing. Light, heat radiation, ultra-violet light, cosmic radiation, Gamma rays (from radio-active materials), X-rays, and microwaves are all forms of Electromagnetic Radiation. The only difference between them lies in the wavelength. *Figure 3.27* shows the electromagnetic spectrum, and the different types of waves which are part of it, and *Table 3.7* indicates sources of this radiation. All these waves obey *Equations 3.56* to *3.58*, and all can be modelled as a wave or as a particle according to the situation.

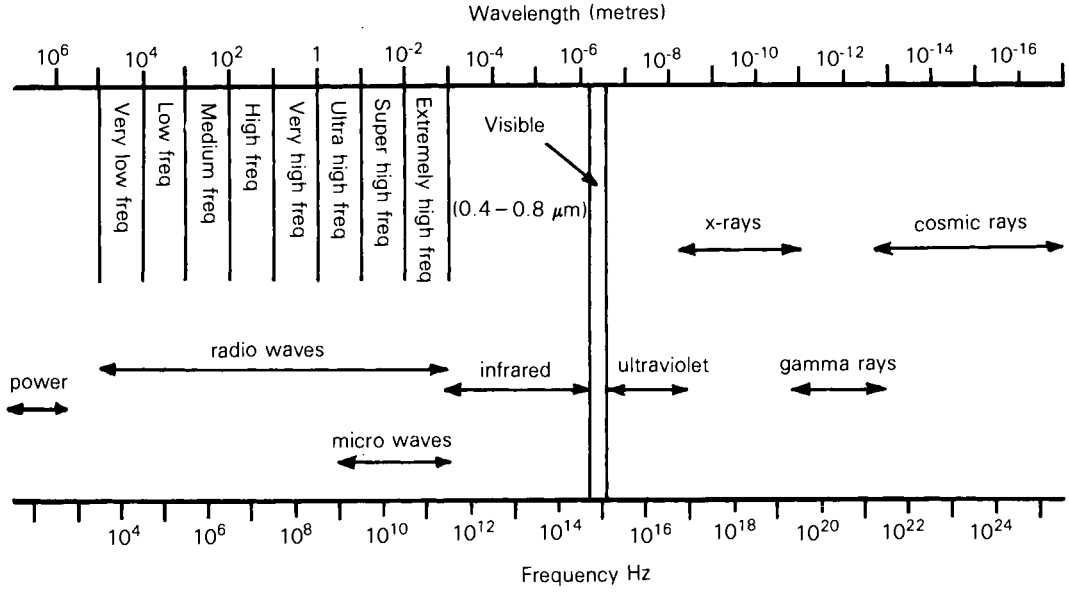


Figure 3.27 Electromagnetic spectrum.

Table 3.7 Sources of electromagmetic radiation

Type	Sources
Power	Emission by power transmission lines (around 50-200 Hz)
Radio	Oscillating electrical circuits (amplitude varies)
VHF and UHF	Electrical circuits (Used by TV stations)
FM radio	Electrical circuits which vary frequency (7.5-95 MHz)
Microwaves	Radar, microwave ovens
Far Infrared	Molecular rotations
Near Infrared	Molecular vibrations, radiative heaters, hot bodies
Visible light	Electron transitions between outer orbits of atoms
Ultraviolet	Electron transitions, mercury lamps
X-rays	Electron transitions between inner orbits, X-ray machines
Gamma rays	Changes in nuclear energy levels, radioactivity, nuclear bombs
Cosmic rays	Nuclear processes, outer space

Stimulation of the retina of the eye is only brought about by waves of a very narrow band of wavelengths compared with the known range of electromagnetic radiation. The visible light spectrum covers the range of wavelengths between 0.40 and 0.8×10^{-6} m. Radiation in the visible spectrum, together with radiation of even shorter wavelengths, is commonly known as Short wave Radiation. Within the visible spectrum the shortest wavelengths appear to us as blue light and the longest ones as red. Wavelengths shorter than the visible blue (or violet to be precise) are called ultra-violet (0.4×10^{-6} to 5×10^{-9} m), while X-rays (used in medicine), Gamma rays and Cosmic rays are shorter still. Short wavelengths have a high penetration ability and are damaging to living tissue.

After light, we are most aware of electromagnetic radiation in the form of heat. Waves which are slightly longer than the red visible waves are called infra-red (0.8×10^{-6} m to 1 mm). This long wave radiation cannot be seen, but can be felt: ie, it is readily absorbed by our bodies and converted to heat. Further along the spectrum, wavelengths of a few centimetres are used in radar, and longer wavelengths still are used in radio communication.

3.18.2 Visible radiation and the eye

Although this spectral band represents only a fraction of the whole, it is of great biological importance and in order to define it and its parts exactly, it is necessary to utilise very small units. Those customarily used are the micron (one thousandth of a millimetre, or 10^{-6} m, or 1 μm). The Angstrom unit (10^{-10} metre) is no longer a recommended SI unit. The human eye is stimulated by light. However if light of different wavelengths (ie different colours) is carefully produced so that equal amounts of energy are present in each wavelength the stimulation of the human eye by these different wavelengths is not equal. The eye is most stimulated by the energy of light in the green region (about 0.550 μm). Thus in this example the green light would appear to be brightest. For this reason, as well as others, the human eye makes an inexact measuring instrument for assessing relative energy values in the visible spectrum.

In the past many measurements of light have been made using units based on the response of the human eye, ie measurements of brightness rather than total energy. Such units are of great use to the illumination engineer and architect, but they are not of much value to plant physiologists studying plant processes such as photosynthesis or phototropism. There are, therefore, two kinds of units in current use.

a. The lumen

The first is based on the standard visual sensitivity curve and a standard light source (the standard candle or candela) where the unit of luminous flux (another word for energy flow or power) is the lumen. The lumen is the flux emitted in unit solid angle (steradian) by a point source of one candle power.

b. The watt

The more scientific unit is based on power, ie radiant flux from a source measured in Watts. Such units are applicable to measurements of radiation inside the visible spectrum as well as outside. A common method of expressing incoming solar radiation is as energy received in unit time on unit area of a horizontal surface (Watts per square metre). This is known as the Insolation.

In studying the effect of light in Agriculture and Horticulture, there are three basic factors to be considered. First there is the intensity of the light, ie the energy falling on unit area in unit time. This is important in relation to photosynthesis, growth, pigment formation and phototropic responses in plants. Second the quality of the light, (ie its wavelength) is important, and third, the duration of the light, ie the above two factors related to time. Knowledge of the duration of light is of vital importance with regard to the study of the effect of day length on such things as flowering, dormancy and leaf fall, etc.

Solar radiation

The sun can be considered as a nearly spherical "black body" (see Chapter 7) at a mean distance from the earth of 150×10^{-6} km with a surface temperature of about 6,000°C. It is much hotter inside (up to 10^{7}°C). It is estimated that the mean intensity of the radiation from the sun is around 1360 W m^{-2} (mean value). This is termed the "Solar Constant", and represents the total power arriving from the sun at the top of the earth's atmosphere (integrated over all wavelengths).

Solar spectrum

The spectral composition of radiation received at the outside of the earth's atmosphere is shown in *Figure 3.28.* It can be seen that a little more than half of the radiation is in the non-visible infra-red region.

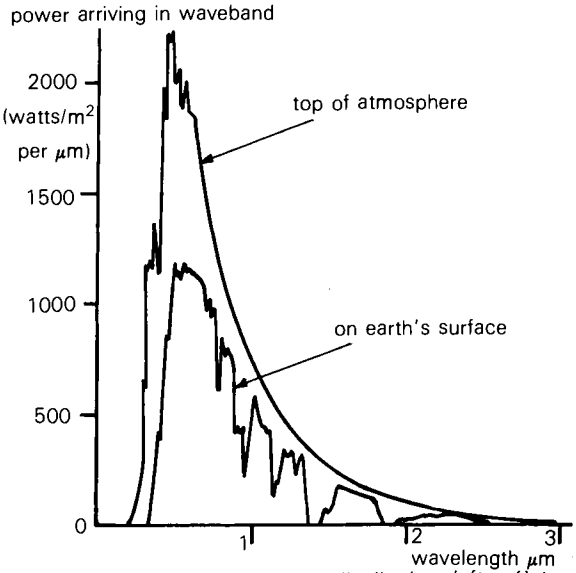


Figure 3.28 Solar power distribution (after Gates, *Scientific American*, 1971).

Solar radiation at the earth's surface

Solar radiation travels through space almost without loss (other than that the power density will be reduced as the inverse square of the distance) until it reaches the earth's atmosphere. Its intensity is then reduced in two ways:

a. The atmosphere absorbs and reflects the solar energy, reducing its intensity by an amount dependent on how far the radiation has to travel through it. How much atmosphere it has travelled through will vary according to the altitude of the sun. This is quantified as follows: the thickness of the atmosphere traversed when the sun is at its zenith (directly overhead) is termed "unit air mass". The air mass, m, at any other sun position, is the ratio of the distance travelled through the atmosphere to the unit air mass.

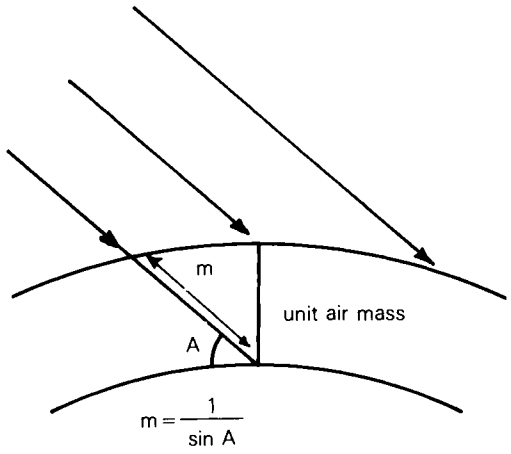


Figure 3.29 Calculation of air mass.

From *Figure 3.29*, we can see that the air mass is given by:

$$m = \frac{1}{\sin A} \qquad \textbf{Equation 3.59}$$

where A is the altitude of the sun.

The total energy arriving is reduced to the values in *Table 3.8*.

Table 3.8 Reduction in solar radiation (clear sky conditions)

Air mass in	Solar altitude	Energy density W m^{-2}
0	–	1350 (Solar constant)
1	90°	900
2	30°	750
3	20°	600
5	5°	400

The radiation is not absorbed equally at all wavelengths. The earth's ozone layer removes the potentially harmful ultra-violet radiation, while carbon dioxide and water vapour molecules absorb certain wavelengths in the infra-red region very strongly. The result is the pattern shown in *Figure 3.28*.

b. The intensity of light falling on a unit area of ground will also be reduced if the light is at an angle, simply because the light is spread over a wider area. This is given by:

Intensity on horizontal surface
= Beam intensity × sin A

Equation 3.60

This means that sun facing slopes receive more radiation per unit area than others, and so grass grows better in general on these slopes in spring. However, in hot dry conditions these slopes will dry up quicker.

3.19 CONSERVATION OF ENERGY

We have considered the different forms of energy. Now we will consider the rules which govern the way in which energy is converted from one form to another.

The first rule is:

> *In any process energy is always conserved, ie, it cannot be created or destroyed.**

Energy can be converted from one form to other forms. Thus kinetic energy can be converted into potential energy, which is what happens after a stone is thrown vertically up into the air. The opposite happens when an object falls.

Example

Calculate the velocity of a hay bale weighing 25 kg if it falls off a stack 4 m high.

Solution: $PE = M\ g\ h = 25 \times 9.8 \times 4 = 980$ J

Now, by the principle of conservation of energy, the KE after falling 4 m will equal the PE beforehand, so:

$KE = 1/2\ M\ v^2 = 980$

Hence $v^2 = \dfrac{980 \times 2}{25} = 78.4$

ie, $v = 8.85$ m/s

Mechanical energy can also be converted into heat. For example, this occurs most noticeably when one is drilling metal with a blunt drill bit, but also occurs whenever frictional forces are involved. It can also be converted into other forms, such as sound.

The conversion to heat can be complete – ie, all the mechanical energy can become heat. Unfortunately the reverse is not true. The second rule (also called the second law of thermodynamics) says:

> *Heat cannot be converted completely into work.*

This rule is one of the best tested and proven laws of nature we know. It means in effect that events always go one way, in that in the end mechanical energy will eventually end up as heat. The cliche about "things are getting hotter" is certainly true in a universal sense! We will come back to this law again in the Chapter on power systems.

It is possible for some heat to be converted into work. This is one essential process in the internal combustion engine, for example. However the efficiency of the process is very low (only about 30 to 40% of the energy from petrol actually comes out in the form of useful mechanical energy from the engine).

For the present we will avoid the implications of the second rule by saying that in many cases we can ignore friction and heating effects as a first approximation, and use the first rule to calculate the mechanical energy of a body. For example, we can calculate the pressure energy in a fluid as its potential energy (which is related to the height of the pipe it is in), and its kinetic energy (which depends upon its velocity of flow) alter.

Example

A racing car travelling at 180 km per hour crashes into a solid brick wall. If all the energy is converted to heat the car, what will the temperature rise be? Assume the car has a mass of 800 kg, and the specific heat is 500 J kg^{-1} $°C^{-1}$.

Solution: First we need the speed in m/s:

180 km/hr = 180 / 3.6 = 50 m/s

Thus the kinetic energy is given by:

$KE = 0.5 \times 800 \times 50 \times 50 = 1 \times 10^6$ J

The temperature rise is therefore given by:

$$\delta T = \frac{E}{M\ S} = \frac{10^6}{800 \times 500} = 2.5°C$$

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* This statement is only true if one ignores Einstein's relativity theory which allows energy to be converted into matter and vice versa. Such an event occurs only in nuclear and astronomical processes. And although these are vital to sustain human and natural life, we will ignore these possibilities here.

3.20 ENERGY UNITS

The SI unit of energy, the joule, is really quite small. We usually need to discuss energy in terms of at least MegaJoules (MJ). Alternatively a very convenient unit which is particularly popular in the electrical industry is the kilowatt hour (kW h). This is the energy used by a device (which has a rating of 1 kW) in 1 hour. The relationship between these units is simply:

1 kW h = 3.6 MJ **Equation 3.61**

This conversion is worth remembering.

3.21 EFFICIENCY

A term which is used a great deal in engineering (and everywhere else!) is Efficiency. As usual we will say what we mean by the term.

Efficiency is defined in a quite straightforward manner. For any system, such as an engine, a motor or a pulley, it is given by:

$$\text{Efficiency} = \frac{\text{What you get out}}{\text{What you put in}}$$

Equation 3.62

This rather vague looking definition is in fact very useful, providing that, in each case both terms are specified, and they are stated in the same units. Thus, for example, the efficiency

of an electric motor would be defined as the ratio of the useful power coming out in watts, to the electrical power going in, also in watts. The efficiency of a water pump is the ratio of the power which is put into the water by the pump to the power which enters the pump via the drive shaft. An engine's efficiency is the ratio of the power output on the drive shaft to the chemical energy in the fuel used by the engine per second, both expressed in watts (ie, joules per second). The efficiency of a water heater would be defined as the ratio of the heat put into the water divided by the energy input in the form of electricity or solid fuel, both measured in joules. From these examples it is apparent that efficiency can be defined either in terms of the total energy required during a process, or by the rate at which the process is happening.

3.22 FURTHER PROBLEMS

1. Can you explain why it is not wise to undo the wheel nuts on a car when it is jacked up, without loosening them while the car is still on the ground? Use the model of the couple.
2. What is the component of a force of 300 N at (a) 30°, (b) 60°, (c) 90° to its line of action?
3. What is the moment of a 150 N force applied by a wrench 200 mm long?
4. A fence strainer is loaded by four fence lines. These run due North (0°), due West (270°), ESE (112.5°), and SWS (202.5°), and the forces are 1500 N, 2500 N, 1200 N and 600 N respectively. Find the resultant, and discuss where a stay should be placed.
5. An oil in a container has a mass of 8000 kg. The container is a cylinder 3 m high and 2 m in diameter. Calculate the specific weight of the oil.
6. Calculate the mass of water in kg in a pipe 5 m long with an internal diameter of 200 mm.
7. Would you describe the following following materials as brittle or ductile: paper, cellotape, grass, jelly, a rubber eraser, rock, timber, perspex, a polythene bag, maize seed.
8. Calculate the stress on a 2 mm diameter wire if the load is 1500 N, in MPa.
9. A wire is under a stress of 300 MPa. If E = 200 GPa, calculate the extension of a 750 m length.
10. Distinguish between the following pairs of terms (ie for each pair explain what the terms mean, and the difference between them).
    (a) brittle and ductile
    (b) elastic and plastic
    (c) strain and extension
    (d) load and stress
    (e) weight and mass
11. State the SI units of the following: (a) mass, (b) g, (c) weight, (d) force, (e) acceleration, (f) power, (g) velocity.
12. A man tries to push his car to start it but cannot move it. Is there a force on the car? If yes, list the force(s). Is the man doing work on the car?
13. A golfer hits a golf ball perfectly, and it shoots up in the air on its way to the green. Are there any forces on the golf ball in flight? If yes, list them.
14. An object weighs 560 N on earth. What is its mass?
15. Define the terms power and work, and state the relationship between them.
16. State the conditions for equilibrium.
17. State the formula for calculating the energy required to heat a substance. Define all terms used and state their units.
18. Calculate the energy required to heat 100 kg of a liquid (S = 3000 SI units) from 10°C to 90°C.
19. 100 litres of fluid "weighs" 80 kg. Calculate its specific gravity.
20. Express Newtons in terms of kg, m and s.
21. What is the "normal reaction"?
22. What is the C of G of a body (explain in terms of gravitational forces).
23. What is the specific heat of water (State size and units).
24. The C of G of a gate weighing 60 kg is 2.5 m from the hinge. The gate is 6 m wide and 1 m high. Calculate the moment about the hinge.
25. The mass of a block of lead is 226.8 kg. Its dimensions are 200 mm × 500

mm × 200 mm. What is the density of lead?

26. Calculate the extension produced by a force of 1500 N on a 1.6 mm diameter steel wire (E = 210 GPa), if its initial length is 200 m, and the wire remained fully elastic.
27. If the wire in the previous problem were made of steel with a yield point of 500 MPa and tensile strength of 1300 MPa, what would happen to the wire? Would, or has, the elastic model provided any useful information?
28. Discuss what is meant by the term hardness.
29. A gas of volume 3 m^3 at 20 °C is heated to 327 °C at constant pressure. What is its new volume?
30. A sheep weighing 50 kg charges a fence and is halted within a distance of 300 mm. If the maximum deceleration the sheep can withstand is 60 m s^{-2}, what is the maximum impact velocity before injury? Assume constant deceleration. What is the maximum force?
31. A tractor weighing 3 tonne accelerates from 10 to 16 m/s in 3 seconds. If the draught force opposing motion is 1300 N, calculate the average power output from the engine.
32. A farmer on a motorcycle can brake at a maximum rate of 5 m s^{-2}. While travelling at 50 km/hr he or she sees that the track has caved in directly ahead and 20 m away. Can he or she stop in time?
33. Calculate the expansion of a 200 m length of 4.0 mm diameter wire at 1500 N tension at 0 °C if the temperature rises to 30 °C. What will the new tension be?
34. A gas at 0 °C in a rigid container is heated. What temperature will be reached when its pressure has doubled?
35. How many molecules will a gas contain if it has a volume of 30 m^3, at a pressure of 3 bar and a temperature of 27 °C. (Hint: Find the volume at STP.)
36. A roof has a span of eight m and a mass of two tonne, with its C of G at the centre. Two m to one side of the centre a water tank is located with a mass of three tonne, and on the opposite side a cantilever structure is erected which protrudes from the side of the building. This has a mass of 0.5 tonne, and its C of G is located a distance 1.5 m from the wall (outside the building). Calculate the normal reactions on the two walls.
37. A hay bale with a mass of 25 kg falls from a height of 5 m. Calculate the velocity when it hits the ground, using the principle of the conservation of energy.
38. A post driver of mass 400 kg falls with velocity 10 m/s on to a post of mass 200 kg. After impact both travel on together. Calculate the loss of kinetic energy.
39. A 200 kg deer charges a fence but is stopped. If the deer's speed was 30 km/hour on impact, how much energy did the fence absorb?
40. A farmer is pulling a hay bale off the back of a trailer. Draw the diagram showing all the forces acting on the bale, using a free body diagram. Be careful to define each force, separating reactions into their normal and tangential components. If the bale weighs 25 kg, what is the minimum force the farmer must apply in order to move the bale if the coefficient of friction is 0.6?
41. A four wheel drive tractor is pulling a plough up a slope of 20 °. If the total force opposing motion is 12 kN, and the coefficient of friction between the driving wheels and the ground is 0.25, calculate the mass of the tractor which will be needed.
42. If the tractor in the previous example is ploughing at 10 km/hr, and the plough weighs 500 kg, what is the power output of the engine?
43. A single axle trailer is loaded with coils of wire weighing 1.5 tonne. The coils are located 1.1 m behind the axle. The trailer has a mass of 1 tonne, and its centre of gravity lies 0.5 m in front of the axle. The hitching point is 3 m in front of the axle.
    (a) Calculate the reactions at the axle and the hitching point, and discuss the implications.
    (b) Calculate where the wire should be placed to produce a downward force of 100 N on the hitching point.
44. If the structure shown in *Figure 3.20a* has a load of 30 kN at AB and a load of 40 kN at BC, calculate the loads in the

beams.

45. A 12 m span bridge has a UDL of 4 kN/m. It also carries a load of 20 kN 4 m from one end and another load of 15 kN 3 m from the other. Calculate the maximum bending moment, and plot the BM and sheer force diagrams.
46. A cantilever beam must carry a mass of 200 kg, at a distance of 4 m from the support wall. Allowing a factor of safety of 5, how deep should a 50 mm wide timber beam be to sustain this mass, given the tensile strength of the timber is 12.4 MPa.
47. What force is required on a pane of glass to stop a 50 gramme hailstone travelling at 30 m/s in a distance of 3 mm?

3.23 AIMS OF THIS CHAPTER

When you have studied this chapter and tried the problems, by refering to the book, you should be able to:

1. Describe and use models which explain how our physical world behaves (in particular, models of forces, loads, and stresses, and their effects on materials).
2. Explain and use the terms force, moment, component of a force, load, couple, stress, strain, pressure, etc, which describe the environment.
3. Explain how materials behave when exposed to environmental factors, using appropriate models and technical terms in the correct manner.
4. Discuss in detail the behaviour of solids under tensile stresses, explaining elastic and plastic behaviour.
5. Solve problems involving elasticity theory.
6. Explain and use models which describe the behaviour of gases.
7. Solve dynamic problems involving uniform acceleration.
8. Explain and use the friction model.
9. Analyse and determine the forces and stresses in simple frameworks and beams.
10. Discuss and use the models of work, energy, and power.
11. Discuss and use the models which describe thermal phenomena, including heat transfer concepts.
12. Describe the nature of electromagnetic radiation, and discuss the reasons for requiring more than one model to describe its behaviour.
13. Explain the principle of the conservation of energy.
14. Explain and use the term efficiency.

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Workshop methods

Chapter 4

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4.1 INTRODUCTION

Nowadays the design of farm machinery has been vastly improved using modern welding and fabrication methods, giving equipment which is strong, durable and not unduly heavy. In this chapter we will describe some of the main methods of joining and cutting metals. This includes soldering, welding and cutting with oxygen-acetylene equipment and electric arc welders, brazing, and bronze welding. In each case the equipment required is considered, and the principles of the techniques are outlined. Then the principles of the heat treatment of steels will be described. The chapter concludes with a brief note on the use of farm workshop tools. Space prevents us from discussing other methods, such as glueing, bolting, rivetting, or using other proprietary joining systems. However some of these are described in Chapter 8 in relation to the construction of buildings.

In all cases this type of work is potentially dangerous. The risks include fire, burns, electrocution, inhalation of dangerous gases given off in the processes, or injury as a result of spilling highly corrosive chemicals. Good protective clothing (especially strong shoes and eye protection), and a well lit and ventilated work space are essential prerequisites. Some safety precautions are given here, but it is strongly recommended that any potential user should take a proper training course at a recognised college or workshop. There is an art to working with metals, which is not hard to pick up, but it is an area where practice directed by a skilled practitioner is the best form of instruction.

It is also worth warning against attempting to modify farm equipment without thought about the implications. For example, most farm tractors nowadays have safety cabs. These are fitted to protect the driver if the tractor should overturn, an all to common occurrence. These safety cabs are welded structures which are carefully designed, manufactured and tested to withstand the stresses generated in an overturn. However, on-farm surveys have found that many safety frames had been modified by dealers or owners (adding hooks for radios, or coats, fitting rain shields etc). Such apparently minor alterations can seriously weaken the structure, and should never be attempted (*Figure 4.1*).



Figure 4.1 The safety frame on a tractor should never be modified by the operator. On this experimental tractor at Queensland Agricultural College (Gatton) a different change has been made: the wheel base has been widened. Modifications like this also require careful engineering design and fabrication by experts.

4.2 SOLDERING

Soldering is a widely used method of joining metals together both in manufacturing and in repair work. It is a process that can be mastered by anyone for it is not difficult and requires only a few tools. On a farm good soldering has many applications, including repairs to tanks, buckets, petrol tanks and pipes. Metals which are commonly soldered are copper, brass, steel, stainless steel, and tinned or galvanised metals. Solder is made from lead and tin alloyed in varying proportions to change the properties of the mixture. The most commonly used solders are:

(i) 50/50 solder, made of equal parts of lead and tin. This is the most commonly used solder for general repair work. Its melting point is about 200 °C.

(ii) 60/40 solder, made from 60% tin and 40% lead. It has a lower melting point than 50/50 solder, sets more quickly and flows more smoothly. Its main use is where a perfectly smooth finish is required for ease in cleaning.

(iii) Wiping metal is made from 30% tin and 70% lead. This is used by plumbers in making "wiped joints" when joining lead pipes to sink wastes, etc. and by panel beaters for filling dents in car bodies. It is then called body solder. This solder has a relatively high melting point and sets slowly, remaining in a pasty, plastic condition for some time, enabling the shaping of the joint or repair.

4.2.1 Equipment

For general repair work a heavy soldering iron is better than a light one. A light iron does not store sufficient heat to deal with other than very small jobs and requires frequent reheating. An iron weighing 450 to 680 grammes will handle most jobs with an ample reserve of heat. Where the size of the job is such that the iron will need reheating several times much time will be saved by using two irons, with one heating while the other is in use. Petrol or propane soldering irons are excellent for medium to heavy work, as no time is lost in waiting for irons to heat, and the amount of heat can be controlled accurately. They are also convenient when working up a ladder on spouting and for other similar jobs. For occasional use on a farm, however, the high cost of the petrol soldering iron is not normally justified. Electric soldering irons, unless of a very heavy duty type (ie, fitted with elements of 200-300 watts), lack the capacity to deal with larger jobs. For fine work on electrical components and circuits an electric iron of 60 watts is adequate.

A wire brush for dealing with scaly surfaces and some coarse and fine emery cloth are sufficient to clean the surfaces to be soldered. Caustic soda or other detergents will deal effectively with fatty and greasy materials. Petrol is not generally recommended because of potential health problems.

4.2.2 Procedure

Like many other jobs soldering is a straightforward process if the correct methods are followed. The right way of tackling the job also makes the work very much easier and produces the most efficient joint. The following points should be noted.

First, adequate heat is required. To solder two pieces of metal together, sufficient heat must flow from the soldering iron to raise the temperature of both metals slightly above the melting point of the solder. This allows the solder to flow freely and is the secret of successful soldering. Solder must flow with heat and cannot be rubbed on. To achieve this the soldering iron must be big enough to deal with the job in hand and also must be kept hot enough to keep the solder flowing freely, without over-heating the "tinning" on the tip of the iron to the point where it becomes tinged with a yellow oxide film.

Next, the correct flux should be used. A flux is a chemical which is used to keep the surfaces clean and free from oxide scale. When a metal is heated the oxygen in the air is able to attack it very readily as the temperature rises. A flux prevents this by forming a protective film between the metal and the air. Most fluxes will also remove any small traces of oxide left on the surface after cleaning. Common fluxes include:

(a) Muriatic acid (spirits of salts). This is a commercial grade of hydrochloric acid and is used on all galvanised iron.

(b) Proprietary brands of soldering fluid. These usually contain zinc and ammonium chlorides in a water solution. They are used for copper, brass, tinplate, zinc, steel and cast iron. A substitute for soldering fluid can be made by dissolving strips of zinc in muriatic acid until no further reaction takes place, and then filtering. It can be used on all solderable metals including stainless steel.

(c) Phosphoric acid. This acid is used in the concentrated form for soldering stainless steel.

(d) Resins and soldering paste. These fluxes can be used for electrical work. They are non-corrosive and should be chosen when soldering battery clamps to starter cables, etc. The work must be thoroughly cleaned beforehand.

The first three fluxes mentioned above are highly corrosive especially if spilt! All traces of the flux should be cleaned from the finished work with a wet rag. Fluxes can cause serious injury if they get into the eye.

Third, clean surfaces are an essential prerequisite. Solder will not bond to a surface which is coated with scale, tarnish, rust, grease or fat. Rusty and scaly surfaces must be cleaned with a wire brush and emery cloth until they are bright and shiny. Any grease or fat should be removed with a solvent, or if necessary, with caustic soda.

4.2.3 Joints

In all cases the fit between the metals being joined must be as close as possible, for the better the fit the stronger will be the soldered joint. In sheet metal work various joints are used. The lap joint is the simplest joint to

prepare and is made by overlapping the two metal edges by 3 mm to 20 mm according to the size of work. Care should be taken to ensure that the solder flows right through the overlap. The tensile strength of solder is only about 50 MPa compared with at least 400 MPa for steel so the lap joint cannot be expected to carry much load.

A lock joint involves folding and interlocking the two sheets. The strength of this joint lies in the interlocking of the two folded edges and solder is used only to make the joint watertight and to give a smooth finish to the seam. It is used in the manufacture of vats and small to medium tanks, and boxes, etc.

A rivetted joint can also be soldered. If rivets are used to join two seams together, and both the rivets and the joint are sealed with solder, a strong watertight job results. This joint is used in the construction of bigger tanks where the size of the work would make the lock joint impractical. Rivets are also useful in smaller work to hold parts in position for soldering. The quickest method of fitting rivets is to punch against a block of wood or lead.

4.2.4 Care of soldering irons

Irons must be kept clean and properly tinned. A separate container of flux should be reserved to plunge the iron into each time it is withdrawn from the heat source and whenever the tip becomes dirty. If the iron is over-heated the "tinning" on the tip is burnt and the surface must be filed down to clean, bright copper, heated, dipped quickly into the soldering fluid and recoated with solder.

Aluminium and zinc based diecast metals are not easily soldered. Pure aluminium and a few of its alloys can be soldered by using a special aluminium flux and an aluminium solder to tin the surfaces, followed by normal solder. If the alloy is not known exactly it is usually better to repair by welding. Zinc base diecastings cannot be soldered. In some cases they can be welded, but in others no repair is possible.

4.3 WELDING USING OXYGEN-ACETYLENE APPARATUS

Welding plays an important part, not only in fabricating equipment, but also in extending the life of all types of machinery. It can eliminate costly replacements and is a valuable tool in routine repair and maintenence work. There are two main types of welding equipment: these are oxygen-acetylene and electric arc. For oxygen-acetylene welding and cutting, the basic equipment consists of a welding torch, an oxygen cylinder, an acetylene cylinder, a cutting attachment, regulators, hoses, goggles, a cylinder key and a nozzle cleaner (*Figure 4.2*). Cylinders are generally rented from the supplier. Empty cylinders are usually returned to the nearest depot, and exchanged for full ones.



Figure 4.2(a) Welding and cutting plant for general construction, engineering and repair, and maintenance work (NZIG).

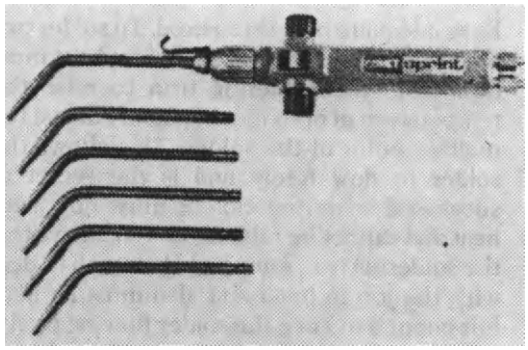


Figure 4.2(b) Comet Sprint welding torch (NZIG).

The gases used are very different in their properties. Acetylene (C_2H_2) is so dangerous that it cannot even be stored as a gas, but must be dissolved in acetone under pressure. Pure oxygen by itself is technically non-flammable, but it supports and accelerates combustion. If it is in contact with other substances (including even small traces of grease and lubricating oil) it makes them highly flammable.

Welding equipment requires careful handling to maintain its efficiency and to avoid any hazard in use. To appreciate the necessity for these basic precautions, a sound working knowledge of the plant is helpful.

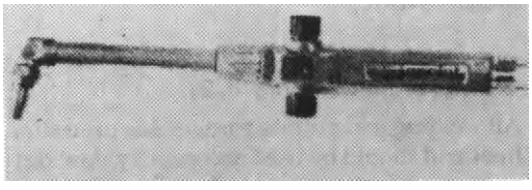


Figure 4.2(c) Fitted with cutting attachment (NZIG).

4.3.1 Cylinders

Compressed gas cylinders are safe for the purpose for which they are intended and should not be handled roughly or otherwise abused.

The construction of these cylinders differs according to the gas that is stored. Oxygen cylinders are made from a high grade steel with a wall thickness of about 10 mm. They are hollow inside with no packing and are fitted with a cylinder valve and regulator connection for right hand threads only. When fully charged the pressure will be between 130 bar and 200 bar, depending upon the type of cylinder (1 bar = 100 kPa).

Acetylene cylinders have a thinner wall than the oxygen ones but are filled inside with a porous substance. This used to be kapok, asbestos or charcoal, but is nowadays a compound of lime, silica, charcoal and asbestos. This porous material is saturated with liquid acetone which has the property of dissolving acetylene. Acetylene cannot be safely compressed in an open container, but by using acetone a large quantity of gas can be dissolved with perfect safety at a pressure of around 15 bar. However when the acetylene is taken out of the acetone and fed through the equipment the regulator should not be set to deliver the gas at more than 1 bar. Equipment for using acetylene is designed to work at this maximum pressure, but in many operations the pressure required can be as low as 0.5 bar.

All fuel gas cylinders are required by law to be fitted with a safety device. This can be either a fusible plug, a bursting disc or a spring loaded relief valve. This safety device may be in the base, the shoulder of the cylinder, or even in the valve itself. Acetylene cylinders are fitted with left hand regulator threads so that wrong connections cannot be made. Acetylene cylinders should be used and stored in the upright position to avoid the possibility of drawing out liquid acetone. If transported horizontally cylinders should be placed upright for at least one hour before using. Never, in any circumstances, attempt to refill an acetylene cylinder.

When handling and using cylinders the following precautions should be observed:

(i) Never drop cylinders or allow them to strike each other violently,
(ii) Never attempt to mix gases in a cylinder or to fill an exhausted cylinder from a full one,
(iii) Never tamper with safety devices in valves or cylinders,
(iv) Open cylinder valves slowly and only with the proper key,
(v) Ensure the threads on regulators and other connections are the same as those on cylinder valve outlets. Never force connections that do not fit.
(vi) Never store cylinders near inflammable materials such as petrol, oil, or waste, etc.
(vii) Cylinders must be protected against excessive rise in temperature; and should not be exposed to continuous dampness.

Particular rules for oxygen cylinders

(i) Never allow oil or grease to come into contact with oxygen cylinders, valves, or regulators, etc.
(ii) Never use oxygen as a substitute for compressed air. It is dangerous to use oxygen for blowing out pipe lines, etc.

4.3.2 Regulators

Both oxygen and acetylene are stored at pressures much greater than those required for welding and cutting. Also the pressures used in welding and cutting vary with the thickness of metal. To reduce cylinder

pressures to the required level regulators are used. For clear distinction, acetylene regulators are painted red and oxygen black. A cross-section of a regulator is shown in *Figure 4.3*. Gas cannot flow from the cylinder to the torch until the control knob is turned,



Figure 4.3(a) Comweld compact oxygen regulator (NZIG).

compressing the spring until the diaphragm is flexed sufficiently to open the valve. Gas will then flow into the low pressure chamber until the gas pressure builds up sufficiently to force the diaphragm towards the valve, allowing the seat to return to the valve, shutting off the flow of gas from the cylinder. Thus altering the control knob will change the low pressure level.

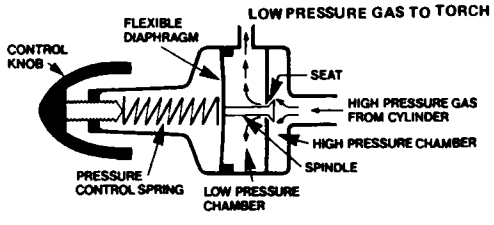


Figure 4.3(b) Cross-section of regulator. When the torch valve is opened the gas pressure in the low pressure chamber is reduced. This allows the pressure control spring to distort the flexible diaphragm. This pushes the spindle away from the seat, allowing gas to enter from the high pressure chamber (NZIG).

Regulators must be treated carefully if they are to function properly. When admitting gas from cylinders, the valve should be opened slowly to prevent a sudden rush of gas at high pressure to the regulator which may damage the seating of the needle valve. This causes the regulator pressure to climb when the torch is turned off and makes accurate flame adjustment very difficult. Dust and grit must not be allowed to enter regulators.

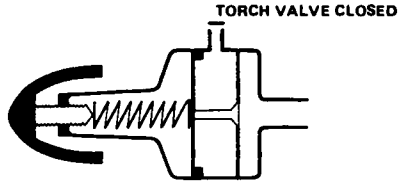


Figure 4.3(c) Cross-section of regulator. When the torch valve is closed pressure builds up in the low pressure chamber forcing the diaphragm back against the pressure control spring. This allows the spindle to seat home shutting off the gas supply from the high pressure chamber (NZIG).

4.3.3 Torches (*Figure 4.2*)

All welding and cutting torches are precision built and should be used accordingly. Any dirt or dust admitted to a torch will cause wear or blockage and must be avoided. All welding and cutting tips should be kept clean and in good order and should only be cleaned with a sharp wooden stick and never with wire etc. Once the gases leave the valves they are thoroughly mixed and are then taken to the tip where they burn, giving a highly concentrated flame with a temperature of over 3,300°C. The lighting up procedure involves first checking that the correct tip for the work has been chosen. Then the acetylene valve on the torch is opened about one quarter of a turn, and the pressure adjusting screw on the acetylene regulator is adjusted until the correct pressure is obtained. The acetylene valve on the torch is then closed and the process is repeated for the oxygen valve. Next the acetylene valve is opened slightly, and (pointing the torch away from the operator) the acetylene is lit. The size of the flame is adjusted until the intense black soot disappears, and the oxygen valve is opened gently until the correct flame is obtained. This depends on the work involved (*Figure 4.4*).



Figure 4.4(a) Neutral flame (equal quantities of oxygen and acetylene). A neutral flame is used for steel, stainless steel, copper and aluminium.



Figure 4.4(b) Oxidising flame (excess oxygen). An oxidising flame is used for brass.

To shut off the flame the acetylene valve is closed first, and then the oxygen valve. The pressure adjusting screws on both regulators are unscrewed, and then both cylinder valves are closed. Finally both torch valves are

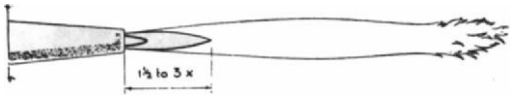


Figure 4.4(c) Carburising flame (excess acetylene). A carburising flame is used for hardfacing.

opened to release pressure in the hose, and closed again. Particular care must be paid to the closing of torch valves, since they are very delicate and are easily damaged by overtightening. This results in leaking valves. Light finger pressure only is required.

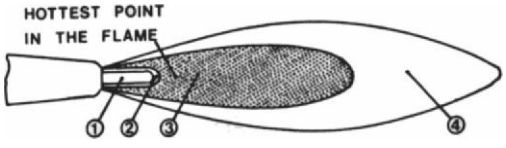


Figure 4.4(d) Section of oxy-acetylene flame (NZIG).

4.3.4 Safety Precautions

With welding and gas cutting a very strict watch must be kept to prevent the start of a blaze from stray sparks or slag. Care must be taken to keep oil or grease away from welding and cutting. All plant connections should be checked regularly for leaks, using soapy water.

Sometimes, oil or petrol tanks need repairing. Unfortunately, one or two people in New Zealand die every year because of mishaps when attempting to apply heat or hot work processes to containers which have contained flammable materials. One major problem is that most leaks appear around a welded joint. In some cases the construction is of a lap type, and even though a lot of trouble is taken to clean the tank, when the heat is applied, a residue of flammable material is released and vaporised from the seam area. This creates a flammable cloud inside the vessel and an explosion follows. Before carrying out these types of activities you should consider the cost effectiveness of the repair. It may be cheaper and will be safer to replace the components. If the job must still be done, then cleaning should be carried out with large volumes of steam at as high a temperature as possible. Failing this an alternative is to scour the tank with strong caustic soda solution and then rinse several times with clean water. Following this the tank should be turned so that the part to be welded is uppermost, and the tank filled with water nearly up to the position to be welded. It is important to leave the vent open. On no account should welding gear be used on closed containers, since the heating can cause the tank to explode. In some cases steam can be allowed to flow through the tank while welding is in progress.

4.3.5 Setting up a new plant

When new equipment is purchased, a number of steps are needed to complete the assembly. These include methods for seating valves, purging tubes and checking for leaks. A guide or, preferably, qualified advice should be obtained. In fact, a recognised training course is essential for new users.

4.3.6 Procedure for gas cutting

The ease with which the oxygen-acetylene cutting torch can cut through thin and thick sections of iron and steel makes it an extremely useful tool for both maintenance and new work. A small spot of the steel to be cut is heated almost to the melting point, and then a jet of pure oxygen is directed against this spot. Instant reaction between the iron in the steel and the oxygen cutting jet is produced with considerable heat release, so the iron oxide which is formed melts and is blown away. The heat produced by the reaction between the oxygen and the iron raises the temperature of the next layer of metal so that it, in turn, is oxidised and blown away. This action is so rapid that a continuous cut is made in the steel.

In a cutting torch the stream of oxygen doing the cutting issues from a jet in the centre of the tip of the torch. Depending on how the torch is held and guided, any cut, straight, curved, irregular or bevelled may be made. Depending on the size of tip used, steel up to 300 mm in thickness can be cut with a hand torch. Since the cutting process depends on

a chemical reaction between the oxygen and the iron in the steel, the process can only be used on iron or on various types of steel. Stainless steel and similar special steels cannot be cut satisfactorily with a hand cutting torch.

With practice an operator can make bolt holes in plate without too much slack. Bevel cutting is particularly useful in preparing for welding. Circle cutting and straight line cutting can be brought to a high standard using roller guide attachments.

Cast iron can be cut with the ordinary hand torch using a modified technique. The cut will be wider and the edges will not have the smooth appearance of a cut in steel. Although much slower than steel cutting it can still save time and effort compared with any other method.

4.3.7 Procedure for welding

As the name implies the fusion welding of steel is a true weld: that is, the two pieces of steel being joined together are actually melted together and the filler rod is added to complete the weld. Provided suitable preparation of the work allows this fusion process to penetrate through the thickness of work, a sound weld will result.

In practice the limit to the successful welding of thicker steel plate is set by economics. As the thickness of the steel to be welded increases, so does the size of the weld tip with a consequent increase in the consumption of welding gas. As a result, plate thicker than 3 mm is usually welded by electric arc. However, in the sheet metal field, oxygen-acetylene welding has many advantages and is used extensively by panel beaters and sheet metal workers.

There is no need for the edges of sheet metal to be bevelled in steel up to 3 mm, and unless the steel is very rusty, no cleaning is required prior to welding. The edges to be welded must be carefully cut and fitted accurately. Large gaps require a lot of heat and filler rod, and usually cause excessive buckling. A neutral flame is required using a welding tip sized to suit the steel being ioined.

With the tip of the inner cone held about 1.5 mm from the work the steel will quickly heat to a bright orange colour and then melt. With the torch held correctly, both sides of the seam will melt together and then, and not before, the filler rod may be added to the molten pool of metal (*Figure 4.5*). Filler rod



Figure 4.5(a) The weld progression is established, by forming the weld pool, then lifting the filler rod up.

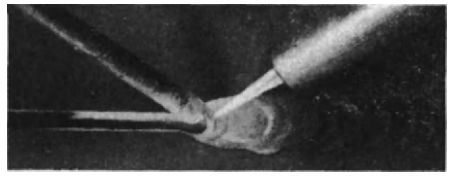


Figure 4.5(b) Move the torch along to melt the next section of the plates.

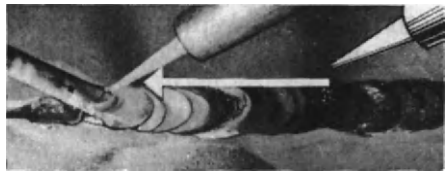


Figure 4.5(c) The motion of the torch is straight along the weld, at constant height, without weaving.

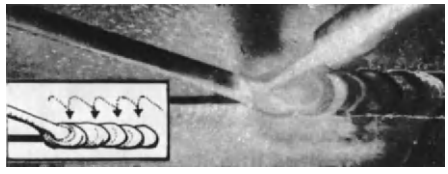


Figure 4.5(d) Motion of the filler rods shown by arrows. At the end of each movement the rod is pushed into the weld pool (NZIG).

must not be melted and dropped onto steel that is only hot and not molten. The process is a continuous one and should leave a smooth weld with just a faint ripple on the surface. A good weld must penetrate completely through the steel being welded (*Figure 4.5*). Tack welding (short welds along the seam) is often used to hold work together while the weld is being made.

4.3.8 Building up and hard facing

In addition to joining steel, fusion welding is also used to build up worn parts and surfaces to the point where they can be machined to size and then put back into service, often at a fraction of the cost of a new part. If, instead of building up with a normal steel filler rod, a special alloy steel is used, a considerable

improvement in wear resistance can be expected. Ploughshares, grader blades, cultivator tips and many other parts subject to much wear and abrasion have shown a marked increase in service life when hard faced with suitable material.

Hard facing alloys are available in a wide range of hardness and toughness. However, the very hard materials are somewhat brittle and care is needed to select the best material for any job.

4.4 ELECTRIC ARC WELDING

Electric arc welding is the main alternative to gas welding. It is possible to learn to do simple jobs relatively quickly. There are two types of electric arc welders on farms. These are AC transformer welders and DC generator welders. The AC transformer welder is available in a wide range of sizes and costs. In essence it is little more than a step down transformer (see Chapter 7) which reduces the voltage from 230 volts to only a few volts, but with a corresponding increase in current. A 3 mm electrode requires a current of 130 amps and is suitable for light work. A 4 mm electrode requires 160 amps and will handle quite heavy jobs in a reasonable time.

The workshop models of AC welders are heavy duty machines designed for continuous service and when properly installed run from a 400 volt, three phase power supply (Chapter 7). This requires a power supply, a special plug and a permit from the local supply authority. Farmers should consult their local power board before purchasing any welder to be sure that transformers and power cables are adequate to carry the heavy fluctuating power load.

Small welders with ratings around 130 amps are available in a wide range of sizes and prices. These are operated from a 230 volt single phase supply and are often run from a 3 pin wall outlet (eg *Figure 4.6*). Many of these machines are intended for intermittent use only. Some have a 25% duty cycle rating (ie in any hour of use the actual welding time must not exceed 15 minutes: when this rating is exceeded the windings of the machine overheat, the insulation is damaged causing a short circuit, and the machine "burns out" with smoke pouring from the transformer). These very small welders are very useful for small jobs in places where a 400 volt supply is not available. They may be taken up ladders and into difficult places. For farm use the 25% duty cycle and the maximum rating of 130 amps may be a limitation.

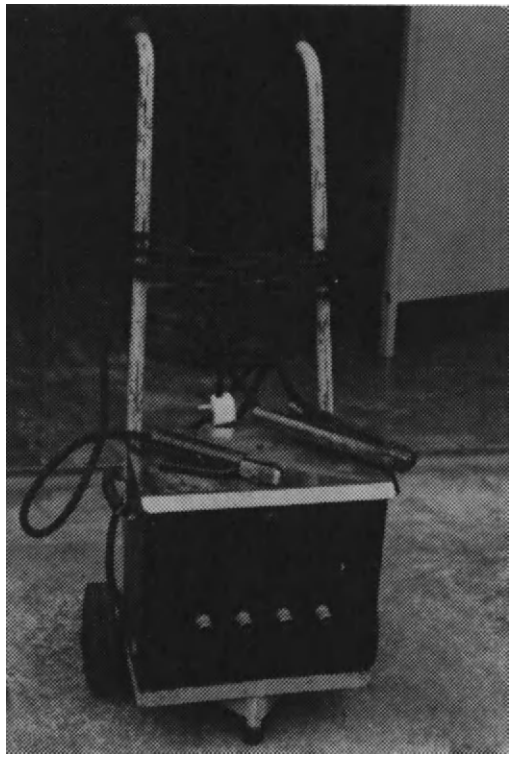


Figure 4.6 A small 230 volt arc welder suitable for light farm work.

DC welding generators may be driven by a tractor power take off, a petrol or diesel engine, or an AC electric motor. When driven by the power take off the DC welder may be made a completely portable unit and used either in a workshop or in the field. When driven by an engine the unit may be trailer mounted to give similar portability. The engine must be governed to drive the generator at the required speed (eg 2800 rpm).

As well as the welder, welding cables, a ground clamp, an electrode holder, safety glasses, a hand shield, a chipping hammer, a wire brush, good gloves, and dark coloured protective clothing will be required (*Figure 4.7*).

4.4.1 Safety precautions

An electric arc emits invisible ultra-violet radiation which causes eye and skin burns

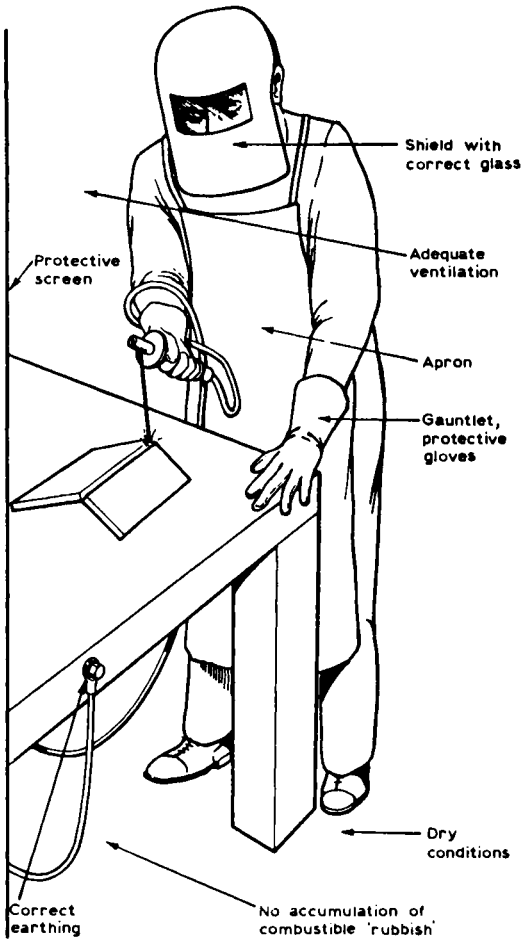


Figure 4.7 Arc welding in practice (Sully).

that show up later. One should never look at an electric arc without using the coloured lenses in the shield or helmet. The hand shields used for arc welding are fitted with a tinted lens and a clear lens. Neither of these lenses has an impact rating, and anyone carrying out arc welding operations should always wear safety glasses underneath the hand shield. This will not only help to protect the eyes in the event of an impact, but the safety glasses will also stop many of the harmful rays produced if an arc is struck before the shield is lowered (this happens quite often unintentionally when positioning the rod). Arc radiation can also cause a burn similar to sunburn so the body must be protected with suitable clothing. In addition white or reflective clothing should not be worn, as the arc is strong enough to reflect off this, passing under the mask and into the eyes.

Electrical safety is also important. Although the maximum voltage from electric welders is seldom more than 70 volts, care should be taken to weld on a dry floor. Welding cables should be kept in good condition. When the ends become frayed, shorten them or discard the whole cable.

All welding should be done well away from combustible materials, as fires are easily started by the sparks from electric welding. As stated before, any trace of inflammable materials such as petrol, kerosene or diesel must be removed before attempting to weld containers. Most importantly, never attempt to weld a sealed container, since the gases inside will heat up and explode. Adequate ventilation when welding is essential, particularly when welding galvanised iron. Many of the health problems which follow from welding operations are related to the position of the work in relation to the operator's head. Frequently operators keep their head in the plume of fume. Care should be taken to avoid this.

4.4.2 Welding electrodes

There are many types of welding electrodes but a few should be adequate for all farm requirements. Do not purchase large quantities of electrodes at any one time. It is better to renew your stock from time to time as electrodes tend to deteriorate, particularly in a humid atmosphere. They should be stored in a dry place as damp electrodes will make welding difficult and may produce poor welds.

Electrodes are sold in sizes from 6 mm down to 1.5 mm. For farm use a good general purpose rod in 3.1 and 4.0 mm sizes is adequate. Other special electrodes can be purchased later if required.

4.4.3 Flux coatings

The flux coating on an electrode has many purposes and without it the electrode is useless. It provides gases which shield the molten metal from the atmosphere. It also provides a covering of slag for the hot metal, preventing oxidation, hardness and porosity in the weld metal, and it controls the flow of the molten metal in the arc stream.

4.4.4 Current setting

Many factors will affect the required welding

current. Two basic factors are size of rod and thickness of metal. Each packet of electrodes will show the manufacturer's recommended welding currents. Most 3.1 mm electrodes have a current range between 90 to 135 amperes and in practice most welding with this size would be done with a current of about 120 amperes. Thinner plate will naturally require a lower setting (otherwise a hole will be produced), while thicker plate will require more heat and a higher amperage. With AC welders, variations in line voltage also affect the heat of the arc and during a peak load period the current setting may have to be increased. Practical experience will soon enable you to know when the current setting is either high or low. Overhead and vertical welds require less current than those in the flat position. Excessively long extension leads on the power supply to an arc welder (particularly a single phase unit), will cause problems. Severe damage can result if the operator tries to increase the output voltage in order to overcome an inadequate power supply.

4.4.5 Weld preparation

Plates to be welded should be cleaned with a wire brush so that loose rust and paint are removed. Oil and grease must also be removed before welding is attempted. When producing a butt weld (where the plates are joined edge to edge), plates up to 6 mm thick should be spaced about 3 mm apart, tack welded, and then welded from both sides. Thicker plates up to 12 mm thick must be bevelled to an angle of approximately 30° by either grinding or gas cutting before tacking and welding. For plates thicker than 12 mm, and for all round and square sections, a double vee must be cut on both pieces leaving about 3 mm of metal in the centre. Welds are then deposited on both sides until the weld surfaces are flush with the top of the plate. Butt welds require 100% penetration right through the thickness of the metal before adequate strength can be expected from the weld. Correct preparation and careful welding will give a weld that will be stronger than the parent metal, but if two thick plates are merely butted together and welded, the joint can break very easily.

Fillet welds are used to join two plates at right angles. After tacking in position, welds are made on both sides taking care that the weld metal penetrates right into the corners. On a long length, welds are placed on opposite sides alternately to minimise distortion.

4.4.6 Distortion

When metal is deposited in place it is molten and on cooling must contract. If welding is carried out without any thought being given to this problem considerable warping and distortion can occur. Before each weld is made consider carefully which way the distortion may pull, so that steps may be taken to reduce the effects. Some of the methods used include tacking the work so that the pull of weld will bring the places into the correct position when welded, balancing the pull by welding from alternate sides of the joint, tack welding temporary stays in position to restrain the work while welding (which can be removed when finished), or straightening the job when finished either cold, or by heating the welds and then pulling or hammering the job into the correct position.

4.4.7 Weldable metals

All good quality mild steels can be easily welded using general purpose electrodes. Cast iron, spring steels and alloy steels can be welded using special electrodes and special techniques. Unless one is handling these materials frequently they are better left to the professional welder.

4.4.8 Hard facing electrodes

Hard facing electrodes are available in a wide range of hardness and toughness. They are expensive and rather specialised techniques are required to apply them.

4.4.9 Arc cutting

Where a workshop is not equipped with an oxygen-acetylene cutting torch, cutting of metals may be done with the arc welder. Here the higher amperage machines perform much better, since they can use large electrodes which give more heat. Special cutting electrodes are available which will cut steel cast iron and most metals. Cutting with the arc is largely a melting process and so the finished cut cannot be compared with the smooth finish of the oxygen-acetylene cutter. However, the method can be used for many jobs such as bevelling plate for welding, cutting off broken machine parts, and piercing holes in plate.

4.4.10 Comparison of gas and electric welders

In general engineering there is little competition between gas and electric equipment. Each has a definite field where one is superior to the other. To be completely equipped to handle all jobs both plants are required. A comparison of the two is given in *Table 4.1.*

Table 4.1 Comparison of gas and electric arc welders.

GAS	ELECTRIC
Cutting torch ideal for quick, clean accurate cutting of steel.	Cutting slow and ragged—compromise only.
Excellent for welding thin sheet metal up to 4 mm.	Difficult to weld without burning holes.
Excellent for bronze welding cast and malleable iron.	Not suited to bronze welding. Can weld cast iron using special rods but tricky.
Slow and expensive for steel thicker than 4 mm.	Quick and cheap in all heavier steel.
Ideal for brazing copper and brass and for aluminium welding and brazing.	Not suitable for brazing. Requires special type to weld aluminium.
Useful for heating, straightening, and bending components.	Not suitable for heating, straightening, and bending components.
Good for light hard facing.	Good for heavy hard facing

4.5 LOW TEMPERATURE BRAZING

Brazing is a technique of joining metals where the melting point of the filler rod is below that of the metals being joined. At the correct temperature, and with the aid of a flux, the filler rod flows over the heated surfaces, bonding firmly to give a joint that in many cases is stronger than the parent metal. As the parent metals are not melted, there is less distortion and a low intensity flame may be used. Many jobs can be done using a good blowlamp.

4.5.1 Joints

Brazing requires a different joint preparation from welding. The aim is to provide a good area of contact between the two pieces being joined. As brazing metal flows very thinly when heated, joints should be a reasonably close fit. Much strength can be lost if there are large gaps to be filled.

4.5.2 Brazing rods

There are three common types of rod. They all contain silver and are known commercially in New Zealand as Easyflo, Silfos and Silbralloy. They are a development from an older brazing material known as silver solder. They are easy to use and will produce good joints when used with the correct metals. Easyflo contains 50% silver and will join copper, brass, steel, stainless steel, monel metal and michrome. It is used when a smooth joint with maximum ductility is required. Silfos contains 15% silver, and is used with copper, brass and bronze. It has the advantage of making a fairly strong joint. It does not require a flux on copper and is used extensively for plumbing. A third rod, silbralloy, contains only 2% silver and is a cheaper rod where the joint need not be particularly strong.

All metal surfaces must be thoroughly clean before brazing can be attempted. All scale must be removed with a file or emery cloth until the surface is bright and shiny. Any grease must be removed with white spirits.

Except when using Silfos on copper a flux must always be used when brazing. The flux, which is in a powder form, melts when heated providing an effective barrier between the air and the cleaned metal surfaces. In addition, chemicals present in the flux exert a strong cleaning action on any traces of oxides which may be present, providing a perfect surface for the brazing material to bond onto. Finally, the flux acts as a wetting agent allowing the filler rod to flow right through the joint. In

difficult work the flux may be mixed with water to form a stiff paste and applied to the job before heating is started.

Heating may be done using a blowlamp, LPG or butane torch, air acetylene torch, or an oxygen-acetylene torch. The only requirement is that the heat is applied evenly until the flux melts and appears as a clear varnish. This indicates that the correct temperature to apply the brazing rod has been reached. Overheating should be avoided. The heated parts of the job should melt the rod, rather than the flame itself. Building up a fillet outside the joint does not add any appreciable strength to the joint.

After the molten brazing alloy is completely solidified the job may be moved, and all traces of flux must be removed with a wire brush and water.

4.6 BRONZE WELDING

Bronze welding is a development of the older process of brazing. The basic theory of the process is that molten brass or bronze will flow onto and bond to a properly heated and fluxed surface of a metal of higher melting point. This bond can be stronger than cast iron.

The bronze is added to the weld in the form of a rod, and the job and rod are both brought to the requisite temperature by an oxygen-acetylene flame. The base metal must never be melted. Cleanliness is essential. All oil, grease, and scale must be removed. Even after cleaning, many metals retain a superficial coating of oxide that would prevent the bronze weld metal from bonding properly with the base metal. Therefore, a flux is required which contains materials which will chemically remove this coating. Where the preparation has been done by grinding, the surface must always be finished by filing with a relatively coarse file. If this is not done the bronze will not flow onto the ground surface properly. With a rougher surface the bronze is able to key itself to the steel surface producing a stronger joint.

When preparing broken parts it is necessary to "vee" some of the metal out in order to produce a strong job. In light sections this need only be done from one side leaving a thin line of the original crack to facilitate alignment. Thicker sections should be veed from both sides to an angle of approximately 80°. A slightly oxidising flame is required, particularly for galvanised iron.

Bronze welding can be applied to most steels, cast iron, galvanised iron, malleable iron, and copper. Special fluxes are required for galvanised iron and malleable iron.

When using bronze welding there must be ample ventilation. Some rods give off zinc fumes when heated and the operator should avoid inhaling these as they may produce nausea. This risk is much greater when welding galvanised iron. If work must be done in a confined space a respirator should be worn, or forced ventilation used.

4.7 NOTES ON THE USE OF FARM WORKSHOP TOOLS

Horticultural workshops and farm workshops are rarely the cleanest and tidiest places in the world. Despite the difficulty, it is always worth trying to keep the area as tidy as possible. Time lost trying to find tools and other objects can eat into the day, and make life very tedious. It is therefore a good idea to have particular places to put all tools where they can be found easily, and where they will be protected from water and condensation, etc. Many tools need to be kept lightly oiled to protect them, and all cutting tools should be kept sharp (and stored well away from places where children have access). A clean bench also makes work much easier and successful.

4.7.1 Tool sharpening

Sharp tools are the mark of a good worker. Only a poor worker or an amateur will struggle along with a dull tool rather than take time to sharpen it, because the time required is soon regained in faster and better work. Tool sharpening can be carried out with the aid of a selection of files of various types, lengths and degrees of coarseness to suit the tools being sharpened. Files are sufficiently hardened so that they will sharpen all but the very hardest of edged tools. In addition a grinding wheel, either hand or power driven, is required. A double ended 200 mm grinder fitted with both a coarse and fine grinding wheel and powered by a 0.37 kW electric motor is a good farm tool. Grinding wheels are capable of grinding the hardest of steels

and when correctly used do not soften the steel of the tool being sharpened.

Oilstones are necessary where a fine edge is required, such as on a wood chisel or knife. A combination stone with one side made of coarse or medium-grain abrasive and the other made of fine-grain abrasive is the most useful for general farm use. Tools may be sharpened by using any of the above three items, either singly or by following one process after another depending on the condition of the tool being sharpened and the fineness of edge required. Tool sharpening requires good equipment for the best results.

4.7.2 A warning about grinders

Many eye injuries are caused by grinding wheels. You should never use these machines without adequate guards in place, and never grind without wearing safety goggles. The workrest should be kept adjusted so that the gap between it and the face of the wheel is never more than 1.5 mm. If the wheel wears and the gap is allowed to increase, small jobs are easily jammed, often taking your fingers at the same time. For the same reason it is sound practice to hold small work firmly with lock joint pliers. Most modern grinding machines are also fitted with a tongue guard at the top of the opening to the workface used by the operator. These should also be kept in place and properly adjusted.

4.7.3 Other methods of joining components

In addition to the more permanent methods of joining materials described above, it is possible to use a range of other methods. These range from the simple nut and bolt, to special fixing systems which are sometimes used for galvanised steel roofing or greenhouse claddings. Rivetting and glueing methods can also be used to produce strong joints. The method chosen for joining will depend upon the service environment of the components (especially vibration and corrosion factors), the strength and flexibility requirements, the cost, the need for disassembly for maintenance, and even the look of the finished product. A full discussion is outside the scope of this book, and the interested reader is referred to the references.

4.8 EXERCISES

Refer to the aims as listed below.

4.9 AIMS OF THIS CHAPTER

After reading this chapter you should be able to:

1. Outline the principles, techniques and differences between soldering, brazing, and welding.
2. Describe the equipment requirements for these processes.
3. List some safety and health precautions which should be considered before starting these processes.

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Hydraulics

Chapter 5

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5.1 INTRODUCTION

Hydraulics is the study of the properties of fluids. In agriculture the most common fluid is water (*Figure 5.1*), and much of this chapter will be concerned with it. However other fluids, such as oil, slurry, air, refrigerants, and sprays are also of importance. In some situations it is possible to use fluid models to describe the behaviour of crops such as corn, or other grains in bulk. However, serious underestimates of the forces produced in grain stores and silos have been made in the past, using over-simplified fluid models, which have resulted in the failure of such buildings, sometimes with tragic consequences. It is therefore advisable to treat the following chapter as relating only to proper fluids.



Figure 5.1 Water—the source of life (Huka Falls, New Zealand).

In horticulture and agriculture the properties of fluids are important in many situations, but not all of them are obvious. Here are some examples:

a. Farm water supplies

We will consider in some detail the design of farm and house water supplies. This includes a brief consideration of crop and stock water requirements and the location of troughs. The philosophy of designing a water supply is worth stating here: a water supply for a farm involves the use of materials and components which have a lifetime of around 50 years. It is therefore worth designing the system in the knowledge that it could still be operating well after you retire. What you install you will have to work with until you leave the farm. If you are designing a supply for someone else, it will still be your monument, and it would be a pity if it did not work as well as it could have done. A well designed water supply requires planning and preparation. It also requires a great deal of surveying work initially, to establish water sources, ground levels, sites for tanks, troughs, and dams, routes for pipes, and identifying possible obstacles or other problems.

b. Irrigation

Crops require water, and there are many methods of applying water to growing crops. These include surface application, spraying and trickle irrigation techniques. The principles given here apply just as much to greenhouse irrigation as to hill country sheep farms.

c. Heat exchangers and heating systems

The performance of heat exchangers depends on the properties of the fluid. Fluids are used to transfer heat around hot water pipes. The thermal properties of fluids will be considered in a later chapter.

d. Air compressors and fans

For ventilation, drying and heating purposes, compressible fluids (gases) are used. The properties of these differ from water, which is essentially incompressible.

e. Milking machines

The efficient harvesting of milk involves a fluid system which involves the flow properties of a mixture of air and milk. The study of this two phase system is well beyond the scope of this book. However the principles of milking machines are considered in another chapter.

f. Sport

An Australian farmer friend of mine made the first project on his newly purchased farm the construction of a floodlit tennis court. In fact by letting it to the local town's sports club the profit per hectare from this enterprise vastly exceeded anything else he ever attempted! While the flight of a tennis or golf ball, or even an aircraft, is not about to be discussed, above all else the young farmer must be adaptable, and quick and able in applying his or her knowledge to unexpected areas.

5.2 WATER SUPPLY REQUIREMENTS

All living things require water for survival. Above this level the provision of a plentiful supply of water means that production levels can be improved, and health, hygiene and the quality of life can be raised. A water supply must be both adequate and good, ie, there must be enough water, and it must be fit for consumption. Some plants will thrive on brackish (undrinkable) water, but many will not. High salt levels restrict the choice of plant severely. Stock are frequently expected to drink water which would be rejected by most people, even though there is no medical reason why the standard of water for stock should not be as high as that for humans. The design of a water supply requires a number of inputs. Water requirements should be identified first. Once the requirements are determined, possible water sources should be established. These two factors supply the planning data from which the system can be selected and designed. Finally the system can be installed.

Specific details of the water requirements depend upon the type of enterprise and the climate. For example in Britain the maximum requirements for stock are quoted as typically 75 litres per day for dairy cows, and 8 litres per day for sheep (Electricity Council, 1983). Other stock such as cattle and horses require a maximum of 45 litres per day. Pigs require 15 litres while 100 chickens will consume 60 litres per day. Irrigation requirements for crops depend upon the crop, the soil type and the climate: in summer, in New Zealand, the evaporation rate can be as high as 7 mm or 7 litres of water per square metre of crop cover. If this is to be replenished by irrigation somewhat more than this will be required to allow for losses through spray drift and percolation. Domestic requirements have been put at around 500 to 1000 litres per day for a family of four. All of these values vary according to local conditions, and in practice the volumes and flow rates of water for a particular purpose will have to be calculated from common sense, experiment, or from data available from books, or consultants. Irrigation requirements can be based on the calculated evapotranspiration rates for the area under the worst conditions, while stock and domestic requirements are reasonably well known for most types of animal and use. One use which may be missed is for fighting fires. If your house is on fire, a nearby store of between ten and twenty thousand litres with a 75 mm outlet will give the local fire fighters a chance to do something. Otherwise you lose your building! Swimming pools can have a very practical purpose.

It is always advisable to allow a considerable margin for future requirements. Land use may change, and extra water may be needed. Extra land may be obtained, or neighbours may be interested in sharing a facility. An over-designed system will cope, while one which provides only the minimum requirements will give little satisfaction in the long term, and upgrading will be very costly. Fortunately the nature of water supply design, involving the selection of the right sized pipe and pump to cope with the job, inherently

involves an element of over-design, since the aim is to use the most economic sizes which will provide the maximum predicted demand. This usually involves choosing equipment which will enable more water to be supplied than is required. However it is very much easier to reduce the flow rate with a valve than to find a way of increasing it in an under-sized system.

Planning

For farm water supplies, a good survey is essential. An aerial photograph of the farm is ideal, combined with a survey to establish the topography of any proposed routes. The reduced levels and position of all sources, locations to be supplied, and previous water supplies should be shown. Once the pipe route has been selected, a landwheel can be used to go over the route and establish the exact pipelengths involved for the purposes of ordering pipes or for contract specifications.

Sources

Water can be obtained from lakes, streams, rivers, wells, springs, or artificial dams. Of these the last is usually the most expensive option. It is important to know the flow rate available from the source, and we will discuss methods of determining flows in rivers, streams and wells. If the flow is inadequate at certain times of the year then some form of buffer storage will be required. Water quality of a source should be checked if there is any doubt. Chemical and bacteriological tests will indicate whether the water is fit for human, crop or stock use. Iron contamination is a frequent problem, but it is possible to treat the water to remove the iron. Similarly in chalk soils water may contain calcium carbonate, which causes water pipes to "fur up" with time. Treatment is possible but not often required, except where the water is to be heated. In most countries permission is required from local authorities before water can be used for agricultural or industrial purposes.

Having outlined some of the principles involved in developing a water supply, we will now consider the way in which fluids behave. First we will remind ourselves of some of the basic properties of materials which were introduced in Chapter 3, and which are particularly relevant to the models which aid us in our study of fluids.

5.3 BASIC PROPERTIES

The *Specific Weight* of a substance (m) is the weight per unit volume. Its units are N m^{-3} and it is closely related to the *Density* (ϱ) which is the mass per unit volume (kg m^{-3}). Obviously,

$$\gamma = \varrho g \qquad \textbf{Equation 5.1}$$

For water $\gamma = 9.8 \times 10^3$ N m^{-3}, since $\varrho =$ 1000 kg m^{-3}, and $g = 9.8$ m s^{-2}.

The *Specific Volume* is occasionally used in the literature. This is the inverse of the specific weight, ie, the volume per unit weight.

The *Specific Gravity* (SG) is the ratio of the density of the liquid to that of water. Thus

$$SG = \frac{\varrho_{liquid}}{\varrho_{water}} = \frac{\gamma_{liquid}}{\gamma_{water}} \qquad \textbf{Equation 5.2}$$

The *Absolute Viscosity* (μ) measure is used to determine how easily the fluid deforms. If a liquid is sheared between two plates (see *Figure 3.13*) then the liquid in contact with each plate moves at the same speed as the plate, so that a velocity gradient develops between the two plates. Experimentally one finds that the velocity v of any filament of the liquid is proportional to the distance y from the lower plate. The viscosity can be determined in special apparatus, and is obtained from the relationship between the shear stress τ and the rate of change of velocity with distance, and is obtained from:

$$\tau = \mu \frac{dv}{dy} \qquad \textbf{Equation 5.3}$$

In a pipe, or in a river, the flow at the sides is very small, and it increases towards the centre. This has implications when one is considering the effect of the roughness of the wall of a pipe on the flow. This will be discussed shortly. Substances like treacle or honey have a high absolute viscosity, while water has a low value of 1.002×10^{-3} N s m^{-2} at 20°C. The viscosity varies with temperature; values increase with temperature in gases, but decrease as the temperature rises in liquids.

The *Kinematic Viscosity* is also common in the literature, and is just the absolute viscosity divided by the density, ie:

$$s = \frac{\tau}{\varrho} \qquad \textbf{Equation 5.4}$$

5.4 HYDROSTATICS

We begin by considering how fluids behave when they are at rest (that is, there is no bulk movement of the fluid: the molecules will still be moving around inside the fluid itself). In these models we will neglect effects due to surface tension, a phenomenon which can affect fluid behaviour significantly in small channels less than a few mm wide.

5.4.1 Pressure

Pressure is the same thing as stress. It is the force per unit area applied to or by a fluid. The units of pressure are worth discussing. The basic SI unit is the Newton per square metre ($N\ m^{-2}$), also known as the Pascal (Pa), which is a very tiny unit indeed (a layer of water 0.1 mm thick is enough to produce 1 Pa). To avoid such tiny units the Bar is often used. This is equal to 10^5 Pa. By coincidence it is almost the same as the pressure due to the earth's atmosphere. In fact an *Atmosphere* is another measure of pressure, with a value of 1.013 bar. As we shall see shortly, the pressure in a fluid is governed by how deep the fluid is, and this leads to another very common form of pressure measurement. This is the height in metres of a column of fluid which would generate the same pressure. This is called the *Head*. Thus 1 atmosphere is equal to 10.33 metres of water, or 760 mm of Mercury. These values are listed in *Table 5.1*.

Table 5.1 Relationships between pressure measurements

$1N\ m^{-2}$	= 1 Pascal (Pa)
1 bar	= 10^5 Pa
1 Atmosphere	= 1.013×10^5 Pa
1 metre water	= 9.80×10^3 Pa
Hence 1 Atmosphere	= 10.33 metres of water
	= 760 mm Mercury

5.4.2 Pressure in a fluid

Let us consider a column of a fluid H metres high in a cylinder D metres in diameter (*Figure 5.2*). If the column is upright, then the pressure on the end of the cylinder will be the weight of the fluid divided by the area of the end. If the specific weight of the fluid is γ then the pressure is:

$$P = \frac{(\pi\ D^2/4)\gamma H}{(\pi\ D^2/4)}$$

ie, $P = \gamma H$ **Equation 5.5**

Thus the pressure is equal to the height of the fluid column multiplied by the specific weight.

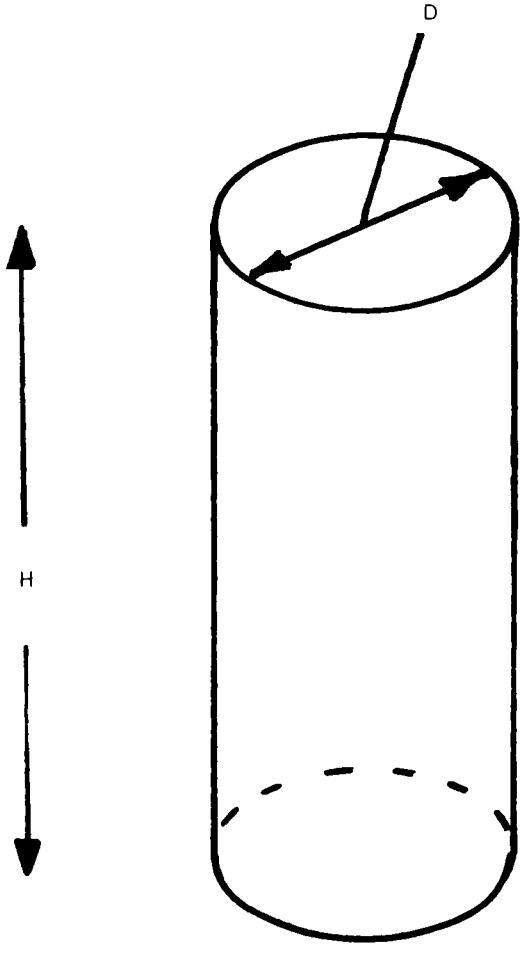


Figure 5.2 Pressure in a fluid.

This may seem very straightforward (and it is!) but the simplicity can cause you to overlook the important implications. First the pressure does not depend upon the size of the pipe or cylinder. A 10 mm diameter column of water in a small pipe can generate the same pressure as would be produced at the bottom

of a lake, if the height of the water is the same. Second the pressure will increase with the depth of the fluid (if the fluid is a liquid with a constant specific weight the pressure increases linearly with depth, while in a gas the rate of increase in pressure will not be linear since the gas itself will get denser). Thus if a pipe contains water at rest the greatest pressure in the pipe will be at the lowest point of the pipeline. When the water is moving other factors can affect the pressure, and the situation may change, but it is very important to check that the pressures produced in the static case can be sustained by the pipe!

Third, the pressure will be the same at all points which are at the same depth in a fluid system, when it is at rest. This applies regardless of how far apart the points are, or whether or not they are part of the same container, or whether they are connected by a narrow pipe or a large pipe. This fact is very useful for solving certain problems in hydrostatics.

Example

Calculate (a) the pressure P and (b) the force F on the bottom of a water tank 5 m by 8 m and filled to a depth of 6 m with water.

Solution: $P = \gamma H = 9.8 \times 10^3 \times 6$
$= 58.8 \times 10^3 \text{ N m}^{-2}$

Note the size of the tank is not required yet. However the force equals the pressure × area, or

$F = 58.8 \times 10^3 \times 5 \times 8 = 2{,}350 \text{ kN}$

5.4.3 Pascal's law

Pascal's law states that at any point in a fluid the pressure is transmitted in all directions. This seems a little strange at first but it just means that if a block of metal or any other object is put inside a fluid then the pressure on each side is equal to the pressure at that depth. Again our experience shows that this model is a perfectly good description of reality. It means that the force on any submerged surface can be calculated, and some examples will illustrate the types of problem this helps to solve.

Example

Find the force on the water sluice gate shown in *Figure 5.3*, where $H_1 = 4$ m, $H_2 = 8$ m and the width of the gate B is 3 m.

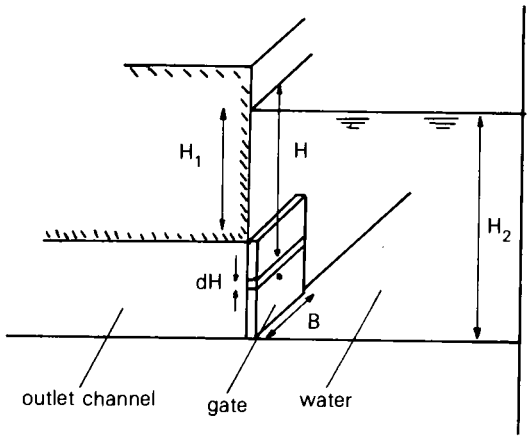


Figure 5.3 Force on a sluice gate.

Solution: At any depth H, from *Equation 5.5*:

$P = \gamma H$

Now H varies and so it is necessary to consider a small element dH as shown and integrate over the entire area of the gate.

For the element shown, the force equals the pressure times the area or

$dF = \gamma \, H \, dH \, B$

Integrating, $F = \gamma \, B \int H \, dH$
$= 0.5 \, \gamma \, B \, (H_2^2 - H_1^2)$

Now the area of the gate $A = (H_2 - H_1)B$ so the force can be written as

$F = \gamma \, H_c \, A$ **Equation 5.6**

where H_c is the depth of the centre of area (the centroid) of the gate, given in this case by the formula:

$$H_c = \frac{H_1 + H_2}{2}$$ **Equation 5.7**

In fact this equation applies to any shape of gate, including gates which are not vertical, where the centre of area is known or can be calculated. You may like to prove this yourself for a gate at an angle θ to the horizontal.

Inserting values gives

$$F = 9.8 \times 10^3 \times \frac{(4+8)}{2} \times 3 \times 4$$

$$= 7.056 \times 10^5 \text{ N}$$

The above calculation tells us how large the force will be. In order to specify the force completely, the line of action of the force is also required. The point on the gate through

which this acts is called the *Centre of Pressure*. If the pressure were uniform, it would be through the centre of area. However because the pressure increases with depth it will be lower than the centre of area, and it can be shown by integration that the depth of the centre of pressure is given by:

$$H_p = H_c + \frac{I \sin^2\theta}{H_c A} \qquad \textbf{Equation 5.8}$$

where θ is the angle of the gate to the horizontal, A is the total area, and I is a special parameter called the second moment of area. It depends upon the shape and size of the gate. Values of I for some shapes have been given in *Table 3.4*.

5.4.4 Buoyancy

Next we must briefly consider why things float. A body placed in water floats because a net upwards force is produced which equals its weight. Once the forces are balanced the resultant force is zero so the body stays at rest, ie it floats. The size of the force was worked out long ago by the ancient Greek philosopher Archimedes, and the principle retains his name. It follows from Pascal's law. If we consider a rectangular body with a bottom of cross-sectional area A floating at a depth H in a fluid then the upward pressure on the bottom will be simply:

$$P = \gamma H$$

The total upward force will thus be:

$$F = P A = \gamma H A \qquad \textbf{Equation 5.9}$$

but this is exactly the same as if we multiplied the volume of fluid displaced by the body ($H \times A$) by its specific weight. In other words, the upthrust on a body is equal to the weight of the fluid displaced by the body. Thus floating occurs when:

The weight of the body is equal to the weight of the fluid displaced by the body.

Example 1

Floats are required to support a 100 mm diameter water pipe over a pond. The pipe must stay out of the pond, and each float must support a 20 m length of pipe when it is full of a fluid of specific weight 11.4×10^3 N/m^3. How big must the float be if the empty pipe weighs 40 kg? Assume that each float will weigh 10 kg.

Solution: Total weight to be carried = weight of pipe + float + fluid in the pipe.

The fluid in the pipe will weigh $\gamma \times$ vol

$$= \frac{\gamma \times 20 \times \pi(0.1)^2}{4} = 1790.7 \text{ N}$$

Hence the total weight is $10 \times 9.8 + 40 \times 9.8 + 1790.7 = 2280.7$ N

Now the upthrust = $\gamma \times$ vol displaced

$$\text{Hence volume to be displaced} = \frac{2280.7}{9.8 \times 10^3}$$

$$= 0.233 \text{ m}^3$$

Thus each float must be at least 0.233 m^3 in volume.

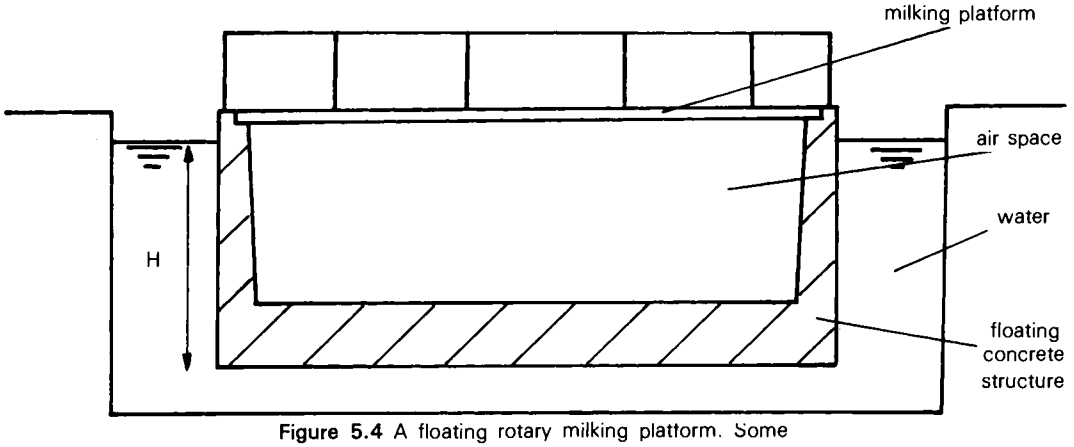


Figure 5.4 A floating rotary milking platform. Some designs include a separate floating section between the two shown, so that the container for the platform itself floats inside another water jacket.

Example 2

A rotary milking platform is to be designed so that it floats on a layer of water. If the platform and stock weigh 120 tonnes, and it is 10 m in diameter, how deep must it be in the water for support? A cross section of such a milking unit is shown in *Figure 5.4.*

Solution: Upthrust = weight of water displaced = weight of platform (Mg)

$$\text{Now upthrust} = \frac{\gamma \times H \times (\pi \times 10^2)}{4}$$

$$= 769.7 \times 10^3 \text{ H}$$

where H is the depth of the water as in the Figure.

$$\text{Thus H} = \frac{120 \times 10^3 \times 9.8}{769.7 \times 10^3} = 1.53 \text{ m}$$

Note that although the water must be 1.53 m deep, only a very small quantity is needed (enough to ensure that the parts have adequate clearance – say 100 mm). Platforms such as these have several advantages over conventional rotaries which must be supported by large steel roller bearings. Some designs include a further floating section in between the two shown in the Figure, so that the container for the water on which the platform floats is actually itself floating inside another container! This allows for easy stock movement.

5.4.5 Hydraulic lift

The principles we have just outlined give rise to some useful machines. A hydraulic lift enables a small force to lift a large mass, as shown in *Figure 5.5a.* Using Pascal's law, the

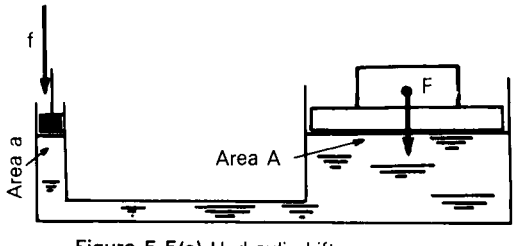


Figure 5.5(a) Hydraulic Lift.

pressure under each side of the lift must be equal. Therefore the forces on either side are given by

$$\frac{f}{a} = \frac{F}{A} \qquad \textbf{Equation 5.10}$$

Thus a small pump generating a force f can raise the large load on the other side.

5.4.6 Hydraulic actuator (*Figure 5.5b*)

The actuator is a device which uses fluid pressure to produce a force which can drive an arm (which may then open or close ventilation ducts, etc). The size of the piston can be chosen so that it produces enough force from the pressure to drive the arm. In this way a low pressure pump can be used to produce a very large force.

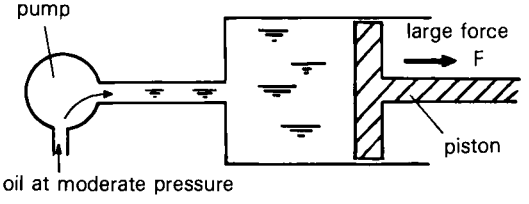


Figure 5.5(b) Hydraulic actuator.

5.4.7 Absolute and gauge pressure

Everything on the surface of the earth is under pressure. This pressure is produced because the earth has an atmosphere consisting of a mixture of gases called air about 100 km thick. The air is a fluid and produces a pressure which varies with the depth and density of the air. This pressure is the atmospheric pressure and it has a value of about 100 kPa, or 1 bar. As discussed in Chapter 2, atmospheric pressure falls as the height increases. This is because its value is determined by the weight of the column of air above the point in question, and just as the pressure falls as we move up from the bottom of a container of water, so the pressure in the air falls as we go up. The value of the pressure is more complicated because the air is itself compressed, so that its density varies. Atmospheric pressure also varies with time depending on the weather conditions at any place. Weather forecasts usually quote air pressures in millibars (mbar).

In practice when we measure the pressure in a pipe with a pressure gauge we will invariably be measuring the pressure relative to the atmospheric pressure at that time. In other words the reading will give the pressure above atmospheric pressure, and this is called gauge pressure. Normally there will be no problem in using this value and so we do not

convert to the true value or Absolute Pressure by adding the value of the atmospheric pressure at the time of the reading. The exceptions arise when we need to use the value of pressure above absolute zero (eg, when using the gas laws, or in barometric surveying). It is therefore important to be aware of the difference.

Sometimes the pressure can be below the local atmospheric value. This happens in milking machines, and in water supplies where it can cause problems. The effect is called a vacuum, and is sometimes described as a vacuum of so many kPa. A vacuum of 30 kPa is in effect an absolute pressure of $100 - 30 = 70$ kPa (assuming the atmospheric pressure is 100 kPa at the time). It is important to be quite clear about whether one is talking about vacuum or pressure (is a vacuum of 70 kPa greater or lesser than a vacuum of 40 kPa?—it depends what you mean!). Thus if atmospheric pressure is 100 kPa a vacuum of 10 kPa is equal to 90 kPa absolute pressure, and a vacuum of 50 kPa, the value at which most milking machines operate, is equal to 50 kPa absolute pressure.

At zero absolute pressure there are no molecules to create a pressure, so the maximum vacuum which can be obtained is numerically equal to atmospheric pressure, whatever that may be. However for practical purposes vacuum indicating instruments are usually scaled as 0 to -100 kPa or 0 to -1 bar.

5.4.8 Pressure measurement

a. Atmospheric pressure (absolute)

A Barometer measures atmospheric pressure (*Figure 5.6a*). A simple barometer consists of a long tube which is first filled with mercury, and then mounted in the inverted position as shown. The pressure of the air on the mercury holds the mercury in the tube, against its own weight. When the column of mercury is too heavy for the atmospheric pressure to support it, the mercury is no longer held in the top of the tube and it drops, and a vacuum is formed at the top. The height of the column above the level of the mercury in the reservoir is a measure of the atmospheric pressure. Pressures are often quoted in mm of mercury but these can easily be converted to Pascals or bars since:

$$P = h\ \gamma_{mercury}\ (Pa)$$

where $\gamma_{mercury} = 133\ kN\ m^{-3}$

Equation 5.11

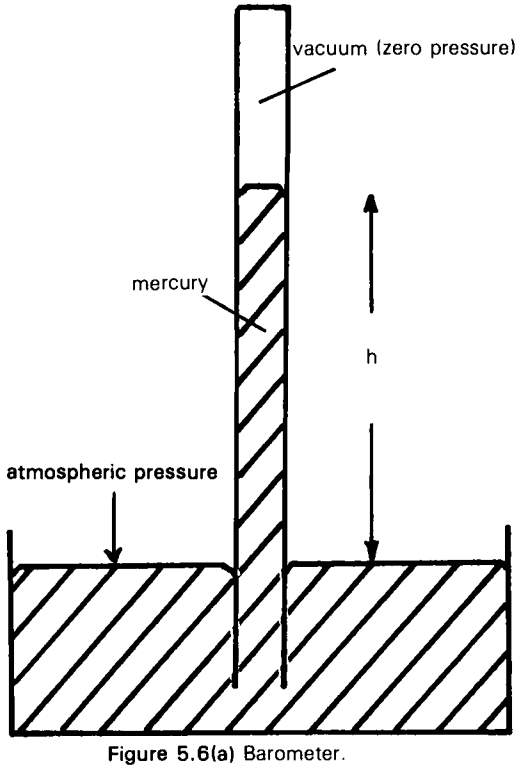


Figure 5.6(a) Barometer.

b. Gauge Pressure

All of the following instruments measure the pressure above atmospheric pressure.

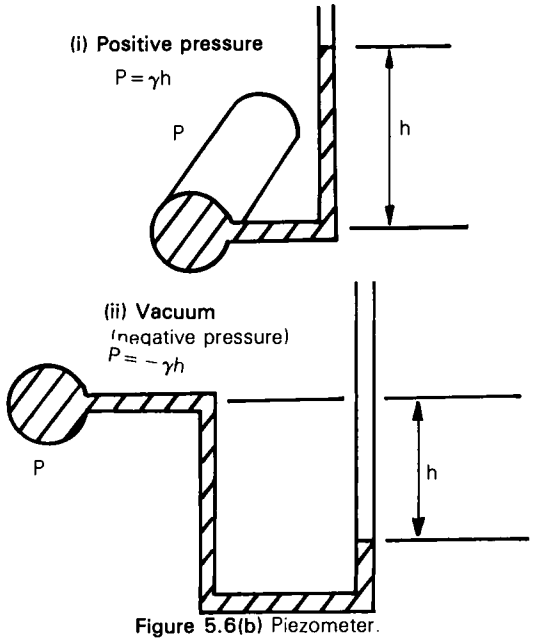
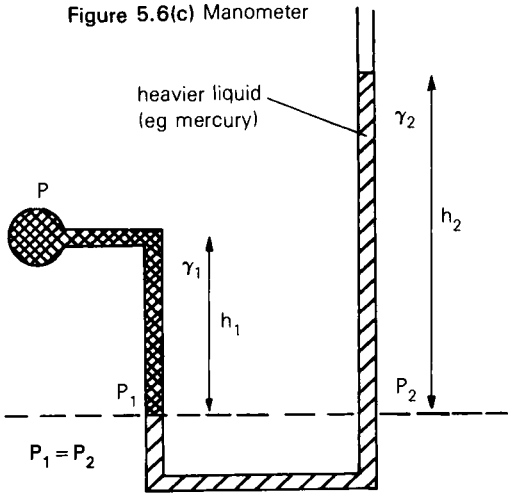


Figure 5.6(b) Piezometer.

Piezometer (*Figure 5.6b*)

In its simplest form, this is just a hole drilled in a pipe, and a tube inserted. The height of the tube is a measure of the pressure at the point. Unfortunately, a pressure of say five bars in a water pipe would result in a vertical tube 50 metres long! This is not a realistic option and so other devices are used.

Figure 5.6(c) Manometer



Manometer (*Figure 5.6c*)

The principle is the same as the piezometer, but a denser liquid is used to produce the force to balance the pressure. The pressure is given by:

$$P = \gamma_2 h_2 - \gamma_1 h_1 \qquad \textbf{Equation 5.12}$$

The manometer can be used for liquids and gases. Often mercury is used as the pressurising liquid.

Bourdon gauge (*Figure 5.7*)

These gauges are very common. The pressure is applied to the inside of the curved pipe. This causes the pipe to straighten, which makes the pointer move, giving a reading on the dial. These gauges are excellent for indicating the pressure visually, and are widely used in agriculture. They can be adapted to give an electronic output, but this is not common.

Semiconductor pressure sensors

Another development of the silicon revolution, these devices provide an electronic output which can be used to control the pressure in any particular system. The cost of these sensors depends on the accuracy required. A sensor can be chosen according to the range of pressures to be measured.

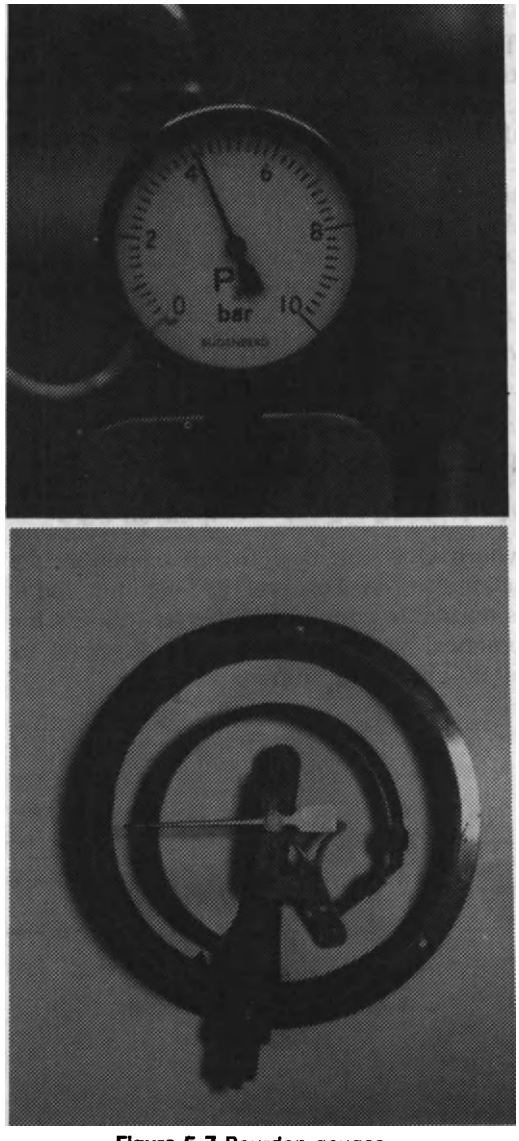


Figure 5.7 Bourdon gauges.

5.5 HYDRODYNAMICS

Hydrodynamics is the study of fluids in motion. In this chapter we will consider only steady state situations, ie, where the flow does not change (rapidly) with time. There are two crucial mathematical models which govern the flow of a fluid. These are the *Continuity Equation*, which is basically a statement of the conservation of matter, and *Bernoulli's Equation*, which is the conservation of

energy statement for fluids. We will consider these equations for a liquid, ie, an incompressible fluid.

5.5.1 Continuity equation

The continuity equation expresses the fact that what goes in at one end of a pipe must come out of the other end at the same time if the amount of fluid in the pipe is to be conserved. Consider a section of pipe where the cross-sectional area changes from A_1 to A_2 m^2 (*Figure 5.8*). If the average velocities of the liquid in the pipe are v_1 and v_2 m/s as shown, then in one second the volume of liquid entering the section will be:

$\text{vol} = v_1 A_1$ m^3/s

while the volume leaving is:

$\text{vol} = v_2 A_2$ m^3/s

Thus for conservation,

$$v_1 A_1 = v_2 A_2 = Q \qquad \textbf{Equation 5.13}$$

where Q is the flow in cubic metres per second (m^3/s). This is a very big unit, and it is normal to convert to litres per minute for practical situations. One m^3/s is equal to 60,000 litres per minute.

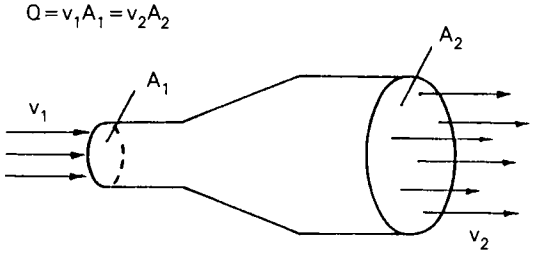


Figure 5.8 The continuity equation.

Example

A pipe carries 50 l/s of water, and changes its diameter from 150 mm to 200 mm. Find the average velocities in each section.

Solution: Convert the flow to m^3/s:

$Q = 50 \text{ l/s} = 50 \times 10^{-3} = 0.05 \text{ m}^3/\text{s}$

$$A_1 = \frac{\pi(0.15)^2}{4} = 0.01767 \text{ m}^2$$

Similarly, $A_2 = 0.03142$ m^2

$$\text{Thus } v_1 = \frac{Q}{A_1} = \frac{0.05}{0.01767} = 2.83 \text{ m/s}$$

$$\text{and } v_2 = \frac{Q}{A_2} = \frac{0.05}{0.03142} = 1.59 \text{ m/s}$$

5.5.2 Bernoulli's equation

Bernoulli's equation is a mathematical model of a fluid, which is based on energy considerations. There are three energy terms for fluids: the first two are the normal terms found for solid bodies. Thus the energy associated with motion is the kinetic energy, or $1/2\ Mv^2$, where M is the mass being considered, and v is the velocity, while the potential energy is Mgh, where h is the height above a chosen reference height. The units are Joules. For a fluid there is a third term, due to the pressure the fluid is exerting. The pressure energy is found by considering the potential of the fluid to do work. This is equal to the product of the pressure and the volume or PV_L.* Again the units are joules.

Combining these three terms we can state the law of conservation of energy as:

$$\frac{Mv^2}{2} + Mgh + PV_L = \text{constant} \qquad \textbf{Equation 5.14}$$

If we divide this equation by Mg and substitute γ for M/V_L we obtain

$$\frac{v^2}{2g} + h + \frac{P}{\gamma} = \text{constant} \qquad \textbf{Equation 5.15}$$

This means that when energy is conserved the value of the terms on the left are the same at any point along the pipeline. A more useful form of the equation is to write:

$$h_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g} = h_2 + \frac{P_2^2}{\gamma} + \frac{v_2^2}{2g} \qquad \textbf{Equation 5.16}$$

where v_1, P_1, and h_1 refer to the velocity (m/s), pressure (Pa), and height (m) at point 1 etc (*Figure 5.9*). The equation holds for the case where the flow is steady and frictionless, and the fluid is incompressible.

Finally we can rearrange *Equation 5.16* by putting all the terms on one side. This then gives an equation which describes the relationship between the changes in the three energy terms:

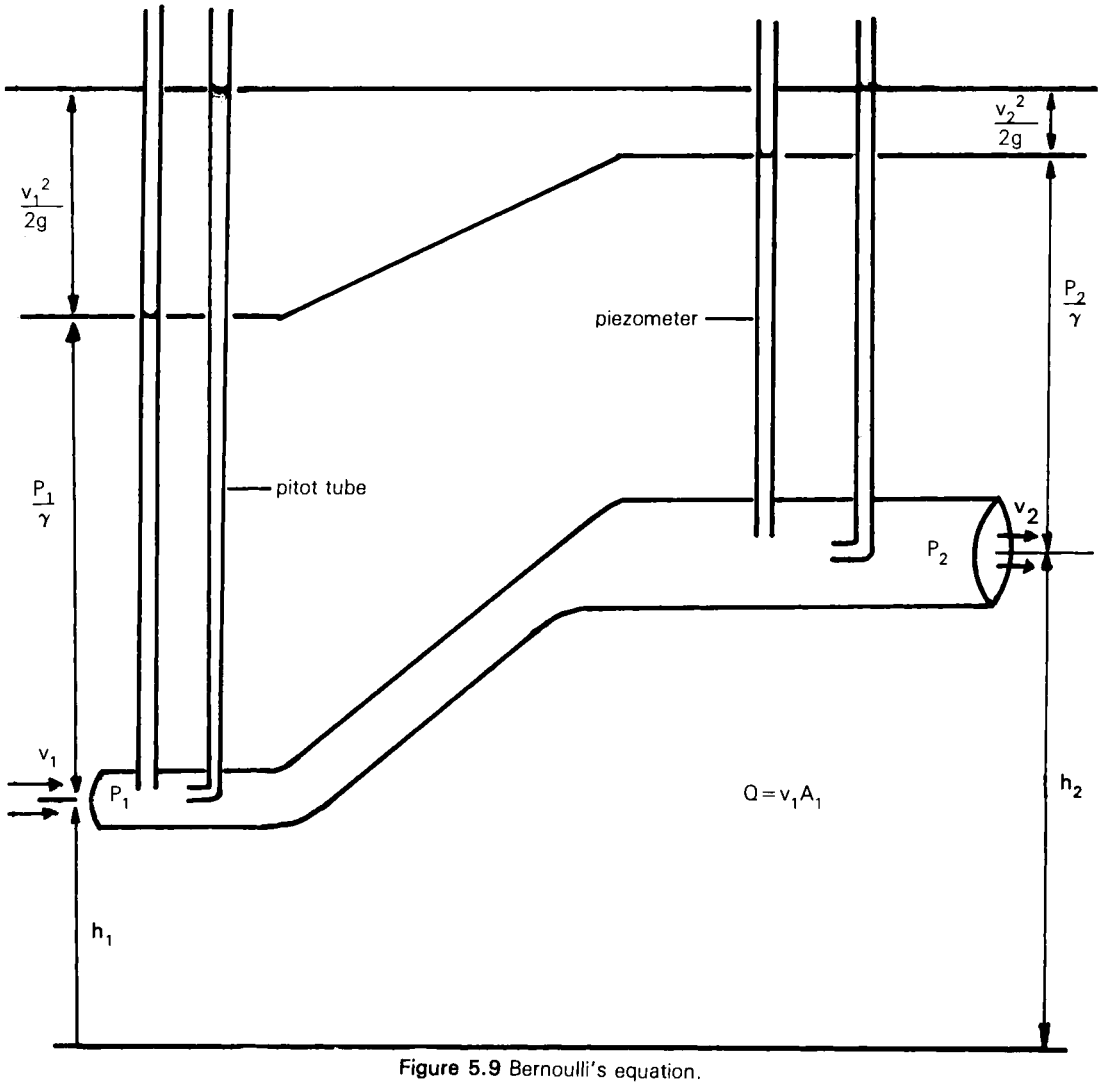


Figure 5.9 Bernoulli's equation.

$$h_2 - h_1 + \frac{P_2 - P_1}{\gamma} + \frac{v_2^2 - v_1^2}{2g} = 0$$

Equation 5.17

It is more than a coincidence that all three terms in these equations have units of metres. They are effectively the equivalent heights of columns of the liquid, and are referred to as the pressure head, velocity head and potential head. These heads can be shown in a diagram (*Figure 5.9*). The total head is shown by the top line. It consists of the three components added together at every point. The conservation of energy condition means that the total head is constant along the pipe, even though the three components may change. In the figure the pressure in the pipe has changed to P_2 at the end. In practice if this were the end of the pipeline then this final pressure will be an important factor in the design of the system. It is called the *Residual Head* in the pipe, and will be discussed shortly.

Example 1

A nozzle emits water as shown in *Figure 5.10a*. Calculate the required input pressure

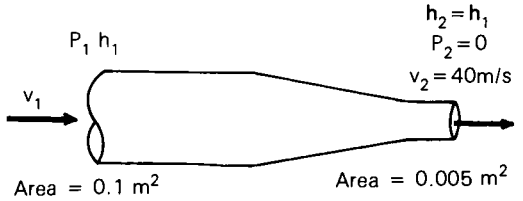


Figure 5.10(a) Horizontal pipe.

to produce a velocity of 40 m/s. In addition calculate the velocity in the supply pipe.

Solution: First we need to know the flow Q. From the Continuity Equation (5.13):

$Q = v_2 A_2 = 40 \times 0.005 = 0.2 \text{ m}^3/\text{s}$

$$\text{Hence } v_1 = \frac{Q}{A_1} = \frac{0.2}{0.1} = 2 \text{ m/s}$$

Now we can apply Bernoulli's equation (*Figure 5.17*), noting that there is no height change so that $h_2 - h_1 = 0$, and $P_2 = 0$ since the nozzle emits the water into the (unpressurised) atmosphere. Thus:

$$\frac{P_1 - 0}{\gamma} = \frac{v_2^2 - v_1^2}{2g}$$

$$= \frac{(40)^2 - (2)^2}{2 \times 9.80} = 81.42 \text{ m}$$

Hence $P_1 = 81.42 \times 9.8 \times 10^3$
$= 798{,}000$
$Pa = 7.98$ bar

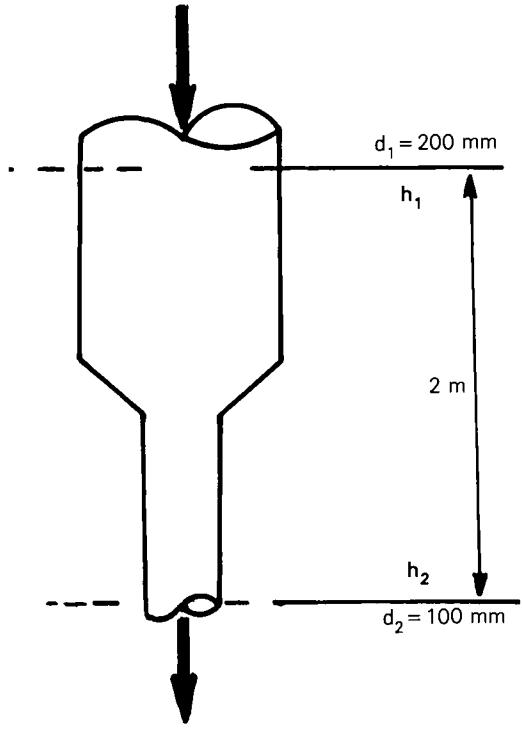


Figure 5.10(b) Vertical pipe.

Example 2

If, instead of the nozzle the water enters a pipe where the pressure is 0.5 bar, calculate the pipe pressure.

Solution: In this case the pressure difference is the same: the overall pressure is simply increased to $7.98 + 0.50 = 8.48$ bar.

You may have noticed that the pressure has dropped as it passed from the wide pipe to the narrow one. This is what actually happens, although it may at first appear to be the opposite of what one might expect. What is happening is that the water must flow at the same flow rate through the narrower pipe, and to do this it must travel faster. Thus the kinetic energy must go up, and since the total energy stays constant, the pressure energy must drop. This means that the pressure must fall. This is a case of our model being better than our intuition!

Example 3

Find the pressure change in the vertical drainpipe in *Figure 5.10b* between points 1 and 2.

Solution: First we must calculate the areas and the velocities:

$$v_1 = \frac{Q}{A_1} = \frac{0.1 \times 4}{\pi(0.2)^2} = 3.183 \text{ m/s}$$

$$\text{Similarly, } v_2 = \frac{Q}{A_2} = \frac{0.1 \times 4}{\pi(0.1)^2}$$

$$= 12.73 \text{ m/s}$$

Now $h_2 - h_1 = h_2 - (h_2 + 2) = -2$ m

So using Bernoulli's Equation (*5.17*) gives:

$$\frac{P_1 - P_2}{\gamma} = -2 + \frac{(12.73)^2 - (3.183)^2}{2 \times 9.80} = 5.754 \text{ m}$$

Hence $P_2 - P_1 = 5.754 \times 9.8 \times 10^3$
$= 56400$
$Pa = 0.564$ bar

Example 4

If the pressure at 2 is to be above zero, what is the smallest head of water required to produce the flow?

Solution: From the previous solution the required head is 5.75 m. This implies that the water would back up to this height if the water were entering the area that the pipe drained at the above rate. The implications for the design of roof drains should be obvious!

It is also appropriate to note that this example would underestimate the head required because it ignores any frictional losses in pressure (see later).

* For any object of volume V to exist under a pressure P, external work must have been done to make room for it.

5.5.3 Flow through an orifice (Torricelli's Theorem)

If we consider the energy at the two points marked 1 and 2 in *Figure 5.11a*, where a fluid is flowing out of a smooth hole in the side of a tank, then the energy just outside the tank at point 2 is entirely kinetic. At point 1 the energy is just the potential head since there is negligible velocity and no pressure at this point (other than atmospheric).

Figure 5.11 Flow through an orifice.

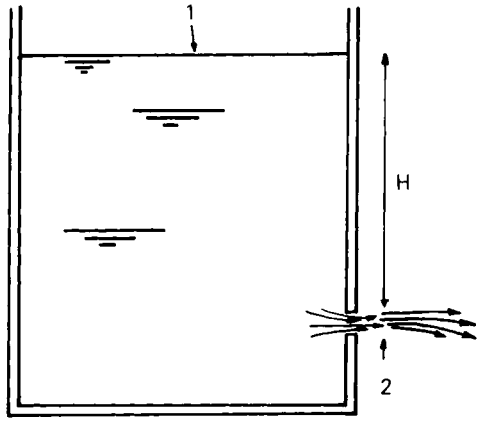


Figure 5.11(a) General view.

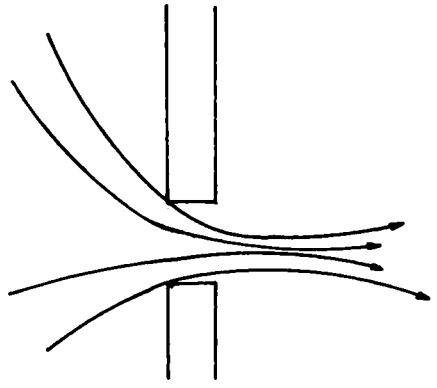


Figure 5.11(b) Close-up of orifice.

Thus only these two terms are not zero so Bernoulli's equation becomes:

$$H_1 + 0 + 0 = 0 + 0 + \frac{v_2^2}{2g}$$

Equation 5.18

Rearranging and dropping the subscripts gives the velocity of the jet:

$$v = \sqrt{(2gH)}$$ **Equation 5.19**

It looks as if the actual discharge can then be found, providing the area of the nozzle is known. Unfortunately, this is not quite correct, because as the fluid flows through the orifice, it does so in streamlines which converge on the orifice during their approach, and continue to converge after the jet has left the orifice (*Figure 5.11b*). The effective area of the discharge is thus somewhat less than the area of the orifice. It is called the Vena Contracta, and is about 64% of the true area. In addition in real fluids viscous effects reduce the velocity by around 3%. These two effects are combined together to give what is called the *Coefficient of Discharge* C_d. Its value depends upon the boundary geometry around the orifice, and also upon surface tension effects, but typically it is around 0.63 for simple circular holes. Thus the flow from an orifice is given by:

$$Q = C_d\, A\, \sqrt{(2gH)}$$ **Equation 5.20**

where A is the actual area of the orifice, and H is the head.

Example

A 13 mm diameter nozzle is run at a head of 35 m. If 31.75 kg of water is collected in 15 seconds, calculate the Coefficient of Discharge C_d.

Solution: First we must calculate the flow in m^3/s. Since 1 kg has a volume of 1 litre, and 1 litre $= 10^{-3}$ m^3:

$$Q = \frac{31.75 \times 1 \times 10^{-3}}{15} = 0.002116 \text{ m}^3/\text{s}$$

Now the area of the nozzle is

$$A = \frac{\pi(0.013)^2}{4} = 0.0001327 \text{ m}^2$$

$$\text{Hence } C_d = \frac{Q}{A\sqrt{(2gH)}}$$

$$= \frac{0.002116}{0.0001327 \times \sqrt{(2 \times 9.80 \times 35)}}$$

$$= 0.609$$

Note that although the question involved a head, the method would apply equally well if the operating pressure had been given instead.

5.6 MEASUREMENT OF FLOW RATE IN PIPES

Many types of flowmeter have been developed. Some of the most common are described below.

5.6.1 Turbine flowmeter (*Figure 5.12a*)

The turbine rotates as the water moves past it. The turbine can either drive a mechanical counter, or can trigger a magnetic counter as the blade passes by a sensor. Mechanical turbines cause some resistance to the flow of water, which may be a disadvantage in some situations. They will not measure very small flows as the turbine's bearings are never entirely free of friction. There are a wide range of different turbine meters on the market, with different characteristics, including flow range, size, minimum starting flow rate, and impedance to flow. Mechanical meters are direct reading, relatively inexpensive, and can be robust. They have a relatively high minimum starting flow rate.

Figure 5.12 Flowmeters.

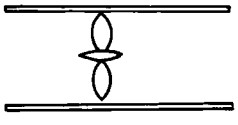


Figure 5.12(a) Turbine flowmeter.

5.6.2 Orifice plate (*Figure 5.12b*)

The orifice plate is a circular plate with a circular hole in the centre. The orifice is carefully machined with a sharp leading edge, and a taper on the downstream side. This plate is inserted into the pipe, usually being bolted between two flanges. The plate causes a drop in pressure from one side to the other and by measuring the pressure drop the flow can be determined. The pressure tappings are located one pipe diameter upstream and half the pipe diameter downstream.

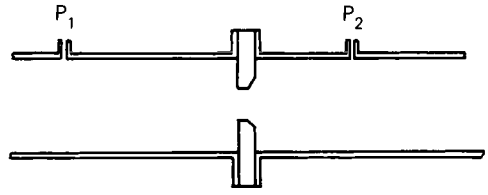


Figure 5.12(b) Orifice plate.

The flow rate is derived from Torricelli's equation, and is given by:

$$Q = C_d \, E \, A_2 \left[\frac{2g\,(P_1 - P_2)}{\gamma}\right]^{1/2}$$

Equation 5.21

where C_d is the coefficient of discharge, A_2 is the cross-sectional area of the constriction, P_1 and P_2 are the pressures on the two gauges, γ is the specific weight of the fluid, and g is the acceleration due to gravity. The term E is known as the velocity of approach factor and is given by:

$$E = \frac{A_1}{\sqrt{(A_1^2 - A_2^2)}}$$

Equation 5.22

where A_1 is the cross-sectional area of the pipe.

E is normally close to 1.0 since A_2 is usually much less than A_1. For an orifice plate, C_d is normally around 0.61.

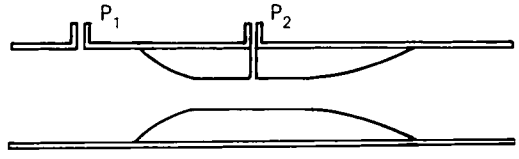


Figure 5.12(c) Venturi flowmeter.

5.6.3 Venturi flowmeter (*Figure 5.12c*)

This works in the same way as an orifice plate, except that the venturi does not cause such a high pressure drop in the flow. The pressure drop is measured between the points indicated. The tappings are distributed around the circumference of the pipe in both locations. The meter is machined from non-corrosive materials. The flow rate is also given by *Equation 5.21*, except that C_d is around

0.99. For very high accuracy work, other minor correcting factors are sometimes applied, but these have only very small effects on the result.

5.6.4 Doppler flowmeter

All of the above meters are placed in the pipeline and obstruct the flow to some extent, and the pipe must be cut in order to insert the meter. When a pipe system already exists, this can be a major problem. Doppler meters can be attached to the outside of the pipe, and do not intrude into the flow in any way. The meter works by sending an ultrasonic pulse into the liquid, and detecting the reflected pulse from small impurities (such as air bubbles) in the liquid. These meters are expensive, and will not operate unless the flow velocity exceeds around 0.5 m/s. The liquid must also contain some form of impurity, although entrapped air is sufficient.

5.6.5 Mass flow meters

The above meters measure the volume of fluid passing the meter. If the specific weight of the fluid varies, or one is trying to measure the flow of a liquid containing a large fraction of air (the obvious example is milk flow in a milking machine), then volume meters will give highly erroneous results if the mass flow is required. Sophisticated mass flow meters have been developed, which measure the mass flow by determining the inertia of the liquid. This is achieved by making the fluid flow around a thin walled pipe in the meter which has a twist in it. The fluid must turn through a bend as it passes through the meter and the forces produced are measured. These meters are very expensive.

5.6.6 Open channel flow measurement

Often the flow in a river or drain needs to be measured. This can also be done in a variety of ways. If the waterway is not to be disturbed by any permanent measuring system, a velocity meter can be used to measure the flow at a series of points across the stream, and providing the shape of the river-bed at the point is also known, then the flow can be calculated. However this is a laborious and not particularly accurate method. Much better measurements can be obtained if a permanent weir is built as shown in *Figure 5.13*.

Figure 5.13 Permanent weirs.

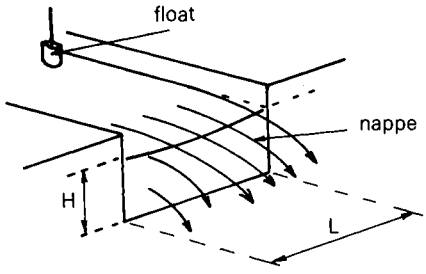


Figure 5.13(a) Rectangular weir.

In *Figure 5.13a* a rectangular weir is shown. This is the simplest shape and can be used where the flow does not change very much, since it can then be constructed to give a reasonably accurate reading over the flow range required. The flow is calculated from the height of water flowing over the weir, and is measured by a float placed some distance upstream as shown. In order to get good readings the upstream area must be large enough to allow the water level to be stable. The formula for the flow rate is obtained by considering the flow through an orifice, and integrating over the area of the rectangle (left as an exercise for the reader). The result is that the flow in cubic metres per second is given by:

$$Q = \frac{2\ C_d\ L\ \sqrt{(2gH^3)}}{3}$$

Equation 5.23

where H is the height over the weir in metres, L is the length of the weir, and C_d is the coefficient of discharge. It is necessary to make a small correction to allow for the Vena Contracta effect at the sides of the weir. This correction can be made by replacing L in the equation by $(L - 0.2H)$.

The rectangular weir has one disadvantage: the accuracy is very poor for very small flows,

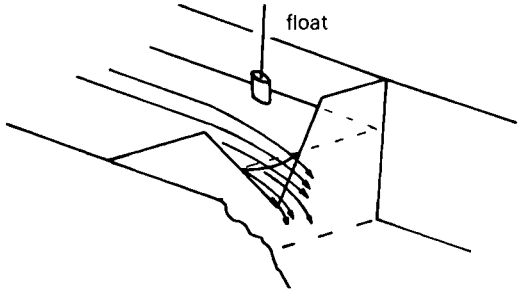


Figure 5.13(b) V-notch weir.

so if the flow varies to any great extent, there will be problems at the lower end of the range. This problem can be overcome by using a V-notch weir (*Figure 5.13b*). The main advantage of the V-notch weir is that it maintains the same accuracy over a wide range of flow rates. The flow rate is calculated as follows:

Consider the flow of water over the notch in a narrow strip dh thick, as shown in *Figure 5.13c*. At the strip the velocity of flow is given

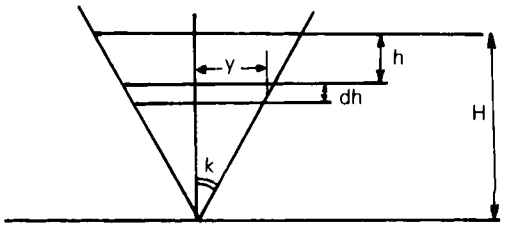


Figure 5.13(c) Flow of water over a v-notch weir.

from Torricelli's formula (*Equation 5.19*) by:

$v = C_d \sqrt{(2gh)}$

Hence the flow over the notch through the strip is given by:

dQ = velocity x cross-sectional area

$= C_d \sqrt{(2gh)} \times 2\ dh\ (H - h) \tan k$

since $y = (H - h) \tan k$

Integrating over the whole area:

$$Q = 2\ C_d \sqrt{(2g)} \tan k \int_0^H (H - h) \sqrt{h}\ dh$$

$$= 2\ C_d \sqrt{(2g)} \tan k \left[\frac{2H\ h^{3/2}}{3} - \frac{2\ h^{5/2}}{5} \right]_0^H$$

$$\text{ie} \quad Q = \frac{8\ C_d \sqrt{(2g)} \tan k\ H^{5/2}}{15}$$

Equation 5.24

If $C_d = 0.6$, and $k = 45°$, then

$$Q = 1.42 H^{5/2}\ m^3\ sec^{-1}$$

Equation 5.25

In practice the flow rate can be determined from the height of the water by reference to a calibration graph. Again the upstream region must be designed properly. A well constructed V-notch has an accuracy of 0.5%, which is adequate for most agricultural applications. It is very useful for gauging the flow of farm streams over a long period of time, and it is not too difficult to record the flow automatically. Such a measurement is necessary if the stream is being considered as a source of power or water.

5.6.7 Velocity head measurement

The velocity of a fluid can be measured by any of the flow meters described earlier, providing the diameter of the pipe is known. The turbine meter in fact measures velocity rather than flow. The sum of the velocity and pressure heads can be measured directly using a pitot tube (*Figure 5.9*). This device is the same as a piezometer except that the end is bent in a right angle to face directly into the flow. The result is that the head rises to the static pressure, or the pressure which the flow would have if it were stopped.

If the velocity head is required this can be obtained by subtracting the piezometer reading from the pitot tube reading. The total energy can be obtained by simply adding the height of the pipe to the reading.

5.7 HEAD LOSS, PUMPING AND BERNOULLI'S EQUATION

We have said that *Equation 5.16* states the conservation of energy law. In fact it ignores the fact that in real situations mechanical energy is converted into other forms of energy such as heat by frictional forces. In any real fluid system this loss of energy is highly significant and the calculation of it forms the main part of any design study. In addition we can add energy to liquid in a pipe by using a pump. This has the effect of raising the pressure energy of the liquid. The effects of these two factors alter Bernoulli's equation to:

$$h_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + E - HL = h_2 + \frac{P_2}{\gamma} + \frac{v_2^2}{2g}$$

Equation 5.26

where E is the head produced by the pump, and HL is known as the *Head Loss* in the pipe due to friction. This is shown in *Figure 5.14*. As the liquid flows along the pipe friction causes the total head to fall at a steady rate. Thus at the right hand end of the pipe the head has fallen to the level shown, and the remaining or residual pressure suffers in

consequence, since the potential and velocity heads are fixed by the position and flow in the pipe. Thus pipe friction reduces the residual head available at the end of the pipe.

at the start of a pipeline which branches off into another paddock or greenhouse. The residual head required at the start to drive the required volume of water through that pipe

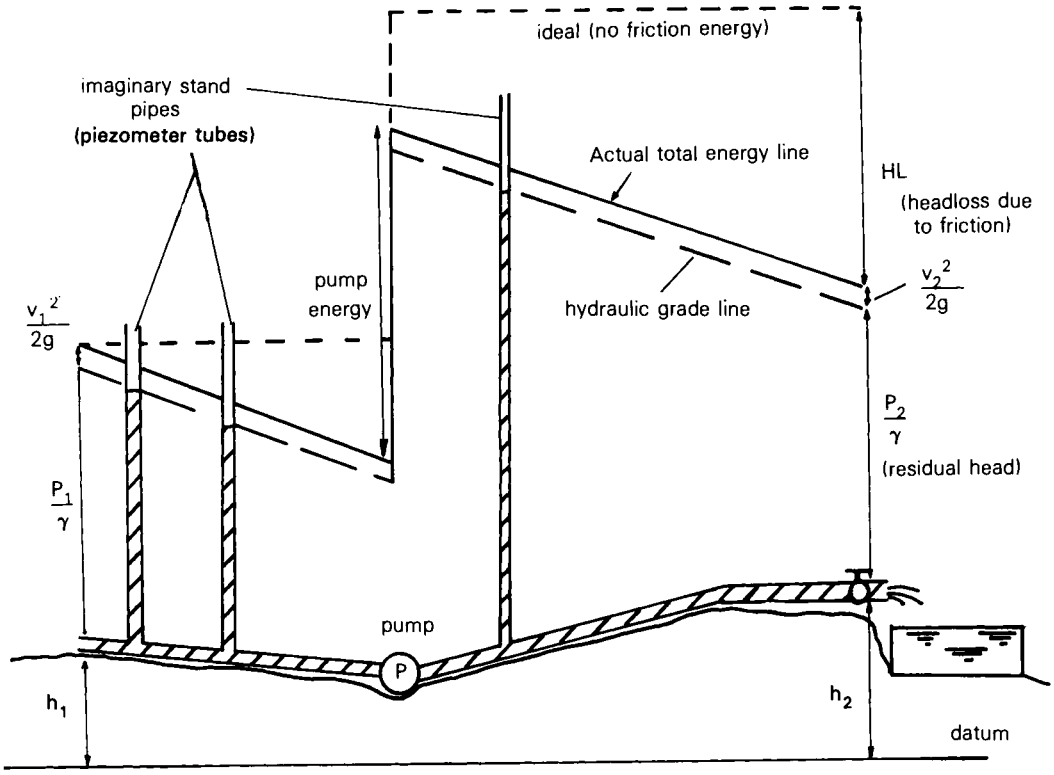


Figure 5.14 Bernoulli's equation in practice.

5.7.1 Residual head

The residual head is a useful concept, which can simplify design work. Almost always, at the end of a pipeline the water will have to flow through a tap, or valve of some kind. There will be a further loss of water pressure as the water passes through this restriction. For example, in order to flow into a water trough through a ballcock, the water pressure will have to force the valve open, and overcome the frictional head loss through the valve. Thus in most cases of designing a water supply, after the water has gone through the pipeline, some extra head will be needed at the end of the pipeline. This extra bit of head can be conveniently referred to as the Residual Head in the pipeline. Typical values of residual heads are given in *Table 5.2*. The residual head is also a useful concept for designing water supplies where the pipe divides off into other pipelines. It can be used to describe the head which will be required can be calculated, and the whole system designed so that these heads are available at these points. The residual head may also be the head required for the next block of an irrigation system in an orchard, where there are several blocks in series.

Table 5.2 Typical residual head values for pipe outlet fittings

Water outlet fitting	Flow (l/min)	Residual head (m)
Trough valve	45	3
Trough valve	80	7
Trough valve	110	21
Yard washdown hose nozzle	180-450	30
Domestic shower	9	6
Garden hose	12	15-30

Note that the residual head required at the end of a pipeline will generally vary with the flow rate through the end fixture, and so strictly it is not a fixed value at all. However the design process is simplified if a fixed (maximum) value is assumed. If a very accurate calculation is required, then the residual head concept should be dropped, and instead the head loss of the device should be plotted to establish the precise system curve as a function of flow, as discussed elsewhere.

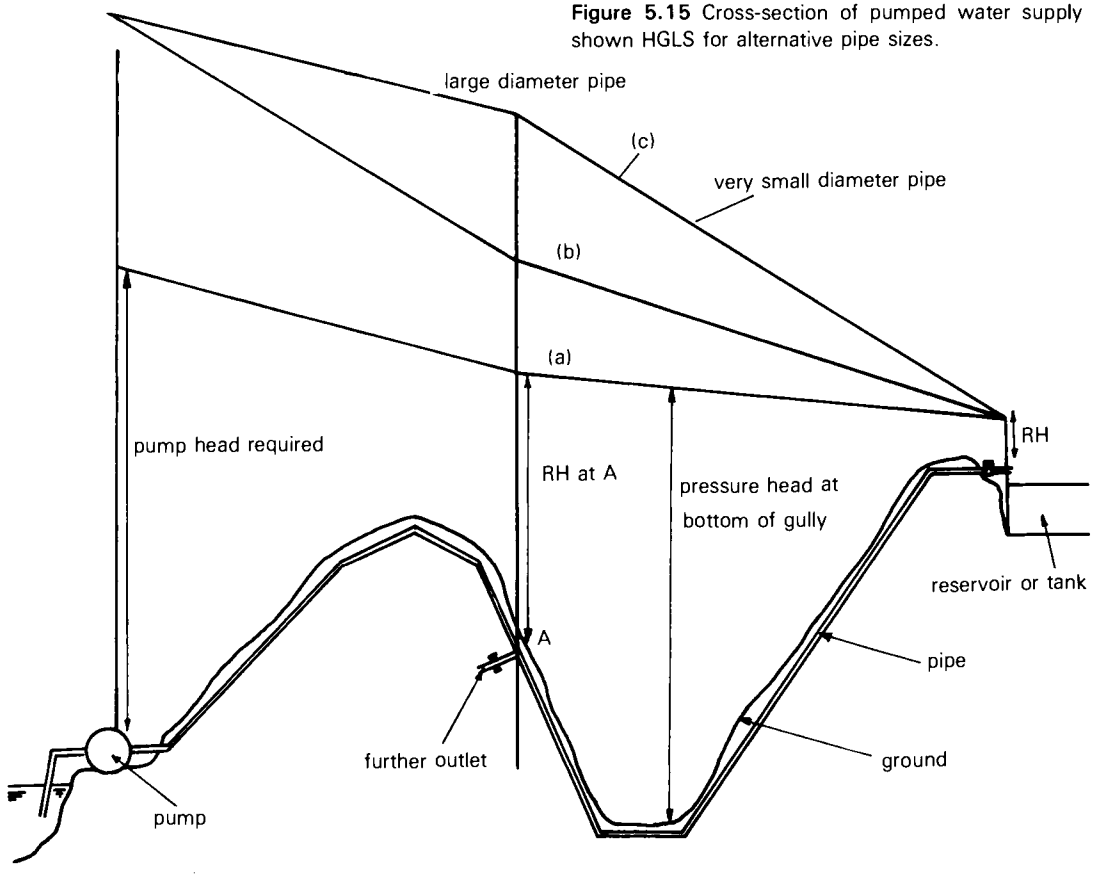
5.7.2 Hydraulic grade line (HGL)

In most farm situations, the flow rate is not more than 2 m/s. The velocity head is $v^2/2g$. This is no more than 0.2 m, and can be ignored. If the velocity head is subtracted from the total head the resulting curve, which consists of the pressure head plus potential head, is called the Hydraulic Grade Line. This line is the one used for most water supply designs. It is shown in *Figure 5.14* as the thick chained line.

In most design situations the farmer will have a requirement for a specific flow rate of water at one or more places on the farm. This data forms the basis of the design, and should be defined with care, allowing a margin for future expansion. In addition the reduced levels of the proposed pipeline over the ground will also need to be obtained. The HGL is extremely useful in designing the water supply system given this data.

An example is shown in *Figure 5.15*. Here the ground profile and the HGLs for various pipe systems have been plotted. These must be plotted from the right hand side, ie starting from the end of the pipeline. The first thing to be established is the residual head required at the end of the pipe. This is estimated by determining how much pressure will be needed at the end of the pipeline (to operate the valves or outlet devices properly, or for the next section of the water supply). Once this is known the HGL can be drawn by calculating the head loss in the pipe at the required flow. Note that at the point A there will be a second outlet, which may be a piped water supply to another paddock or greenhouse. When water is taken off at this

Figure 5.15 Cross-section of pumped water supply shown HGLS for alternative pipe sizes.



point, the flow between A and the pump will be higher and hence the HGL will be steeper. *Figure 5.15* shows three alternative pipe selections. Design (a) will require a large diameter pipe, while the pipe for design (b) will be smaller. However the pump will have to operate at a much greater head in order to deliver the required flow, and so will be more expensive. In design (c) savings are made by using a small diameter pipe after point A, but changing to the large diameter pipe for the section between A and the pump where the flow is greatest, in order to keep the total head required at the pump down. The choice of design will depend upon the cost of these and any other options which will fit the requirements.

It is easy to see at a glance the pressure requirements of the pipe at all points along the pipeline. For example, the gully may be deep enough to require a stronger pipe in the bottom of the gully, due to the increased head. The residual head for the outlet at A can also be determined, and alterations made to the design if there would be insufficient head available for the requirements at this outlet. The HGL also defines the delivery head which the pump will be required to supply. The head will naturally depend on the pipe size and type. A larger head (and hence a larger pump with greater running costs) will be required if a smaller diameter pipe is used.

In pumped systems maximum pressure in the pipe occurs when the pump is operating and water is flowing. This is not always the case in water supplies, especially if the system is a gravity feed type. In these cases the pressure can be highest when the flow is off (*Figure 5.16*). Pipe friction serves to reduce the pressure at a point in the pipe, and the static head gives the highest pressure. It is therefore important to check the static situation to ensure that the maximum pressure is known before the pipe is specified. In some community water supplies where water is plentiful, great cost savings have been made by designing a system where the flow is always maintained, regardless of demand. The flow is such that pipe friction reduces the pipe pressure and cheaper pipes can be used. A blockage at the outlets of such a system could be disastrous, and the users are not allowed to stop the flow onto their properties.

5.8 HEAD LOSS IN A PIPE

We will now consider ways of calculating the head loss in fluid systems. To begin, let us consider the simple case of a pipe of constant diameter which is L metres long, and in which the fluid has a pressure head of h_1 metres at the start, and a residual head at the end of h_2 (*Figure 5.17*). In this situation the head falls linearly with distance along the pipe. Thus at any point along the pipe, the head loss can be calculated by simple proportions: ie, at a distance y from the start the head loss is given by:

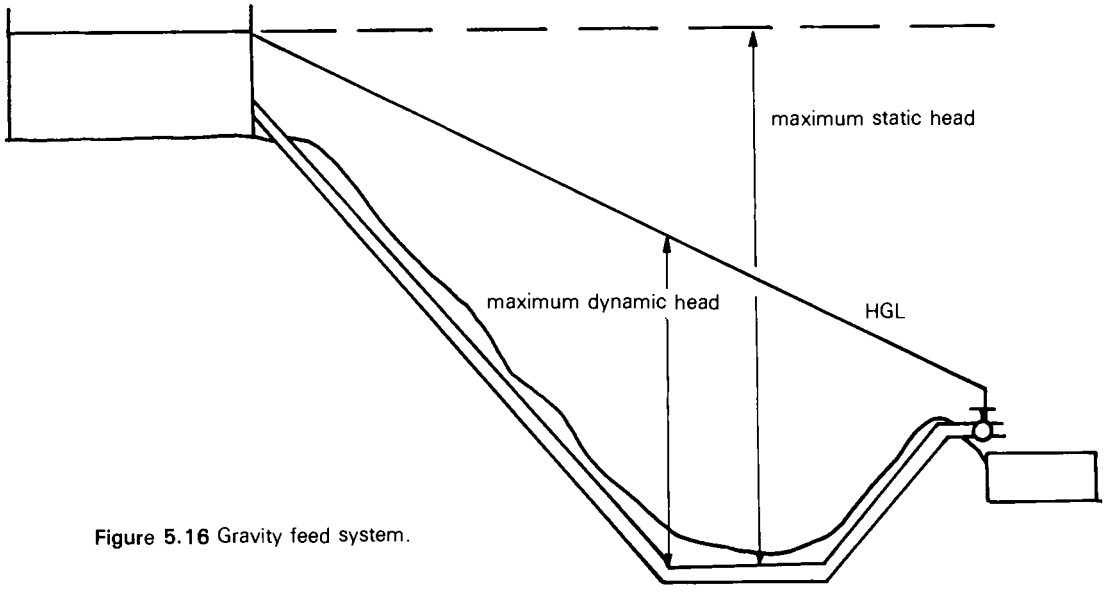


Figure 5.16 Gravity feed system.

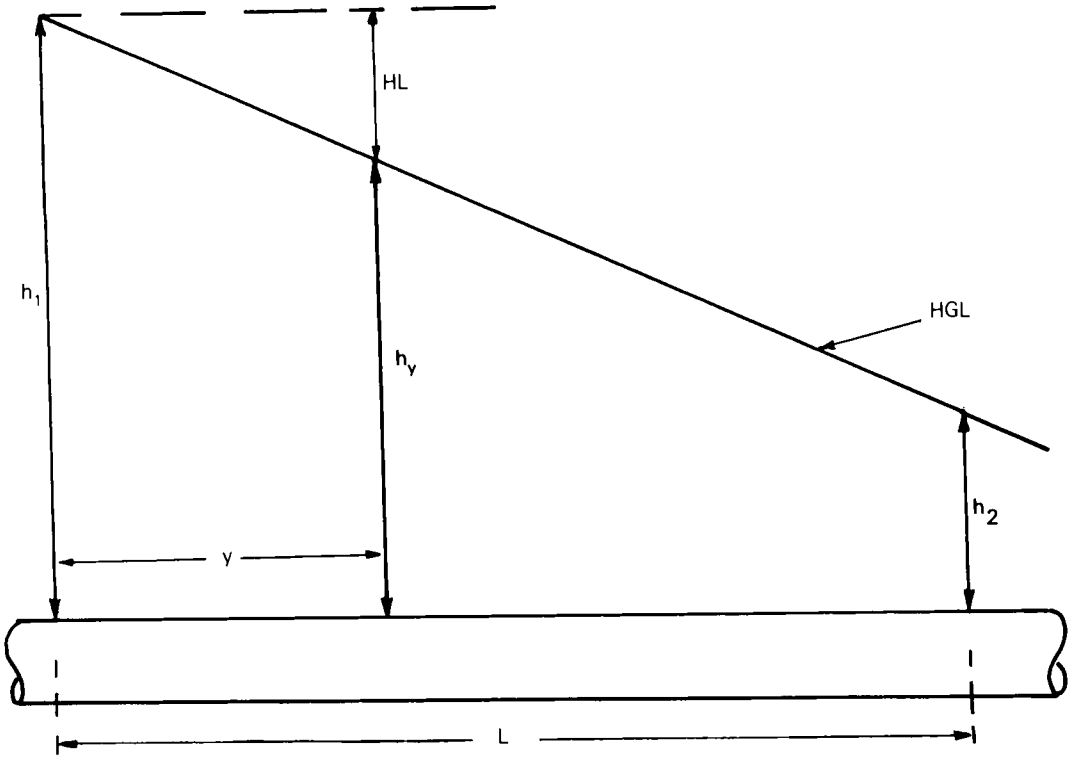


Figure 5.17 Calculation of head loss along a pipe.

$$HL = \frac{y(h_1 - h_2)}{L} \qquad \textbf{Equation 5.27}$$

The head at y (h_y) can be found by subtraction.

5.8.1 Example of the use of the hydraulic grade line

In *Figure 5.18* a pipeline is shown which feeds water from a reservoir on a hill to a trough. In between there is a small rise. The pipe must follow the curve of the ground of course, since in practice it will be buried only a little below the ground (typically 0.6 m or less). When the water is flowing, the HGL follows the line shown, and as can be seen, it cuts through the rise. The implications of this are that the pressure at this point becomes negative, ie, less than atmospheric. The effect of this is quite serious. Air dissolved in the water will be released, and will collect in a pocket at the top of the rise, while more air will be sucked in through any fine holes. The result will be a water supply which is irregular, containing a mixture of air pockets and water. The solution will be to use a larger pipe with a lower head loss for the first part of the pipeline, so that the HGL clears the rise (as shown by the dotted line). Thereafter a smaller pipe can be used.

5.9 DESIGN CRITERION FOR WATER SUPPLIES

Most water supply designs are done on a worst case basis. This means that the maximum probable required flow is calculated, and then the design is completed on the basis of this flow. This means that the system will be designed to supply the maximum flow likely to occur, and for most of its life it will not need to work at this level. However, since the water supply has a working life of 50 years, the chances are that the requirements will change, and it is much better to have a system that can cope with future demands than one which is designed to minimise the initial cost and which later proves to be inadequate.

The design of a water supply involves many factors, and the HGL will play a key part. In order to plot it we need to know what the

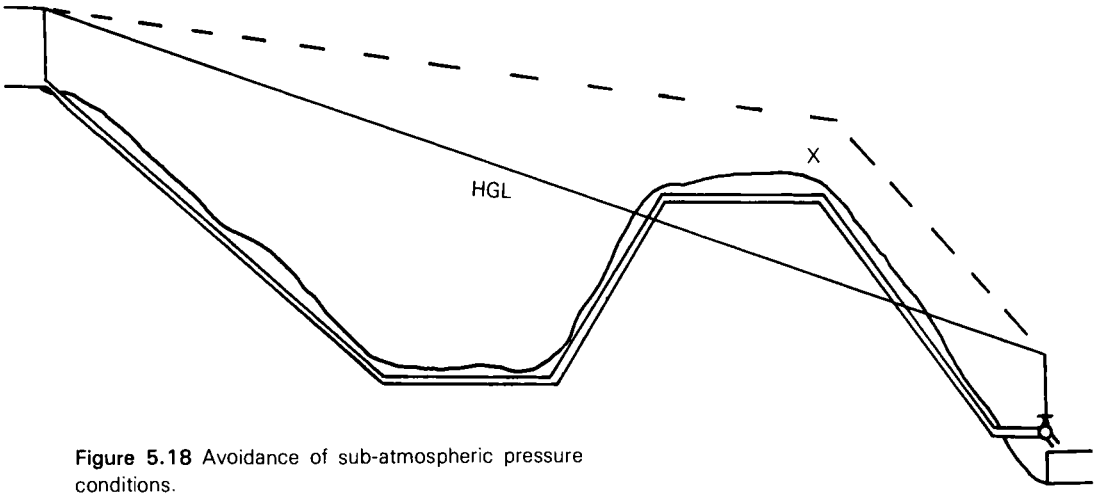


Figure 5.18 Avoidance of sub-atmospheric pressure conditions.

head loss in a pipe will be for any flow or range of flow rates, and we must consider this next.

5.10 ESTIMATION OF HEAD LOSS

5.10.1 Calculation

There are two main ways of working out the head loss in practice. The first is to use mathematical models which describe fluid flow. The models are based on a number of experimentally derived formulae, and depend on various fluid properties.

a. Reynolds number

Fluid behaviour is characterised by a very important factor called the Reynolds Number. This is simply a dimensionless number calculated for any flow situation. It is defined as:

$$\text{Re} = \frac{\varrho \, v \, d}{\mu} \qquad \textbf{Equation 5.28}$$

where ϱ is the density of the fluid (kg m^{-3}), v is the velocity of the flow (m/s), d is the most crucial length affecting the flow (in a pipe this is the pipe diameter), and μ is the absolute viscosity (N s m^{-2}). You can check that Re is indeed dimensionless.

The Reynolds number of a flow tells us a lot about that flow. For any fluid in any situation, if Re is less than 2000, then the flow will be lamina, ie, it will be a smooth streamlined flow so that the fluid particles move in straight lines or curves in the direction of flow. If Re is greater than 4000 the flow is turbulent: the fluid motion is erratic and the particles are continually being mixed up, twisting and moving in circles and eddies. Between these two values either type of flow can occur, depending upon the particular situation. It will always be one or the other. The transition from one type of flow to the other will occur suddenly at a particular value of Re between 2000 and 4000, but it is difficult to estimate beforehand what the value will be.

Example

An oil flows at 95 litres per second through a 35 mm diameter pipe. If the density is 920 kg m^{-3}, and $\mu = 9.05 \times 10^{-2}$ N s m^{-2}, calculate the Re and state the type of flow.

Solution:

$$\text{Area of pipe} = \frac{\pi \times (0.035)^2}{4}$$

$$= 0.000962 \text{ m}^2$$

$$\text{Hence velocity v} = \frac{Q}{A} = \frac{95 \times 10^{-3}}{0.000962}$$

$$= 98.74 \text{ m/s}$$

$$\text{Thus Re} = \frac{920 \times 0.035 \times 98.74}{0.0905} = 35132$$

Since this is greater than 4000 we can immediately state that the flow is turbulent (it is also very fast!).

b. Darcy's Equation

Experiments on a wide range of fluids flowing in long pipes have shown that the head loss is given by the model:

$$HL = \frac{f\, l\, v^2}{2\, g\, d} \qquad \textbf{Equation 5.29}$$

where l is the (equivalent) length of the pipe, d is the diameter, v is the velocity of the fluid, g is the acceleration due to gravity and f is a dimensionless friction factor which depends upon the Reynolds number and the properties of the pipe.

The friction factor f is the only thing which is not obvious. If the flow is lamina (ie, Re is less than 2000), then f is given by the formula:

$$f = \frac{64}{Re} \qquad \textbf{Equation 5.30}$$

so that by substituting in *Equation 5.31*, the head loss is given by the Hagen-Poiseuille formula:

$$HL = \frac{32\, \mu\, l\, v}{\gamma\, d^2} \qquad \textbf{Equation 5.31}$$

where γ is the specific weight of the fluid.

If the flow is turbulent, *Equation 5.31* no longer applies. As the Reynolds number increases the flow becomes more turbulent and the friction factor becomes less and less dependent upon it. At very high Reynolds numbers, f is independent of Re but instead depends upon the roughness of the inner surface of the pipe. There are several equations which can be used to calculate the value of f, but they are complex. Instead it is possible to use the Moody Diagram (*Figure 5.19*). In this diagram, in which the vertical axis is the value of f, and the horizontal axis is Re, there are several curves. On the left, for Re less than 2000, there is one straight line, representing *Equation 5.30* (zone 1). The value of f in the critical zone (zone 2, where $2000 < Re < 4000$) is not well defined, depending largely on whether the flow is lamina or turbulent. Above Reynolds numbers of 4000, the value of f depends on which curve one choses, and this is determined by the relative roughness of the pipe. The relative roughness is defined as the ratio of the roughness (e) of the inner surface of the pipe (measured using a special instrument a little like a gramophone needle) divided by the diameter of the pipe. The roughness is a measure of the average height of asperities on the pipe's surface. Typical values are listed in *Table 5.3*.

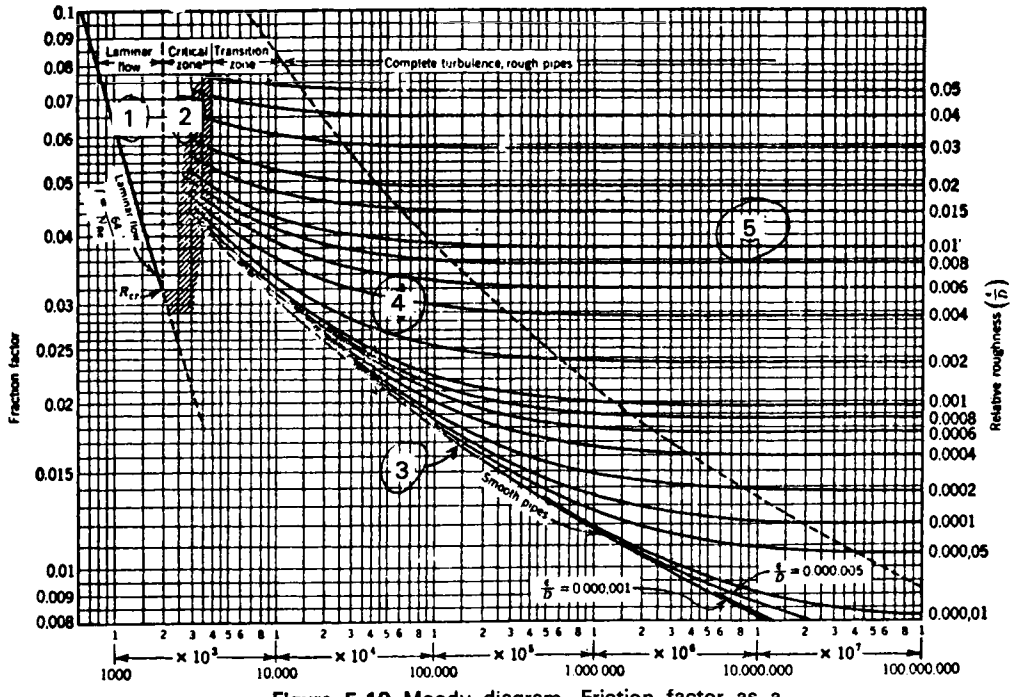


Figure 5.19 Moody diagram. Friction factor as a function of Reynolds number with relative roughness as a parameter.

Table 5.3 Roughness values for pipe materials (millimetres)

Concrete	0.2 - 5.0
Cast iron	0.25
New galvanised iron	0.125
Old galvanised iron	0.15
PVC	0.04
New polythene	0.015
Old polythene	0.018
Drawn tubing (steam pipes)	0.046

In the transition zone (zone 4) the friction factor depends on both the Reynolds number and the relative roughness. In the completely turbulent region (zone 5), f is independent of Re but depends only on the relative roughness. In the turbulent region the lowest curve represents the value of f in very smooth pipes (zone 3). This means hydrodynamically smooth. This behaviour can be explained by thinking about the actual flow of a fluid in a pipe. At the surface of the pipe there is a very thin layer called the lamina sublayer which is scarcely moving. Further into the pipe the flow becomes turbulent (*Figure 5.20*). If the

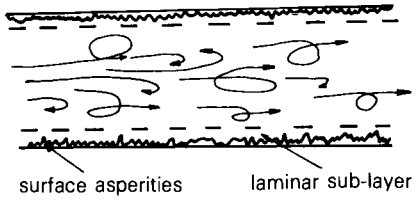


Figure 5.20(a) "Smooth" pipe.

lamina sublayer covers the surface asperities, then they do not affect the flow and the pipe is essentially smooth (*Figure 5.20a*), so the friction factor will be the value for a smooth pipe (zone 3). However as the flow becomes more turbulent the lamina sublayer gets narrower and narrower, so that the asperities begin to have an effect. In the completely turbulent region the lamina sublayer has broken down completely so that the asperities are fully exposed to the turbulent flow (*Figure 5.20b*).

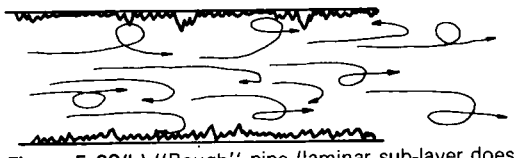


Figure 5.20(b) "Rough" pipe (laminar sub-layer does not cover asperities).

Use of the Moody diagram requires a series of steps as follows:

a. Calculate the Reynolds number,
b. Calculate the relative roughness e/d,
c. Select the appropriate e/d curve from the right until it intersects the Re value,
d. Read horizontally across from the intersection to get the value of f from the left hand axis.

The value of f is then used in Darcy's equation to give the head loss. The Moody diagram applies to all fluids, including milk, water, detergent, and air, providing the values of the terms are known.

Example

Calculate the head loss for water in 100 metres of polythene pipe 25 mm in diameter at a flow of 20 litres per minute ($\mu = 1.002 \times 10^{-3}$ N m s^{-2}) if the roughness of the pipe is 0.015 mm.

Solution: The velocity of the flow is given by

$$v = \frac{Q}{A} = \frac{20 \times 10^{-3} \times 4}{\pi(0.025)^2 \times 60} = 0.679 \text{ m/s}$$

The Reynolds number is thus

$$Re = \frac{1000 \times 0.025 \times 0.679}{1.002 \times 10^{-3}} = 16943$$

(ie, turbulent flow)

The relative roughness

$$= \frac{e}{d}$$

$$= \frac{0.000015}{0.025} = 0.0006$$

From the Moody diagram, following the 0.0006 curve from the right until it reaches an Re value of 16943, and then reading horizontally across to the left hand axis gives a friction factor of f = 0.028.

We now substitute in the Darcy equation to give

$$HL = \frac{f\, l\, v^2}{2\, g\, d} = \frac{0.028 \times 100 \times (0.679)^2}{2 \times 9.80 \times 0.025}$$

$$= 2.63 \text{ metres head loss}$$

As the above example shows the method produces an answer but takes a large number of calculations. While this may be the only

way for unusual fluids or pipes, most of the time we will be dealing with water in standard pipes. In this case there is a much quicker solution, which is to use the work of others to give us head loss figures directly in tables.

5.10.2 Head loss tables

The calculations described above have great general applicability, they take a while to work out, and they require a number of different parameters to be input. When it comes to the flow of water in a pipe there is not a lot of point in repeating the same calculation over and over again, and so most manufacturers of pipe produce tables of the results of their head loss calculations for their products. In some cases the tables are based on experiment since this gives more reliable results. Head loss tables for a selection of pipe types and sizes are given in *Table 5.4*. These tables give the head loss at various flows for 100 m of the pipe in question. It should be noted that head loss tables only apply to the fluid in question. If a different fluid is to be used the tables do not apply.

A little explanation is required. In the tables the pipes are described in terms of their nominal diameter. This is the size used to order the pipes by and may bear little relationship to the actual size of the pipe itself. It tends to be related to the size of the

Table 5.4 Head loss tables for various types of pipe
Head loss in metres per 100 metres length of pipe (Massey University)

(a) LOW DENSITY POLYTHENE PIPE (White Stripe)

Nominal Size mm.	15	20	25	32	40	50
Actual Bore mm.	12	19	25	31	38	50
Flow litre/min						
5	7.0	0.9	0.2			
10	22.0	3.2	0.7	0.3		
15	50.0	7.0	1.5	0.6		
20	82.0	11.0	2.5	0.9	0.4	
25		16.0	3.6	1.3	0.6	
30		23.0	5.0	1.8	0.8	0.2
35		29.0	6.5	2.3	1.0	0.25
40			8.0	3.0	1.3	0.32
50			12.0	4.1	1.8	0.5
60			17.0	6.1	2.5	0.7
70				7.8	3.2	0.9
80				9.5	4.1	1.2
90				13.0	5.0	1.5
100				15.0	6.0	1.8
120					7.5	2.6
140					10.0	3.0
160						4.1
180						5.0
200						6.0
Maximum Working Head Metres	90	80	65	50	45	35

Figures underlined indicate approximately 2 m/sec velocity. Avoid higher flows if possible.

(b) MEDIUM GRADE NEW GALVANISED PIPE

Nominal Size mm.	15	20	25	32	40	50
Actual Bore mm.	16	21	27	36	42	53
Flow litre/min						
5	1.7	0.4				
10	6.6	1.5	0.5			
15	16.0	3.3	1.1			
20	26.0	5.7	1.9	0.5		
25	40.0	9.0	3.0	0.8		
30	55.0	12.5	4.0	1.1	0.5	
35		17.0	5.2	1.5	0.7	
40		21.5	7.0	1.9	0.9	
50		32.0	11.5	2.9	1.4	0.42
60			17.0	4.3	2.1	0.6
70			23.0	6.0	2.9	0.9
80			29.0	7.2	3.6	1.1
90				9.0	4.4	1.3
100				12.0	5.6	1.8
120				17.0	7.8	2.3
140					11.0	3.2
160					13.5	4.1
180					17.5	5.2
200						6.2
225						8.0
250						10.0
300						16.5
Maximum Working Head Metres	200	200	200	165	165	165

fittings used to join the pipes together. The critical factor affecting the pipe friction is the internal diameter and this is also given in the table.

In practice it is recommended that the velocity of the water should not exceed 2 m/s, as the head loss becomes extremely large beyond this.

The table also gives the maximum pressure that the pipes should be subjected to. Exceeding this pressure is not recommended. The pressure should be checked both at maximum flow and when there is no flow at all. This latter point should always be checked, since in some situations the pressure at no flow could be higher than at full flow.

5.10.3 Effect of pipe diameter and relative roughness of the pipe

It is quite normal to expect that the flow through a plastic pipe will be greater than that through a steel pipe, simply because the plastic is smoother. In fact this is one of the least important factors affecting the flow in agricultural and horticultural situations! This can be seen clearly if we play around a little with Darcy's equation and the Moody diagram. In Darcy's equation (*5.29*), the head loss is proportional to the velocity squared (v) divided by the pipe diameter. However, if we write Darcy's equation in terms of the flow rate, we get:

(c) PVC PIPE CLASS E

Nominal Size mm.	15	20	25	32	40	50
Actual Bore mm.	18	23	29	37	42	52
Flow litre/min						
5	1.2	0.3				
10	4.2	1.1	0.4			
15	8.7	2.5	0.8			
20	15.0	4.2	1.4	0.4		
25	22.0	6.5	2.1	0.7		
30		9.8	2.8	0.9	0.5	0.2
35		12.5	3.7	1.1	0.6	0.26
40		16.0	4.7	1.5	0.8	0.32
50		24.5	7.0	2.2	1.2	0.48
60			9.9	2.9	1.5	0.65
70			12.5	3.8	2.1	0.8
80			16.0	4.8	2.7	1.0
90				5.8	3.3	1.3
100				7.0	3.9	1.5
120				9.5	5.4	2.1
140					7.0	2.7
160					9.0	3.4
180					11.0	4.0
200					13.0	4.9
225						6.0
275						8.3

Maximum Working Head, all sizes.

Class B 60 m
Class C 90 m
Class D 120 m
Class E 150 m

$$HL = \frac{f\,l\,v^2}{2\,g\,d} = \frac{16\,f\,l\,Q^2}{2\,g\,d\,(\pi d^2)^2} = \frac{k}{d^5}$$

Equation 5.32

where k is a constant for a particular flow rate in a particular length of pipe.

Thus the head loss depends inversely on the diameter raised to the power of five! Thus if we halved the diameter the head loss would increase by a factor of 32. Even a 10% reduction in diameter results in an increase in head loss of 60%.

In comparison if we look at the worst possible case (a flow in the fully turbulent zone), the Moody diagram tells us that the effect of doubling the surface roughness is to increase the friction factor (and hence the head loss) by at most 20%. A 10% change in roughness has scarcely any effect.

5.10.4 Pressure classifications

Manufacturers of plastic pipes have decided upon a classification of pipes, which indicates the maximum working head. This classification is given in *Table 5.4*. Thus Class B means that the working pressure should not exceed 60 metres. Classes C, D, and E have maximum working heads of 90, 120 and 150 metres respectively. This does not mean that the pipes will burst if the pressure exceeds these values. Rather the pipe or the joints may fail over a period of time if subjected to over-pressures, and the manufacturers will take no responsibility for any failure.

(d) HIGH DENSITY POLYTHENE PIPE CLASS "C"

Nominal Size mm.	15	20	25	32	40	50
Flow litre/min						
5	3.8	0.6	0.2			
10	12.5	1.9	0.75	0.28		
15	26.0	3.8	1.5	0.56	0.27	
20	42.0	6.3	2.5	0.95	0.45	
25		9.2	3.6	1.4	0.67	
30		13.0	5.0	2.0	0.93	0.2
35		17.0	6.5	2.7	1.2	0.27
40			8.0	3.3	1.6	0.34
50			12.2	5.0	2.4	0.52
60			17.0	7.0	3.3	0.7
70				9.0	4.2	0.95
80				11.3	5.4	1.2
90				14.0	6.6	1.5
100					8.0	1.8
120					11.0	2.6
140					14.5	3.4
160						4.3
180						5.4
200						6.6
Maximum Working Head 90 metres, all sizes.						

5.10.5 Fittings and bends

Pipe fittings such as valves, bends and elbows contribute to the head loss in a pipe system. The head loss for each size and type of fitting could be listed in a separate set of tables. However it is much more convenient to use a single table to describe the effect of fittings. This is achieved by quoting in the table the equivalent pipe length of the fitting, that is the length of pipe which would have the same effect on the flow as the fitting itself. These lengths are given in *Table 5.5*. Thus the head loss in a system is found by first finding the effective pipe length by adding the equivalent length of the fittings, and then adding this to the actual pipe length.

Table 5.5 Equivalent pipelengths for various fittings

Friction losses through pipe fittings in terms of equivalent lengths in metres of pipe.

Nominal Size mm	15	20	25	32	40	50
Standard elbow or tee piece	0.5	0.6	0.8	1.1	1.3	1.6
Standard 90° bend	0.5	0.6	0.7	1.0	1.1	1.4
Gate Valve–full open	0.10	0.13	0.17	0.22	0.26	0.34
Saunders 'A' valve–full open	0.9	1.5	1.8	2.6	3.3	3.7

Example

A greenhouse heating pipe system consists of 425 metres of 32 mm Class E PVC pipe, ten elbows, three gate valves, ten 90° bends and eight tees. Find the head loss at 50 litres per minute flow.

Solution: From the head loss tables the equivalent length of pipe can be calculated:

Fitting	Equivalent length	Total Equivalent length
Ten elbows	1.1	11.00
Three gate valves	0.22	0.66
Ten 90° bends	1.0	10.00
Eight tees	1.1	8.80
425 m straight pipe	425.00	425.00
Total Equivalent Length		455.46

Hence equivalent number of 400 m lengths

$$= \frac{455.46}{100} = 4.55 \text{ lengths}$$

Hence from head loss tables at 50 l/min head loss = $2.2 \times 4.55 = 10.03$ m

Some pipeline components such as sprinklers and valves do not have head loss characteristics which can be worked out in this way. The only solution for these components is to obtain data on head loss as a function of flow rate.

below). Note that the curve has a parabolic shape which reflects the fact that the flow in the pipe is turbulent, so that the head loss is proportional to the square of the velocity.

If a special fitting is also involved the system curve can be obtained by taking the head loss of the fitting from the manufacturer's data, and plotting this separately. The total head loss for the whole system (ie, the system curve) can then be found by adding the two together at each point along the curves. If there is also a static head to consider (eg, the pipe goes up a hill) then this can also be added to the head loss curve to give the total dynamic head of the system. These points are illustrated in the following example:

Example

The pipe system described in the previous example supplies water from a pump at a RL of 225 m through a ballcock valve whose head loss characteristics are indicated in *Table 5.6*. The pipe outlet feeds into a tank at a RL of 245 m. Construct the system curve.

Solution: The static head of the system will be simply the difference in the reduced levels, ie, $245 - 225 = 20$ metres. The pipe friction is calculated in *Table 5.6*.

The system curve can be found by plotting the graph of pipe head loss (as in *Figure 5.21a*), and adding the head loss through the valve and the static head graphically, as in *Figure 5.21b*.

Table 5.6 Data for head loss as a function of flow rate for a water supply
(Head losses in metres)

Flow rate (l/min)	0	20	30	40	50	60	80	100	120
Head loss per 100 m	0	0.4	0.9	1.5	2.5	2.9	4.8	7.0	9.5
Head loss in 455 m	0	1.82	4.10	6.84	10.03	13.22	21.89	31.92	43.32
Ball-cock head loss	0	1.2	–	3.5	–	8.3	–	25.5	–
Static head	20	20	20	20	20	20	20	20	20

5.11 SYSTEMS CURVES

It is relatively straightforward to plot a graph of the head loss in a pipe system as a function of the flow rate. This plot is called the System Curve, and an example is shown in *Figure 5.21a*. The curve is for the same system examined in the example above, and to get it head loss tables were used for a series of flow rates, as in *Table 5.6* (see example

The system curve enables one to see the way in which the system responds at different flow rates. If a pump is going to be used the curve is then combined with the pump performance curve to obtain what is known as the operating point. This defines the flow and the head which will be developed when the pump is switched on. This will be considered after we have discussed pumps.

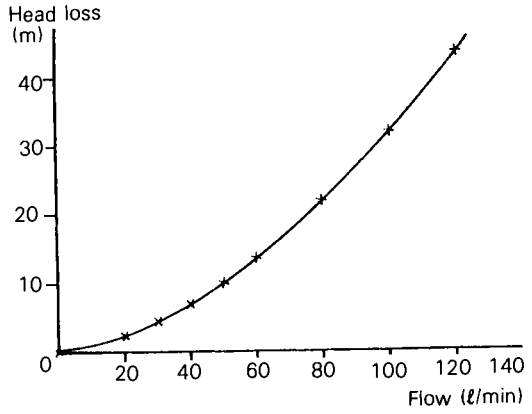


Figure 5.21(a) System curve for pipe (from head loss tables).

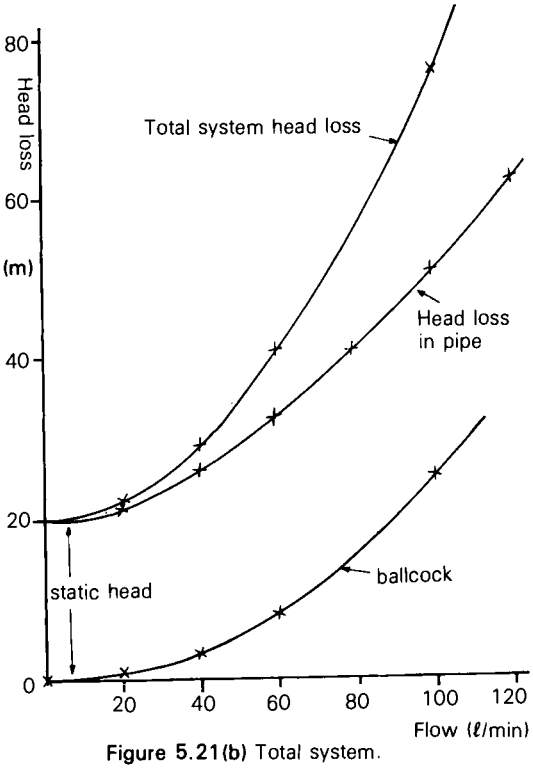


Figure 5.21(b) Total system.

5.11.1 Pipe selection

The selection of the type of pipe depends on a number of factors. Clearly head loss and pressure ratings will be major factors. An analysis of the design usually reduces the choice to one or two options, and cost may then be the deciding factor. The cost of the pipe should include a consideration of installation costs. Polythene pipes are flexible and supplied in coils which may be from 50 to 200 metres long. High density polythene pipe lengths are joined by plastic compression fittings, while low density pipes can be joined with rubber ring joints or by heating if the right seals are not available. Pipes can be installed by digging a trench or by pulling the pipe through the ground using a special mole plough and associated equipment. PVC pipes are usually supplied in six metre lengths and are more rigid. They can also be jointed with rubber ring joint seals, or they can be glue jointed using a solvent cement. Sometimes a trench needs to be dug before they are installed. The costs of these operations may affect the final choice. Galvanised steel pipes need to be joined with appropriate fixings. They are likely to rust over a long period of time and they are expensive. However they will withstand greater pressures than the plastic alternatives. A fourth type of pipe, known as Fibrolite, is a rigid pipe which is used only for community and urban water supplies where very large diameters are needed.

On hill country farms the pressure in the pipe can become large, due to the changes in RL. An alternative to using galvanised pipes in a gravity feed supply is to install pressure break tanks at appropriate intervals. These are simply concrete tanks fitted with a ballcock. The tanks act as a new supply for the next part of the scheme. An example of a water supply for a sheep farm is shown in *Figure 5.22.*

In many installations the choice of the pipe will need to go hand in hand with the selection of a suitable pump to generate the required head. A variety of combinations may be possible. For example one could select a large diameter pipe so that head losses are minimised. The pump will then only need to operate at the lowest head necessary. This means that less power will be required and pumping costs will be reduced. It may be possible to buy a less expensive pump. On the other hand one could spend more money on the pump, and save on the pipe costs by choosing a smaller diameter. In this case the pump will have to work at a higher head, and the pipe friction head losses will be greater. As these friction losses are losses of energy, the system will take more power to run and will therefore be more expensive on electricity. In addition the higher heads could mean more maintenance. In practice the final choice may well end up as a compromise

between these two extremes. However before we get into the economic selection of water supply equipment too seriously perhaps we should take a look at pumps first!

amount of water available in this way will depend not only upon the rainfall, but also upon the catchment area of the source. Streams and springs have a habit of drying

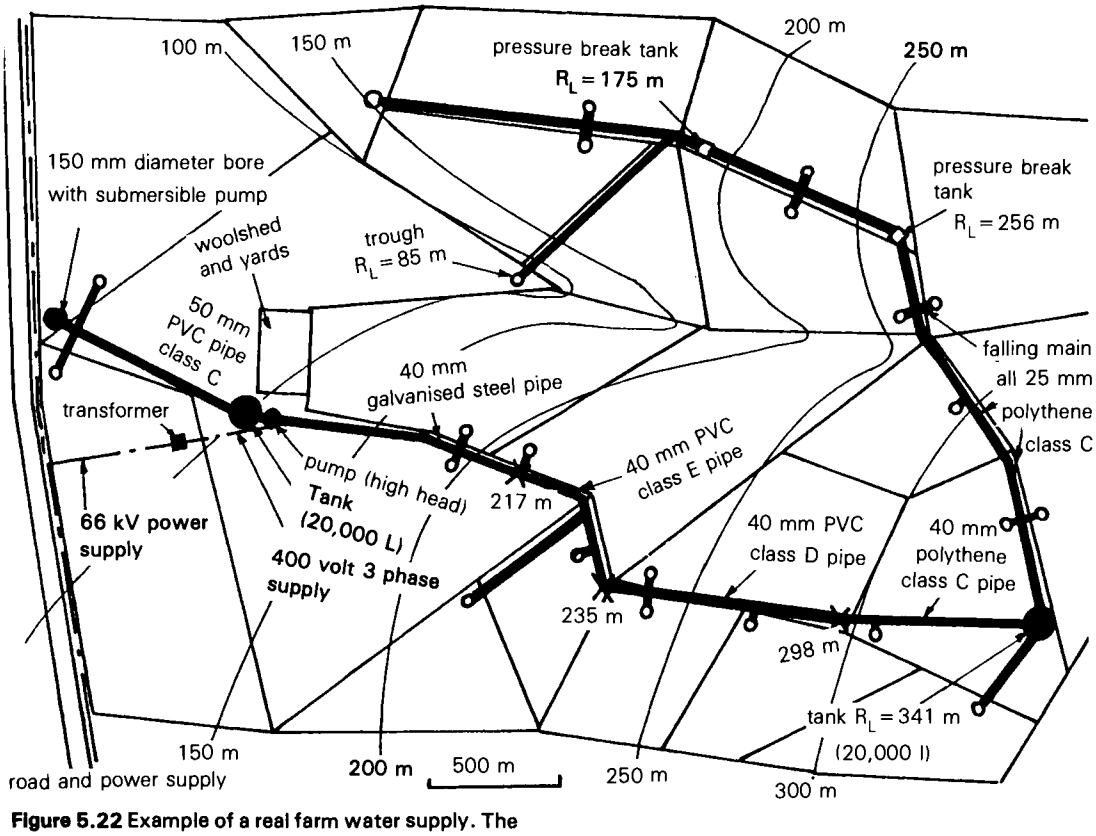


Figure 5.22 Example of a real farm water supply. The pipe is indicated by heavy black lines, and crosses indicate changes in pipe type. Contour lines and fencing subdivisions are also shown. Note that the galvanised steel pipe must be a high-strength grade, and the flow rate from the pump to the highest tank should not be more than around 30 l/minute. Can you work out why?

5.12 PUMPS

5.12.1 Introduction

We have so far looked at the movement of water through pipes. It is now necessary to consider how we make the water move in the first place. There are basically three alternatives.

a. Gravity feed

First we find a convenient hill with water at the top. As long as the rainfall is adequate we can maintain a supply of water from this source, which can then be fed downhill to the paddocks and houses below. The source could be a natural stream, lake, or spring. The up in summer or whenever water is most needed. Artificial lakes can also be used, by constructing a dam across a natural water course. This provides a buffer supply of water for dry periods, and is the most common form of water source for large centres of population. If the catchment area is insufficient it may be possible to pump water from underground or a stream up to a suitable reservoir, and then to reticulate the water by gravity. One problem with gravity feed systems arises if the pipes go uphill at any point. This is likely to result in air locks, as pockets of air collect at the high spots. A relatively even fall on the pipe is therefore preferable.

b. Artesian well

Second we can look for an artesian well, which is a source of water from beneath the ground where the water is in fact at a higher head than the ground level. The water is

trapped underneath an impermeable layer, and when the well is drilled the water flows out of the ground (*Figure 5.23*). The source of the water is usually a range of hills and the supply can be quite reliable. Sometimes the head may be only a few metres, in which case additional pumping will be required. In all cases where a well is not artesian some form of pump will be needed to obtain the water.

5.12.2 Pump characteristics

To understand the performance of a pump it is necessary to be familiar with a number of terms. These are explained with reference to *Figure 5.24*, where water is drawn from a well and delivered to an overhead tank.

The *Static Suction Head*, A, is the vertical height from the water source to the pump.

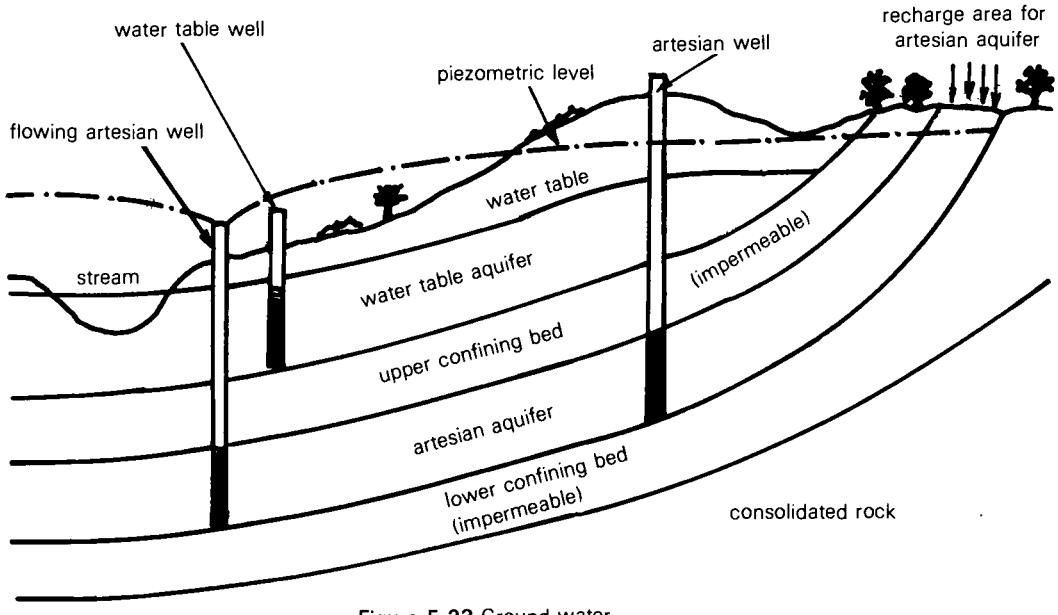


Figure 5.23 Ground water.

c. Pumped supplies

The third means of passing water through pipe networks is to use a pump. The pump is simply a device for increasing the head of a flow of water, as described earlier. Pumps can be used to supply water to a tank or reservoir mounted on top of a hill, so that the water can be reticulated around the farm by gravity using a completely separate pipe. This is called a Falling Main system. Alternatively offtakes can be taken from the pipeline feeding the reservoir. This is called a Rising Main. If the ground is relatively flat the falling main will not be much use, and a pressurised system is required.

There are a wide variety of pumps on the market and their behaviour varies according to the type. We will describe some of the more common types and compare their characteristics.

The *Static Delivery Head*, B, is the vertical height from the pump to the tank, and the *Total Static Head* is A + B. These are the heads which exist when no water is being pumped. Once the flow starts, on the suction side the pump has to overcome not only the static suction head but also the friction head loss in the pipe, including the loss due to any fittings such as filters or valves. This extra head is represented by X and is shown as an equivalent extra head on the suction side. This has important practical applications, since, as we shall see, there is a practical limit to how much suction a pump can produce. Even though the static suction head A may be within the capabilities of the pump, if the suction pipes are too long or too narrow, the total suction friction head X + A may be large enough to prevent the water being lifted by the pump.

Similarly there will always be a friction head, Y, on the delivery side. With a very long

delivery pipe this may represent the larger part of the delivery head. It can be reduced by increasing the diameter of the delivery pipe. The *Total Working Head* (A+B+X+Y) determines the load against which the pump works, and thus the general type of pump required and the power which must be put in to drive the pump.

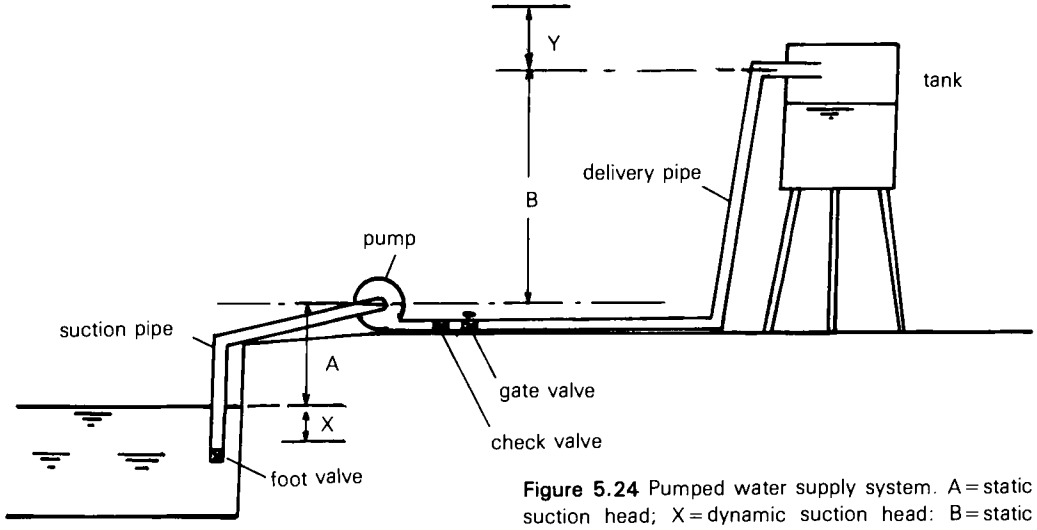


Figure 5.24 Pumped water supply system. A = static suction head; X = dynamic suction head: B = static delivery head; Y = dynamic delivery head.

The flow is of course the discharge in litres per minute. The heads are normally measured in metres, while the speed of the pump is usually quoted in revolutions per minute (rpm).

The pump itself must be driven by a suitable electric motor or engine. In some cases the pump is sold complete with a motor, while in others the motor can be purchased separately. The selection and sizing of the motor has an important bearing upon the operation of the pump, as we shall see later. Adequate provision must be made to ensure that the motor is protected from water and spray, and it must also be well ventilated to prevent overheating. Some pumps (particularly submersible types) have a motor built in.

5.12.3 Driving power and water power

The Driving Power is the output power in watts delivered by the engine or electric motor driving the pump, and is used to calculate the efficiency of the pump. The efficiency of a pump (what you get out divided by what you put in) is always less than 100%.

Water power

The output power which a pump delivers is determined by the Water Power. This can be calculated from the basic concepts of power. By definition power is defined as the force multiplied by the distance moved in one second (Chapter 3). Thus the water power is given by:

WP = Force × Distance moved in one second

$$= (P \times A) \times v = \gamma H A \times \frac{Q}{A} = \gamma H Q$$

so that $WP = \gamma H Q$ **Equation 5.33**

where P is the pressure (change), A is the cross-sectional area, v is the velocity of flow, H is the Head (across the pump) in metres, γ is the specific weight of water, and Q is the flow in m^3 per second.

$$\text{Thus Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Water Power}}{\text{Driving Power}}$$

$$= \frac{\gamma H Q}{\text{Motor Brake Power}}$$

Equation 5.34

To test the performance of a pump the characteristics listed above are measured under closely controlled conditions in the laboratory. A typical pump test facility is shown in *Figure 5.25*. The pump is run over its full operating range, and the data from the tests is presented either in tabular or graphical form. Using these results, which are generally included in pump catalogues, a

pump can be selected which will meet the requirements of any job and which will operate at the best efficiency. Examples of performance graphs for different types of pump are given below.

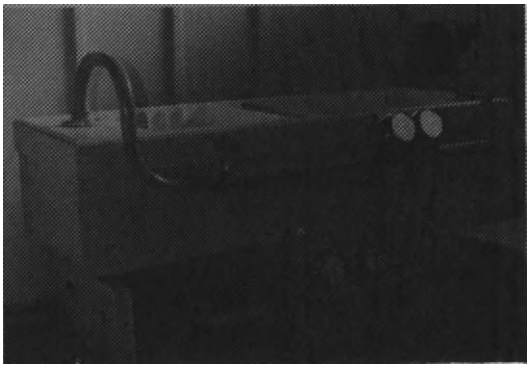


Figure 5.25 Pump test facility.

When selecting a pump there are several points to consider. These include the capacity of the pump (ie, how much water it will pump) together with the pressure it will produce at that flow, the suction head that the pump will produce to draw water out of the source, the efficiency and hence the power requirements, the operating characteristics such as speed of the driving shaft, the ability to handle solids such as grit and sand, the wear of the pump, the amount of maintenance required, and the discharge properties (eg, smooth or intermittent delivery). Finally cost and availability, and the back-up service for replacement parts, need to be considered.

5.13 TYPES OF PUMP

Of the pumps in use on farms, by far the greatest number belong to one of three main types, ie, reciprocating, rotary, and centrifugal. Other types include jet pumps, airlift pumps and hydraulic rams.

5.13.1 Reciprocating pumps

A typical reciprocating pump has a ram or piston working backwards and forwards within a cylinder or pump barrel (*Figure 5.26a*). This motion is usually obtained from a crank-shaft revolving at constant speed, and a connecting rod. Automatic valves control the flow of liquid into and out of the cylinder. Such a piston pump may be single-acting, in which flow occurs only on alternate strokes as the water is sucked in and pushed out each cycle, or double-acting (*Figure 5.26b*), where the flow occurs every stroke. As can be seen

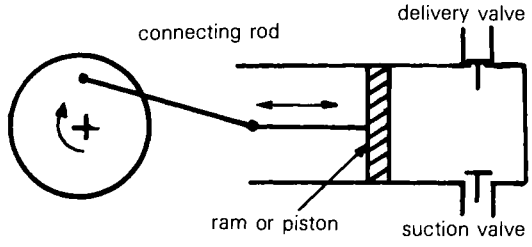


Figure 5.26(a) Single-acting piston pump (schematic).

from the Figure the water in this case is being sucked in on one side of the piston at the same time as it is pumped out on the other. The water is delivered in a series of pulses by these pumps, and so all reciprocating pumps are characterised by the intermittent delivery of the liquid. Reciprocating pumps are common in a variety of situations. As well as on farm water supplies, a bicycle pump is a

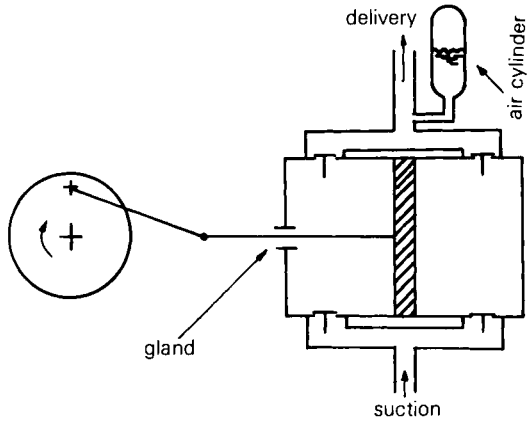


Figure 5.26(b) Double-acting piston pump (section).

simple single acting reciprocating pump, as is the compressor on a refrigerator (Chapter 7). Hand pumps on wells and hydraulic jacks for cars are normally of this design.

A deep-well reciprocating pump operates in the same way as described above, but the crank is at ground level above the well, and the cylinder is placed down the well at the lowest expected water level. A "drop pipe" carries the pumped water from the cylinder to the surface, and long rods transmit the reciprocating motion from crank to piston, as in *Figure 5.27.*

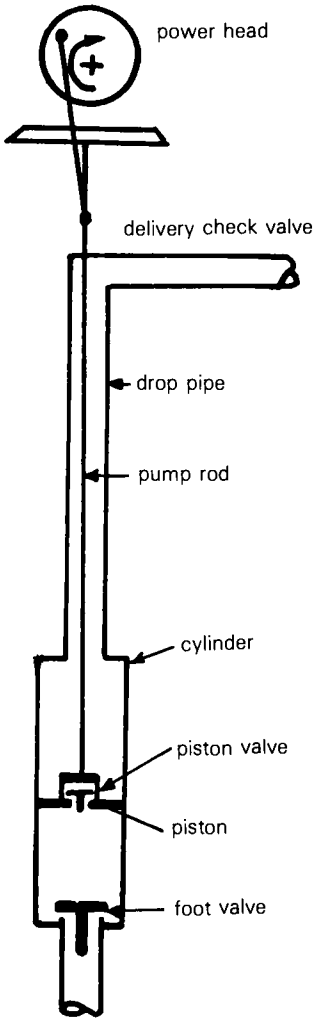


Figure 5.27 Deep-well reciprocating pump.

The diaphragm pump, commonly used for pumping milk, is also a positive displacement reciprocating pump. It works in the same manner as the piston pump, but the piston is replaced with a flexible rubber diaphragm. This is shown in *Figure 5.28*. Diaphragm pumps are easy to strip down and clean, and are made from only stainless steel and rubber, which are acceptable materials for contacting milk. They are also useful for pumping sludges, engine fuels, and for injecting nutrients into irrigation water at regular known quantities.

Performance

Reciprocating pumps are positive

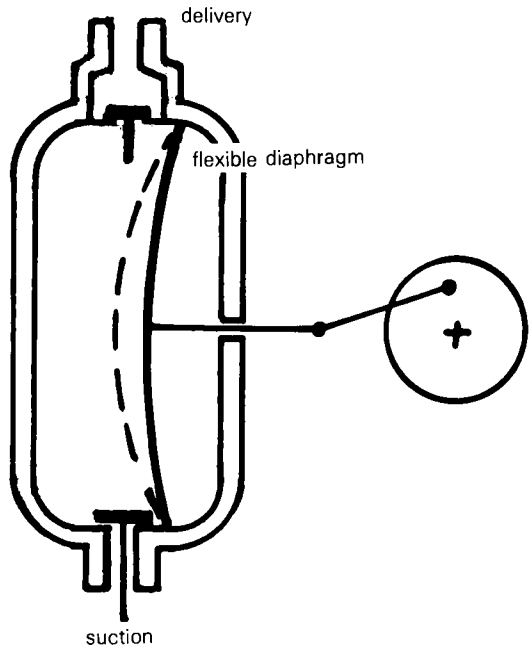


Figure 5.28 Diaphragm pump.

displacement pumps. This means that on every cycle the reciprocating pump delivers a volume of liquid equal to the swept volume of the cylinder. The flow therefore will only change in proportion to the speed of the pump, and is almost independent of delivery head. Thus for a particular pump speed, the head/discharge characteristic is nearly vertical. *Figure 5.29* shows the characteristic

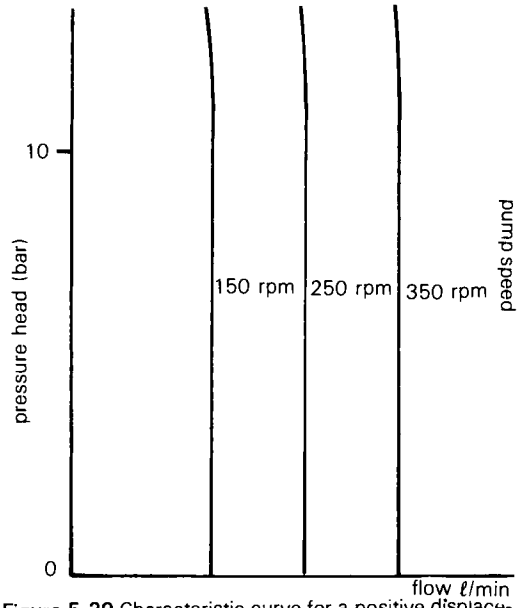


Figure 5.29 Characteristic curve for a positive displacement reciprocating pump.

curve of pressure output (head) as a function of flow. As can be seen the output is essentially independent of the flow. This has important practical implications: the first is that the pump will endeavour to supply the fixed volume of water on every cycle, regardless of the pressure. While this is fine if the delivery system is open it can be disastrous if the output is closed off by a valve. The result will be that the pressure will rise in the delivery side until the pipe expands to take the volume delivered, the pipe bursts, or the pump fails. All these alternatives are highly unsatisfactory, of course. The implication is that a reciprocating pump must never be operated with a closed delivery. This applies equally well to all positive displacement pumps.

The second is that the output flow will be assured regardless of the pipe friction on the delivery side. This is seen to be an advantage by very lazy designers who are reluctant to do simple design calculations. At very high heads the flow rate will start to fall due to leakage under valves and through seals.

Piston pumps are capable of pumping to high heads (200 metres or more), and are quite widely used in water supply work for small flows. However they are quite expensive to buy, and they are not economical for low heads, as the efficiency depends on the flow rate and increases as the flow rate increases. As the head is increased the wear rate also increases and it is not advisable to use them at too great a head. Rather a balance between head and wear rate is preferable. They operate at low speeds, usually in the range of 50-250 rpm, and so a large speed reduction is necessary where a petrol engine or electric motor is used.

Reciprocating pumps are self-priming. This means that if the pump is started with the suction pipe completely dry, the pump will be able to produce a vacuum in the suction side which will suck water up and into the pump. In theory there is a limit of 10.3 metres head (1 atmosphere) to the depth that this can be achieved, and the practical limit is around 8 metres for a good pump in top condition. For design purposes suction lifts of more than 6 metres should be avoided.

The intermittent action of the pump produces a surging flow. This is often unsatisfactory and also reduces the overall efficiency of the pump due to fluid flow effects both on the suction and delivery sides. The pump can also induce water hammer, where the water oscillates violently in the delivery pipes, causing them to vibrate or even resonate, which leads to damage to the pipes and fittings. This effect can be overcome by fitting a suitable air dome on the supply side of the pump (*Figure 5.26b*). This has the effect of acting as a pressure buffer. Each time a discharge surge of water is produced, the water is forced into the dome, compressing the air and absorbing the pressure surge. After the pump discharge has slowed or stopped, the air pressure continues to force the water up the discharge line until the equilibrium pressure is regained. These air domes are normally fitted to the pump as a standard item. There is one small problem: over a period of time the air in the cylinder is absorbed in the water, and so the dome gradually fills up with water. It is therefore necessary to replenish the air by unscrewing the nut on top of the dome and allowing air in. This seems very odd but is the only remedy when the pump delivery becomes irregular after a period of time. Details will be given in the manufacturer's instructions.

Other maintenance of reciprocating pumps includes repacking the gland which provides the seal between the driving shaft and the cylinder. The diaphragm in the diaphragm pump needs replacing at regular intervals, and the piston seal and valves may need attention after a time.

5.13.2 Rotary pumps

There are a variety of rotary pump designs but they all involve a rotating mechanism which draws the fluid in and forces it out at increased pressure. The most common type on farms is the gear pump (*Figure 5.30*). This consists of two cams or gears which mesh together and rotate in opposite directions inside an oval casing. One gear is driven by the motor, and it turns the other. The rotating parts fit the casing closely, and the liquid trapped between them and the casing is forced through the pump as they rotate. A definite amount of water, which depends on the size and shape of the gears, is passed with each revolution.

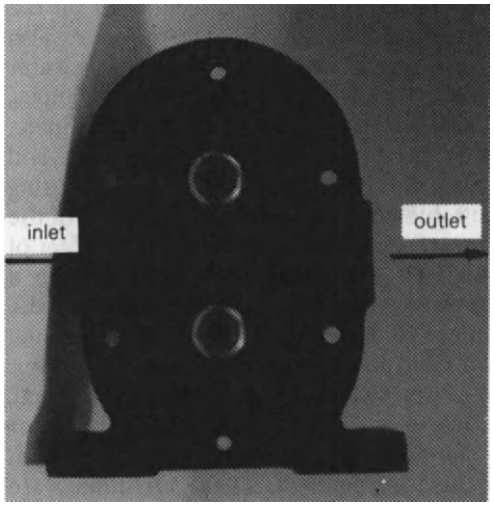


Figure 5.30 Gear pump. Fluid is carried around both gears between the teeth and the casing.

Performance

Rotary pumps are positive displacement pumps, with a head/discharge characteristic similar to reciprocating pumps, and they do not require priming. In addition they provide a steadier flow, and, having no valves, are of simpler construction. They will operate over a wide range of speeds and can be driven from an electric motor. However they can be rather noisy in some situations.

They have almost the same suction characteristics as reciprocating pumps, and will pump against high heads. They have not proved successful for water supply work as they wear badly (especially on the gear teeth) if the water contains sand or grit. A worn gear pump can lose 90% of its capacity quite easily. Their main use is in hydraulic systems and sprayers. They are particularly useful in spraying equipment because they are compact in size, and can be driven conveniently from a tractor power take-off (PTO). One practical point is that the user should always be aware of the wear problem: only clean water should be used to refill sprayer tanks. With most designs the gears can be taken out and replaced the other way round to give a little extra working life. Gear pumps can also be used for the pumping of milk or viscous fluids like molasses.

Other types of rotary pumps

Rotary pumps which incorporate a flexible rubber impeller can be used for many applications (*Figure 5.31*). These can be very useful pumps for operating at small flows, and are quiet in operation. The rubber impeller requires replacement at regular intervals. A different type of impeller is found in the Screw pump (*Figure 5.32*). Here the rotor is a long stainless steel screw sitting inside a rubber casing which is also in the form of a screw. As the rotor turns the fluid is forced along the axis in a series of pockets formed by the two screw shapes. These pumps have been used for specialised applications in the food processing industry, but are rather expensive. Some have been used for pumping sludges in dairies. They can handle fluids containing abrasives (including sand), and have been used for bore hole pumping. They are quiet in operation and have a very gentle action.



Figure 5.31 Sectional view of rotary impeller pump showing mode of operation (Farm Electric Handbook).

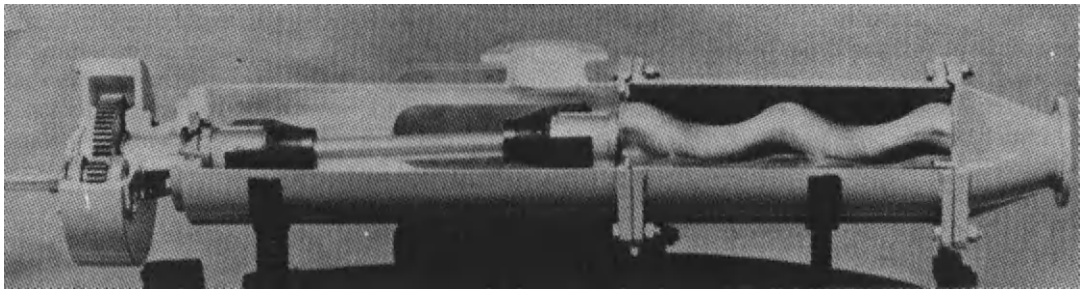


Figure 5.32 Helical screw pump with articulated drive shaft (Farm Electric Handbook).

5.13.3 Centrifugal pumps

Centrifugal pumps are available in a wide range of sizes and shapes. Because of their simplicity of design and low maintenance they are often chosen for the majority of farm and horticultural water supply installations. In a centrifugal pump the rotating part is called the impeller (*Figure 5.33*). It is shaped to force the water from the inlet at the centre of the impeller outwards, so that the water emerges on a tangent to the rotor and at right angles to the pump axis. In effect the rotor applies a centrifugal force to the water giving it a high velocity. This is called radial flow since in the pump the water is propelled radially outwards. The impeller, which is fitted with blades or vanes which are usually curved backwards towards the tips, is fixed to a spindle, and it rotates rapidly inside the casing. The impeller may be of the closed type where the vanes are mounted between discs, or of the open type, consisting of a hub to which the vanes are attached. The open impeller does not have such a high efficiency as the closed type, but is less likely to become clogged and hence is better adapted to handling liquids containing solids. Semi-closed impellers are also used in some pumps. These have an intermediate efficiency and are easy to clean. They are used in the food industry.

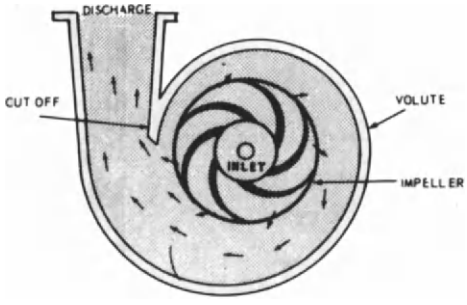


Figure 5.33(a) Volute type of centrifugal pump (State Electricity Commission, Victoria).

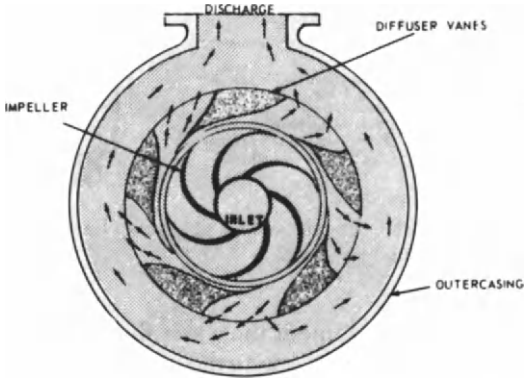


Figure 5.33(b) Diffuser type of centrifugal pump (State Electricity Commission, Victoria).

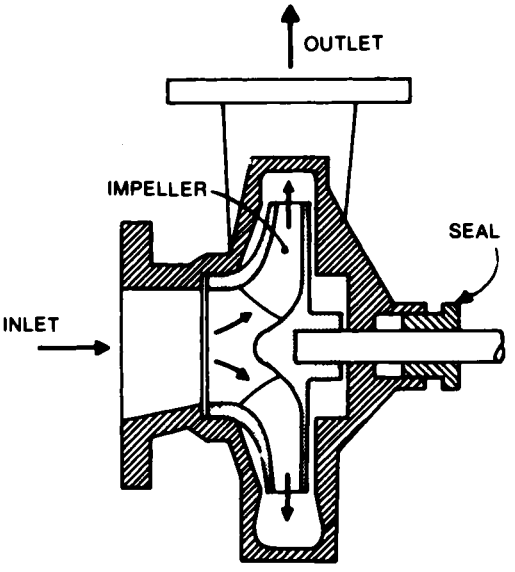


Figure 5.33(c) Side view of centrifugal pump.

The casing of centrifugal pumps may be of the volute or turbine type. In the volute the casing gradually increases in cross-section, causing the velocity head of the water leaving the impeller to be changed into pressure head as the velocity is reduced towards the outlet (*Figure 5.33*). In the turbine, or diffuser type, a series of fixed blades has the same effect: this type is not used much in water supply or irrigation, except in deep well pumps, where the turbine casing shape lends itself to a cylindrical body. Centrifugal pumps with one impeller are called Single-stage pumps. In order to obtain greater flow rates it is possible to use double suction impellers with inlets on both sides of the casing. The effect is the same as having two pumps back to back. This design doubles the capacity without increasing the diameter of the pump, and also eliminates the axial thrust which is generated in the single suction design.

The maximum head to which a single stage centrifugal pump will operate is usually less than 50 metres unless the pump is operated at undesirably high speeds. For higher heads a Multi-Stage pump is used. These are pumps with two or more impellers arranged in such a way that the discharge from one impeller enters the centre, or eye, of the next impeller so that the delivery head is increased in stages (*Figure 5.34*). The head is increased by the same amount in each stage so that very high heads have been attained. Pumps with as many as 32 stages have been built. Obviously the flow through each stage is the same, so the pump does not increase the flow rate at a given head. However if each stage increases the head by say 30 metres, then an eight stage pump will produce a pressure of 240 metres head.

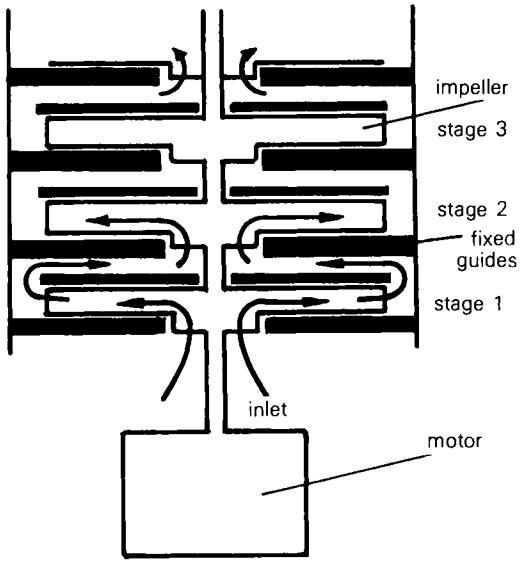


Figure 5.34 Multistage centrifugal pump.

This system is used in many submersible pumps, where pump and motor are both placed below the water surface (*Figure 5.35*).

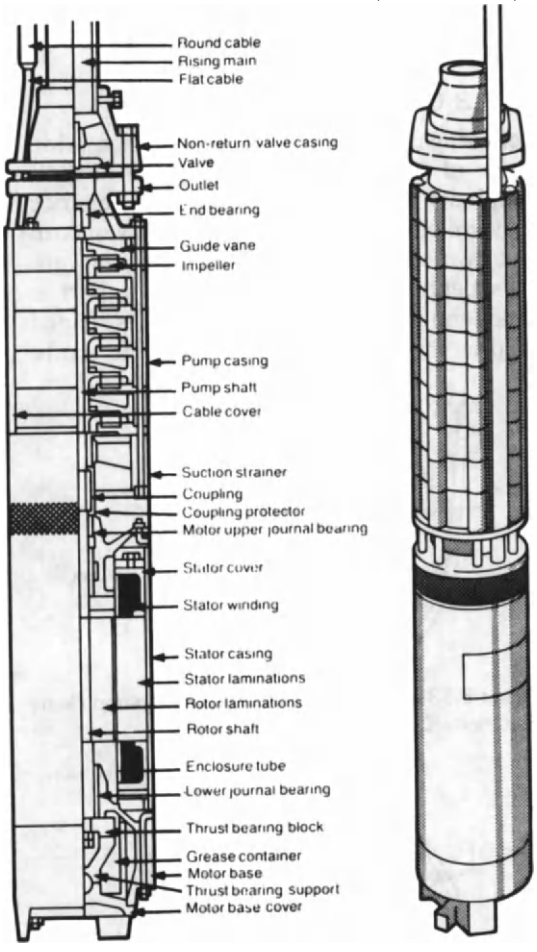


Figure 5.35 Deep-well submersible pump (centrifugal) (Farm Electric Handbook).

In this arrangement the water flows over the motor casing as it enters the pump, producing a vital cooling effect on the motor and preventing overheating. Delivery to the surface is through a riser pipe on which the assembly is suspended. Centrifugal pumps need to be primed before starting unless they are located below the source of water. The suction performance of centrifugal pumps is

not very good, generally less than 5 metres, and they should be placed as near to the water as possible. Proper arrangement of the piping is essential if the pump is to operate at its greatest efficiency. *Figure 5.24* shows a typical centrifugal pump installation. Centrifugal pumps are not self priming. Thus the suction line must already be full of water when the pump is switched on. A foot valve is therefore required, as discussed below, or the pump suction must be filled manually before operation.

Performance

Centrifugal pumps are not positive displacement pumps. This means that the delivery flow will depend on the delivery pressure. Typical performance curves for a centrifugal pump, operated at four speeds, and as obtained in a laboratory test, would appear as in *Figure 5.36* (the heavy lines). This shows that the pump will deliver a flow of water which varies according to the total pressure differential from a peak value at zero operating pressure to no flow at all at the

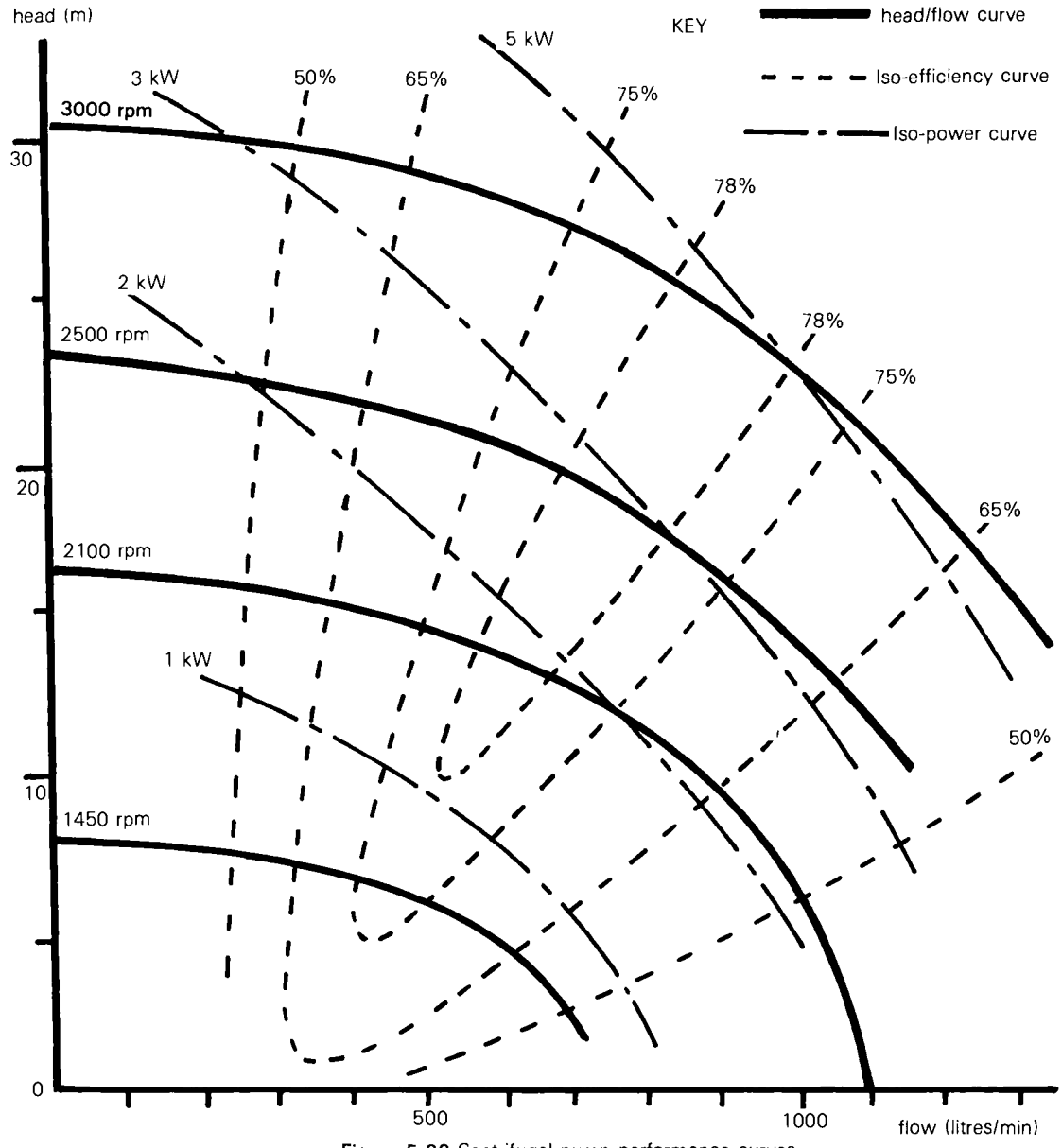


Figure 5.36 Centrifugal pump performance curves.

maximum operating pressure. For example, in the Figure at 2100 rpm, the flow at zero pressure is 1100 l/min, while at no flow the maximum pressure is 17 metres. If the pressure is greater than 17 metres no flow will occur. The water is merely churned around inside the pump but goes nowhere. It is important to realise that this is what happens when the delivery valve is shut: the pump itself has no idea whether or not the delivery is closed or open, or whether the pipe goes uphill and generates too great a static head: all it is aware of is the resulting pressure. For this reason it will not do a centrifugal pump any great harm if it is operated (for a short time) with a fully closed delivery.

The power required by a centrifugal pump also varies depending upon the speed and operating point. Contrary to what one might expect, the maximum power for any given speed is generated at maximum flow rate (and hence at minimum head). Thus the heaviest load on the motor occurs when the pump is operating at full flow, and the least load occurs when the outlet is closed so that no water can flow. In practice some pump manufacturers recommend that the pump be started with the delivery closed, as this reduces the starting load on the motor. However it can also mean that the motor supplied with the pump is a little small for the pump, and it may be better to pay a little more for a pump and motor without this restriction.

If the pump performance test is repeated over the complete speed range of the pump, an overall picture of the operational characteristics of the pump can be obtained. It is also possible to plot on the same graph curves of power consumption and efficiency, as in the Figure. Centrifugal pumps give their best performance at a certain rate of discharge and head, and their efficiency falls off when these conditions are varied. For the pump curves shown the most efficient operating point would be within the area marked out by the iso-efficiency curve for 78% efficiency.

Example

For the pump curves shown in *Figure 5.36* estimate the range of operating points for which the efficiency is greater than 78% at 2500 rpm. What is the power required to be supplied by the motor at the highest flow rate in this range?

Solution: From the iso-efficiency curve the range of flows is between 700 l/min at a head of 20 metres to 840 l/min at 17.4 metres head. At 840 l/min and 17.4 metres head the power required on the pump shaft input will be 3.0 kW.

Thus, for any centrifugal pump at a particular speed, there is a definite head or discharge at which the efficiency is a maximum. However the operating point of the pump is fixed by the system curve (see section 5.13.7 below), and if this point is not at or near peak efficiency, then it is advisable to alter the pump characteristic curve either by increasing the pump speed, or by choosing a different pump with more suitable characteristics. The shape of the performance curve can also aid in selecting a pump: as a general guide a long horizontal portion on a performance curve will mean that the flow rate will vary dramatically for a relatively small change in head, and the pump will not operate satisfactorily in this range.

If the pump is required to handle varying flows, in major water supply systems it is sometimes better to provide several pumps in parallel. Thus a variable number may be operated depending on flow requirements, and all the pumps may be operated at or near peak efficiency. This may be impractical for smaller installations, and the operating point calculation should be based on the maximum demand case.

Affinity laws

For a centrifugal or propeller pump, the delivery head and power input all increase as the speed is increased. The delivery is proportional to speed, head is proportional to the square of the speed, and power input is proportional to the cube of the speed. This means that if we double the speed, the delivery doubles, the head is increased four times, and the power input is increased eight times. These relationships are called the Affinity Laws. They are written:

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2} = \left(\frac{H_1}{H_2}\right)^{1/2} = \left(\frac{WP_1}{WP_2}\right)^{1/3}$$

Equation 5.35

5.13.4 Axial flow pumps

In an axial flow pump the impeller is shaped to force the water from the inlet at the centre of the impeller in the direction of the pump axis : ie, an axial flow. Axial flow machines are more correctly referred to as propeller pumps. A propeller-type pump has only two or four blades, and thus has large unobstructed passages which permit the handling of water containing debris without clogging. On larger pumps the pitch angle of the blades is adjustable for maximum efficiency, so that the pump can operate at high flow and low head or at a higher head and lower flow. A typical installation is shown in *Figure 5.37*. The bell mouth inlet is

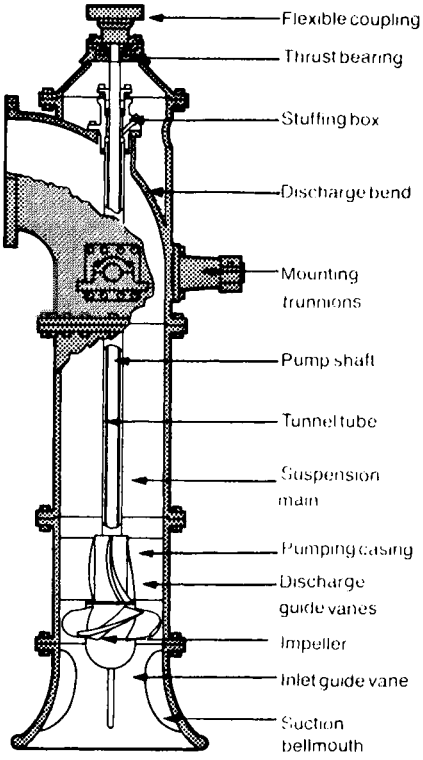


Figure 5.37 Sectional drawing of axial flow pump for land drainage (Farm Electric Handbook).

normally placed below the water level. The risk of cavitation (a phenomenon where vacuum cavities are formed in the water against the blade surfaces: these collapse causing high localised stresses on the blade and rapid wear) is high with this type of pump and so the suction side must be designed to avoid negative pressures. These pumps can be made portable and will operate from a tractor PTO. They are more suited to high flow, low head operation, and are a good choice for flood control and drainage systems. A typical pump will deliver 30,000 l/m at a head of 1 metre. Axial flow pumps operate well at heads of up to around 12 metres. For heads up to 25 metres mixed flow pumps are available which have a flow pattern which is part axial and part radial.

5.13.5 Other types of pump

a. Venturi pump

If we consider Bernoulli's equation for the case of a constriction (as in the Venturi flow meter shown in *Figure 5.12c*) then the pressure change is given by:

$$P_2 - P_1 = \frac{\gamma (v_1^2 - v_2^2)}{2g}$$

Equation 5.36

Since the flow is given by $Q = v_1A_1 = v_2A_2$, thus:

$$v_2 = \frac{v_1 A_1}{A_2}$$

Equation 5.37

$$\text{Hence } P_2 - P_1 = -\frac{\gamma v_1^2 (A_1^2 - A_2^2)}{2gA_2}$$

Equation 5.38

This means that the change in pressure will be negative (ie, the pressure must drop) if the area A_2 is less than the initial area. If the reduction in area is enough the drop in pressure will be big enough to reduce the pressure at the constriction to less than that of the air surrounding the pipe – in effect we are creating a region of negative pressure or a vacuum. If we then drill a hole in the pipe, air (or whatever fluid is surrounding the pipe) will be sucked into the pipe. This is the basic principle of the Venturi pump. An arrangement such as that shown in *Figure 5.38* will extract the water from the well and deliver it to the surface. There is of course a need for a conventional pump to circulate the water down through the pipeline at high velocity. Venturi pumps can be used in situations where the water contains sand and dirt which would damage other pumps. It will also operate at depths of more than 5 metres, when other surface mounted pumps would be unable to draw the necessary suction pressure. Suction lifts of up to 90 m are

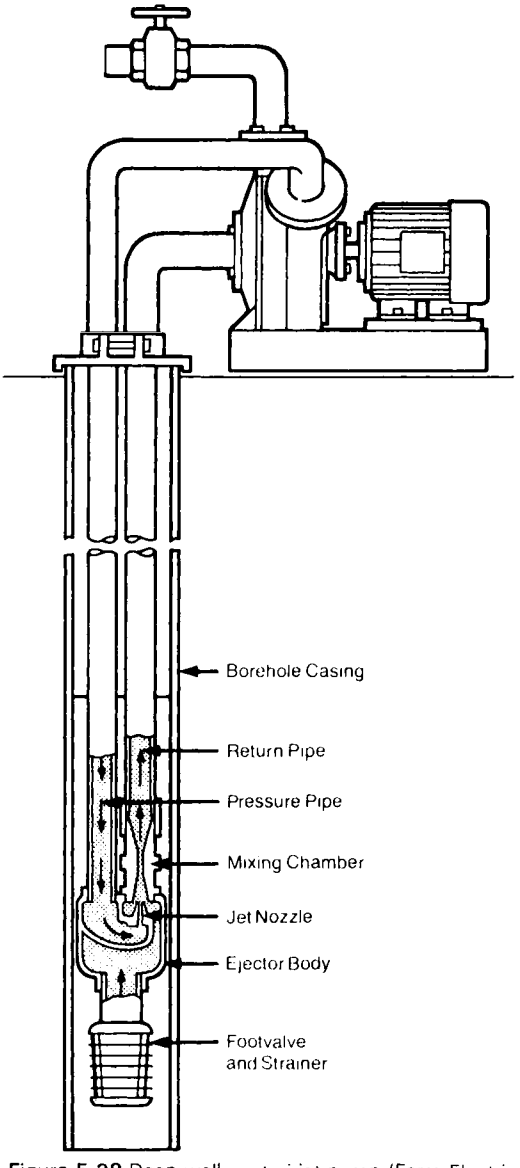


Figure 5.38 Deep well venturi jet pump (Farm Electric Handbook).

possible, although lifts of around 30 m are more common. In practice the volume of water drawn in can be half the volume circulated. Practical systems have an efficiency of typically 70%.

Venturi pumps are also used to inject chemicals into spray and irrigation lines. They can be used to meter chemicals with reasonable accuracy, since the volume of chemical drawn in depends on the volume of water flowing through the constriction. They can therefore be used to meter the flow in fertigation systems for nutrient film techniques (NFT) in soil-less growing systems in greenhouses. They can also be used in dairy sheds to meter cleansing fluids into wash down water for milking equipment. One type of carburettor used to meter petrol into internal combustion engines uses this principle. The principle can be demonstrated very simply by blowing across a straw extending from a bottle of water, and this arrangement is used in very cheap domestic spray pumps.

b. Air Lift Pump

The basic layout of an air lift pump is shown in *Figure 5.39*. Compressed air is forced down into the well, and this has the effect of aerating the water, causing a drop in density. The aerated water is then forced by the water table pressure and the increased air pressure to lift up and into the reservoir. This action is particularly advantageous where the water contains dissolved iron in solution. The air causes oxidation of the soluble Fe^{3+} ions into insoluble Fe^{2+} ions which precipitate out into the bottom of the reservoir. The pump will pump water containing abrasives, but is only suited to small suction heads.

c. Hydraulic ram

This pump has the useful advantage of not requiring a power supply. However it derives its pumping capabilities from the water itself, in effect converting kinetic energy from the full flow into increased pressure energy for a small proportion. In order to work, water must flow into the pump at high velocity, and this normally means that a long, large diameter pipe will be needed as the inlet (*Figure 5.40*). To explain the cycle consider the situation where the valve A has just been opened and water starts to flow through it to waste. Water entering the pipe builds up kinetic energy so that the flow increases through the system. At a critical moment the force on the valve A becomes enough to force it to slam shut. Immediately the flow is stopped abruptly but the water has a large kinetic energy which causes a rapid increase in pressure in the chamber. This pressure rise is sufficient to open valve B so that water is forced (at high pressure) into the delivery line. After a short time the pressure in the chamber will drop again so that valve B closes again. Now valve A can open and the cycle

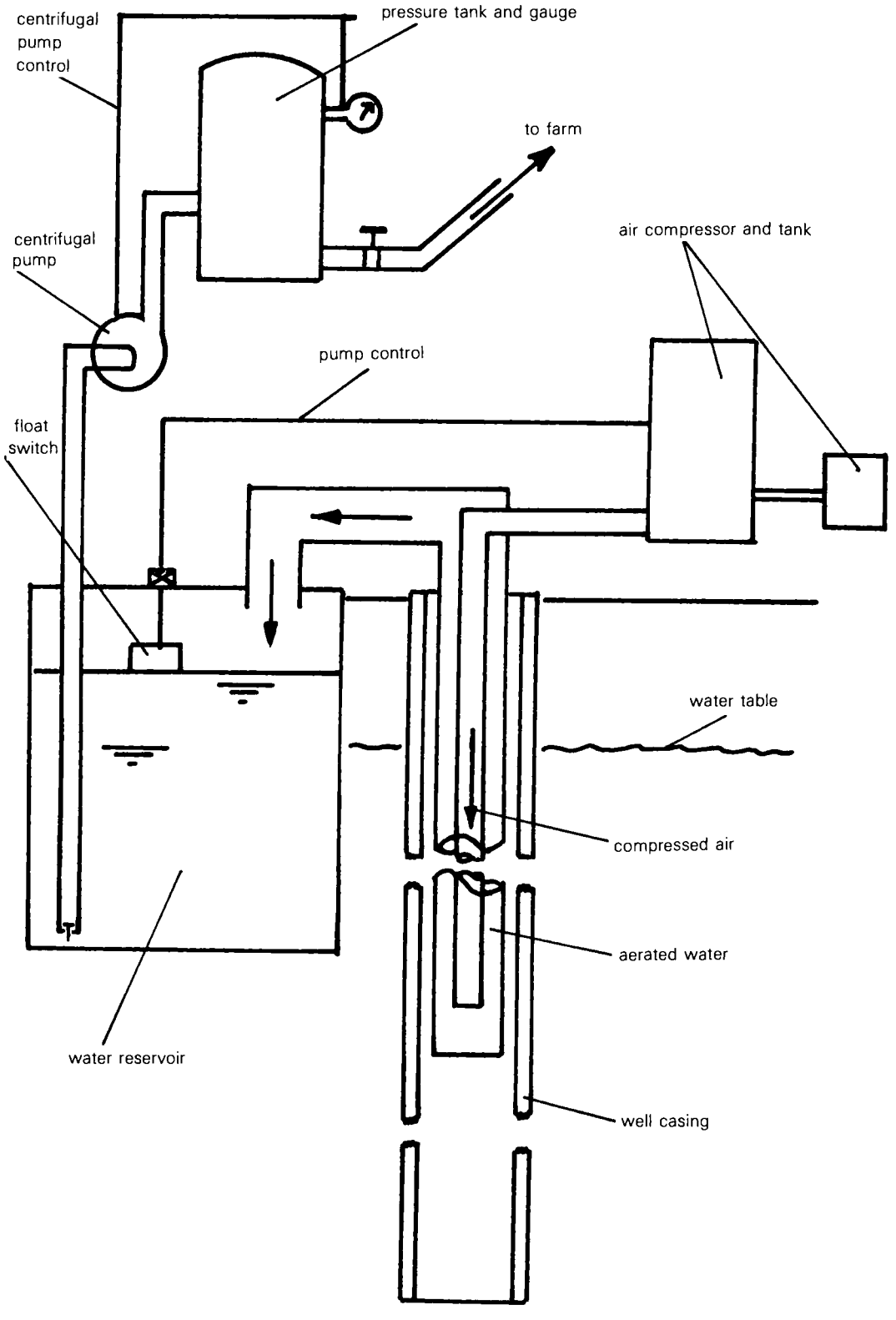


Figure 5.39 Air lift pump.

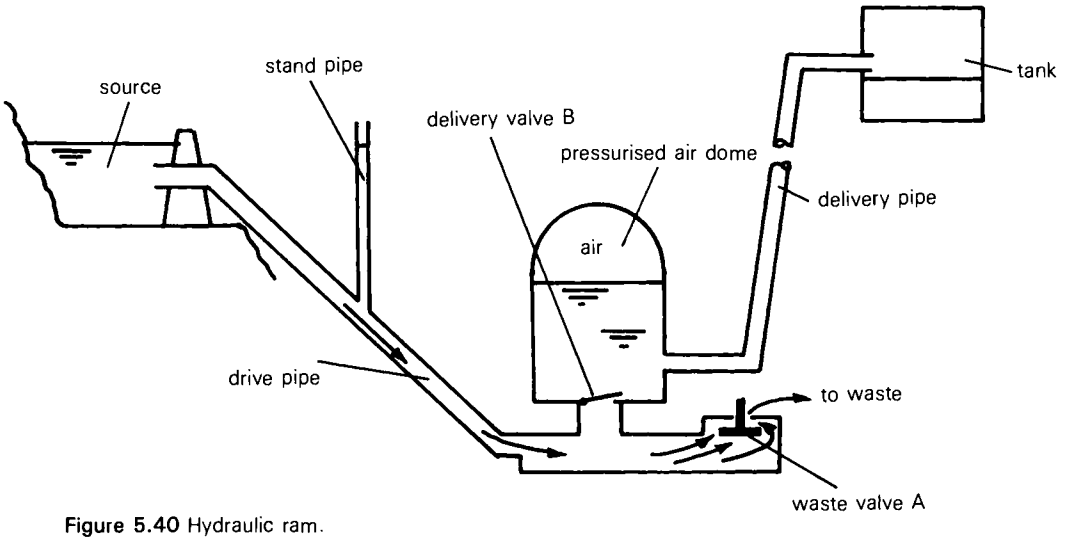


Figure 5.40 Hydraulic ram.

repeats itself. The result is that a small fraction of the water in the stream is pumped up to the higher level, while the majority is dumped out back into the stream but at a lower level. In practice efficiencies can be around 70%, and the water can be pumped to a height of at least ten times the height of the inlet pipe. Obviously the higher the height of pumping the smaller the fraction of water that will be pumped. The flow will be given by:

$$Q = \frac{e\ Q_{in}\ H}{L} \qquad \textbf{Equation 5.39}$$

where H is the net fall of the water, Q_{in} is the total flow, L is the total lift (including the additional head due to pipe friction in the delivery line), and e is the efficiency of the pump. The drive pump must have a head of more than 1 metre. If it has to be excessively long in order to obtain the required head, then a stand pipe is advisable as shown in the figure.

The main disadvantage of the hydraulic ram is that it requires an excess of water, and it can be rather noisy in operation. The delivery is also a non-steady type. The pump is of use in remote situations in hill country where water is plentiful and hills are steep. It must be securely attached to a firm base. Its efficiency can be as high as 80%, depending on the ratio of the delivery head to the drive head. The ram operates at a cycle rate of around 50 cycles per minute.

d. Peristaltic pump (Nylon roller pump)

These pumps consist of a length of flexible tube which is squeezed by a series of moving rollers. Fluid is trapped between the rollers and is therefore forced along the tube. They are used where very small volumes of fluid must be metered accurately and pumped at variable flow rates. As such they find some use in experimental laboratories and the chemical industry. They are a positive displacement pump. They have also been used for low cost garden lawn sprayers (*Figure 5.41*).

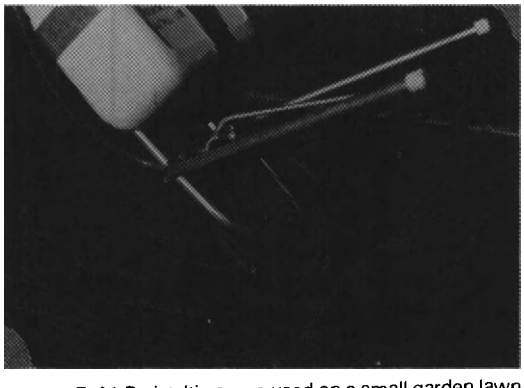


Figure 5.41 Peristaltic pump used on a small garden lawn sprayer. The rubber tube is squeezed as the wheel turns, forcing the spray out of the nozzle.

5.13.6 Summary of pump characteristics

With a knowledge of the characteristics of different pump types, it is relatively easy to select a pump for a particular farm

application. A summary of the different types is given in *Table 5.7*.

Table 5.7 Comparison of pump types

	ADVANTAGES	DISADVANTAGES
Reciprocating Pumps	Positive action. Efficient over a wide range of delivery and head. Self priming. Operate to a high head.	Discharge pulsates. Subject to vibration. Sometimes noisy. Speed reduction required. Often high maintenance.
Rotary Pumps	Positive action. Occupy little space. Wide range of speed. Steady discharge.	Subject to abrasion. Likely to get noisy.
Centrifugal Pumps	Simple design. Quiet operation. Steady discharge. Efficient for pumping large volumes. Suitable for direct connection to electric motor. May be either horizontal or vertical. Can be multi-staged.	Low efficiency at low deliveries. Low suction lift. Must be set near or in water. Require priming.
Propeller Pumps	Generally as centrifugal pumps. Usually vertical mounting. Pump very large quantities at low heads. Widely used for land drainage and flood control.	As centrifugal pumps.

5.13.7 Operating point

We have now considered the performance of pumps and the pipe system, and produced curves of head against flow which represent the head/flow characteristics of both. When we connect a pump into a pipe system the pump will produce a flow of water, and the pipe friction will resist the flow, producing a head which the pump must work against. If we now combine the two curves, the point at which they cross is called the operating point, for the very simple reason that this gives the flow and head when the pump is working (*Figure 5.42*). If it is not obvious to you why this must be so, consider what would happen if the flow produced by the pump was less than the value: the pipe friction would be less than the operating point, while the pump head will be more. The flow would therefore increase towards the operating point, but the pipe friction will also increase, until the two heads match, which will only be at the operating point we have just described. If a pressure gauge is placed just at the pump outlet, it will show this operating point pressure.

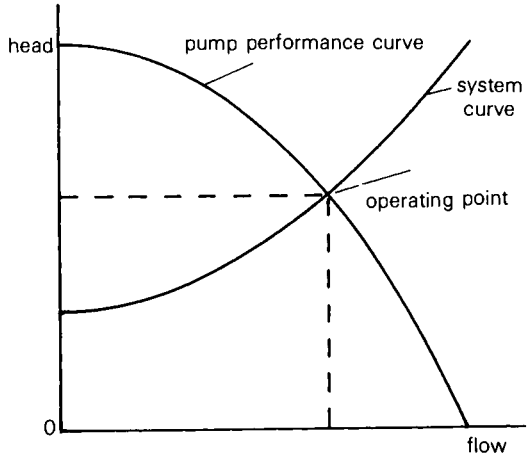


Figure 5.42 Operating point.

The diagram shows the operating point for a centrifugal pump. The same principle applies to positive displacement pumps, but since the pump performance curve is almost vertical the operating point calculation is rather trivial.

The calculation of the operating point is an essential part of the design of a water supply. The entire calculation can be done on paper before any financial commitment is made, and the farmer can avoid wasting money on a system which will not match his or her requirements. Various alternative pump/pipe systems can be considered and the final selection that is made can be based on economics. Thus it may be better to use a smaller pump feeding a system with larger diameter pipes, rather than vice-versa. On energy considerations alone this would be the right way to go, since energy used up overcoming pipe friction is not productive.

Example

The system and single pump performance curves used in *Figure 5.43* represent the supply to an orchard irrigation system. The grower wishes to double the flow of water by adding a second pump identical to the first. If he or she decides to install it in parallel, what flow would he or she get?

Solution: The result of putting the pump in parallel with the first will be to produce a new pump performance curve representing the combined effect of the two pumps together. At each head the flow will be doubled. Unfortunately, the flow rate through the pipe system will not double, because the increase in flow will cause an increase in pipe friction. This is shown in *Figure 5.43* (chained line). The operating point will change from a flow of 53 l/min at a head of 37 m (point A) to a new flow of 66 l/min and a pressure of 45 m (point B). Thus the flow will only increase by 25%.

Suppose instead the pumps had been placed in series, so that all the water flowed through both pumps. Now the head will be doubled for a given flow rate, but once again the increase in flow rate will be quite small, as the dotted line in *Figure 5.43* shows (to 70 l/min at 48 m head at point C).

A flow of 106 l/min would require a pump head of 79 m. The only solutions which will provide the extra water will be to put in a new pipe system, or to select a pump (or pumps) which will provide the flow rate required at the design head. A third alternative could be to increase the speed of the pump or pumps to produce a new performance curve. This may involve obtaining a new motor.

5.13.8 Pump selection

Selecting the best pump out of the vast range available is often difficult. The criteria include capital cost, availability, maintenance, closeness of performance to the desired operating range, efficiency, servicing support and manufacturing variation. The last factor is only found by experience and is determined by quality control at manufacture and the extent to which each pump actually performs in relation to data provided by the manufacturer.

Matching a pump's operating point to its peak efficiency can have a major effect on operating costs. Installing a large pump just to "make sure" will not only increase the capital investment but also the running costs. These costs are concealed from the grower and are often overlooked at the time of evaluating the need for professional design. An oversized pump becomes even more costly as the size of the system increases.

5.14 WELLS (BORES)

Ground water is essentially water which falls as rainfall and is absorbed into the ground rather than being evaporated or returned to the sea in rivers. It slowly returns to the sea through the ground aquifers (rock or sub-soil structures which contain water) at a speed anywhere between hundreds of metres per day down to a few centimetres per year (*Figure 5.23*). In order to use this source of water a hole (or bore) must be bored in the ground down to the aquifer. The hole or well may be as little as 100 mm in diameter, depending on the range of pumps available, and the flow rate required. Increasing the diameter of the bore will have only a small effect on the flow rate from the well, but can affect the long term durability of the well. The maximum flow rate which may be drawn from an aquifer also depends upon the size of the source, and the properties of the aquifer itself.

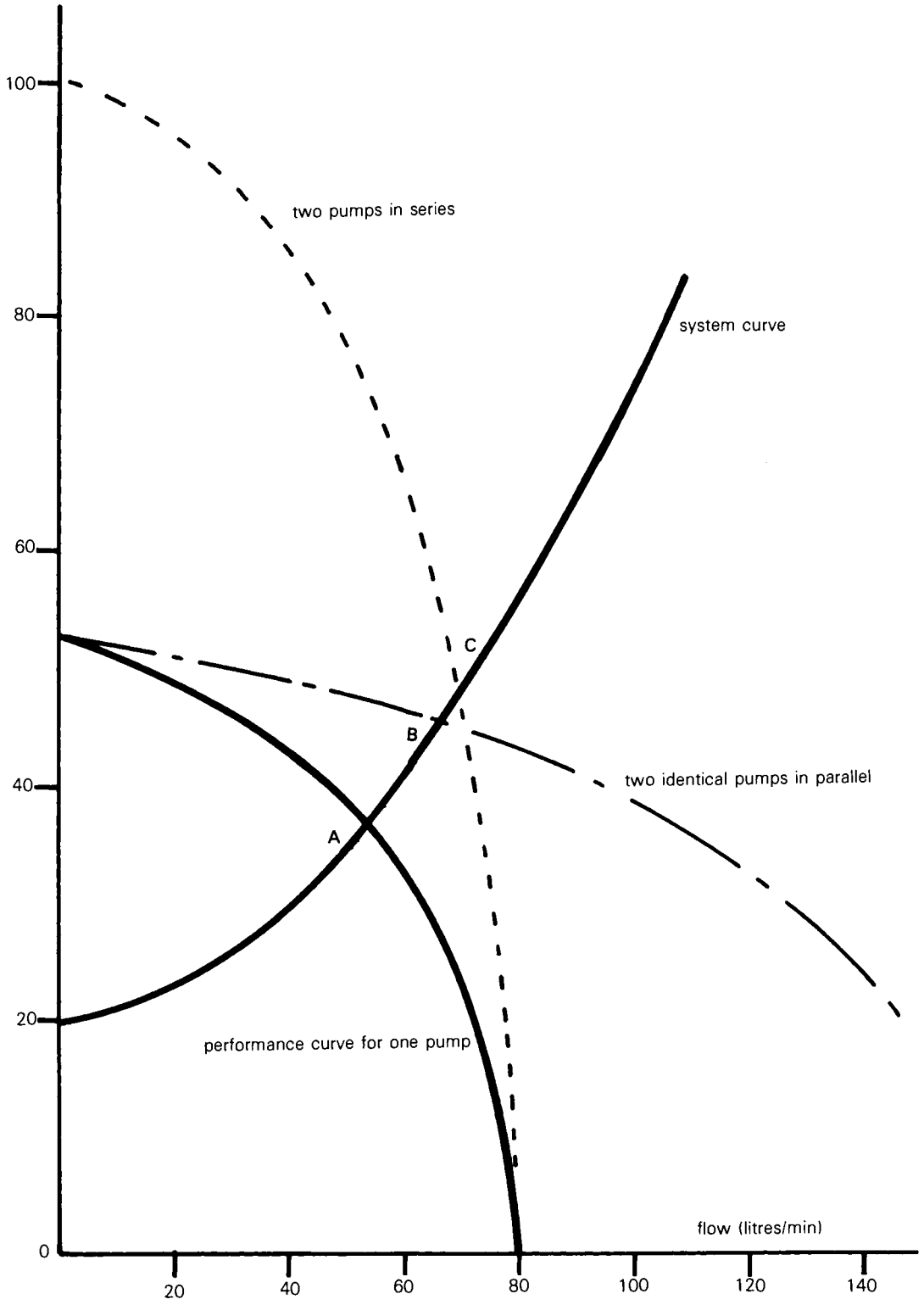


Figure 5.43 Pumps in parallel and series.

The porosity, permeability, and the transmissibility of the aquifer are also key factors. The *Porosity* affects the amount of water per unit volume that the aquifer can hold, since it is a measure of the pore space. Limestone has a porosity of only 1% while a developed soil has a value of around 60%. The *Permeability* is the ability of the soil to transmit water through its pores when subjected to a difference in head. It is expressed as the volume per day per square metre when the head gradient is one metre per metre. Typical values vary from as little as 4 litres per day per square metre to over 2000. It can be measured by radioactive tracers or by dyes in existing wells, by laboratory experiments on soil samples, or by calculation. The *Transmissibility* of an aquifer is the permeability over the whole depth of the aquifer and is expressed as the volume per day per unit width of the aquifer. The range may be between 10^3 and 10^6 litres per day per metre width of aquifer. For irrigation requirements a flow of at least 15,000 litres per day per metre is generally required.

There will usually be a limit to the flow, which will be equal to the rate of replenishment. If too many bores are constructed and too much water is removed, then the wells will dry up. For this reason, in many countries Local Water Authorities control the rights of individuals to draw water from aquifers, and a permit will often be needed before drilling can begin. As a source of water, ground water is often clean and unpolluted. Aquifers tend to be large and able to store great volumes of water, which means that they will continue to supply water in very dry seasons, providing they are replenished in rainy periods.

It is very difficult to predict how much water will be produced from a particular site, since the aquifers are irregular in shape and size. Experienced geologists and well drillers should be able to increase the chances of success, but some risk is inevitable. In all cases the experiences of earlier attempts to drill for water will be a valuable indication of the chances of success. There is rarely any sound reason for choosing the exact spot to drill, but on terraced land the lowest terrace is generally a sensible choice. Obviously the well should be upstream of any sources of contamination such as septic tanks or industrial waste sites. According to Bowden et al (1983) there is no acceptable scientific evidence that water diviners are any more successful than pure chance would indicate. Recently equipment has been developed which uses the scattering of very low frequency radio waves (around 20 kHz) to detect fractured rock surfaces which could contain water.

The construction of a well is shown in *Figure 5.44*. The bore must be cased in with a suitable metal casing to prevent the well from collapsing. In small diameter bores PVC casings have been used. In the region where the water is to be collected the well requires a special screen which is a stainless steel fine mesh casing. This prevents sand from entering the inlet to the pump and damaging the pump. Ideally the area of the screen should be sufficient so that the water flow through it is not more than 0.03 m/s. This may not be possible if the aquifer is narrow. The screen mesh size depends upon the soil particle size in the aquifer. In sandy soils the mesh size is critical and should be chosen by a specialist. If it is too large then the structure around the well may collapse in time. If it is too small then the well will become blocked up with fine particles. Depending upon the type of sand, it should allow not more than half the soil particles through. The mesh size is less critical for gravels. In practice wells are normally "developed" before the permanent pump is installed. This involves surging water back and forwards in the well to displace surrounding fine material into the well so that it can be extracted. A piston in the well, bursts of compressed air, or chemical methods can be used. Another method involves using another pump to extract water at more than full capacity for two or three days. The pump should be switched on and off frequently to give the best effects. Developing removes the fine soil particles so that when the permanent pump is placed in position at the bottom of the well it is not worn by them. Even more importantly, it increases the flow into the well substantially.

Figure 5.44 also indicates the effect of drawing water from the well in terms of the change in the level of the water table in the aquifer. The water table will drop in the vicinity of the well by an amount known as the drawdown. Measurement of the drawdown is an important factor in estimating the maximum flow that can be obtained from

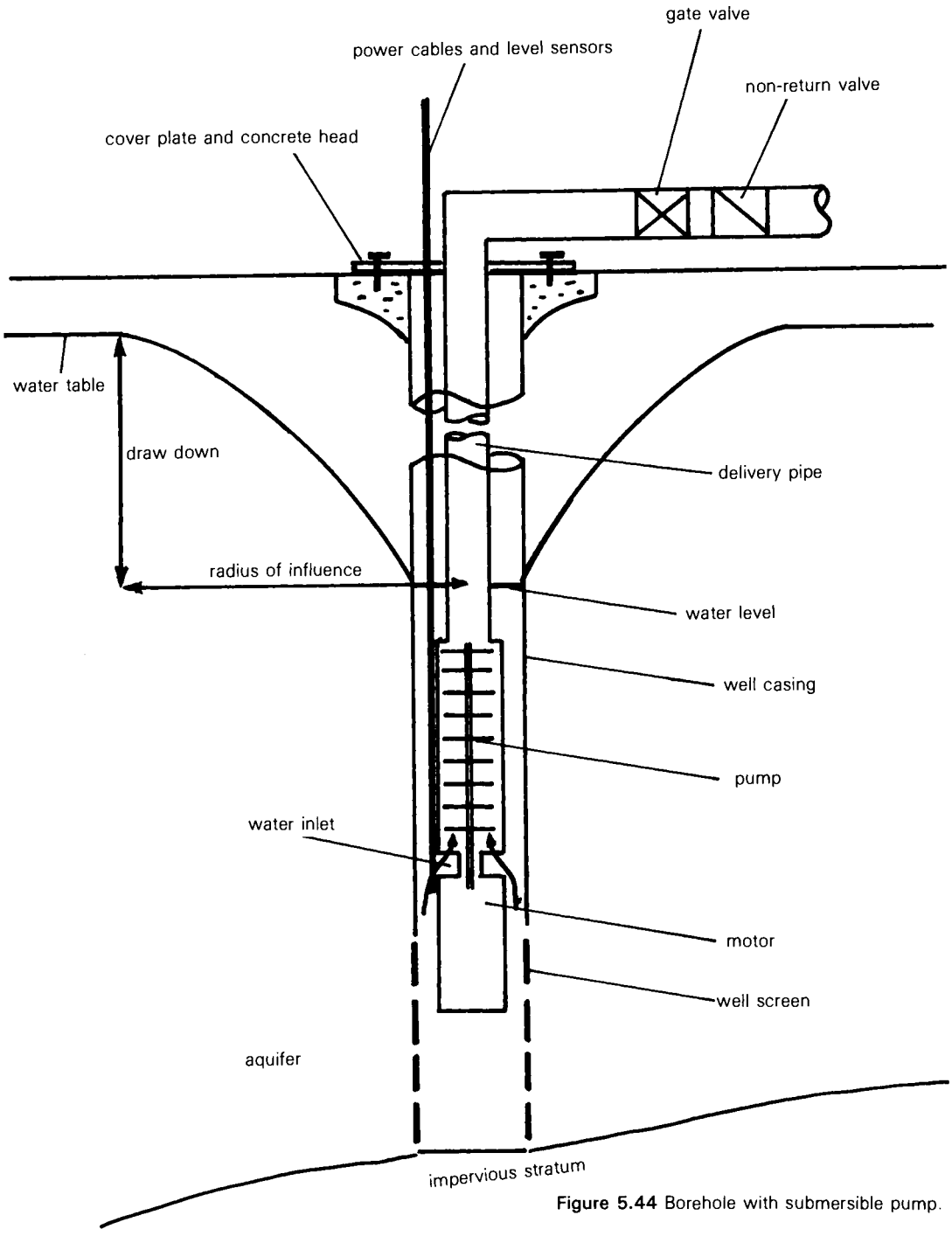


Figure 5.44 Borehole with submersible pump.

the well. This will then enable a pump of the correct capacity to be chosen and installed. Obviously if the drawdown is too large the water will be admitted only through the lower part of the well screen and so the flow rate will inevitably fall off – in effect the suction head will increase. The drawdown measurements can also be used as a check on the long term effect the well is having on the water resource. The extent of the

drawdown around a well is known as the *Cone of Depression*, and the distance to the limit of the cone is called the *Radius of Influence*. Clearly if the radius is large enough a new well will affect other wells nearby.

Water quality should also be checked by an expert to ensure that the water is fit for the intended use.

5.15 FARM DAMS

In many situations the construction of a dam will provide a reliable source of water throughout the year. Although the design of large earth dams is a complex procedure requiring a very thorough structural design, small earth dams can be constructed relatively easily, providing proper site investigations are conducted, and the dam is built properly and with the right materials. Farm dams should be designed in a systematic fashion and the following design procedure is recommended.

1. Establish water requirements,
2. select site,
3. survey site and prepare contour plan,
4. test soil,
5. calculate catchment yield,
6. design embankment,
7. estimate volumes and storage/excavation ratio,
8. design spillway,
9. design associated structures (eg water draw off etc),
10. prepare contract specifications,
11. prepare schedule of quantities and costs.

Dams are in widespread use for stock watering purposes, but a very large proportion are basically just holes scooped in the ground ("paddock puddles") containing muddy water. They do not constitute a satisfactory water source. The following gives a few brief notes on the principles involved. For detailed information the references should be consulted.

5.15.1 Water requirements

The size of dam or indeed the need to construct it depends on the volume of water to be stored. As a rough guide in New Zealand it should be constructed to hold four months total requirements plus a 20% allowance for evaporation and seepage. Daily requirements will depend upon the stock carried and the amount of water required for irrigation and spraying. These will depend upon the type of enterprise, location and method of application.

5.15.2 Site selection and survey

Site selection is the most critical factor in dam design. Once a potential site has been selected an accurate survey is required to establish volumes for the contract documents. This requires that the contours for the area in and around the dam site be established. The main expense in a dam is the cost of the excavations, and a key term used to assess the value of a dam design and site is the *Storage to Excavation Ratio*. This is the ratio of the volume of water to be stored to the volume of material which must be excavated for placement in the embankment. The survey will enable the storage/excavation ratio to be determined. Ideally the ratio should exceed 5:1. In general the best sites are natural bottlenecks in flat floored gullies. The poorest sites are where the gully has steep narrow sides. Site access should also be considered as it will affect construction costs. The soil type is important. Gravels, sands, saturated soils, springs and soaks should be avoided, and test bores should be made to check for problems. Ideal soils contain about 30% clay with the remainder consisting of equal amounts of well graded silt and sands. Proctor density and associated moisture contents should be established for the embankment materials (as discussed in the chapter on buildings). If the soil type is marginal the seepage can be reduced further by importing a more suitable soil (which can be a very costly option), or by increasing the length of the drainage path by altering the batter slope (ie, the slope of the wall on the far side of the dam). Other alternatives include the use of special cut-off drains and filters, but these are not always very successful. It is also possible to line reservoirs with special synthetic liners or layers of impermeable material.

5.15.3 Catchment yield

Only a fraction of the total rainfall in the catchment area will be collected by the dam, depending on the porosity of the soil. A figure of 12% of the rainfall is sometimes used as a guide to give the estimated annual yield. If the catchment area is too small simple catch

drains can be built to increase the flow of water into the dam.

5.15.4 Embankment design

The basic features of an embankment are shown in *Figure 5.45a*. The cut off trench at the base of the dam is vital, as it acts to key the dam in place, and extends the seepage path for the water. The crest width W in metres must meet the condition that

$$W > 0.2\ H + 1.5 \qquad \textbf{Equation 5.40}$$

where H is the height of the embankment in metres. If the crest is used as an access route then it should also be more than 4.5 metres wide.

Figure 5.45 Dam design.

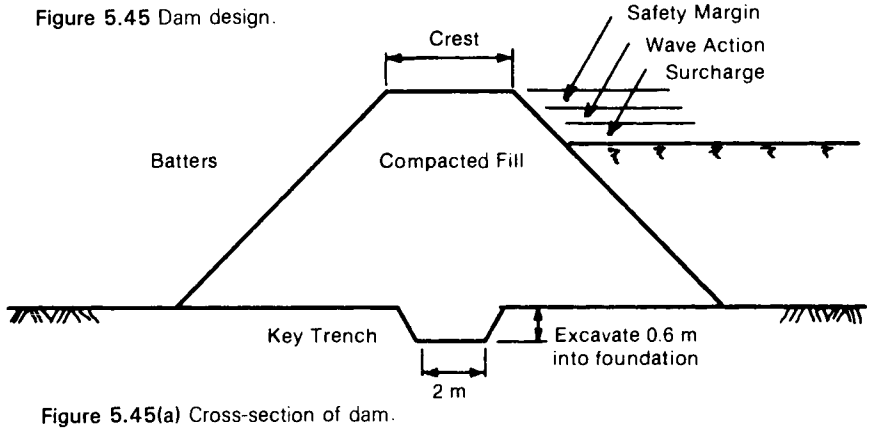


Figure 5.45(a) Cross-section of dam.

When the dam is full the excess water must not flow over the crest, since this will cause erosion and failure of the dam. Instead a properly designed spillway is essential. It must be designed to accommodate the largest probable flood flow. This figure can be calculated from local weather and topographical data. The spillway is then designed using open channel flow theory (eg see references). Spillways which are covered in normal vegetation are the easiest type to construct, but the flood flow velocity must not exceed 2 metres per second, and the spillway must be cut from undisturbed material (ie, not in the dam itself). In addition the spillway should normally be dry when not in use, so that the vegetation will not be waterlogged. This can be achieved by including a plastic trickle tube to allow water to drain away to a little below the spillway base. Such tubes must have anti-seepage collars as described below.

The *Freeboard* is the extra height of the embankment above the spillway, and must allow for wave action, and the surcharge level over the spillway in a flood, together with a safety margin. In addition the top of the dam should be protected against continuous wave

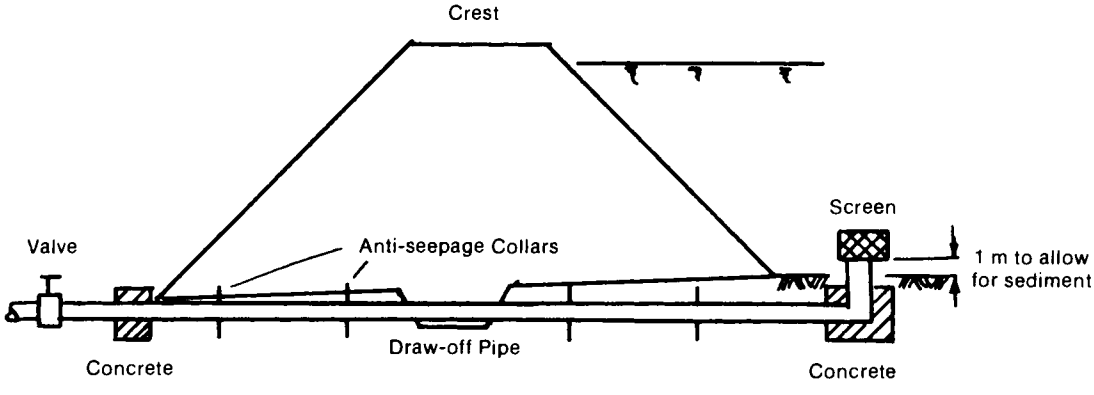


Figure 5.45(b) Dam design.

action. This can be achieved with a boom of PVC pipe anchored 2 metres from the face, with concrete "sandbags", or with suitable hardy grasses which will grow to the water's edge.

The *Batter* is the slope of the embankment wall. The minimum slope of the batter on each side of the dam depends upon the soil type and the height of the dam. For good soils the minimum batter slope on the upstream side varies from 2.5 for a dam of less than 3 metres height to 3.5 for a 6 metre dam. The downstream slope would vary from 2 to 3. The top of the dam and the spillway should be completed by covering with 100 mm of topsoil and oversowing with grass to protect against soil erosion. Stock should not be allowed to graze or drink directly from the dam as this will cause damage and pollute the water.

5.15.5 Water draw-off

A well designed draw-off is essential. *Figure 5.45b* shows a typical arrangement. The pipe should be well secured at each end as shown, and must be fitted with anti-seepage collars. These form a water tight seal against the pipe. Water seeping along the pipe must flow around the collars, so that the seepage path length is significantly extended. The path should be increased by at least 20% by the collars. The screen on the inlet is also essential to prevent blockage problems in the pipe distribution network.

5.16 INSTALLATION NOTES

On farms, if economically possible, all pipes should be buried for protection. This will protect the pipes from stock, farm machinery, sunlight, and will reduce the risk of the water freezing and bursting the pipes (in cooler climates). As far as possible the pipes should follow the fence lines so that they are unlikely to be damaged in the future if deep cultivation is undertaken (eg, mole ploughing to improve drainage).

Troughs should be of adequate size and number for the size of the herd. The trough should be sited on a free draining area if possible, and a generous layer of river gravel should be spread to extend at least 1.5 metres around the trough to reduce pugging. Troughs settle with time, and rigid pvc pipes will be unable to absorb the movement, and may fracture. Polythene pipes are therefore the most satisfactory type of pipe for connecting the trough to the main pipe line. Stock will damage ball valves and water inlets unless these are protected. The water inlet should be designed so that water cannot flow back into the pipe line from the trough if the supply pressure drops to zero, as this will contaminate the water supply. An air gap of at least 60 mm between the inlet and the maximum water level is needed.

Electrical power will also be required for most pumps. This may mean the need for a new supply line or the upgrading of existing transmission lines and transformers. This can be very costly, and the farmer will need to check with the local power authority. Costs of water supply schemes can be high and in many cases a community supply is the most sensible arrangement. Such schemes will be fairly complex and will require the services of experienced designers and technicians for design and construction.

The installation of a pump requires that a number of factors be taken into account. First the pump must be sited near the source of water. If the water must be raised to the surface, the suction side will be under negative pressure, and if air enters the system then the pump may lose its prime. A centrifugal pump will cease to operate under this situation, and some means of repriming the pump (ie, getting the suction full of water again) will be needed. Mobile pump systems often have a simple hand pump for this purpose. It is always preferable to have the suction under positive pressure if possible. Otherwise a foot valve should be fitted to the inlet so that when the pump cycles off the valve closes and water is retained in the suction pipe (*Figure 5.24*). In this figure the foot valve shuts off when the pump switches off, so that the pump does not lose its prime. The check valve prevents water from flowing back through the pump, and the gate valve allows the pump to be isolated for maintenance, etc. In addition a screen should be fitted to prevent grit entering the pump. The size of the mesh will depend to some extent upon the type of pump: piston pumps are slightly more tolerant to grit than closed impeller centrifugal pumps. It is also advisable to avoid any potential areas in the suction pipe where air could collect, such as at bends,

elbows, or reductions in pipe diameter.

On the other hand, the pump site should be chosen so that it is above flood level and on a solid foundation. If severe flooding is common, then it may be advisable to use a small submersible pump to supply a nearby storage tank sited on high ground. The inlet should also be protected from possible flood damage. This can be done with a concrete lined soakwell located on the edge of a stream or river. Slots in the lining allow water to enter.

Isolating valves are worth installing on both sides of the pump, since this means the pump can be isolated and removed if required for maintenance. The valve on the delivery side should be a non-return valve so that water in the delivery pipe cannot flow back through the pump.

On major installations pump control and safety cut outs are advisable. They are particularly important if the operation is to be automated, or, as is the case with irrigation systems for orchards and other horticultural crops, if the water supply is crucial. Safety cut-outs should include a pressure switch. A no-flow or low water cut-out is advisable, as these conditions can occur if the pump loses its prime or a pressure switch fails. Under these conditions it is possible to damage the pump, resulting in a loss of irrigation at what will inevitably be a critical time. It is also recommended that an ammeter be installed to give a long term assessment of pump performance. An increase in current indicates the onset of bearing problems, blockages or shaft binding. Preventative maintenance can then be carried out before the system fails. It is advisable to fit shut-off valves at suitable positions so that the repairs and maintenance can be done without shutting off the entire water system. Smaller shut-off valves on each trough are also useful in practice.

5.16.1 Control methods

A number of methods of controlling pumps have been developed. If the pump is supplying water into a tank, trough or reservoir, a float switch which floats on top of the water in the tank can be designed so that it operates a switch to cut the pump off when the float reaches a predetermined level. Alternatively a level sensor system can be used. Here the electrical impedance between three metal probes at different heights is monitored continuously. When the water level is below the middle probe the impedance between the earthed lower probe and this probe is high, and the pump is switched on. This situation continues until the water reaches the upper probe, causing a drop in its impedance. This is the signal to switch the pump off, which is sent to the controller located near the pump. The signal is sent by wire in small systems, but increasingly telemetry is being used for larger installations involving long distances.

Pressure tank (*Figure 5.46*)

These methods depend upon the level of water. Other devices rely on the water pressure. In the pressure tank system, the pump delivers water to a suitable pressure tank so that the pressure increases. A pressure sensitive switch then operates to turn the pump off when the pressure reaches a predetermined value, and on again when the pressure drops too low. It is essential for the system to have a reserve of some sort so that the pump does not cycle on and off at the slightest loss of water. The pressure tank (*Figure 5.46a*) does this. The tank consists

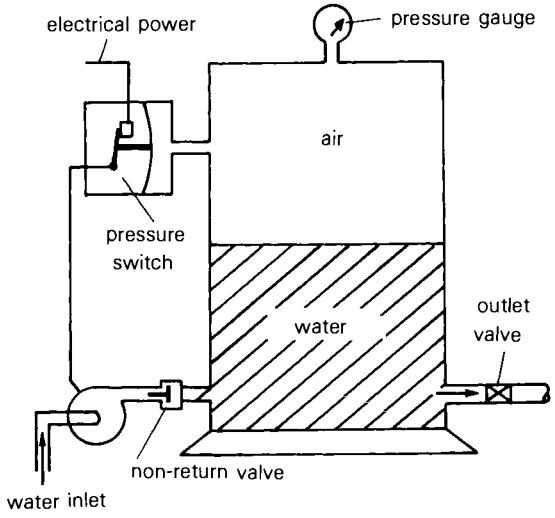


Figure 5.46(a) Pressure tank layout.

of a large tank initially filled with air (usually at a pressure of a few bars). As the pump operates the tank fills with water and the air pressure rises according to Boyle's Law

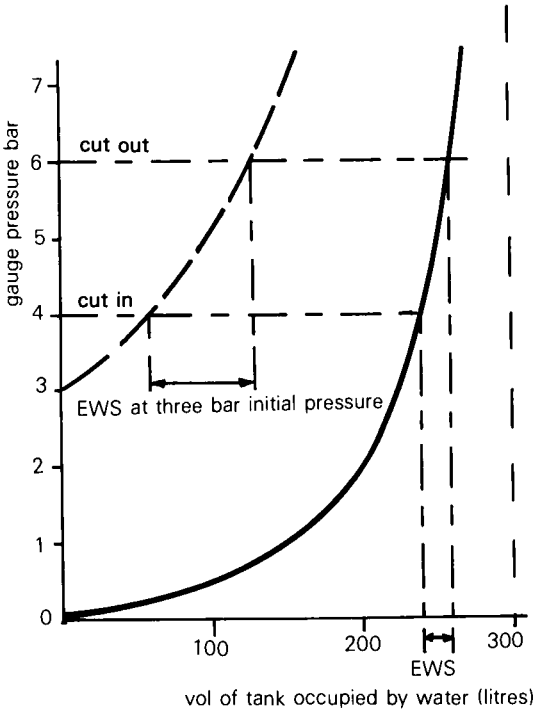


Figure 5.46(b) Effective water storage.

(Chapter 3). When the pressure exceeds the set value (the cut-out pressure) the pressure switch operates to stop the pump. Water can now be drawn off until the pressure falls below another value (the cut-in pressure), when the pump is again switched on (*Figure 5.46b*). In this way the pump need not operate whenever a small draw-off is taken. The *Effective Water Storage* (EWS) is the amount of water stored between cut-out and cut-in. It is generally quite small (no more than 10% of the total volume of the tank).

Example

Calculate the EWS of a tank whose total volume is 300 litres, if the cut-in pressure is 4 bar (gauge pressure), the cut-out is 6 bar, and the tank has no water in initially when it is at atmospheric pressure (1 bar absolute), as in *Figure 5.46b*.

Solution: Boyle's Law states that $P_1V_1 = P_2V_2$, where the subscripts refer to any two different states. Thus initially $P_1 = 1$ bar, and $V_1 = 300$ litres. At the cut-out pressure $P_2 = 6 + 1 = 7$ bar absolute, and the volume of air is given by:

$$V_2 = \frac{P_1V_1}{P_2} = \frac{1 \times 300}{7} = 42.8 \text{ litres}$$

The water volume will therefore be $300 - 42.8 = 257.2$ litres.

Similarly at cut-in (Absolute pressure = 4 + 1 = 5 bar) the volume of water will be:

$$300 - \frac{1 \times 300}{5} = 300 - 60 = 240 \text{ litres}$$

The EWS is therefore the difference or $257.2 - 240 = 17.2$ litres.

It is worth noting that the EWS can be increased by increasing the pressure difference (particularly by keeping the cut-in pressure as low as possible), or by pressurising the cylinder with air initially. A repeat of the calculations with P_1 set at 3 bar would demonstrate this, giving a value of 68.6 litres (the chained curve in *Figure 5.46b*).

However there are two major problems: first the tanks are expensive, and second air is soluble in water (the solubility varies with the pressure), so that over a period of time the tank will lose its charge of air, becoming "waterlogged". It must be recharged with air. For these reasons other pressurising devices have been developed. The simplest modification to the pressure tank is to place a rubber diaphragm between the air and the water. This prevents the air from being dissolved in the water. In modern systems the pressure tank has been reduced in size and modified to produce the "Aquacell", a much smaller device with only a small EWS. The water is contained inside a rubber bladder, and a modified check valve is used to restrict the flow of water into the aquacell when the pump is on. This overcomes the problem of rapid cycling which would result from the small EWS of the cell.

Pressure switch systems

An alternative system involves the use of a pressure switch located at the pump. The principle is that when the pump is operating the pressure will stay at a level determined by the flow rate and the operating point on the system curve. When the supply requirements are met, and no more water is required, the delivery valve to the last tank or trough to be filled will shut, the pressure in the pipe will rise and the flow of water will be reduced. The pressure switch is set so that the pump is switched off when the pressure reaches a predetermined value. It remains for

the pump to be switched on again when more water is required. This is normally achieved by using a simple timer device, so that the pump automatically switches on again after a given time interval, regardless of the pressure in the pipe. If no water has been used in the interim it will switch off again quickly, but if water has been used, the pump will operate until the tanks are refilled.

Trickle irrigation pumps may be controlled by a relay, which is activated directly by the irrigation controller. Direct relays with pressure switch over-rides are generally the most reliable.

5.16.2 Valves

In order to adjust the flow of water it is necessary to use valves. There are a large number of different types of valves which are used in water supplies to control the flow rate or the pressure. Important parameters for valves are the sealing performance, the pressure loss through the valve, cavitation effects and wear properties, waterhammer effects, and noise attenuation properties. They will be described in terms of their use rather than method of operation. Fuller details can be found in the references, particularly in the book by Zappe (1987).

a. Manual valves

Manual valves are operated by hand! They are used to stop and start the flow, to control it, or to divert it. There are four main types. The *Closing-Down* type has a stopper like component which is wound away from a sealing face or seat. In general, these types have a higher flow resistance than the others, and are best suited to situations where flow rate adjustment is required, rather than just on/off control. Solids suspended in the flow can cause problems due to deposits which are trapped on the seat. The *Slide* or *Gate Valve* design involves a gate which is moved across the flow path of the water. Gate valves are not normally used when flow rate control is required, because good control is only achieved when the valve is almost shut. However they are good for on/off operation, and can handle suspended solids. The *Rotary Valve* involves a disc-like plug which is rotated within the flow path, so that when the disc is at right angles to the flow channel the flow is cut off. This type is used in carburettors in engines to control the mixture of petrol and air, (called the butterfly valve, because the disc is very thin) while a very simple valve of this type uses a steel ball with a hole drilled through the centre through which the fluid can flow. This type is used in hand garden sprayers. The fourth main type is a *Flexing Body* design, where the valve body itself is flexible and is bent by the closing mechanism to restrict the flow.

Valves used for diverting the flow must have three or more ports. They can be of any design, although most are the rotating type, involving a plug or ball.

b. Check valves

Check valves, or non-return valves, are used to prevent the backflow of fluid. They are very common on the inlet to centrifugal pumps and other water intakes, where they are called *Foot Valves*. In this case the valve prevents the pump losing its prime. Check valves must operate quickly as soon as the flow stops, so that there is no build up of backflow velocity. Otherwise on closure the valve could cause a pressure surge, with damaging effects on the pipe and valve. The valve should be designed so that when it is open there is very little resistance to flow.

Check valves can be very simple in design. Common types used in agriculture include ball designs where the ball closes off the inlet due to the water pressure when there is no flow. When flow starts the ball is pushed up off the seat by the water pressure allowing the water to flow. Alternatively a flap is used, which is normally held open by the flow, but falls across the inlet as soon as the flow stops.

c. Pressure relief valves

These valves operate if the pressure in the pipe system gets above a preset value. The valve is designed to operate to reduce the excess pressure, and to reset itself when the pressure has dropped. This may involve opening the valve to allow some fluid to escape, or closing the valve to reduce the flow currently passing through it, thereby reducing the upstream pressure. The valve can therefore be used to set the pressure at a particular level. Pressure relief valves are automatic, although they can usually be adjusted manually to alter the pressure at which the valve operates. Their function is

frequently one of safety, and they should never be omitted, blocked off, or illegally tampered with if a design calls for one. They are very important in heating systems, particularly where steam is used, in most domestic hot water systems, and in pressure tanks. They are used in trickle irrigation systems, both to control pressure, and also for safety. In some cases excess fluid goes to waste, while in others it is simply circulated back to a low pressure reservoir.

d. Rupture discs

Rupture discs are safety devices which operate to save a system from a dangerous failure due to over-pressure. Once a disc has ruptured it must be replaced. They are sometimes included as a secondary safety device in addition to a pressure relief valve.

e. Other automatic valves

It is possible to obtain automatic versions of most of the manual valves described above. On/off valves can be controlled by electrical solenoids, while flow control valves can be operated by a motor driven linkage. The ballcock valve is an example of an automatic valve which operates through the action of a lever. One end is attached to a float, and the other covers the inlet orifice.

Pressure regulating valves operate to maintain the downstream pressure at a constant value, and these and other valves of importance in trickle irrigation systems are discussed in section 5.21.5 below.

5.17 IRRIGATION SYSTEMS

Crops grow well when their environment provides the right balance of air, water, and nutrients in the right places. Irrigation is the application of additional water to the land with the intention of supplying water to the crop. The advantages of adding water to increase crop production have been recognised throughout history, and a number of irrigation methods have been developed through the centuries. These range from simple flooding of the land, to sophisticated automatic systems which add moisture in response to soil moisture deficits. These methods can be roughly classified into sub-surface, surface, sprinkler or trickle irrigation. We will describe these in a moment, but first it is necessary to establish how much water the irrigation system should apply.

5.17.1 Plant water requirements

This is where we immediately encounter the biggest difficulty in irrigation design. Just how much water does a plant require, or more specifically, how much water must we deposit into the soil, how often, at what flow rate, and where in relation to the plant? None of these questions are easy to answer, and they depend on a large number of factors, which would require several volumes to discuss adequately. Instead we will state some simplified models which are used to give the required numbers. These models depend on a number of empirical factors which will be described, and which are available from various sources. Better models are continually being developed, and can be found in more advanced books and scientific journals.

5.17.2 The soil

Soil consists of solid, water and air, (and some engineering models of it are discussed in Chapter 8). A good agricultural soil must provide enough water and air in the soil for good plant growth. However, the air and water components compete for the available pore space between the soil particles and a combination of over-irrigation and poor drainage will cause too much of the pore space to be filled with water, resulting in low aeration and hence limited plant growth. The water content by volume is the ratio of the volume occupied by water to the overall bulk volume of the soil. For design purposes, it is necessary to know the amount of water actually available to the plant. The soil holds a small amount of moisture very tightly which makes it unavailable to plant roots. The lower limit for soil moisture content is called the *Permanent Wilting Point* (PWP) which is defined as the soil water content below which plants will wilt permanently. The PWP can be measured by using special equipment to produce the maximum suction a plant root can apply to the soil water (15 bars), and then determining the moisture content left in the soil by weighing, drying, and reweighing.

At the other extreme, the *Field Capacity* (FC) of a soil is defined as the amount of water retained by a uniform soil in the field after it has been thoroughly soaked and when

drainage has become negligible. Water in excess of field capacity will not be held by the soil for any appreciable length of time. The *Water Holding Capacity* (WHC) of the soil for irrigation purposes is defined as the depth of water held between field capacity and permanent wilting point per metre depth of soil.

Although the FC and PWP are somewhat arbitrary, the available moisture between the PWP and the FC is an adequate measure for irrigation design. As a guide, *Table 5.8* gives a list of broad soil types and their approximate water holding capacities.

Table 5.8 Mean available water holding capacities of soils (NZS 5103)

Character of soil	Water holding capacity (mm/m depth)	
	Up to 0.3 m deep	Below 0.3 m deep
Sand	150	50
Loamy sand	180	110
Sandy loam	230	150
Fine sandy loam	220	150
Silt loam	220	150
Clay loam	180	110
Clay	175	110
Peat	200-250	At least 200-250

These values must be treated cautiously as the total available moisture content of a soil cannot be assessed simply by classification on a textural basis as above. More reliable figures are available from relevant texts (eg DSIR, 1968, or New Zealand Standard 5103). The soil moisture deficit at which irrigation should start varies with the plant, but typical values are a deficit of 20% to 60%, ie when the water content has dropped by 20% to 60% of the water holding capacity.

5.17.3 Root volume

The main functions of plant roots are (a) to supply the plant with water and other nutrients, and (b) to provide anchorage in the soil. The plant can only obtain water from those parts of the soil which contain roots, and therefore the soil volume that can be used for water storage will depend on the distribution of the plant roots. The vertical root distribution varies with depth. Between 60% and 80% of a plant's roots occur in the first 50% of the total root depth. This is called the *Effective Root Depth*, and is used to estimate the soil moisture reserves available to the plant. As far as area is concerned, it is generally accepted that the potential extent of horizontal root growth is equivalent to the ground area covered by the foliage of the plant.

Information regarding the canopy area and effective root depth of various crops can be obtained from horticultural advisers, irrigation textbooks, or NZS 5103. A typical list of effective root depths is given in *Table 5.9*.

Table 5.9 Effective root depths for various crops under irrigation (m)

Strawberries	0.3
Kiwifruit	0.5
Lemons	0.5
Oranges	0.6
Grapefruit	0.8
Tomatoes	0.3

Site conditions such as a high water table or impermeable soil layers can affect the root development significantly.

The potentially available water storage in the root zone is given by:

$$WSp = WHC \times D_r \qquad \textbf{Equation 5.41}$$

Where WSp is the potential root water storage (mm), WHC is the water holding capacity (mm/m), and D_r is the effective root depth (m).

5.17.4 Root water requirements

Experiments have suggested that it is unnecessary to water the whole root volume of a plant. The percentage to be watered depends on the plant. Some plants continue to grow fairly well even when water is supplied to only one quarter of the roots. However, if the roots must provide good anchorage against wind loads, then the root structure will have to be allowed to develop more fully. Minimum allowable values for the wetted root volume have yet to be established, but a commonly used figure is 30% of the potential root volume for widely spaced tree crops.

5.17.5 Calculation of water requirement per irrigation

Normally crops are irrigated at regular intervals, which allows for the sequential watering of blocks on larger properties. The total volume of water per irrigation (V) required to fill the proportion of the root volume chosen is given by:

$$V = WHC\ D_r\ A\ f_w\ f_A\ f \qquad \textbf{Equation 5.42}$$

where V is the volume of water applied (litres), WHC is the water holding capacity (mm/m), D_r is the effective root depth (m), A is the area of the field (m^2), f_w is the fraction of the soil root volume watered, f_A is the fraction of the total area containing roots and to be irrigated (for systems in which the water is only applied around individual plants or rows, and not over the entire field), and where f is the allowable soil moisture deficit as a fraction of the WHC. This last factor f is needed because it is advisable to re-irrigate some time before PWP is reached if maximum transpiration rates and hence growth are to be maintained. The minimum acceptable moisture content will depend on the crop, the soil and other environmental conditions. For example, under high transpiration rates it is advisable to maintain high moisture contents in the soil to reduce stress on the plants. Similarly, in sandy soils, better movement of water through the soil to the plant roots results if the soil is kept at higher moisture contents.

This value (V) is the basis of the hydraulic design. It gives the total volume in litres required per field per irrigation. If the entire ground area is covered uniformly by the irrigation system then f_A is equal to one. If plants are watered individually then:

$$f_A = \frac{NA_p}{A}$$

where N is the number of plants and A_p is the surface root area of each plant.

5.17.6 Calculation of irrigation interval

Before the application rate can be calculated it is necessary to determine the time between irrigations, ie the irrigation interval. This can be determined if the rate at which water is lost from the root storage volume by transpiration and drainage is known, or if a suitable sensor can be used to measure the soil moisture content directly.

a. Calculation of water loss

Water stored in the root zone is taken up by the plant roots and lost to the atmosphere from the leaves. In some crops, transpiration rates can reach 8 mm per day, depending on the particular plant, the climate, and the availability of soil moisture and nutrient. The rate can be calculated from the following formula (based on Jobling, 1974) which includes corrections for percolation losses and crop differences:

$$W = X\ Y\ Z\ A_w\ E_{pan} \qquad \textbf{Equation 5.43}$$

Where W is the water used (litres/day), X is the crop factor, Y is the percolation factor, Z is the soil evaporation factor, A_w is the total wetted area of the soil (m^2), and E_{pan} is the evaporation loss from a standard pan (mm/day). These terms need some explanation!

The standard pan (US Class A pan) is a cylindrical container of fixed dimensions from which evaporation rates are recorded at meteorological stations. Daily calculated figures are often published in local papers. It is generally found that the potential transpiration loss from a crop adequately supplied with water and nutrients is equivalent to approximately 80% of the evaporation from a standard pan. For this reason E_{pan} is sometimes multiplied by a factor of 0.8. However, a more conservative estimate is given if the potential transpiration loss is taken to be equal to E_{pan}. Irrigation designs are normally based on the average daily evaporation for the month of maximum evaporation. On very hot dry days this value for E_{pan} will underestimate the evaporation significantly, but for 90 to 95% of the time it is adequate.

The crop factor (X) in *Equation 5.43*, allows for the different physiological characteristics of crops. The crop factor is the ratio of the evapotranspiration of the crop to that of grass in pasture. It can allow for normal husbandry techniques, and may include a ground cover correction for fully established crops.

Most crops have crop factors close to one. The main exceptions (see literature) are vegetables in dry climates (1.2), and orchards in moderate climates (0.8).

The percolation factor (Y) accounts for losses in the soil. In an efficiently operated irrigation scheme losses should be small and a value of

1 for Y can be used except where porous sands or gravels are encountered, in which case a value of 1.15 is used.

The soil evaporation factor (Z) takes into account the evaporation loss from the surface of the soil where there is no crop cover. This depends on the extent of ground cover and the rate of evaporation from the soil surface. The latter is generally assumed to be half that of the pan rate. For a complete canopy Z is equal to 1. When the ground cover is incomplete (eg young trees) Z can be obtained from the empirical equations:

$Z = 0.5\ (1 + GC)$ for GC less than 0.625

or $Z = 1.3\ GC$ for GC greater than 0.625

Equation 5.44

where GC is the plan area of the plant canopy as a fraction of the total wetted area per plant. (this formula is based on recommendations given by James Plastic, 1984, which is based on NZAEI data).

b. Direct measurement

Ideally, water should be applied whenever the soil water content falls below a set level. In practice soil moisture measurement is difficult and has to be found indirectly. For example, a tensiometer measures the suction pressure a soil can develop in absorbing water through a porous layer, and this can be related to the soil moisture content. These devices have been used to initiate irrigation either manually or automatically, whenever the pressure exceeds a set value such as -0.7 bar. Unfortunately the system can sometimes prove to be unreliable, due to the limitations of the tensiometer itself, the local variations in soil properties which means that several readings are needed to obtain a result, and the further need to adjust the set point according to the rate of transpiration (at high transpiration rates irrigation should be started earlier). The exact position of the tensiometer relative to the emitter in trickle systems can also be critical. In many areas local consultants or research institutes can advise growers on irrigation rates on a day to day basis.

The irrigation interval may be calculated from:

$$I = \frac{V}{W}$$ **Equation 5.45**

where I is the irrigation interval (days), V is the volume of water applied (*Equation 5.42*), and W is the water used per day (*Equation 5.43*).

This completes our brief overview of the requirements of the plant. We will now look at the different ways of applying this water.

5.18 SUB-SURFACE IRRIGATION

In sub-surface irrigation the water is applied below the surface of the soil, by allowing the water table to move up through the root zone by capillary action (for details see Withers and Vipond, 1974). This method can be practised in peat soils, by temporarily damming drains so that the water table is raised.

5.19 SURFACE IRRIGATION

Surface irrigation is a very common method of irrigation, especially in arid regions. Surface irrigation techniques vary from wild flooding, where the flow of water is essentially uncontrolled, to other methods where flow is controlled by furrows, corrugations, border dykes, contour dykes or basins. Except in the case of wild flooding, efficient surface irrigation requires grading of the land surface to control the flow of water. The extent of grading will depend on the topography and can be very expensive. Efficiencies of operation are usually substantially lower than sprinkler and trickle irrigation. It is estimated that on average only 30-40% of the applied water is actually used by the plants, although efficiencies of up to 65% can be achieved by good design.

Border dyke irrigation can be used successfully in some areas. Water is supplied through a series of canals running between the paddocks (*Figure 5.47*). The land is divided up into a series of small strips, over which the water is allowed to flow for a fixed time. The flow is controlled by a series of gates in the canal. Each gate is open except the last so that the last group of three or four strips in a row is flooded. After a preset time the next gate drops shut so that the water is diverted to flood the next strips immediately upstream. This continues until the entire area has been watered. The process is usually automatic, except that the gates must be

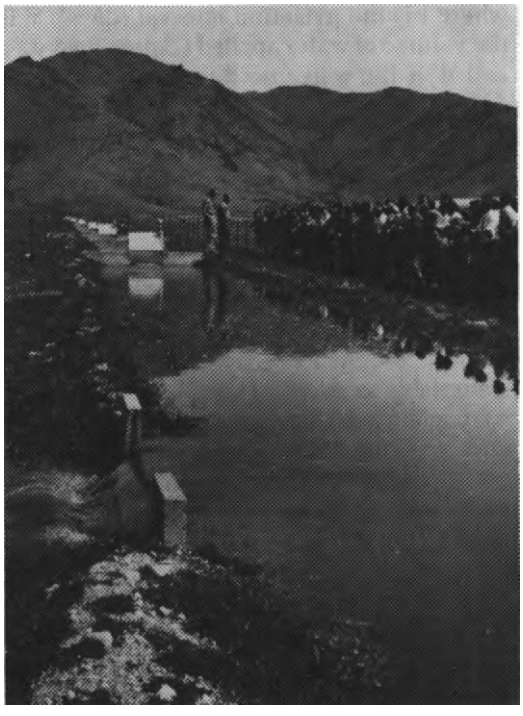


Figure 5.47(a) Water pours over a sill into the field (DSIR).

reopened manually whenever irrigation is required. The capital costs of border dyke systems on suitable land are often similar to those of sprinkler systems, but the operating costs are much lower.

Although the method is used to irrigate arable crops, the same principles have been used in the Netherlands and elsewhere to irrigate pot plants in greenhouses. The plants are grown on a concrete base with a raised edge. Each section of the floor is flooded for a short time with a nutrient rich solution pumped from a storage tank under the house. The fluid drains back into the tank after use.



Figure 5.47(b) Aerial view of border dyke irrigation (DSIR).

5.20 SPRINKLER IRRIGATION

5.20.1 Principles and uniformity requirements

In sprinkler irrigation systems the water is piped to the field through mains pipes, which are often permanently buried underground. Hydrants are built at regular intervals and the irrigation pipes (laterals) are connected to them. The water is then distributed by nozzles or sprinklers placed at regular intervals along the lateral. Sprinklers generally produce one or two rotating jets of water, although some produce a fan pattern. The rotating impact sprinkler consists of a nozzle producing a jet of water, part of which impacts against a small plate. This plate moves sideways out of the jet, and in doing so pushes against a spring and strikes another plate which moves the nozzle around a short distance, so that the nozzle gradually rotates around. These sprinklers operate at pressures of around 2 to 5 bar, although pressures of up to 10 bar are used in larger versions.

A measure of the distribution uniformity for sprinklers was developed by Christiansen (1942). The *Uniformity Coefficient* (CU) is computed from field measurements of the depths of water collected in open cans placed at regular intervals within the sprinkled area, and is defined as:

$$C_u = 100 \quad 1 - \frac{\Sigma d}{T}$$

Equation 5.46

where Σd means finding the difference between the depth of water in each can, and the average depth of water collected in the cans, and adding up all these differences, and T is the total depth of water collected in all the cans. The coefficient may be calculated for one sprinkler or for a set of sprinklers. Its value is affected by the water pressure, the wind conditions, and the sprinkler spacing, and can be quoted by manufacturers as a function of all these variables. A value of 1000% implies a completely uniform application. In practice values of around 85% are quite satisfactory.

The soil is not only the storage medium but it is also the means of distribution of water to the plant roots. With a conventional irrigation system, the whole land area is covered by overlaping sprinklers, ie by

spacing them along laterals at about 60% of the wetted diameter and by shifting the laterals by about the same. This gives a roughly even depth of water over the whole area (New Zealand Standards Association, 1973).

Unfortunately, the water distribution from a sprinkler is rarely uniform, so the water will not be uniformly spread over the land. The throw also depends on water pressure, which will vary along the lateral due to head losses. The spacing of sprinklers along a lateral is thus not a straightforward problem, and the manufacturer's literature should be consulted.

Not all of the water supplied by the system reaches the crop. There are application losses due to wind drift or runoff, so that the water does not enter the soil. Losses also occur due to evaporation from the groun surface and from wetted vegetation, and undesired percolation from below the root zone of the crop (if salt is a problem leaching may be designed into the system, but this should be considered separately). These losses are accounted for by defining the *Field Efficiency* (R_f) which is the ratio of the water available to the plant to the total water applied. In practice E_f is normally around 90-95%.

Sprinkler irrigation systems generally provide reasonably uniform applications of water, although strong winds can cause problems. They are more adaptable to variable topography than surface irrigation. The application rate can also be controlled easily, making them suitable for a wide variety of soils. With automation, sprinkler irrigation can be very efficient, although evaporation losses and non-uniform spray distributins can occur in high winds. Typically about 75% of the applied water is used by the plants. Recently, small sprinklers, known as mini or micro-sprinklers, have become popular in horticultural irrigation systems. These have a smaller wetted diameter, typically between 1 and 5 metres. Application rates and pressure requirements are lower, and they are less affected by wind. The pressure requirement has a major effect on the running costs of the system, since the power requirement depends on the water pressure at the pump (*Equation 5.33*). Thus big guns and systems which project the water high in the air will use more energy, and have greater running costs.

Sprinklers can be classified as fixed, static, or moving. Permanent sprinkler systems are suitable for intensively cultivated areas growing high income crops, such as flowers, fruits or vegetables. Light-weight portable pipes with slip joining connections are common, although in view of the higher labour cost in moving these systems, such applications tend to be limited to high value crops. Automatic and semi-automatic self propelling systems with intermittent or continuous movement are now widely accepted worldwide.

5.20.2 Fixed systems

Fixed or semi-permanent sprinkler irrigation systems have been in use for many years. Permanent systems with buried pipes and fixed sprinklers are widely used in parks, playing fields and golf courses. Older designs consist of rigid pipelines (or laterals) with nozzles at regular intervals. These lines can be moved with effort, but in some cases must remain in position for at least the life of the crop. One design, the oscillating nozzle system, uses simple jet nozzles screwed into the lateral, and the pipe itself turns to spread the water over the whole area around the pipe. These designs are limited to various horticultural crops. However, with the introduction of lightweight aluminium tubing with quick release couplings, and the rotating impact sprinkler, irrigation of all types of agricultural and horticultural crops is now economically possible. Even so the labour input can be very high, and there are few cases where it would be considered economic to install systems which needed to be removed regularly by hand.

Micro-sprinklers are a modern development of the fixed sprinkler system. Because of their low cost they can be installed permanently in an orchard, and need not be moved. They are also well suited to protected cropping systems, since they can direct the water to the specific places where the crops are growing. These will be considered again later as part of the discussion on trickle irrigation.

5.20.3 Static systems (*Figure 5.48*)

These irrigators can be moved easily, but remain stationary while working. In the end-pull system the lateral is mounted on wheels. After irrigating an area the lateral is



Figure 5.48(a) Manual shift system with rotating impact sprinklers.

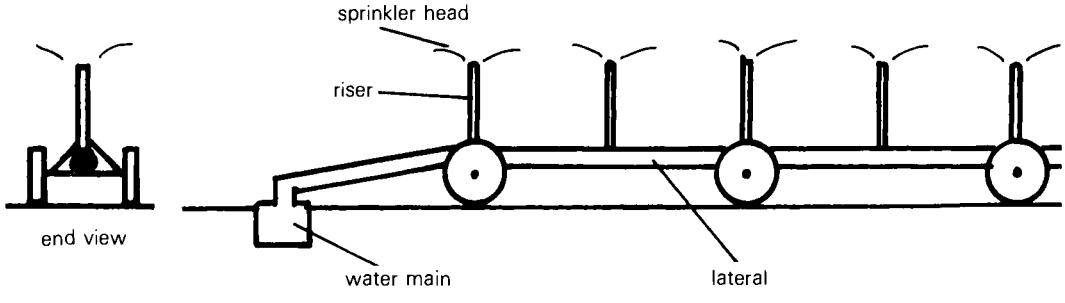


Figure 5.48(b) End roll.

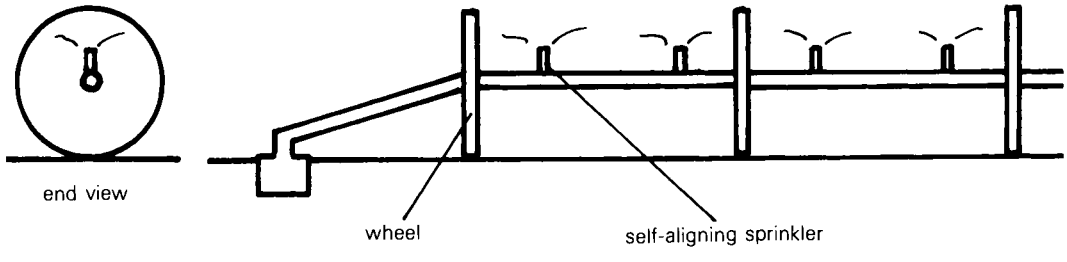


Figure 5.48(c) Side roll.

disconnected from the mains and towed from one end to the next site. The nozzles are usually the rotating impact type. The side-roll irrigator also has wheels but these allow the lateral to be moved sideways. In another variation swivelling wheels allow the lateral to be moved across the paddock at an angle of 45°. The nozzles are maintained upright by a suitable counter-weight arrangement, and the line is moved by hand or mechanical

power. In the latter case the power is transmitted along the lateral to the wheels by hydraulic means, so that the lateral stays in a straight line. Another type is the fire-hose and self-erecting sprinkler system, which is unrolled from a tractor driving down the line. On pressurising the sprinklers are designed to erect themselves. After irrigation they fold back down again, and the tractor can reverse to wind the reel up again.

Giant sprinkler systems involve a large steel boom (40 to 80 metres long) which is pivoted centrally and rotates every one or two minutes. The boom carries a lateral with nozzles at regular intervals along its length. For example, a 73 m boom will irrigate a circle of 150 m diameter, requiring 75 m^3/hr of water at a pressure of 6 bar, giving an irrigation rate of 4.2 mm/hr. A rotating gun irrigator is a single rotating nozzle which fires the water at high pressure as far as possible (typically 50 to 60 metres). It is limited to grassland use, and has a large power consumption, since the water pressure must be high.

5.20.4 Moving irrigators (*Figure 5.49*)

In this group the irrigator moves automatically as it is working along the field. Some are pulled by cables, driven by a winch which is powered by water bled off the main supply to the irrigator itself. The irrigator may be a wide spray boom, or a rain gun. In some designs the supply hose is laid out in the field first, and the irrigator winds it in as it moves. In others the irrigator can lay or pick up the hose. Hose reel irrigators use the hose itself to do the pulling. Centre pivot irrigators are used in some parts of the world where land and economics allow. These consist of a pipe supported about 4 m off the ground by a series of towers, and connected to a central supply point. The towers all move around the centre in line. Sprinklers along the pipe are designed to give a uniform irrigation rate as the pipe rotates. The pipe can be several hundred metres in length. The system must be controlled by a computer to ensure that the towers stay in line as they move.

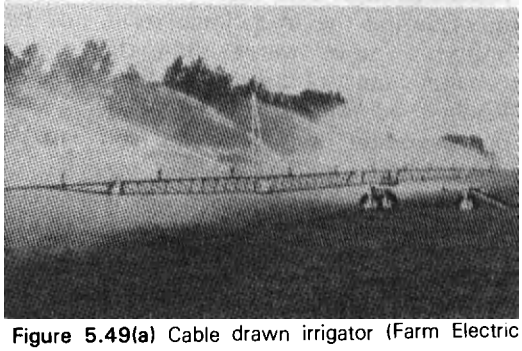


Figure 5.49(a) Cable drawn irrigator (Farm Electric Handbook).



Figure 5.49(b) Big gun.

5.21 TRICKLE IRRIGATION

Increasing use is being made of trickle or drip systems which apply water at very low flow rates, often to individual plants. Such rates are achieved by using specially designed emitters or porous tubes. A typical emitter might apply water at a rate of between 2 and 10 litres per hour. This minimises evaporation losses and limits irrigation to the root zone of plants, so that a well designed trickle irrigation system is probably the most efficient method of applying water. It is especially well suited to fruit, perennials, and high value crops, but not necessarily to annual row crops.

5.21.1 Advantages and disadvantages of trickle irrigation

Trickle irrigation has numerous advantages over other irrigation methods. There is more efficient use of water since the water is placed

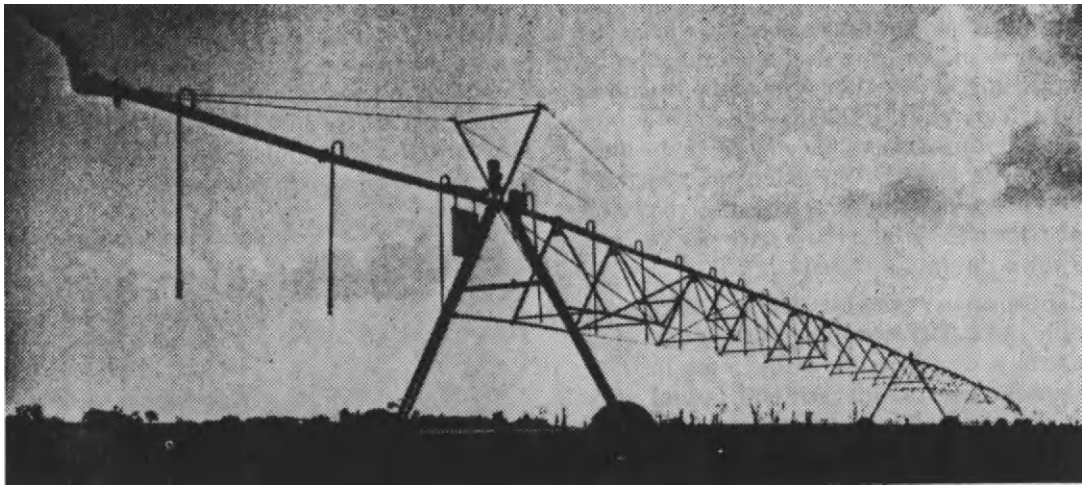


Figure 5.49(c) Centre pivot (Culpin).

only where it is needed by the plant (*Figure 5.50*). Direct losses by evaporation are minimised, and water can be saved by controlling application rates accurately. A well managed trickle system gives effective soil aeration and a nearly constant soil moisture condition in the root zone. This can give a better plant response than other forms of irrigation. Nutrients can be supplied to the plant roots efficiently through the irrigation water (a process known as *Fertigation*). By minimising the wetting of the soil surface and the plant foliage, trickle irrigation can reduce many insect, disease, and fungus problems.



Figure 5.50(a) Trickle irrigation (Massey University).



Figure 5.50(b) Minisprinkler irrigation (Massey University).

When saline (salty) waters must be used trickle irrigation makes it possible to maintain a continuously high soil moisture content. As plants take up water most of the salt is left behind. However, these salts are usually pushed towards the fringes of the wetted soil mass during the irrigation season, and by applying more water than the plants consume, most of the salt can be pushed or leached below the root zone. Thus, the concentration of salts in the soil can be minimised by a flushing effect, especially if the irrigation system is operated during the wet season. On sensitive crops trickle irrigation avoids problems of leaf burn due to salts.

Several benefits result from keeping part of the soil surface dry during trickle irrigation.

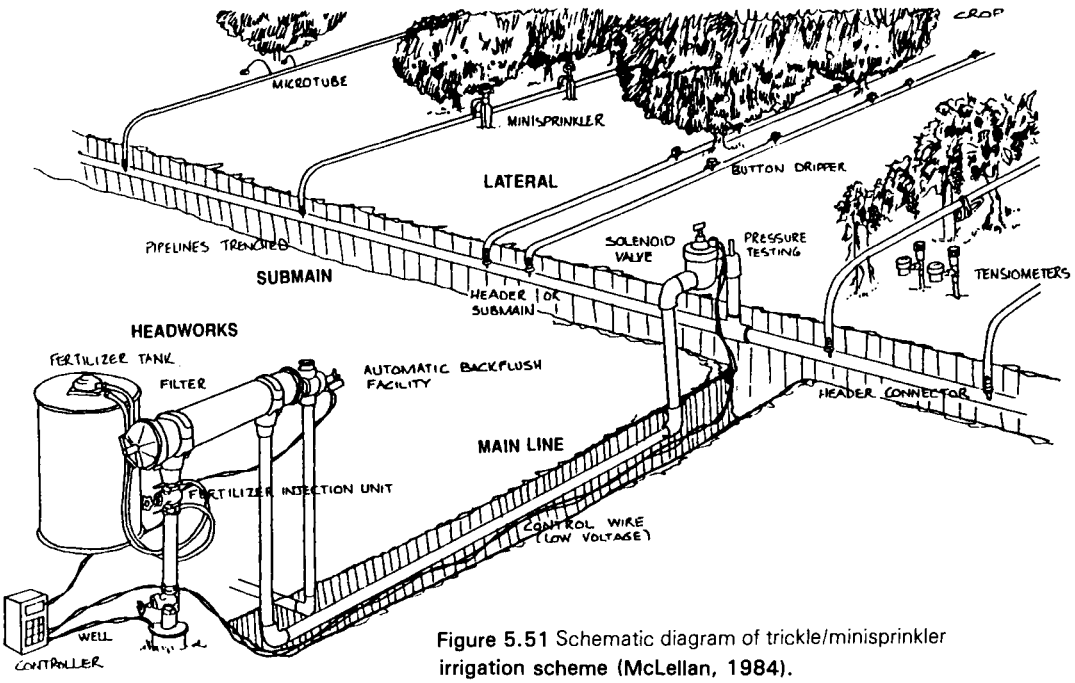


Figure 5.51 Schematic diagram of trickle/minisprinkler irrigation scheme (McLellan, 1984).

Irrigation activities do not interfere seriously with related work such as cultivation, spraying, picking and hauling. It results in less soil crusting, and fewer compaction problems. The potential for surface run-off is reduced to a minimum, and in arid areas trickle-irrigated orchards have been kept fairly free of weeds because the dry surfaces between rows inhibit weed growth. Trickle irrigation systems are less affected by wind. They operate at relatively low water pressures and the application efficiency is generally high, resulting in reduced pipe sizes and power requirements. They are well suited to irrigating crops growing under plastic and in greenhouses.

Clogging of the small passageways in the emitters can be the most serious problem that occurs with trickle irrigation. Chemical, physical or biological blockages can occur, and therefore good filtration is essential. It is often difficult to detect a clogged emitter.

A concentration of roots adjacent to the wetted areas is observed in some conditions, thus allowing a smaller percentage of ground area to be wetted to achieve the desired degree of root wetting. However, this is not always the case and is less likely if the plant is not totally dependent on the irrigation system for its water supply. Root growth occurs in the spring and it will explore the total area available when soil moisture is not limiting. If the irrigation system does not wet the same area in summer, then some roots will not be watered sufficiently, and moisture stress is possible. The roots of a plant also serve as its anchor, and fruit trees can be blown over by wind if the root growth is restricted. The extent of the wetted volume should therefore be a major consideration in the design of a trickle irrigation system.

5.21.2 Trickle irrigation systems

The general layout of a trickle irrigation scheme is shown in *Figure 5.51*. There are three main sections, the laterals and sub-mains, the main line, and the head works. The main line and sub-mains are normally buried. The lateral lines come to the surface from the sub-main and either lie on the surface or are tied on a support wire running the length of the row. Discharge points are inserted at predetermined spacings along the lateral.

5.21.3 Discharge points

The discharge points deliver water to the soil. The three main classes are drippers, mini-sprinklers, and lateral emitters (*Figure 5.52*).

a. Drippers

A dripper is simply a device which delivers water at a single point on the ground, so that any horizontal movement depends on the soil properties. Typically, the wetted area may vary from 0.3 to 0.8 m in diameter, depending on the soil type and also the flow rate. The simplest possible dripper would be a hole punched into the water pipe, but unfortunately such a dripper would be more like a small fountain! Instead it is necessary to use a suitable outlet device which restricts

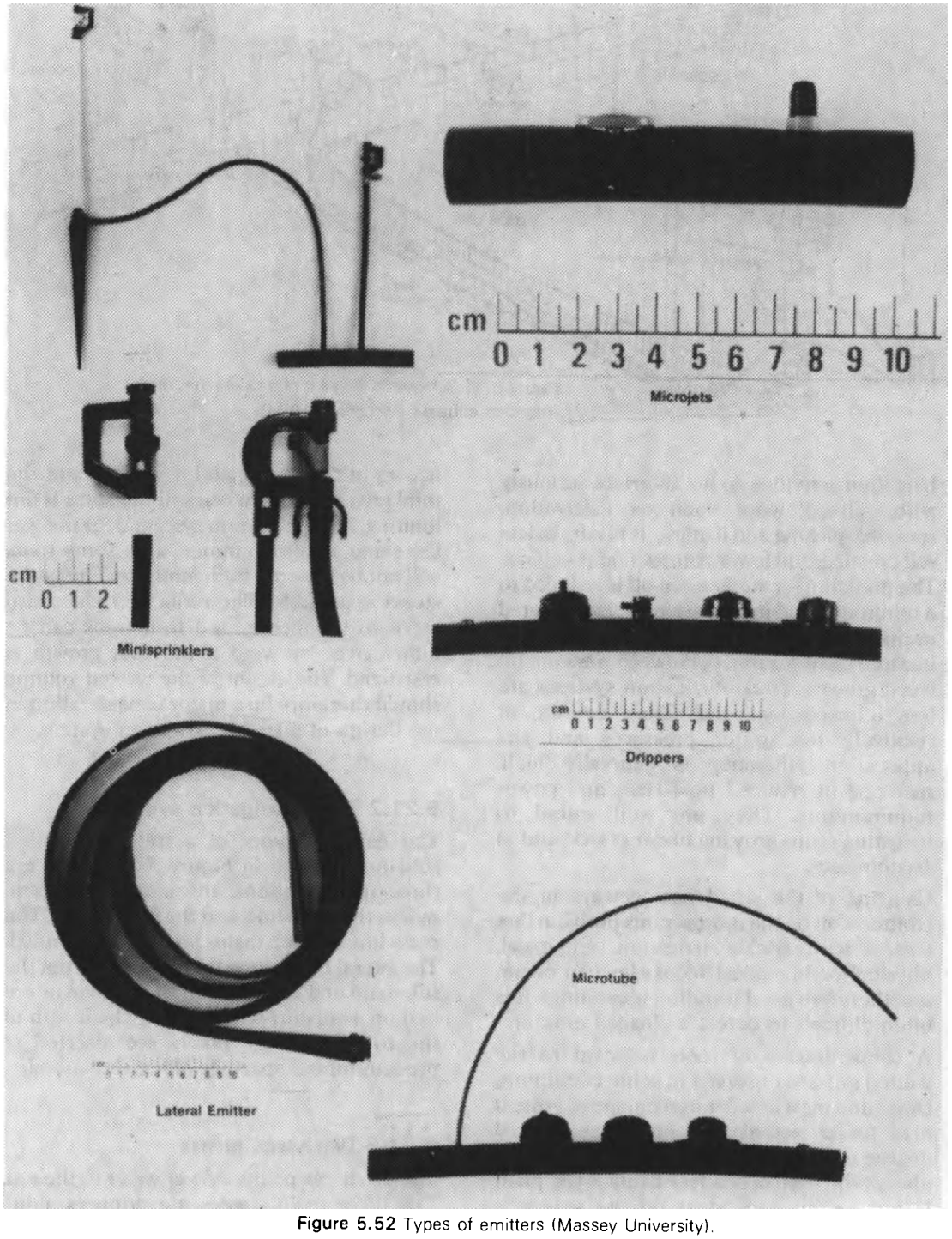


Figure 5.52 Types of emitters (Massey University).

the flow of water to a few litres per hour. Such a flow rate is similar to that from a dripping tap, and hence the name. The main types of drippers are microtubes and emitters. A microtube emitter is simply a predetermined length of plastic pipe with a very small internal diameter (0.5-1.0 mm). It works because the tube has a very high head loss (eg a 0.5mm microtube has a head loss of 18 metres per metre at a flow of 1 litre per hour), so that it only allows a small flow of water out. The head loss per metre can be calculated from Darcy's Equation (*Equation 5.29*). Emitters, on the other hand, are specially manufactured devices which can be inserted into the pipeline so that they allow water out at a restricted flow rate. Some emitters are designed to form a section of the lateral pipe, but most are inserted into the side of the lateral.

Some emitters are designed to be compensating. This means that they emit the same flow rate of water regardless of the pressure in the supply pipe (at least over the operating range of the device) so that smaller diameter laterals can be used in spite of the increased head loss.

When assessing the quality or suitability of emitters, the manufacturing quality and variability, the robustness, maintenance requirements, cost, and availability are important factors. Lifetimes can be difficult to assess and usually the buyer is dependent upon the reliability of the manufacturer's data. Variability is quite critical and is measured by the *Coefficient of Manufacturing Variation* (C_v). A low value of C_v (eg below 0.03) implies a small variation in characteristics which implies that the flow rate of each emitter will be close to the specification. Values of C_v greater than 0.10 are considered marginal at best (Rout, 1982).

The cost per unit is a major factor in emitter selection since so many are needed. In this respect microtubes have a significant advantage, and careful thought is required before this advantage is ignored. Once a system is designed for a particular emitter, any replacements should be of the same type in order to give the same flow. Thus, a check on the long-term supply prospects is often helpful.

b. Mini-sprinklers (*Figure 5.52*)

Mini-sprinklers use various sized orifices to give the desired head/flow relationship. Mini-sprinklers may be screwed directly into the lateral, attached to the lateral via a rigid riser tube, or they may be mounted on a stake and attached via a flexible hose. The type of attachment is dependent upon the application and the design must take into account any resulting pressure changes at the nozzle.

The selection criteria for mini-sprinklers are similar to those for drippers, but in addition, the nature of the spray pattern (wetted diameter, droplet size, and the uniformity of the spray) should be considered. The wetted diameter, which depends on the pressure, must be known in order to position the mini-sprinklers. If the units are placed too close to the plant, excessive watering occurs where the spray strikes the plant.

c. Emitter laterals

Emitter laterals combine the two functions of lateral and emitter. They vary from pipes with porous walls to units where the water is discharged at specific points along the pipe. They are limited to row crops or closely planted vines where a continuous wetted strip is required.

5.21.4 Pipes for laterals and mains

For trickle irrigation and minisprinkler systems, the pressure is low, and the laterals can be made from thin-walled polythene pipe with a pressure rating of only 30 m. PVC may be used for laterals in special situations, eg a greenhouse, but its use is mainly confined to mains and sub-mains. Most joints involve a friction grip, and close fits are essential for good connections. Thus, care should be taken with the size specifications. For example, some manufacturers and suppliers specify the internal diameter for lateral tubing, while others quote the outside diameter. Thus a 16 mm fitting could suit a 13 mm pipe!

Header connectors are required to attach the lateral to the sub-main. A good quality header connector, fitting firmly into the lateral and sub-main, is essential, as the joint is usually buried and is often under access ways which can be subjected to heavy traffic.

5.21.5 Valves

Because of the low pressure rating of trickle

irrigation pipes, special valves are often required to prevent high pressures. Air inlet valves are sometimes required on steep country or on long lines, since a large vacuum can be produced as the line drains after irrigation. They are placed at the highest point of the lateral, and allow air into the lines to stop the lateral collapsing. On the other hand, line flush valves are placed at the end of the laterals. They allow the laterals to drain or fill rapidly, thus flushing the lines clean. The valves are spring loaded and close when the system reaches working pressure. They are used where it is considered preferable to empty the lines. An air inlet valve is usually required if flush valves are used.

In some cases lateral failures have occurred due to pressure surges when the water is turned on. Although this could be overcome by air release valves at the end of each line, the cost would be very high and a better solution may be to install slow opening valves or two stage valves in the head works or sub-mains. In practice the emitters themselves serve as relief valves, allowing the entrapped air to escape. Manual isolation of each block, or the whole system, for filter cleaning and maintenance is desirable.

Pressure regulating valves (PRVs) stabilise the operating pressure within a block. They are usually spring loaded and may be either fixed or adjustable to give the desired operating conditions. PRVs are required if the pressure to each block is likely to vary, as is the case, for example, if a number of different blocks are operating at any one time. If all blocks are watered sequentially, so that the pressure at the block take-off is constant, there is little need for PRVs.

Electrically operated solenoids are the most common type of automatic control valve. They are available in a number of configurations, eg normally-open or normally-closed, 24V or 240V, and AC or DC. Hydraulic control valves are also available. These are powered by water pressure.

5.21.6 Filters

Water quality is the most important single factor in mini-sprinkler and trickle irrigation, and the correct filtration system is essential. The type and size of filter depends on the flow rate, the pressure loss, and the solids load. The total volume and nature of the suspended solids and their particle size distribution should be known before selecting the system. Filters should remove particles about a quarter of the smallest flow diameter in the system. For example, a 0.1 mm (140 mesh) filter would be required for microtube of 0.5 mm internal diameter. All filters need to be regularly cleaned or back-washed, with the cleaning water running to waste. The frequency of cleaning will depend on the water quality. In systems where the water quality is poor, pressure losses through the filter are likely as deposits build up. In this case higher initial pressures may be necessary, with pressure reducing valves in each block or the headworks to offset the variations in pressure.

There are three categories of filters. Mesh Screens (*Figure 5.53a*) consist of a screen, filter cloth or a set of rings which provide a fixed mesh size. They will not hold a large quantity of suspended solids without blocking, but they are essential as the final stage of treatment to ensure that no solids above a fixed size enter the system. Centrifugal Filters (*Figure 5.53b*) use the different density of suspended solids to spin them out of the irrigation flow. They work well to remove solid particles such as sand, but they cannot remove organic material. Sand Filters (*Figure 5.53c*) remove organic material from the water. The size of the sand filter is determined from the water flow rate, the allowable pressure loss, and the solids load. They have a reasonably large capacity for holding filtered material compared with the other filters. Unlike mesh filters the quality of the discharge cannot be totally controlled and a mesh filter should always be placed downstream of a sand filter.

5.21.7 Fertiliser injection (fertigation)

The controlled watering of every tree or vine provides the ideal opportunity to control the amount of fertiliser applied. This control can match the stage of growth of the plant and levels can be altered to suit conditions (eg, increasing nitrate levels to force growth, or reducing nitrogen levels in crops as the fruit develops). The use of soluble nutrients gives rapid plant response. In addition, improved crop responses result and the labour and equipment for side applications of fertiliser are not required. However, the irrigation system must be designed to wet an adequate

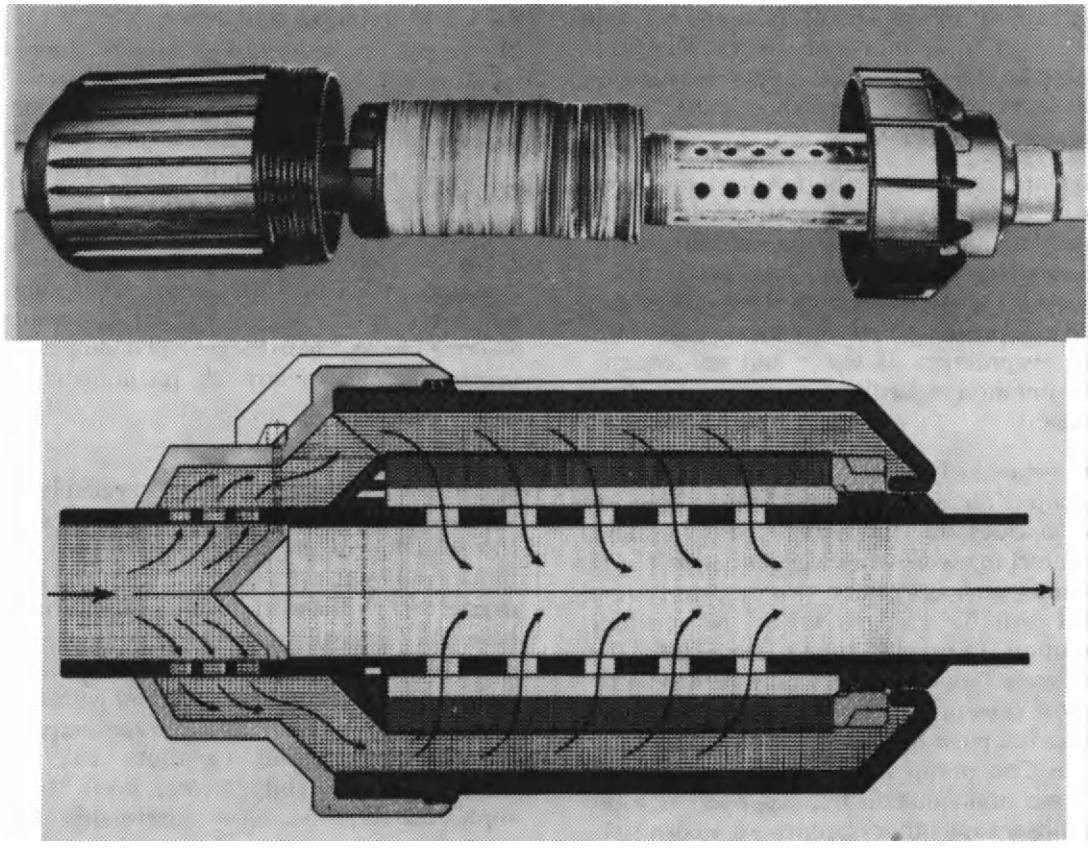


Figure 5.53(a) Mesh screen filter (Arkal).

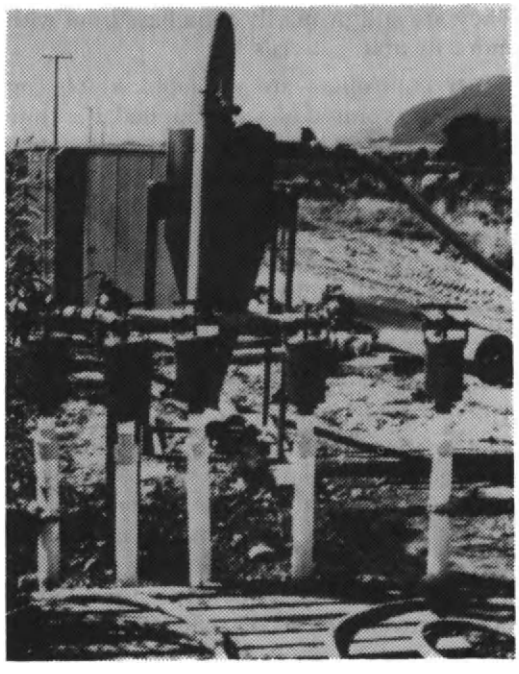


Figure 5.53(b) Centrifugal filter. The centrifugal filter is shown at the back of a bank of screen filters.

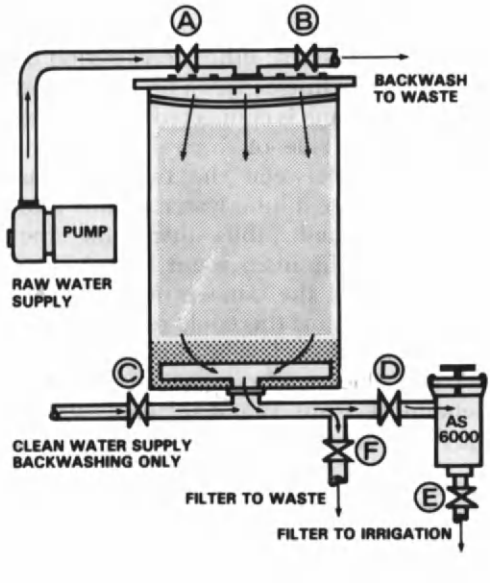


Figure 5.53(c) Sand filter.

percentage of the roots, and must be well managed. In addition, only soluble fertilisers can be used, and careful checks and records of leaf analyses, etc, should be made (Mannering, 1986).

The management of the fertiliser injection process involves pre-wetting, fertiliser injection, and flushing. A final flushing with clean water minimises any losses of fertiliser through volatilisation from the soil surface, and also prevents emitter blocking caused by the evaporation of water and subsequent precipitation of fertiliser in the emitter flow paths.

Any chemical injection apparatus requires an accurate metering system. There are various techniques for metering the chemical. Venturi injectors work well. Other metering pumps, such as a rotary, gear or piston pump can also be used to inject the fertiliser solution from the supply tank into the pressure line. The pump may be driven by water pressure, or may be operated by an electrical pulse from a flow meter in the water line. The pump must develop a pressure greater than that in the pipeline. As most fertilisers and other chemicals are corrosive, the pump must be made from corrosion resistant materials.

In the dilution tank, or pressure differential system, the chemicals are contained in a sealed tank able to withstand the maximum operating pressure of the water at the point of injection. A valve or other constriction in the water supply line causes a pressure drop in the line. The tank is connected by separate pipes on either side of the valve and the pressure drop between the two pipes is sufficient to cause a little water to flow into the chemical tank, thus displacing the chemicals into the main water line. As the chemical is used the concentration in the tank will drop off and this could result in poor control of fertiliser levels. Some systems include a flexible membrane, which separates the chemical from the displacing water, thereby preventing dilution.

All chemical injection systems must be equipped with vacuum breaking (antisiphon) valves placed upstream from the injection point. This will prevent chemical contamination of the water supply in the event of water or power failures.

5.21.8 Monitoring equipment

Clients and designers often choose to ignore monitoring equipment requirements, partly because the returns for the capital investment are not immediately obvious. This is often a false economy and in sophisticated systems monitoring equipment is often essential for optimum efficiency. This includes pressure gauges, a conductivity meter for fertiliser injection, and a flow meter for monitoring water use or for scheduling irrigation to different blocks. Such devices will often prove worthwhile and are strongly recommended where appropriate.

5.21.9 Automation

Automatic control equipment is available at various levels of complexity and price, and the selection of the controller is primarily influenced by the size of the system and the degree of sophistication required. Simple time base units, typically with 4 to 12 stations, are available. These units have a built in clock and each station can be watered for a pre-set time each day. Dual programmes, repeat functions, and other variations can be obtained at a slightly greater cost. More sophisticated time base controllers can service over 100 stations and can be programmed to provide water on different days, with different fertiliser sequences, etc. They are still primarily time based but with more flexible patterns.

Other controllers are available which can adjust the volume of water applied, the time of irrigation, and fertiliser inputs, using data from field sensors, such as tensiometers or neutron probe moisture meters. More flexible computerised control systems provide complete water scheduling for the optimum control of soil moisture and fertiliser levels throughout a season. Greenhouse environmental controllers may also control the irrigation system.

The design of an automatic system requires a knowledge of the system hardware and the management system. Cable sizes to the block solenoids and total power loads on each controller station have to be calculated. Failure to do this can result in large voltage losses in the wires so that solenoids fail to open, or overloads in controller circuits occur.

5.21.10 Water application rates

For a trickle irrigation system the time

required to apply the water can be calculated from the formula:

$$I_t = \frac{V_p}{q_a \, n \, E_a} \qquad \textbf{Equation 5.47}$$

Where I_t is the irrigation duration (hr), V_p is the volume of water per plant per irrigation (litres/plant), q_a is the average emitter flow (litres/hr), n is the number of emitters per plant, and E_a is the total system efficiency (as a fraction) which allows for uniformity variations and microsprinkler application losses.

If the calculated irrigation duration exceeds the irrigation interval (*Equation 5.45*), or allows insufficient down-time for repairs and maintenance, then the irrigation duration must be reduced. This can be achieved by increasing the emitter flow rate or the number of emitters per plant. As a result total system flows will be greater and pressure requirements may be increased. A similar formula can be used to check other irrigation systems.

A low application rate requires smaller sized equipment, thereby reducing costs, but a longer application period is required. The maximum time available is determined by the interval between irrigations, modified according to the number of separate blocks requiring irrigation, the type of soil being watered, and any factors of safety included in the design. In large horticultural enterprises, the flow rate in the main-line can be reduced by watering in several blocks, with the time apportioned between them.

Example

Calculate the application rate per tree and irrigation interval for a close planted deciduous orchard planted at 2 metre spacings in the row and 5 metres between the rows (the area per plant is thus 10 m^2). The peak pan evaporation is 5 mm/day. Assume a crop factor of 0.85 full ground cover, and no percolation losses.

Solution: The peak water requirements of each plant is given by *Equation 5.43*:

$W = 0.85 \times 5 \times 10 = 42.5$ litres/plant per day

Suppose the effective root depth is found to be 0.5 m, and the water holding capacity of the soil is 100 mm/m. If the allowable water deficit is taken to be 0.4 (40% of WHC), and if 50% of the potential root volume were able to be wetted, then the volume of water applied for one plant is found from *Equation 5.42*:

$V = 0.4 \times 100 \times 0.5 \times 10 \times 0.5$

$= 100$ litres/plant

The irrigation interval is thus:

$I = 100/42.5 = 2.33$ days

On this basis a two day interval would be selected.

Unfortunately we have neglected the way in which the emitters distribute the water to the soil, and this must now be considered.

To achieve 50% wetting of the potential root zone the emitters chosen must have a combined wetted area of 5 m^2. This could be achieved by one mini-sprinkler, producing a wetted diameter of 2.52 m, or two mini-sprinklers, each producing a wetted diameter of 1.78 m. Unfortunately, in the first choice, as the plants are placed every 2 m along the row, the mini-sprinklers must also be placed every 2 m. Their wetted patterns will therefore overlap by 0.52 m giving an overlap of 0.543 m^2.

Suppose that a mini-sprinkler is chosen which gives a 2.52 m diameter wetted pattern when operating at 20 m head, and delivers 35 litres/hr. The wetted volume will be 44.6% of the potential root volume, since each sprinkler has a wetted area of 5.0 m^2 less than 0.543 m^2 overlap. The volume of water to replenish the storage volume without percolation losses or spreading would be only 84.6 litres/plant, and the irrigation interval would need to be reduced to 1.99 days, or 2 days in practice. If the total system efficiency is assumed to be 68% (90% absolute emission uniformity and 75% field efficiency), then the irrigation duration is given by *Equation 5.47* as:

$$I_t = \frac{84.6}{35 \times 1 \times 0.68} = 3.55 \text{ hrs}$$

The actual volume required to be pumped will be:

$V_a = 35 \times 3.55 \times 1 = 124$ litres/plant

at an application rate of 35 litres/hr-plant.

If the orchard was divided into 6 blocks the time to irrigate the orchard would be 21 hours. To this must be added the time to water shelter belts. There is, however,

adequate time allowance for underestimates in design, and for system maintenance and repairs.

The second choice, with two mini-sprinklers per plant being placed at 1 m spacings along the row, would give a 0.8 m overlap, or 33% of the wetted area. Ignoring any horizontal water movement in the soil, the resulting overlaps will decrease the wetted volume, and may cause increased run-off and percolation, thus reducing the total system efficiency. If mini-sprinklers were chosen with 2 m wetted diameters at 2 m intervals to avoid overlap, the wetted area would be reduced to 3.1 m^2, and only 31% of the potential root volume would be watered. In this case the amount of water that would fill the root storage volume would be only 62 litres/plant, (cf 100 litres/plant previously). The irrigation interval would have to be reduced to 1.4 days, or in practice, one day.

To summarise, the head and flow at the emitters and the number of blocks have been specified, which will allow the designer to progress to the selection of the laterals and sub-mains.

5.21.11 Lateral and sub-main selection

As the water flows along the laterals, the pipe friction causes a continuous drop in pressure, which depends on the pipe size and type, and the water flow rate. In trickle irrigation systems these factors must be balanced to ensure that each emitter is at the correct pressure to produce the required flow. The allowable variation in flow specified in the design of an irrigation system fixes the acceptable pressure changes across the block, since the pressure affects the flow from the emitters.

On level ground the pipe sizes are selected so that the pressure along the sub-main and laterals stays within the design limits. This may involve changing lateral pipe sizes one or two times down a row to optimise the cost-effectiveness of the system. Where microtube is used it is often more economic to change microtube lengths down the lateral to accommodate the changes in pressure. Unfortunately, in New Zealand, level ground is rare (and can never be estimated by eye!). Therefore it is essential to survey the area, usually at 0.5 m contour height intervals, so that the effects of changes in ground height on the lateral pressure can be found.

Computer programmes are available which will take survey data from either level or theodolite tachometric surveys and produce contour plans on automatic plotting equipment.

5.21.12 The use of "Polyplot" for sizing laterals

Polyplot is a graphical method for calculating the net lateral pressure. It was refined by GA Jobling, for the New Zealand Agricultural Engineering Institute (Jobling, 1972 and 1974) from a graphical method developed by the ICI Computer Group in Australia (Herbert, 1971). Normal head loss tables cannot be used for the calculation of the pressure loss along a lateral line because the flow reduces uniformly to zero along the pipe, and so special head loss curves are used, which take this reduction in flow into account (*Figure 5.54*).

To utilise these curves, the flow in the lateral is defined by the *Specific Discharge Ratio* (SDR). This is the discharge per outlet divided by the distance between outlets:

$$\text{SDR} = \frac{\text{Discharge per outlet (litres/hr)}}{\text{Distance between outlets (m)}}$$

Equation 6.48

For example, if the emitter flow is 8 litres per hour and the spacing of each emitter is 2 m, then the SDR is 4 litres per hour per metre. As long as there are 10 or more outlets then laterals having the same SDR values will follow the same head loss curve (approximately). The SDR and the internal diameter of the pipe can then be used to determine the working curve. On the top left hand corner of *Figure 5.54*, a graph is reproduced where the internal diameter is defined along the ordinate (vertical) axis. The graph consists of a series of straight lines with SDR values, with the working curve number on the abscissa (the horizontal axis). By locating the point where the SDR line and internal diameter line cross, the working curve value can be read off the abscissa. This value identifies the working curve to be used on the main diagram in *Figure 5.54*.

The method of utilising the working curve is to take a piece of tracing paper and draw on it the ordinate axis and the working curve

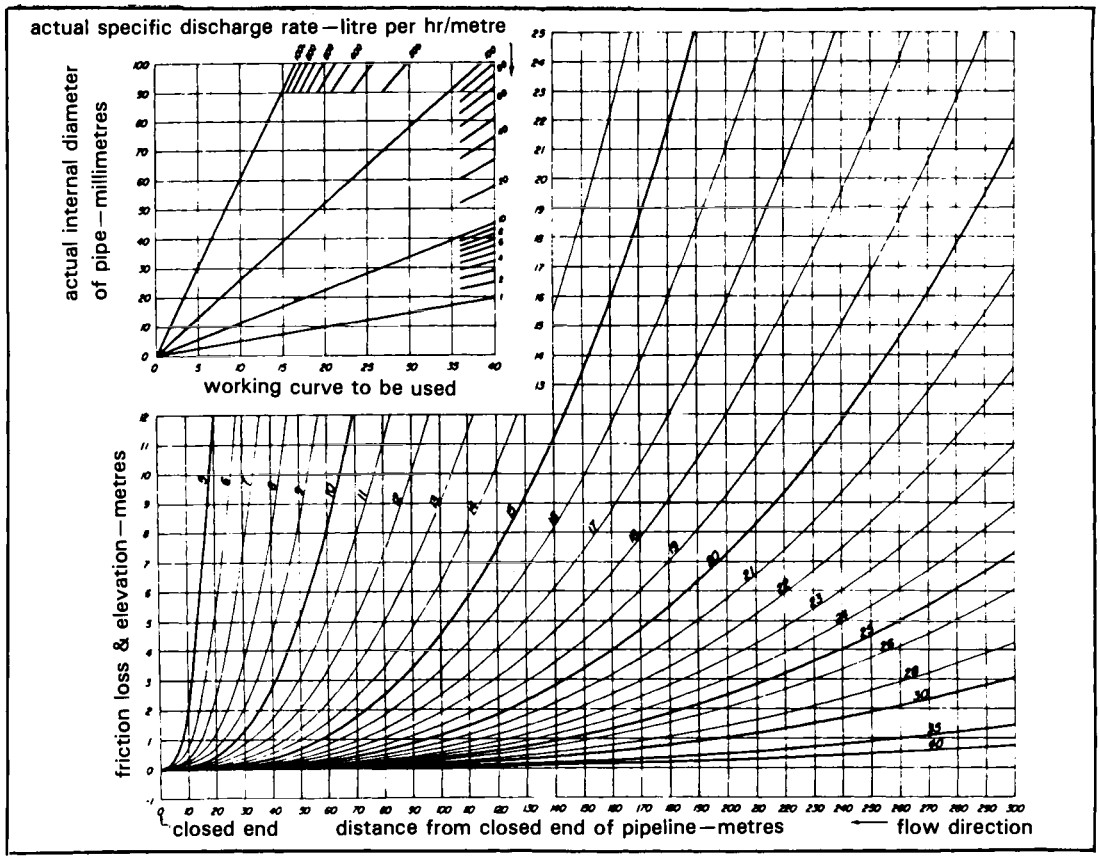


Figure 5.54 Graphical design for pipelines with flow decreasing uniformly to zero (Irrigation and Water Supply Comm Qld 1971).

specified. A separate piece of tracing paper is then used to plot the actual profile of the terrain over which the lateral is to run, using the same ordinate and abscissa scales as the Polyplot diagram. It should be noted that the closed end (ie the end furthest from the water inlet) is the origin of the chart. Thus the water flows from right to left.

As long as the ordinate (vertical) axes of both the ground profile and the working curve coincide, the two curves can be used to find the net lateral pressure at any point.

Figure 5.55a illustrates the use of the two together. The difference between the working curve and the ground profile gives the net pressure. The difference at the open end, between the ground profile curve and the working curve, has been set here at 10 m, the design operating pressure. The net pressure, or the head available at any point along the lateral line, can now be determined.

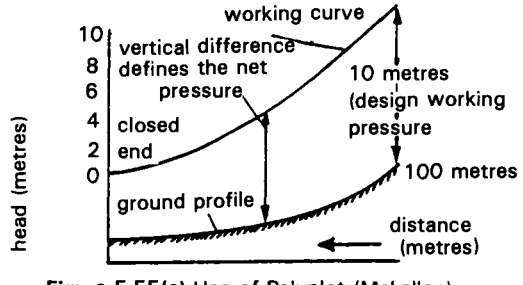


Figure 5.55(a) Use of Polyplot (McLellan).

In trickle and micro-sprinkler irrigation design the aim is to achieve even watering to each crop unit, by maintaining the pressure in the laterals to within certain design limits. A generally accepted pressure variation used is 10% of the design operating pressure.

This is done graphically by marking in lines parallel to the ground profile at the chosen tolerances. In *Figure 5.55b* the two tolerance lines are shown; one at 1 m above the ground profile line and one at 1 m below (10% of the 10 m design pressure).

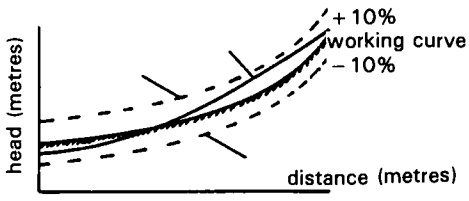


Figure 5.55(b) Checking tolerances (McLellan).

To determine the diameter of the single pipe which will maintain the pressure within the design tolerances, the working curve is matched to the ground contour. The working curve is started at ground level at the open end of the ground profile. If the curve goes outside the two tolerance lines anywhere along the length of the lateral, a larger pipe diameter must be tried, ie a working curve of higher number. In *Figure 5.55b*, a working curve is shown which fits between the +10% lines.

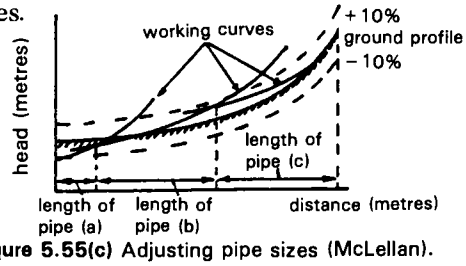


Figure 5.55(c) Adjusting pipe sizes (McLellan).

It is possible to use several pipe sizes down a lateral. In this case the procedure differs from the above. Starting at the closed end and with the smallest pipe size, the maximum length that can be fitted within the tolerance limits is determined. When doing this the tracing paper with the working curve drawn on it can be slid up or down on the underlying ground profile plot to obtain the best match, making sure the ordinate axes coincide. Once it is decided what maximum length of the smallest and, by implication, cheapest diameter pipe can be used, the tracing paper is slid down to where the working curve for the next pipe size and the profile match best. This process is repeated until the lateral has been designed up to the inlet end. *Figure 5.55c* shows an example of this.

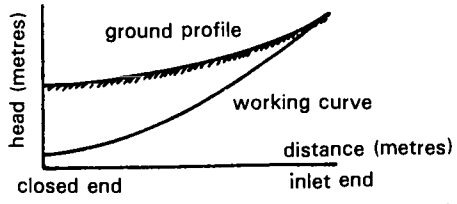


Figure 5.55(d) Estimation of microtube length (McLellan).

If the design allows for a variation of pressure along a constant diameter lateral with microtube of varying lengths being used to obtain uniform irrigation, the process is different again. The working curves are chosen as before and the ground contour plotted. By starting the friction curve at ground level at the open end of the profile, the difference between ground level and the friction curve will be the deviation in pressure (*Figure 5.55d*). The deviation can be used to calculate the net pressure at any point along the lateral. The length of microtube can then be calculated from the head loss data from the microtube.

Computer programs are available for fitting polyplot curves to ground contours.

In practice it is normal to design only every tenth lateral on even terrain and to interpolate for intermediate laterals. System pressure drops occur in both the lateral and the sub-main. Sub-mains feeding laterals with equal discharges can be designed in exactly the same way as the laterals using the friction curves in *Figure 5.54*. It should be remembered that a substantial variation in pressure can occur along the sub-main owing to differences in elevation, and this must be allowed for when designing the laterals.

5.21.13 Trickle systems in greenhouses

Low pressure spray systems are ideal for irrigation, misting and other purposes in greenhouses. *Figure 5.56* shows some examples of installations which perform various functions.

5.21.14 Bubbler irrigation

An alternative low cost system of localised irrigation is known as bubbler irrigation (Hillel, 1988). It is a further simplification of the trickle irrigation principle, and is suited to orchards where the crops are widely spaced. The water is fed through pipes to open vertical tubes (risers) placed at each plant where the water is needed. There is no emitter as such so the water simply flows out of the pipe. A small basin is formed in the soil around each riser so that the water spreads out to fill the basin. By making the basin the same size as the root area, the water can be distributed evenly. The water can be applied for a short time so that it does not overflow the basin.

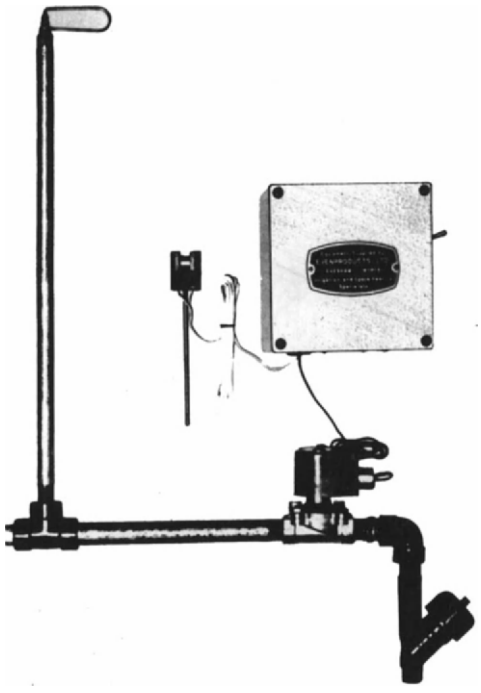


Figure 5.56(a) Artificial leaf system for controlling misting (Farm Electric).



Figure 5.56(b) Fully computerised trickle irrigation system applied to tomatoes (Farm Electric).

The major advantages of this system are that the material costs are minimised: low strength plastic pipe can be used since the required pressure is very low. In fact the head need only be a few cm, so that expensive pumps may not be required. There is some extra work involved in constructing the basins around the plants, but these can be hand dug as the sides need only be a few cm high. Getting uniform delivery to each site is a more serious problem. This requires accurate calculation and measurement, as the height of the top of the riser is critical. In practice some fine adjustment will probably be necessary, and it would be a system which needs to be checked regularly. It would be very easy for a tree to receive either no water or too much, and this could cause problems. However the system would be well suited to situations where minimum material installation cost is important, and where maintenance of specialised equipment is a problem.

5.22 HORTICULTURAL SPRAYING

Spraying forms an important part of modern horticulture and agriculture. The principles of fluid flow apply equally well to such systems. There are many different types of spray system, ranging from the simple back pack sprayer with a nozzle on the end of a length of tube, to high pressure air blast sprayers for orchards (*Figure 5.57*). In all cases the object is to produce as complete a coverage of the target area as possible. This requires that the liquid is broken into small fine droplets. This can be achieved in a variety of ways. If the fluid is forced out of a fine nozzle by a high pressure then atomisation will occur (ie, the fluid is broken into small droplets). This produces a wide

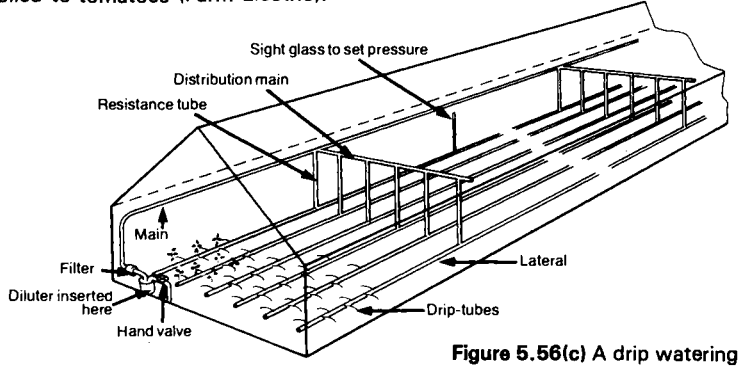
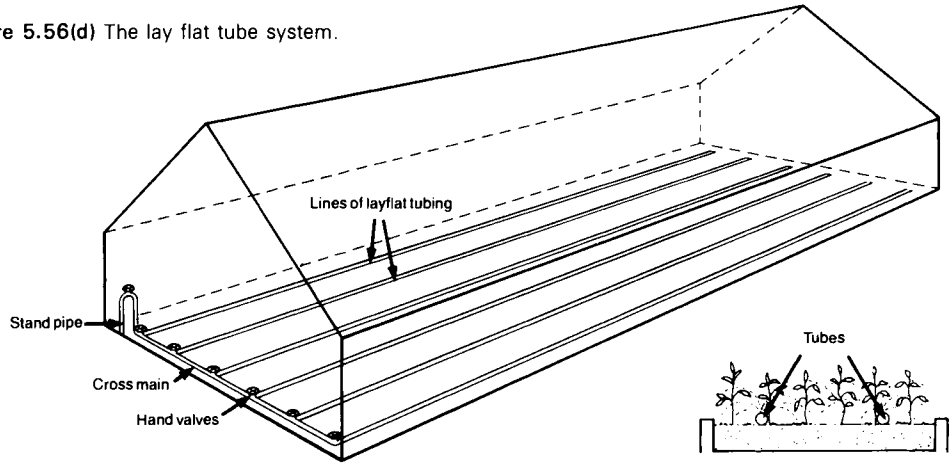


Figure 5.56(c) A drip watering system (Farm Electric).

Figure 5.56(d) The lay flat tube system.



range of droplet sizes. The nozzle is prone to rapid wear. Atomisation can also be achieved by feeding the liquid onto a spinning disc, so that the droplets are flung out radially. These produce a more uniform droplet size, which can be adjusted by altering the speed of rotation. An airblast sprayer shatters the fluid into droplets by virtue of a strong blast of air. This breaks up any large droplets. Another method involves charging the liquid electrically so that electrostatic charges cause the liquid to disperse. These require special formulations of the spray liquid.



Figure 5.57 Orchard air-blast sprayer (Silvan Maber).

The design of spraying systems requires the careful selection of pressures and nozzle sizes to produce the desired distribution of spray. For example in the air blast orchard sprayer, the nozzles will all be of different size, depending on how the spray is to be distributed amongst the parts of the tree. Thus, a grower may require that two thirds of the spray will go into the upper third of the tree, and would therefore fit larger nozzles in the upper positions. In all cases calibration of the sprayer equipment is extremely important. Details are given in textbooks (eg, NZAEI, 1984).

All sprays should be treated as being potentially harmful to humans. Proper clothing should always be worn, and you should wash carefully after work. Some chemicals are absorbed through the skin, so your feet, hands, and head should be covered. Breathing masks are also essential for many sprays.

5.23 WATER HAMMER

Water hammer is an unpleasant phenomenon which occurs when the flow of water in a pipe is suddenly interrupted. This can occur when a valve is shut relatively quickly, or when a pump starts up or is shut down. The water flowing along the pipe still possesses momentum, and if the flow is stopped or reduced suddenly at one point in the pipeline, it takes a finite time for the entire flow to stop. The net effect is that shock waves will pass up and down the pipeline, reflecting at the ends or at constrictions, and causing surges of high and low pressure which can seriously damage the pipe or the fittings. A characteristic hammering noise is also often generated. The analysis of water hammer is quite complex. As a general guide the condition for the avoidance of water hammer is that the time taken to close off the flow must be greater than a critical value. This is given by:

$$T > \frac{2\,l}{C} \qquad \textbf{Equation 5.49}$$

where l is the length of the pipe, and C is the velocity of the pressure wave in the pipe. The value of C depends upon the material the pipe is made from. For PVC C is around 480 m/s, for polythene it is about 380 m/s, while for iron pipes the value of C is around 1300 m/s. If the closing time is shorter than T then water hammer is possible, and the excess pressure head can be estimated from the formula:

$$H = \frac{C\,V}{g} \qquad \textbf{Equation 5.50}$$

where V is the change in velocity of flow of the fluid. This extra head must be added to the existing head in the pipeline to obtain the working pressure. If the pipeline is long then the closure time of a valve may need to be quite large in order to avoid water hammer.

Example

Calculate T and H for a PVC pipe 1500 m long if the water is flowing at 2 m/s. If the normal working head was 50 metres, what class of pipe would be required to withstand the water hammer?

Solution: For PVC, C = 480 m/s, so the critical closing time is

$$T = \frac{2 \times 1500}{480} = 6.25 \text{ seconds}$$

If the valve closes off the flow faster than this, or the pump cuts in and out too quickly, then the estimate for the possible pressure surge is given by:

$$H = \frac{480 \times 2}{9.80} = 98.0 \text{ metres head}$$

(or about 10 bars!).

As this figure must be added to the working head the total surge head would be $50 + 98 = 148$ metres. Only pipes of class E or better would be able to withstand this pressure.

Negative pressures can also be generated, so that a pressure of -48 metres could also be applied briefly. In some instances, pipes or fittings have collapsed rather than split due to water hammer. The problems of water hammer can be overcome by extending the closing time of valves, or by reducing the velocity of flow of the water in the pipe. It is also possible to fit accumulators and dampers to absorb the shock.

Even in small installations, such as domestic systems, water hammer can be an annoying problem. In these cases it is often caused by the oscillation of the small shut off valve at the end of the line. This can vibrate when it is close to being totally shut, causing noisy pipes. The problem can often be solved by fitting a new valve, or by roughening the sliding surfaces of the valve (not the sealing surfaces!), so that it moves a little less freely.

5.24 DRAINAGE

Life is never simple for a horticulturalist or a farmer. For some reason plant life is designed to require not only water but also air to be available in the root area. Either there is too little water, and we must irrigate, or there is too much, and we must provide drainage. Some soils, such as sands and silts, are self-draining and require no special attention (the water holding capacities of soils are discussed in Chapter 8). Within a few hours of a rain-storm, all the excess water will have drained away, and the pore space will begin to recover some air. In heavier soils, such as clays and silt loams, the soil can remain wet and puddled for days or weeks. Symptoms of poorly drained soils are evident even in dry conditions. These include a rough pasture surface (caused by stock treading or pugging the soil when it was wet), pasture which contains wet-land weeds, or which is obviously drowned out, a subsoil which is very hard to dig when dry, or grey-blue subsoils with yellow-brown patches or mottles. Wetness can be caused not only by excess rainfall on the area which is slow to drain, but also by a hard subsoil pan which causes a perched water table (ie, the water is trapped at the surface in a sort of impermeable bowl), by seepage from higher ground, or by the presence of a high water table due to the lack of, or damage to, drains in the area. Wet soil affects root activity, the effectiveness of fertilisers and lime, and prevents cultivating equipment from being used at the right time, so that planting dates can be missed. Pasture utilisation by stock is reduced, and disease problems are more common, not to mention the development of undesirable weeds. For example, in New Zealand approximately 40% of agricultural

land would benefit from drainage (Bowler,1980).

5.24.1 Types of drainage

Surface drains

Drains may be either on the surface or buried. Surface drains generally remove only the surface run-off, and are relatively ineffective in draining the soil in which plant roots must grow. The exceptions are in peat and sandy soils, where the soil permeability is high. In these cases the drains are in effect controlling the water table level in the soil, and the aim should be to maintain the desired level of water rather than remove all the water. Peat country farmers will block up drains at certain times (such as planting) as a means of irrigating crops. Surface flooding and the operation of rice paddies are extreme examples of this principle.

Surface drains are inexpensive. However the disadvantages are that land is used up, they must be cleaned, weeded, and maintained annually, they restrict access to the land, requiring culverts or bridges to be built, and they could be a stock hazard if not fenced. Small shallow vee drains and grassed waterways provide ways of removing storm water quickly, without these problems.

Subsurface drains

Subsurface drains are more expensive to install, but require less maintenance and overcome all the other problems of surface drains. The simplest type of drain is known as a mole drain (after its natural predecessor!). It is formed by pulling a torpedo shaped implement through the subsoil to form a relatively permanent channel in the soil, at a depth of typically 400 to 500 mm. This process also forms cracks in the soil through which water can move into the mole channel. These mole drains act as the main collectors for the excess water from the soil, and are normally spaced two to three metres apart in New Zealand soils. From the mole the water flows into an outfall, which may be an open drain or a suitable piped drainage system, as described below. The maximum mole length depends on numerous factors and may vary from 10 metres in stony soils, to 100 metres in clean pasture with a 1 in 20 slope. If the slope is less than 1% the mole drain should not run for more than 40 m between collectors (Bowler, 1980; Bidwell, 1978).

The lifetime of a mole drain depends upon a number of factors, and can vary from two years up to 25 or more years. A key factor for a successful mole is that the soil has an appreciable clay content, since it is the action of the mole plough in smearing the clay along the side of the mole which helps to produce a permanent structure. The main cause of the failure of moles is the loss of soil strength due to saturation of the soil around the mole, especially at the top and sides. This state can be avoided providing the mole is not overloaded with water so that positive soil water pressures develop. The mole should flow into a good outfall, and should not have any pockets of water left after the flow has stopped. These requirements can be met by ensuring that the mole slopes steadily towards the outfall and there are no sections which slope the wrong way. This requires good design, careful surveying, and good workmanship in constructing the moles.

The outfalls can be pipes or tiles made from plastic, clay, wood or concrete. The water must be able to flow from the tiles into the outfall easily, so that the moles do not

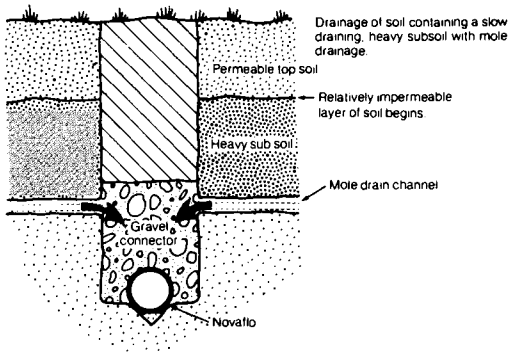


Figure 5.58(a) Drainage of soil containing a slow draining, heavy subsoil with mole drainage.

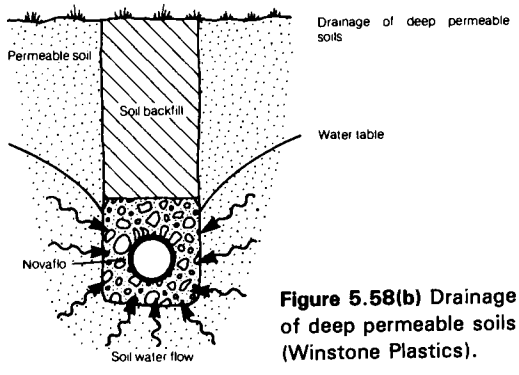


Figure 5.58(b) Drainage of deep permeable soils (Winstone Plastics).

become waterlogged for any appreciable length of time. A gravel filled "connector" (*Figure 5.58*) will provide a suitable porous path for the water. If ceramic tiles are used the water flows into the pipe at the joins between tiles. Nevertheless these should be butted firmly together, as there will still be an ample gap for water to enter. In sandy soils polythene sheet can be placed over the tops of the gaps to prevent sand entering the pipe, and causing silting up.

Plastic drainage pipe is continuous, and contains holes or slots which allow the water in. It is unable to support substantial loads, and care must be taken to ensure that the pipe is well supported with backfill all around it, so that the soil rather than the pipe takes any loads. Careful blinding is required (ie, covering the pipe with a layer of soil or gravel) which covers the pipe and protects it from the impact of any large lumps in the backfill.

The exact depth at which the collector pipes are placed depends on the soil type, but should be deep enough to avoid damage from stock or machinery, including the mole plough! A minimum depth would be 600 mm. The slope of the pipes depends upon the size of the particles likely to enter the drain. The water velocity must be high enough to carry the coarsest particles away. If coarse silt or fine sand can enter then the flow velocity should be at least 0.5 m/s. In 100 mm clay tiles this would require a slope of 1 in 300, while for corrugated plastic pipe its greater head loss characteristics imply that a slope of at least 1 in 160 would be needed (NZAEI, 1973, and Anon, 1982).

Calculation of flow

The design flow can be calculated if the drainage coefficient and the area being drained are known. The drainage coefficient is the depth of water in mm which should be removed in 24 hours to provide for a particular land use. It varies from as little as 5 mm per day for grassland, to up to 50 mm per day for playing fields and horticultural enterprises (Bowler, 1980).

5.25 EXERCISES

1. Find the equivalent pressure in kN/m^2 for: (a) 60 m of water, (b) 72 mm of Hg, (c) 10 m of oil (SG = 0.8).
2. A water pipe is connected to a U-tube mercury manometer. If the mercury differential is 500 mm and the top of the column is 100 mm above the centre of the pipeline, what is the pressure in the pipe?
3. A force of 125 N is exerted by a 10 mm diameter hydraulic ram. What is the system pressure?
4. Water is 14 m deep in a tank. What is the pressure at the bottom of the tank in kN/m^2?
5. A 6 m^2 tank contains liquor of SG = 1.15 to a depth of 5 m. What is the force on each side of the tank?
6. The top of a vertical 1.5 m diameter glass inspection panel let into the side of a tank is 3 m below water level. What is the total force on the glass? If the side of the tank containing the panel slopes at 45°, what will be the total force? Assume the top of the panel is still 3 m below water level.
7. A 150 mm internal diameter pipe has water flowing in it at 3.2 m/s. If the pipe changes to 200 mm internal diameter, what will be the water velocity and the flow in litres per minute and m^3/min?
8. A pump located beside a farm reservoir delivers water at 20 litres/min through a 25 mm polythene pipeline with a total head of 64 m. The pipeline from the pump runs 240 m up a hill to a pressure tank located 19 m above the reservoir. Calculate: (a) the velocity head (and comment on your answer), (b) the pressure in the tank.
9. A 20 mm orifice at the bottom of a tank with 20 m of water in it has a Cd of 0.62. What is the initial rate of discharge in litres/min?
10. A rectangular weir 3 m long has a head over the crest of 1.3 m. If Cd = 0.62, calculate the flow in litres/min (neglecting end contractions).
11. What is the formula for discharge over a 90° vee-notch in m^3/s? If the head over a notch is 230 mm and Cd = 0.61, what is the flow in litres/min?
12. A solvent (SG = 0.69) flows at a rate of 40 litres per hour through a 6 mm I.D. pipe. Calculate the Reynolds number and state what deductions you would make

regarding the flow in the pipe. Take $\mu = 9.9 \times 10^{-4}$ N s m^{-2}.

13. You require to pump water at 400 litres/min through 110 m of new 25 mm galvanised pipe. What will be the total head loss if the line contains six standard elbows and a gate valve (use standard head loss tables).
14. 45 litres per minute of olive oil at 30°C flows through a smooth pipe of 25 mm dia. Find the pressure drop in kN/m^2, per 100 m of pipe. Take SG = 0.92 (at 30°C), and viscosity at 30°C = 9.1×10^{-2} N s m^{-2}.
15. If 0.056 m^3/s of water at 20°C flows in a 150 mm pipe, what is the head loss in 100 m of pipe if the pipe has a uniform absolute roughness of 0.003 m. Assume viscosity = 0.0009 N s m^{-2}.
16. Calculate the head loss per metre in a 0.89 mm diameter microtube if the required flow is 5 litres per hour. Assume (if needed) that e = 0.015 mm, and f = 1.002×10^{-3} N s m^{-2}. If the lateral pressure is 3 bar, how long would the tube need to be? Is the flow lamina or turbulent?
17. Water flows under gravity through a 25 mm ID polythene pipeline from a reservoir at a RL of 65 m as shown in *Figure 5.18*, to a trough at a RL of 30 m. The pipe rises to a RL of 52 m to pass over a hill 233 m from the reservoir. The trough is equipped with a ball valve having flow characteristics as follows when fully open.

Flow (litres/min)	18	36	53	67
Head loss through valve (m water)	1.5	5	9	15

Calculate the pressure in the pipe at the rise X when the ball valve is open in bars. Is this situation desirable?

18. If the pump delivery pressure is 300 kN/m^2 what will be the water power in kW when the flow is 3.4 m^3/min?
19. A small rotary pump delivers 45 litres/min of brine (SG 1.2) against a head of 6.7 m. What will be the input power if the pump efficiency is 30%?
20. A pump has the following characteristics:

Discharge (litres/min)	40	60	80	100
Total head (m)	55	45	34	21

It is used to pump water through a 40 mm pvc pipeline 1000 m long to a reservoir against a static head of 20 m. Draw the system curve and find: (a) the operating point, (b) the power of the driving motor if the pump efficiency is 50%.

21. In a farm supply, water is to be lifted from a dam by a pump and delivered to a hillside reservoir 500 m away and 23 m above the dam. A pump available for this installation has the following characteristics.

Discharge (litres/min)	45	53	62	71	80	89
Total head (metres)	42	40	38	36	34	32

If friction loss is allowed to equal 60 per cent of the static lift, determine: (a) Size of pipe to be used (compare types), (b) the pumping rate, (c) the power output of the electric motor if the pump efficiency equals 55%, (d) the reverse flow rate if the pump and foot valve are removed for servicing.

22. Set out the Bernoulli energy equation and define the terms. In the case of fluid flow in pipes how do pump energy and friction loss affect the equation?
23. An electric deepwell submersible pump has the following characteristics:

Flow (litres/min)	18	36	53	71
Total head (m)	83	80	74	60

You propose to use this pump in a farm water supply scheme from a well through 185 m of pipe to a pressure tank located 18 m above the well water level. Calculate the minimum size of pipe required if the pressure in the tank is to be maintained at 3.1 bars (gauge) when the continuous draw off is at least 53 litres/min (neglect velocity head). Assuming this pipe size and type what would be the continuous flow in the system if the tank pressure dropped to 2.38 bars (gauge)?

24. A planned cowshed effluent disposal system incorporates a "mono" screw type pump drawing from a sump and discharging through 335 m of flexible 50 mm pipeline to an effluent sprinkler. The pump is a positive displacement pump with a discharge of 135 litres/min. The sprinkler characteristics, as quoted by the

maker, are:

Head (metres)	1.7	3.3	5	6.7	
Discharge (litres/min)	75	140	190	215	

Head loss data for the pipe is as follows:

Flow (l/min)	45	90	135	180	220
HL (m/100 m)	0.35	1.7	3.7	6.5	9.8

Calculate: (a) the velocity of the effluent in the pipeline, (b) the head which the pump will develop in operation, (c) the power rating of the motor assuming a pump efficiency of 25%.

25. The following readings were taken during a test on a pump. The flow was measured by a vee-notch, the equation for which is $Q = 1.42\ H^{2.5}$ m^3/sec where H is the head over the notch, in metres.

Head over notch, mm	153	203	254
Pressure at pump outlet, bars	1.72	1.21	0.75
Suction lift, bars	−0.20	−0.21	−0.23

Plot a performance curve for the pump. The pump is used to pump water through a 150 mm pipeline 300 m long against a static head of 9 m water. Friction data for 100 m of 150 mm pipe is as follows:

Flow, (litres/min)	670	1560	2450
Friction, (m/100 m)	0.3	1.74	3.85

Draw a system curve and establish the operating head and discharge.

26. A pump operates at 1470 rpm absorbing 0.1 kW and delivering 30 litres/min at 10 m head. If the speed is stepped up to 2940 rpm what will be the new corresponding conditions?

27. A 13 mm diameter commercial steel pipe 15 m long is used to drain an oil tank. Determine the discharge when the oil level in the tank is 2 m above the exit end of the pipe. Assume $\mu = 5.3 \times 10^{-1}$ N s m^{-2}, $p = 800$ kg/m^3, and $e = 0.00005$ m (hint: assume laminar flow).

5.26 AIMS OF THIS CHAPTER

After reading this chapter and trying the problems you should be able to:

1. Explain why a study of water is vital to agriculture and horticulture, giving examples.
2. Solve problems in hydrostatics involving pressure, Pascal's law, and buoyancy, and describe devices which use the principles of hydrostatics.
3. Distinguish between gauge, absolute and atmospheric pressure, explaining each and describing ways of measuring them.
4. Apply the Continuity equation and Bernoulli's equation to solve problems involving the flow of water in pipes.
5. Discuss methods of measuring flow rates in pipes and open channels, including streams.
6. Explain the term head loss, and use tables or the Moody diagram and Darcy's equation to calculate the head loss in pipes.
7. Use the concepts of the hydraulic grade line and the residual head to design simple water supplies and select pipe sizes for particular applications.
8. Draw and use the system curve for a water supply, and establish the operating point for a given pump.
9. Discuss water sources, and the implications for practical supplies.
10. Describe and compare various types of pumps, listing their characteristics and drawing their performance curves.
11. Outline the main features and requirements for an effective bore water supply.
12. Outline the main features and requirements for an effective farm dam water supply.
13. Describe methods of controlling pumps.
14. Discuss the use of various types of valves.
15. Discuss the requirements of plants for water, and the relevance of soil properties in the design of an irrigation system.
16. Describe different irrigation techniques, including sub-surface, surface, sprinkler, and trickle irrigation systems.
17. Outline the requirements for a fertigation system.
18. Complete an irrigation design and scheduling project for an orchard or greenhouse, including the determination of the pressure requirements in trickle irrigation systems using Jobling's polyplot method.

19. Describe the problem and factors which cause water hammer, and suggest possible solutions.
20. Describe methods of draining land.

5.27 REFERENCES

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Electricity and Electronics

Chapter 6

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6.1 INTRODUCTION

In this chapter the principles of electronics are discussed. The intention is not to make farmers or growers into electronic engineers so much as to create an understanding of some of the key factors which need to be considered in the selection of equipment. Salesmen sometimes seem to create an element of mystery about their electronic products, which implies that it is beyond the intelligence of the average farmer. In fact a good appreciation of one or two key facts combined with an understanding of some of the jargon enables most people to be capable of holding a sensible conversation with a reputable salesman. The ultimate objective of this chapter is that it will help the reader to be able to discuss and select electronic equipment on a sound basis.

Modern electrical equipment offers great opportunities to practical horticulture and agriculture. New automatic equipment has come onto the market, including greenhouse controllers, grain moisture sensors, tractor performance monitors, automatic cow sensing and drafting apparatus, automatic milking systems, and microprocessor based devices for controlling equipment, and recording information such as cow health, performance, milk yield, or weight gain. Now and in the future there will be many situations where you can use electronics to save time, effort and money. While the ability to design electronic equipment is not the aim here, you should certainly be able to understand the capabilities of electronic systems a little better.

Electronic systems are available to the user at various levels of sophistication and completion. At the lower end of the scale it is possible to buy kitsets which can be built up to perform various functions such as burglar alarms, calculators, amplifiers, radios, intercoms, water level indicators, electronic organs, snooze alarms, games, and even computers. The only skills required to make these sets is the ability to use a soldering iron, and to recognise circuit components. Some of these could well be of use to the farmer. At a more sophisticated level (and price), fully engineered systems are available for specific tasks. These should have been thoroughly developed and tested before they are marketed, and full details of the method of operation should be supplied with the equipment. The buyer should certainly inspect the documentation at leisure before committing themselves to the equipment, and should be satisfied that the equipment does do what is claimed. In many cases the seller will include a training session as part of the sale, and may also undertake a consultancy service (free or otherwise). These points should be clearly defined in the purchase agreement beforehand.

Now that digital electronics is so well established in the form of computers and microprocessors, there are four categories of electronic product which one can be offered. The first of these is *Hardware*. This is the real equipment itself, the electronic black box which does all the work. For example hardware includes the computer, the printer, the screen, cables, sockets and plugs. The second is *Software*. This product can only be used on equipment which can be programmed to do one or more functions. Software consists of the programs which must be loaded into the computer in order to instruct the electronics on what to do.

In some equipment some of this software can be already installed in the machine in the form of special components where instructions have been placed. These cannot be removed or replaced except by removing the component. This is often called *Firmware*.

The final type of product is called *Vapourware*. I am not referring to any particular name or firm by this term, but rather in general to equipment (which may be hardware, software or firmware) which "will be available in a month or two". This equipment forms such a large part of some sales promotions that it merits a name of its own. Vapourware can possess a number of features: it is rarely available when promised, it never ends up doing quite what it is supposed to, there are always one or more faults (bugs) when it arrives, and each fault is only discovered after hours of wasted work by the purchaser. It is in the nature of electronic development work that the production of a reliable system takes much longer than anticipated, and therefore it is a good idea to purchase only what is actually presented in its final form, in an "up and running" condition. The only exception to this

rule would apply to reputable companies who will work to the purchaser's specification.

Other points to ensure when selecting electrical equipment are first, that there is a guarantee lasting at least three months and preferably longer. If a component is going to fail it is most likely to do so during the first month or two of operation, and the guarantee should cover this. Second, the purchaser must be very sure that the equipment will do the required task before the purchase is completed. For example, there have been a number of cases where firms have purchased expensive custom made computer systems, complete with preliminary training, but where the customer has not realised that the system has significant shortcomings for some months after the purchase (often because minor changes to the program are called for at the start which inevitably take time to make). In this situation the customer can end up with a very expensive and useless piece of equipment, and the cost of fixing the problem may well be beyond the pocket of the buyer. On expensive equipment trial periods are not an unreasonable arrangement prior to purchase. This will not detect every error or defect, but will at least ensure that the system (and the operator) can handle all the main parts of the work properly.

Having made these comments, let us now go back to the start and describe the models which work well in describing the phenomenon of electricity.

6.2 FUNDAMENTAL PRINCIPLES OF ELECTRONICS

Electricity arises from the flow of electrons along a conductor. Because we cannot see the electrons with our eyes, electricity can appear to be quite complicated. However we can use models to describe what we think is happening, and as long as the model describes what happens in reality, we can use ideas which we are more familiar with. In the model to describe electrical behaviour, there are three main factors which we use. These are the current, the voltage, and the impedance (or resistance). We will describe them and relate them to the behaviour of water flowing in a pipe, since the similarities are considerable. Fluids have already been discussed earlier in this book and so the comparison should help you to understand electricity. Of course, your electricity studies could help your understanding of fluids! *Figure 6.1* shows a basic electrical circuit, with the equivalent fluid circuit underneath. What flows is electrons and water respectively. We will describe each of the three parameters of our model of electricity, and relate it to the fluid equivalent.

Current

In electrical flow, electrons make up the flow or current through the wire. Current is measured in amperes or simply amps. One amp is the equivalent of 6.06×10^{18} electrons passing per second. It is worth emphasising that it is only the flow of electrons through a component that is important, and that electrons are not stored in components or wires to any great extent.

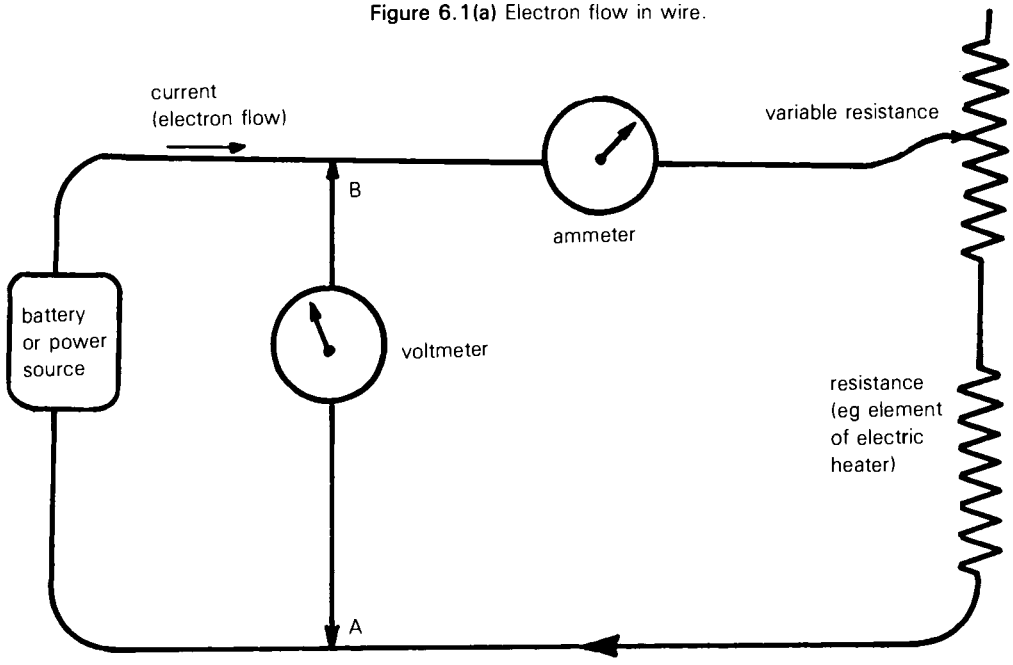
The equivalent of an electrical current in fluids is the flow rate, ie the amount of water passing through each component per second. Neither water nor electrons can be created or destroyed. Some storage is possible in special components built for this purpose, such as a tank in fluids, and a capacitor in electricity. However, in general whatever amount flows into a wire, pipe, or component, must at the same time be flowing out of the other end. Current is measured with an ammeter, which is connected in the circuit as shown. A flowmeter is its fluid equivalent.

Voltage

The voltage is the driving "force" which causes the current to flow through a circuit. Measured in volts, the voltage is produced by the source of power, which may be a battery, a generator or alternator driven by an engine, or the mains power supplied by the National Electricity Board and delivered through the wall socket in your home or farm.

The voltage drives the electrons through the components, overcoming the impedance (resistance). In fluid circuits the pressure or head has the same effect. The voltmeter measures the voltage between two points. It can therefore measure the voltage at a point relative to a reference point, such as the negative terminal of the power source. This is quite often taken as zero volts. In *Figure 6.1a* it is measuring the voltage at point B relative to point A. By comparison the

Figure 6.1(a) Electron flow in wire.



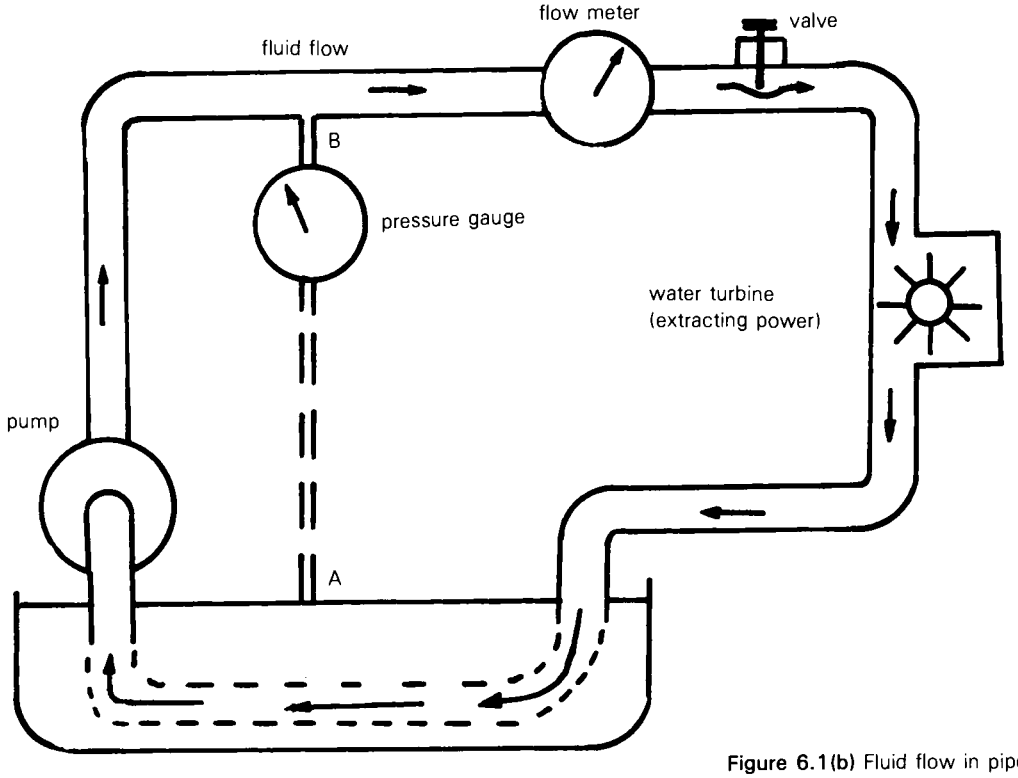


Figure 6.1(b) Fluid flow in pipes.

pressure gauge is measuring the pressure at point B. It is actually the gauge pressure (ie, above or relative to atmospheric pressure, which is what the pressure is at point A in the fluids case). If the voltage does not change with time it is known as a *Fixed* or *DC voltage*. If it does change rapidly with time (eg as in the national mains power supply) it is called an *AC voltage* (DC and AC stand for Direct Current and Alternating Current respectively).

Resistance

Resistance is a measure of the ability of a material to reduce the current flowing through it. It is measured in ohms. The symbol often used for ohm is Ω. All materials resist or impede the flow of electricity (with the exception of some very pure materials at very low temperatures (ie below $-190°C$) called superconductors), although the extent varies widely. Materials with low resistances, such as copper and other metals, are called *Conductors*, while high resistance materials such as plastics are *Insulators*.

When water flows through a system, pipe friction restricts the flow, reducing the head. In much the same way, circuit components impede the current, causing a drop in voltage as the current passes through. In addition valves and other components also reduce the flow. By turning the valve the resistance to flow can be adjusted, thereby altering the head loss through the valve and controlling the flow rate. The equivalent of a valve is a potentiometer (a "pot"), which is simply a variable resistance. As the resistance increases the voltage drop increases across it, and this has the effect of limiting the current. Resistance impedes current flow, and is referred to as one form of *Impedance*.

One major difference between water systems and electrical systems is as follows: in electricity, although the wires connecting components together have a finite resistance, in practice we usually ensure that they are big enough in diameter so that their resistance is negligible compared to that of the components. The main resistance to current flow comes from the circuit components (such as resistors). Thus there is no voltage drop in the wires in *Figure 6.1a*, and the voltage across the resistance is the same as the voltage generated by the battery. As we shall see, useful things only happen when the current flows through a circuit component with some resistance, so the fact that the current is impeded is very useful and important. In comparison pipe friction is almost always an important factor in fluid flow design (and cannot be ignored), but is something we could usually do without!

The inverse of resistance is called the *Conductivity*. The unit of conductivity is the mho.

6.3 OHM'S LAW

Ohm's Law is a simple mathematical model of the relationship betwen the three parameters. It states that the current (I) in a resistive circuit or component is equal to the voltage (V) divided by the resistance (R). It was discovered early in the 19th Century by George Simon Ohm.

$$\text{Thus } I = \frac{V}{R} \qquad \textbf{Equation 6.1}$$

where I is in amps, V in volts, and R is in ohms (this is another major difference between fluids and electricity: in fluids the relationship between flow, head loss, and pipe friction is much more complicated). Ohm's Law applies to any resistive component or group of components and, as we shall see, with minor clarification of the terms, also applies to many other electrical components, and to situations where the voltage is varying rapidly. Do not be fooled by the apparent simplicity; it is a very useful relationship, and well worth getting to understand better. It is the equivalent to all the head loss tables in fluids put together!

Example

A farmer uses a 12 volt battery to power a torch. If the bulb has a resistance of 6 ohms calculate the current.

Solution: apply Ohm's Law:

$I = V/R = 12/6 = 2$ amps

Ohm's law is fundamental to all aspects of electricity and electronics. It is a very simple law but it can take a while to really appreciate what it means. It says that when any two of V, I, and R are known then the other is automatically fixed. So if we know the resistance of a device and the applied voltage, we know the current. Equally well, whenever

the current and resistance are known, the voltage can be calculated. This is a very useful fact, since often when we are designing circuits these values are known. Ohm's law applies to whole circuits, to combinations of components, and to each individual component in a circuit.

Example

The current flowing through a resistance of 20 ohms is 5 amps. What is the voltage drop?

Solution: $V = I\ R = 20 \times 5 = 100$ volts

This means that the voltage must be 100 volts lower on one side than on the other. Using the fluids analogy, in order to get a required flow (current) through a particular pipe with a given friction factor (resistance) the head (voltage) loss must be a fixed value (which can be found from head loss tables).

Example

A current of two amps flows through the resistances shown in *Figure 6.2a*. If the voltage at A is 500 volts, what will the voltage be at B and C?

Figure 6.2 Resistances in series.

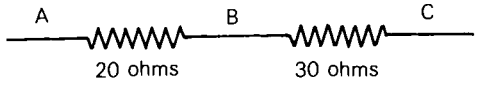


Figure 6.2(a) Two resistances in series.

Solution: apply Ohm's Law to the 20 ohm resistance:

$V_b - V_c = 2 \times 30 = 60$ volts

$V_c = V_b - 60 = 460 - 60 = 400$ volts

6.3.1 The effect of conductors on a circuit

In practice, all conductors offer some resistance to the flow of current. The wire used must be acceptable to meet the needs of the particular circuit. Resistance in the conducting wire depends upon the length of the wire, the cross-sectional area of the wire, and the temperature of the wire. In any circuit, the smallest wire that will not create too much voltage drop is normally used to reduce costs. Excessive resistance due to length, insufficient cross-sectional area, or high temperature can reduce voltages and hinder the normal performance of electrical equipment. It can also produce heat, causing the wire to get hotter. If the wire gets too hot, the insulation will also be damaged. This is why selection of the proper wiring is so important. Cables are rated in terms of their maximum allowable current (*Table 6.1*).

6.3.2 Resistances in series and parallel

When a current flows through a series of resistances, it is like water going through a series of pipes. The resistances simply add together, so that the total resistance of the circuit is the sum of all the resistances. We will use the example in *Figure 6.2b* to specify this.

Table 6.1 Current ratings of standard flexible cables

Maximum Current rating (amps)	Cross-sectional area (mm^2)	Resistance (ohms per km)	Number of strands	Diameter of strand (mm)
6	0.75	26.7	24	0.20
10	1.0	20.0	32	0.20
15	2.5	13.7	30	0.25
20	2.5	8.12	50	0.25
25	4.0	5.09	56	0.30

Let V_a = voltage at A, V_b = voltage at B, and V_c = voltage at C.

Voltage drop across 20 Ω resistance = $V_a - V_b = 20 \times 2 = 40$ volts

Hence $V_b = V_a - 40 = 500 - 40 = 460$ volts

Next, applying Ohm's Law to the 30 ohm resistance:

Example

A farmer runs a shearing shed using a cable connected to a 230 volt power supply (for now we will assume that the voltage is constant at this level). The cable has a resistance of 20 ohms per km, and is 1000 m long. The shearing equipment has a total

resistance of 100Ω. What will the actual voltage across the shearing equipment be?

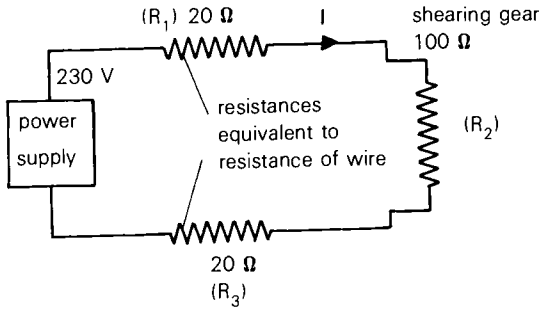


Figure 6.2(b) Equivalent circuit for shearing gear with cable.

Solution: First we need to know the current flow. To find this we need to know the equivalent resistance of the whole circuit.

This is just $R_{Tot} = R_1 + R_2 + R_3$

Equation 6.2

Where R_2 is the voltage across the shearing equipment, and R_1, and R_3 are the resistances of the wire carrying the current out and back respectively. Since the length is 1km, $R_1 = R_3 = 20\Omega$.

Thus, $R_{Tot} = 20 + 100 + 20 = 140\Omega$

Now apply Ohm's law to the whole circuit

$$I = \frac{V}{R} = \frac{230}{140} = 1.643 \text{ amps}$$

This current will flow through all three resistances. To find the voltage drop across the shearing equipment (R_2) we apply Ohm's law to it alone.

Thus $V_2 = I R_2 = 1.643 \times 100 = 164.3$ volts

If the resistances are in parallel, then the reciprocal of the total resistance is given by summing the reciprocals of each resistance. Thus:

$$\frac{1}{R_{Tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Equation 6.3

for three resistors (*Figure 6.3*). From this R_{Tot} can be found by inverting the result. This circuit is important when we consider electric fencing later in this book. In passing let us note that this "reciprocal" model is also very useful in a number of totally different situations, such as in modelling the heat flow through walls in buildings.

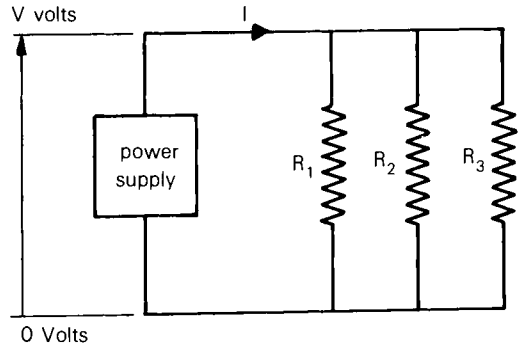


Figure 6.3 Resistances in parallel.

6.4 POWER AND ENERGY CONSUMPTION

When a current flows through a resistance, work is done by the voltage. The rate of doing this work is the power (P), which is found by multiplying the voltage drop across the resistance by the current, or:

$P = V I$ **Equation 6.4**

where P is in watts.

Thus, in the earlier example of the torch (12 volts and 2 amps), the power is given by:

$P = 12 \times 2 = 24$ watts

Power is measured in watts. The power output of many components is a very important value; light bulbs are purchased by their wattage, which indicates how much light will be given off. Heaters are also rated according to the power they will emit. In all electronic components some energy is absorbed and the power is given off as heat. This causes the component to heat up, and unless it can lose the heat to its surroundings it will overheat and self-destruct! Therefore there is always a limit to the power which any component can absorb, and so the voltage and current must be kept below specified values. Most resistors used in electronics only have a power rating of 0.25 watts, since the currents are small. However larger resistors can be obtained if higher power components are needed.

Example

A 100 ohm resistor has a rating of 0.25 watts. What is the maximum voltage which can be applied across it?

Solution: $P = V I = 0.25$

But $V = I R = 100 I$ **Equation 6.5**

Hence substituting for I gives

$$V_{max} = \frac{100 \times 0.25}{V_{max}}$$

so $V_{max} = 5.0$ volts.

From *Equation 6.5* the current will be only 0.05 amps in this case.

Some components require metal fins or heat sinks to be attached to them so that the heat can be conducted and convected away. In some equipment a fan is used to blow cooling air over the components to prevent overheating.

Example

Which will produce more power: a 200 Ω resistor or a 20 Ω resistor (connected to 230 volts)?

Solution: Substituting for I between *Equations 6.1* and *6.4*, gives:

$$P = \frac{V^2}{R}$$

Thus for the 200 Ω resistor the power is 52,900/200 = 264 watts, while the 20 Ω resistor has a power out put of 52,900/20 = 2,645 watts. In the latter case the current will also be ten times bigger (11.5 amps).

At this point, we will defer further discussion of power to the next chapter.

6.5 BATTERIES

Batteries are a convenient source of electrical power. In one form or another they are used extensively in rural industries, because they provide power without the need for connection to the mains electricity supply. Batteries are found in almost all forms of transport as a means of starting the engine and igniting the fuel. Batteries consist of one or more cells. Each cell produces a small fixed voltage (eg 1.5 volts from a lead-zinc battery), and to produce higher voltages the cells must be connected in series.

To obtain the maximum life from a battery regular checking and maintenance is needed. Many batteries will last longer if they are maintained properly. There are two common types of battery. A primary cell converts chemical energy to electrical energy, but is not rechargeable. As electrical energy is drawn from the battery, the chemicals are gradually used up until they become exhausted. The primary battery then has to be replaced. In comparison, Secondary cells can be charged and discharged. When electrical energy is fed into this type of cell it is converted to chemical energy and the cell is in the charged state. When electrical energy is drawn from the cell chemical energy is changed back to the original form until no further useful power can be taken. The cell is then discharged (flat), and must be recharged again.

There are two common types of secondary cell batteries. These are lead acid, and nickel cadmium. Because of cost, lead acid batteries are usually chosen for vehicle electrical systems. Nickel cadmium batteries are expensive but can have a much longer life than the lead acid type. They are available as rechargeable batteries for lanterns, camera flash guns and portable TV sets, as well as a few cars.

6.5.1 Lead acid batteries

The construction of lead acid batteries has improved considerably over the past few years, allowing a significant reduction in size. The basic construction, however, remains the same (*Figure 6.4*). Each cell contains a positive terminal called the anode, which is connected to plates of brown lead dioxide (PbO_2) on a matrix of lead. The negative terminal or cathode, has spongy lead plates on a lead matrix. The plates are made from a thin grid of lead alloy which holds the active material. This is pressed on, in the form of a paste. Both anode and cathode plates are similar when first manufactured, and only differ after the battery has been put through a conditioning procedure. This is normally done before the

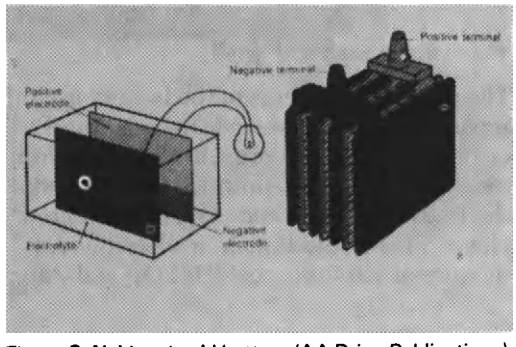


Figure 6.4(a) Lead acid battery (AA Drive Publications).

battery is purchased. The grid also conducts the flow of electric current during charge and discharge. The active materials (the lead dioxide and the spongy lead) can be easily polluted or cracked from their mountings on the lead matrix if the battery is handled carelessly.

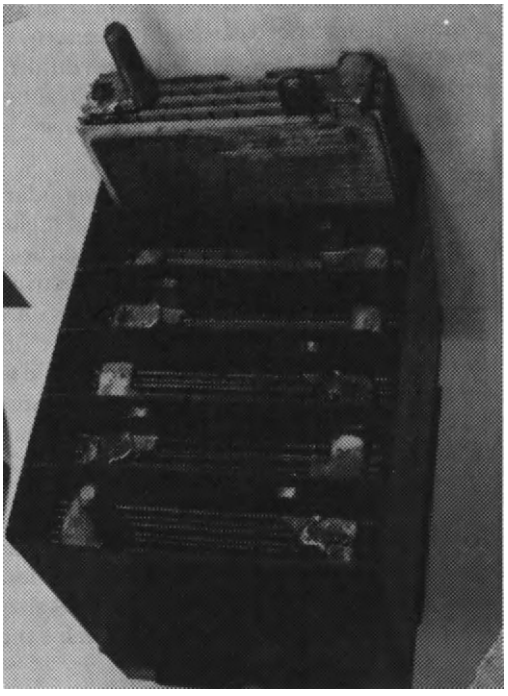


Figure 6.4(b) Lead acid battery.

The other components of the battery are the separators, which are made from porous PVC or fibre glass. These prevent the plates from touching each other. However they also allow the free flow of acid and current between the plates. Finally the liquid, or electrolyte, is a mixture of sulphuric acid (H_2SO_4) and water.

Discharge cycle

When power is drawn from the cell the sulphuric acid acts on both plate materials to form a new compound, lead sulphate ($PbSO_4$). As these sulphate crystals are formed on the plates the acid becomes less concentrated and less dense, until the point is reached when no further useful power can be drawn from the cell. The state of charge can be checked with a hydrometer (a device which measures the density of the liquid and hence indicates the concentration of the acid).

The reactions are as follows: at the positive lead oxide plate:

$$PbO_2 + 4H^+ + SO_4^{--} + 2e^- = PbSO_4 + 2H_2O \qquad \textbf{Equation 6.6}$$

and at the Cathode:

$$Pb + SO_4^{--} = PbSO_4 + 2e^- \qquad \textbf{Equation 6.7}$$

Thus, at the cathode, electrons (e^-) are generated which flow through the external wire circuit to the anode, where they are used in the reaction.

The process of discharge forms crystals of lead sulphate on the plates. The longer and more complete the discharge, the larger the crystals. When the battery is recharged ideally all these crystals should be removed. If the battery is not fully charged to remove all the lead sulphate, then the next discharge will form crystals on the sites of the old crystals. These sites become hard and progressively more difficult to remove by subsequent charging. The crystals become progressively harder and larger, eventually resulting in the "sulphation" of the plates – which means that the active material is permanently converted to the run-down condition. Large crystals may also crack the active material off the plate, thus forming a useless inactive sludge at the bottom of the battery.

Charge cycle

Passing an electric current into a discharged cell will reverse the discharge cycle. Lead sulphate is converted to spongy lead peroxide on the positive plate and spongy lead on the negative plates. At the same time the acid will rise in concentration (and hydrometer reading) and will return to the original strength.

A good guide for charging is to charge at no more than one-tenth of the ampere hour capacity of the battery. For example, for an 80 ampere hour battery, charge at 8 amps. This keeps the battery temperature low and prevents damage. Batteries produce gases which are potentially dangerous, both during charge and discharge. Charging is particularly dangerous, as both hydrogen and oxygen are produced. This mixture is explosive so charging bays should be well ventilated. Naked lights and welding equipment should not be used near charging or recently charged batteries.

Maintenance

For longer battery life, all lead acid batteries should be charged regularly (at least every two to three months) and never allowed to be discharged excessively. They should also be kept toppped up so that the plates are always under the liquid. The active material on the plates can be polluted and inactivated by even very small traces of some metallic salts present in tap and other water. Therefore distilled water should be used for topping up. Some batteries are now produced as sealed units. These do not need to be topped up. However the manufacturer's guidelines should be studied before recharging them.

6.5.2 Nickel cadmium batteries

These batteries produce only 1.2 volts per cell. Unlike lead acid batteries, normally the purchaser must charge them before they can be used for the first time. Longer life is obtained with this type if the batteries are completely discharged before recharging.

6.6 TYPES OF CIRCUIT COMPONENTS

There are numerous types of circuit components available and in use. However there are only a few of major importance, and these will be described briefly below. These are shown in *Figures 6.5* and *6.6*, where the circuit symbol is given.

6.6.1 Resistor (or resistance)

The most common components in electronics are resistors. These are tube shaped, with one connecting wire coming out of each end, and can be easily identified by the coloured bands which indicate their resistance value (*Figure 6.6a*). Made from carbon, resistors are very cheap to produce, and are available with values from less than one ohm to several million ohms. The differences in resistance value are obtained by altering the carbon mix. As discussed above, due to overheating, ordinary resistors are only able to dissipate up to around a watt of power before they are damaged. Larger wire wound resistors can be obtained if a greater power dissipation is required, but these are rare. For most electronic circuits a quarter watt resistor is adequate, since the currents are quite small. Resistances obey Ohm's Law (*Equation 6.1*) under all

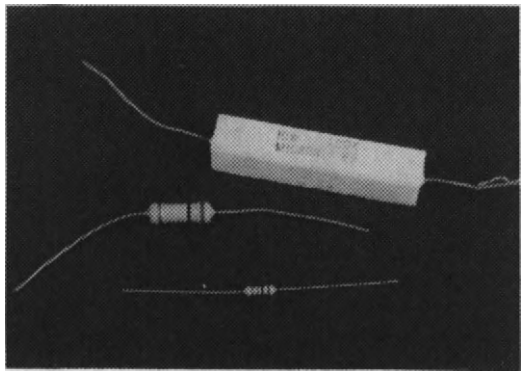


Figure 6.5(a) Resistor. The physical size affects the wattage: those shown will absorb (from the top) 10 W, 0.5 W and 0.25 W before overheating respectively. Their resistance is indicated by the coloured bands or by printing.

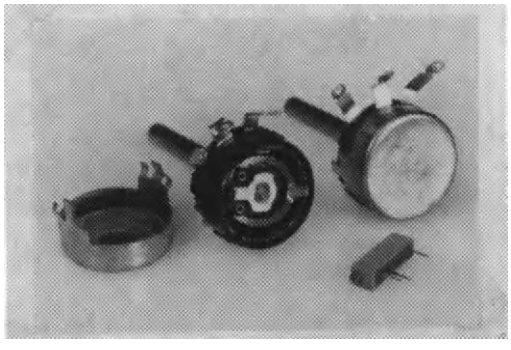


Figure 6.5(b) Variable resistances.

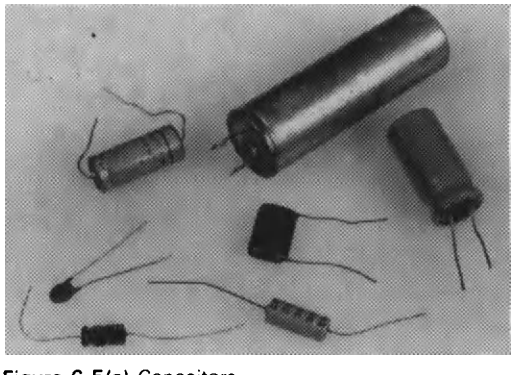


Figure 6.5(c) Capacitors.

circumstances, including the case where the voltage varies with time.

The resistance value of a resistor is determined from the coloured band markings on them. The bands can be seen easily from any position, and each colour represents a number as in *Table 6.2*. The code must be read starting with the band closest to the end of the resistor, and then proceeding towards



Figure 6.5(d) Valve

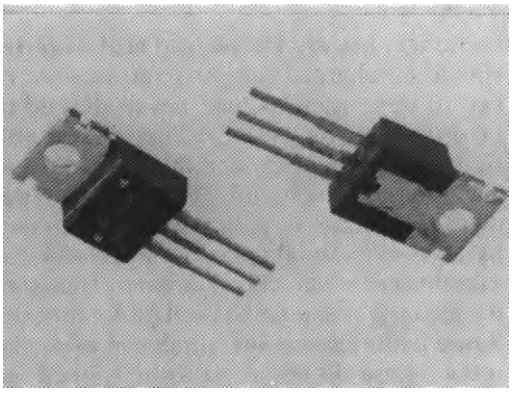


Figure 6.5(g) IC 7805 and 7912 power supply regulator.

the centre. The first two bands give the first and second significant figures of the resistance respectively, while the third gives the number of zeros which follow. For example, if the nearest band to an end is green, and the next is blue, followed by a red band then the resistance will be 56 × 10^2 = 5,600 ohms, or 5.6 kΩ. This is often abbreviated to 5.6 k.

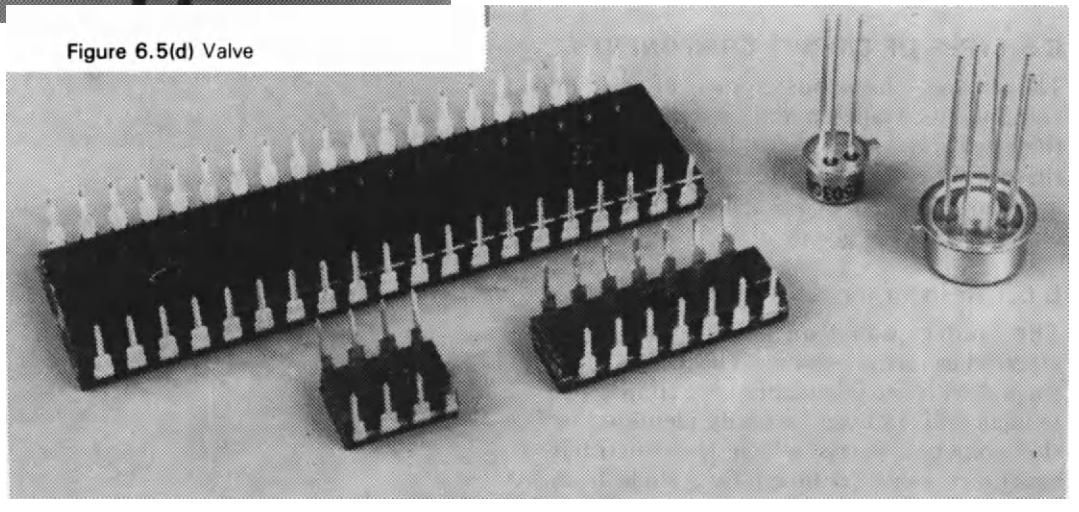


Figure 6.5(e) Integrated circuits.

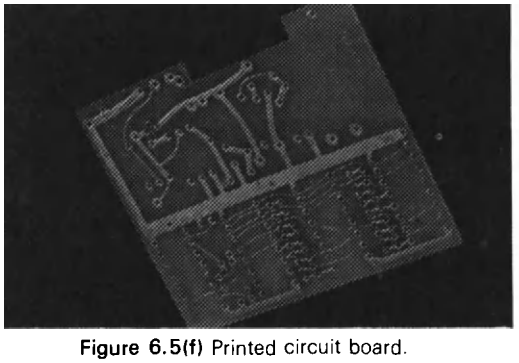


Figure 6.5(f) Printed circuit board.

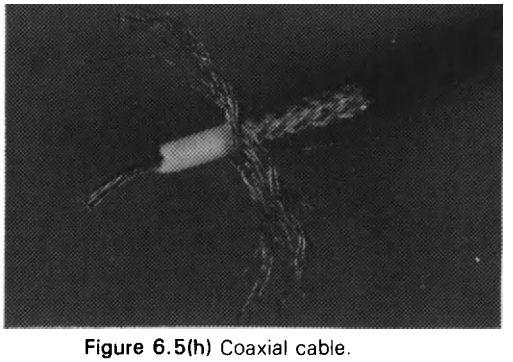


Figure 6.5(h) Coaxial cable.

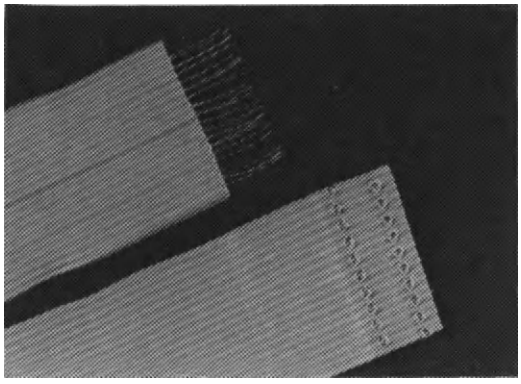


Figure 6.5(i) Ribbon cable. The lower cable has been clamped with an insulation displacement connector which has then been removed to show the connecting points.

Table 6.2 Colour code for resistances

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet (purple)	7
Grey	8
White	9

A fourth band is sometimes printed on the resistor to indicate the manufacturing tolerance; silver indicates a tolerance of 10%, while gold means 5%. These levels of accuracy are adequate for most applications, but tolerances of 2 and 1% are also available (indicated by red and brown tolerance bands respectively, often together with a further sizing band).

6.6.2 Variable resistor (or "pot")

Variable resistors (also called rheostats, potentiometers, or just pots) are frequently needed for control, adjustment or tuning purposes. They have three exterior connections, one of which is connected internally to a moving contact which slides along a carbon track. The other two are joined to the ends of the track. As the resistance depends on the length of track the current has to flow through before reaching the moving contact, the resistance between the middle connection and either of the other two depends on the position of the contact. A pot can therefore be used simply as a variable resistance in a circuit by making connections to two of the three external contacts. However, as the resistance does not alter between the two end connections regardless of the position of the sliding contact, the pot can also be used to apply a variable voltage to a circuit by connecting the end contacts to a voltage supply.

Pots are often used to control the volume and tone of radios and amplifiers, and for other controls. Often the pots are relatively large in size, about 30 mm in diameter, with a central spindle to which a knob can be attached (*Figure 6.5b*). However, smaller pots are also used on circuit boards, and these are rectangular in shape; a small screwdriver is required in order to adjust the resistance. This type is useful when a manufacturer wishes to make factory adjustments to a circuit, and does not want the purchaser to alter the setting subsequently.

Figure 6.6 Circuit symbols and conventions.

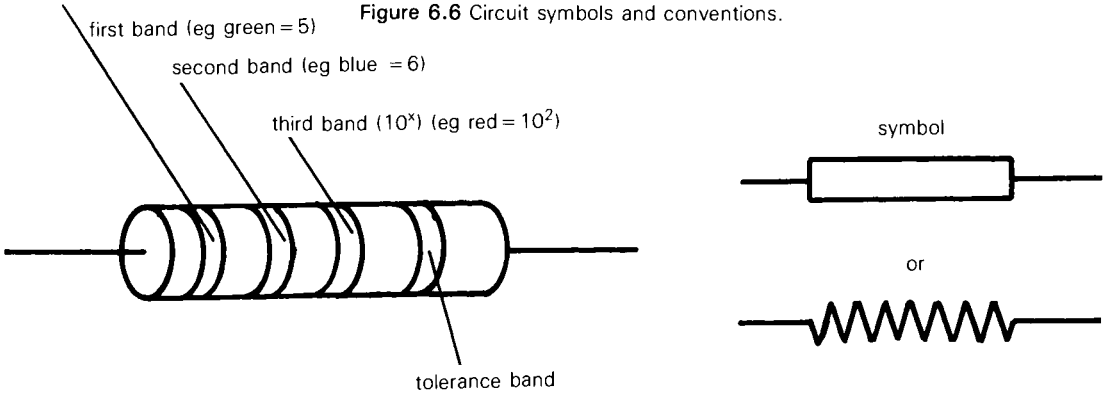


Figure 6.6(a) Resistor.

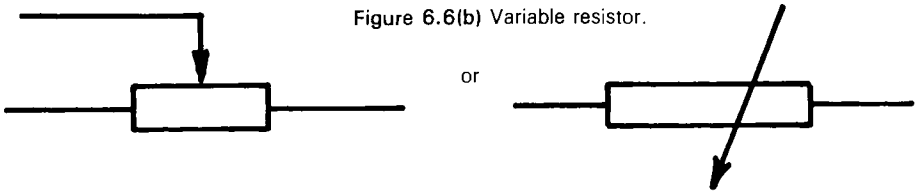


Figure 6.6(b) Variable resistor.

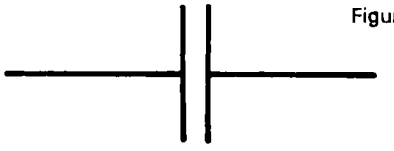


Figure 6.6(c) Capacitor.

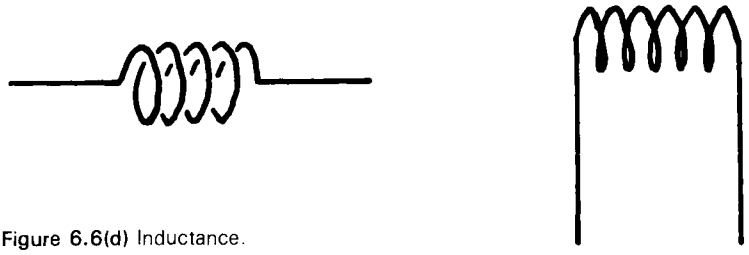


Figure 6.6(d) Inductance.

6.6.3 Capacitor (or condenser) Figure 6.5(c)

A capacitor consists of two metal plates with an insulator sandwiched between them. Electrons cannot flow through the insulator but they can flow onto the plates, when driven by a voltage. This results in the build up of a charge on the plates, causing a voltage to be developed within the insulating material. This opposes the voltage driving the electrons into the capacitor, and when the two voltages are equal the electron flow stops. The time required for this depends on how much charge the capacitor requires in order to develop the opposing voltage. In smaller capacitors only a small charge will cause a big increase in voltage, which can happen quickly, while in larger capacitors the time required to charge them fully can be quite long. Thus when a fixed voltage is applied to a capacitor, after a short time the current ceases, and the capacitor effectively prevents the flow of current. Another way of saying this is that the capacitor has a high impedance to a fixed or DC voltage. On the other hand, when the voltage is varying rapidly, the voltages will never be balanced for long and so there will be a current. In effect the impedance is smaller.

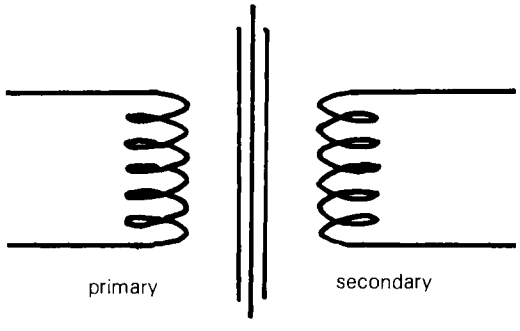


Figure 6.6(e) Transformer.

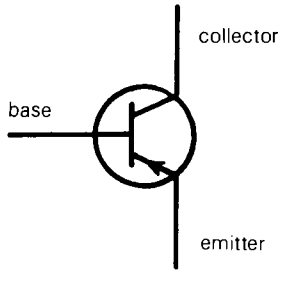


Figure 6.6(f) Transistor (pnp type)

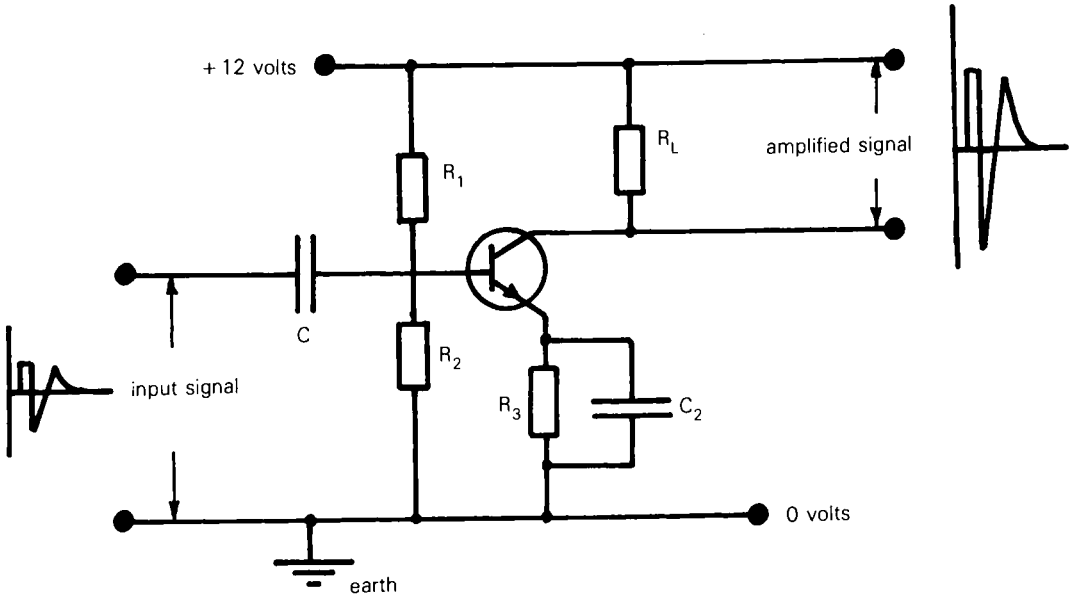
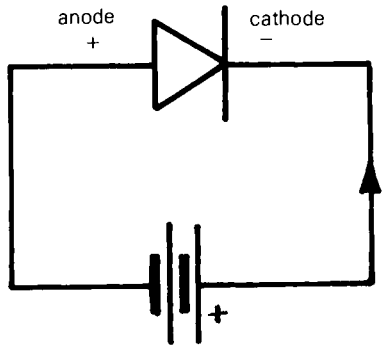
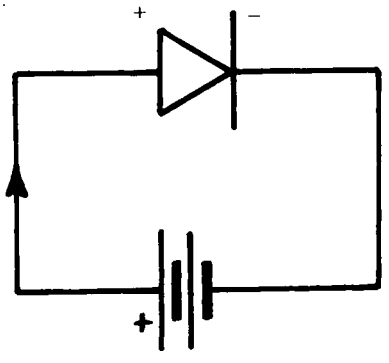
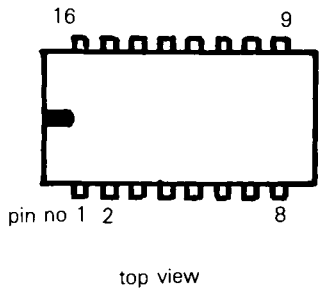


Figure 6.6(g) Simple amplifier circuit for npn transistor.

Figure 6.6(h) Diode.







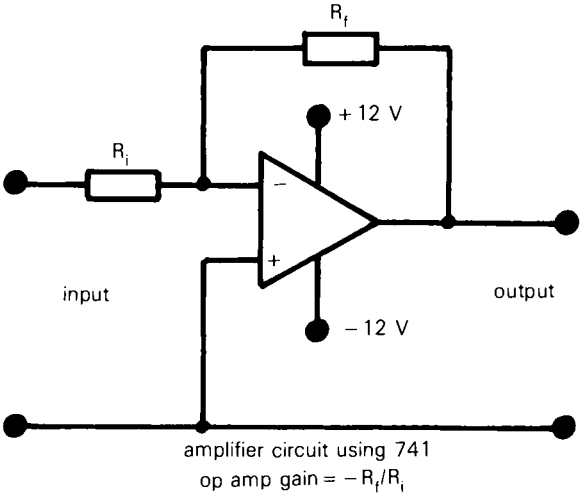


Figure 6.6(i) Integrated circuit.

The size of a capacitor is determined by its capacitance, which is measured in Farads. A farad is a very large unit and usually values are quoted in micro-farads (μF, or 10^{-6} farads) or pico-farads (pF, or 10^{-12} farads). In circuits capacitor values are generally in the range from a few pF to 100 μF.

Capacitors are made from various materials, and come in a range of different shapes and sizes. Ceramic and mylar capacitors make up the smallest types, while tantalum capacitors are generally used when values in the 0.1 to 100 μF range are required. They are polarised, which means that one terminal is marked as positive and must be connected to the positive side of the signal. In circuit diagrams this is clearly shown and it is important not to mix up the two connections. Ceramic and mylar capacitors are not polarised and can be connected either way round.

Electrolytic capacitors can be used when even larger sizes are needed. Thanks to improved manufacturing methods which increase the effective surface area of the plates enormously, they can be obtained in sizes as large as one farad. At this size the discharge time for small current drains can be great. Since modern computer memory chips use only a few microamps to retain information, electrolytic capacitors are very useful for maintaining the voltage on memory chips in the event of the loss of power (deliberate or otherwise), and thereby saving the information stored in them. They are usually marked with their size, and are coloured bright blue or grey. They are also polarised, and must be connected the right way round.

Capacitors obey a modified form of Ohm's Law. This is:

$$V = I Z_c \qquad \textbf{Equation 6.8}$$

where Z_c is the complex impedance, and is given by:

$$Z_c = \frac{1}{(j)\ 2\ \pi\ f\ C} \qquad \textbf{Equation 6.9}$$

where f is the frequency of the applied voltage, C is the capacitance of the condenser in farads, and j is the square root of -1. The last term j looks frightening to non-mathematical students; it need not worry us too much. It means that there is a "phase change" between the applied voltage and the resulting current, which we will discuss later.

It turns out that this rather odd mathematical model describes what happens just the way a good model should! For now note that something interesting happens to the current but that its size is given by *Equation 6.8* above. *Equations 6.8* and *6.9* mean that at high frequency the capacitor acts almost as if it had been replaced by a piece of conducting wire : it has a very low impedance. However, at low frequencies it has a very high impedance, and for fixed voltages the capacitor acts as if there were no connection at all: as if the wire had been cut. Condensers therefore act as high pass filters, allowing rapidly changing AC signals through, but cutting low frequency or steady voltages out.

Example

How would you cut out high frequency electrical noise from a power supply (or a slowly changing electrical signal)?

Solution: Put in a capacitor. We must connect it between the live wire and the earth return wire (*Figure 6.7a*). The capacitor acts as a short for high frequency signals, so they flow down it and are lost, while the slowly changing or fixed voltage signal carries on. This is a crude low pass filter. It will work only if the signal source has a high output impedance (see later).

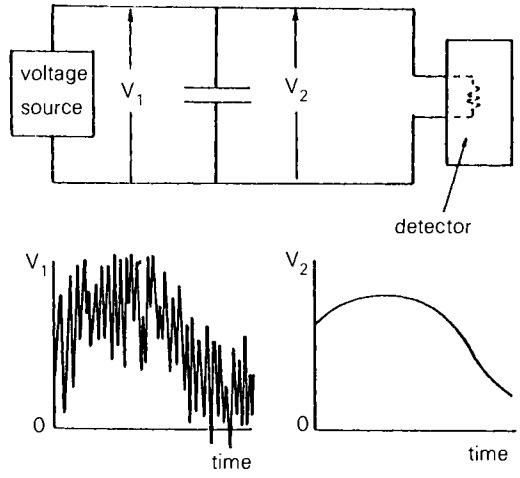


Figure 6.7(a) Elimination of high frequency noise.

Example

If you wanted to eliminate low frequency noise or fixed voltages from a signal how could you do it?

Solution: Again, using a capacitor will do this.

It will cut out the low frequency noise (and any fixed voltages), since it offers a high impedance to these, while it will allow the high frequency signal through. The capacitor therefore acts as a crude high pass filter (*Figure 6.7b*). Only the fast varying parts of the signal get through. This principle is often used in sound system amplifiers, since the sound is processed as a rapidly varying electrical signal.

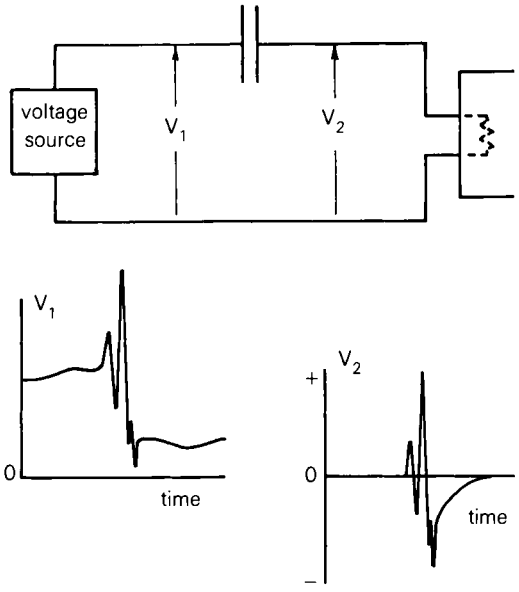


Figure 6.7(b) Elimination of constant voltages.

Inductor (*Figure 6.6d*)

An inductor is essentially a coil of wire or a solenoid. A magnetic field is set up inside the coil whenever there is a current flowing through the wire. What is a magnetic field, I hear you say? That is a good question: it is a model of what happens in the space around a wire carrying a current. We observe things happening near the wire, such as a compass needle being deflected. In order to explain what is happening we try to imagine something in the space around the wire which is affecting the needle. We call this a *Field* and we can even make models of it by drawing lines through the space, which follow the direction in which the compass needle would point. This model works very well in describing what happens. It is safer to avoid trying to think of what might actually be there.

Returning to the inductor with its surrounding magnetic field, when the current changes the magnetic field must also change, and this change is resisted by the field. Thus the inductor tries to oppose any change in the current. The inductor therefore has an impedance which increases as the frequency increases. It is given by:

$$Z_L = (j)\ 2\ \pi\ f\ L \qquad \textbf{Equation 6.10}$$

where L is the inductance in Henries. Again Ohm's law is then:

$$V = I\ Z_L \qquad \textbf{Equation 6.11}$$

The inductor offers no resistance to the flow of current, so long as the current does not change. Only if the current changes does the magnetic field get "upset" and try to prevent things happening. The faster the change (ie the greater the frequency of the changing voltage) the greater the impedance. The inductance is thus the complementary impedance to a capacitor.

Inductances are used in tuning circuits in radios and television. They are relatively uncommon in modern electronic circuits, but certain key components behave as inductive loads. In particular, transformers, relays, and electric motors behave in this way.

6.6.5 Transformer

A transformer is a device for stepping alternating (AC) voltage levels up or down (see next chapter). Thus in national electrical reticulation systems transformers are used to change the voltage level from the very high values on long distance transmission lines to the much lower voltages used for supplying consumers. The transformer consists of two coils "connected" by a laminated iron core (*Figure 6.6e*). Power (or the signal) is fed into the primary coil, and the output is taken from the secondary winding. The ratio of the voltages and currents in the primary and secondary depends on the number of turns of wire in each coil, and are given by:

$$\frac{V_{sec}}{V_{prim}} = \frac{N_{sec}}{N_{prim}} = \frac{I_{prim}}{I_{sec}} \qquad \textbf{Equation 6.12}$$

where N refers to the number of turns of wire in each coil.

The power transferred to the secondary is given by

$$\text{Power} = \frac{e\ V_{sec}\ I_{sec}}{V_{prim}\ I_{prim}}$$

Equation 6.13

where e is the efficiency of the transformer. Transformers can work only on continuously changing voltages.

The transformer is also used on circuit boards and in power supplies to reduce the alternating voltage from the mains to low values of a few volts which can then be rectified (converted to a constant voltage) and used to power electronic components. It also finds an application in providing high output voltages in electric fence energisers and in the coils of car engines. In these cases there are more turns on the secondary winding. Isolating transformers are safety devices which reduce the risk of electrical shock to users of power tools outside. These applications are discussed elsewhere.

6.6.6 Relays

A relay is a device which allows a small voltage output from a low power electronic control circuit to switch a much higher power circuit on or off. The relay can be purely electrical or electro-mechanical (*Figure 6.8*). The latter consists of a coil of wire wrapped around an iron core to form an electromagnet, which attracts a metal contact

Figure 6.8 Relay.

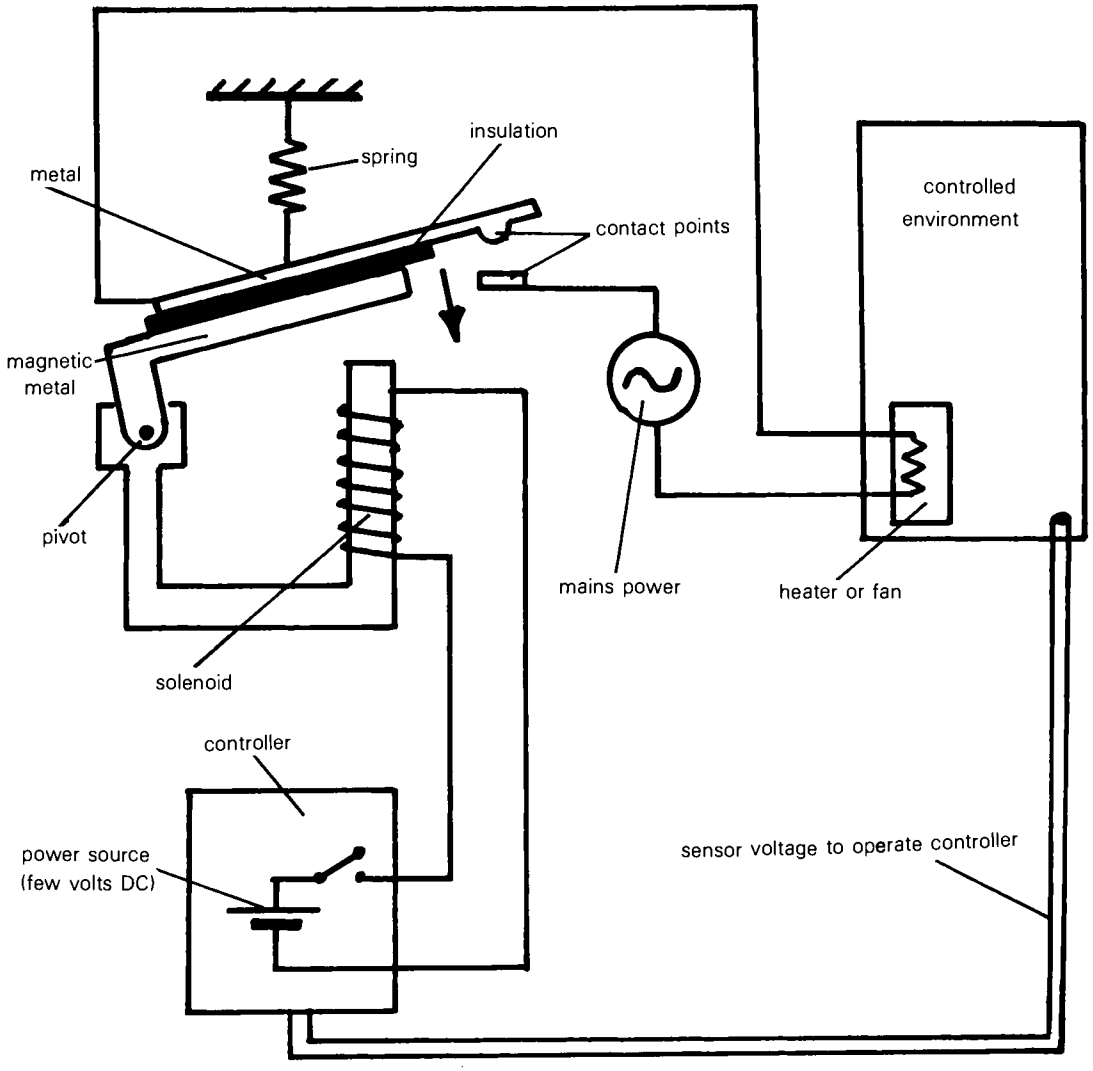


Figure 6.8(a) Electromechanical relay.

towards it when a current flows through the coil. The metal contact then closes the secondary circuit thus supplying power to the motor or other device being controlled. When the current in the coil is switched off, the contact moves back, breaking the circuit and switching off the power to the motor.

Electronic relays behave in a similar manner to transistors, where the small voltage applied to one terminal determines whether or not the relay allows current to pass across the other two terminals.

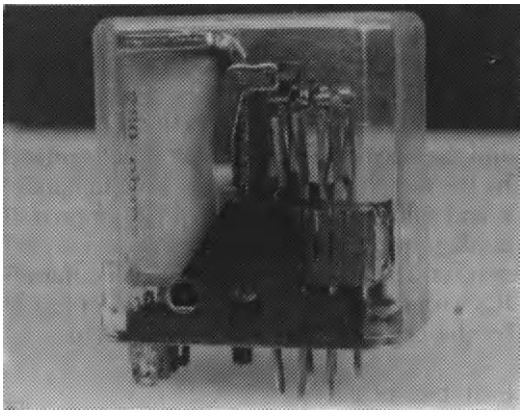


Figure 6.8(b) Relay for mounting directly onto a pcb.

Relays are available in a wide range of sizes, depending on the maximum current and voltage which flows through the secondary. Low power relays are available which can be mounted on a printed circuit board directly.

6.6.7 Thyristor

A thyristor is a device for controlling the power supplied to a system. It works by conducting electricity only for a part of each mains cycle. Thyristors are common in domestic appliances such as light dimmers, electric blankets, and for small electric motor controllers.

6.6.8 Transistors and diodes

Transistors were developed in 1947 and started the electronics revolution. In principle a transistor starts with a slice of pure silicon or germanium (these are semiconductors, and have 4 valency electrons in the outer shell of the atom) which has been "doped" with small amounts of certain elements (boron, indium, or aluminium, which all have only 3 valency electrons). This doping gives the semiconductor very particular electrical properties. We can call this a p-type layer. On both sides a layer of silicon doped with different elements (phosphorus, arsenic or antimony, which have 5 valency electrons) is fused (n-type layers). This creates a three layer device which has remarkable characteristics: the resistance to current flow depends critically on the voltage differences between each outer layer and the middle layer, so that current flow can be controlled by altering the voltage level on the middle layer or "base". The transistor therefore has three connecting wires (*Figures 6.5* and *6.6*) and is called an npn transistor. Reversing the layer types gives a pnp transistor.

The semiconductor diode is like a transistor but has only two layers (one p, one n) and hence two connections. It allows electricity to flow one way only (*Figure 6.6h*). It is therefore very useful for removing unwanted negative voltages. This is important when we need to convert AC voltages to DC levels as discussed later.

6.6.9 Printed circuit board (P.C.B.)

Printed circuit boards (*Figure 6.5*) are used to mount and connect components in most electronic devices. The reasons are not hard to see: modern circuits often have large numbers of components in them, and many circuit components require 16, 20, or even 40 or more connections. If this was done by wires soldered to each contact, the resulting bird's nest of wires would quickly become impractical to build, difficult to assemble, and impossible to repair! In addition the likelihood of making a wiring error would be very high, and the chances of finding the mistake and fixing it would be very small. To overcome this problem, the PCB has been developed. Instead of wire the connections are made by copper tracks which are "printed" onto the board, and the components are soldered to the tracks, thereby mounting them firmly in position. This makes assembly very easy, errors can be found quickly, and faulty components can be identified and replaced quickly. It gives the added advantage of reducing further the physical size of the circuit.

PCBs are made from a thin piece of rigid plastic or fibreglass, with a layer of copper on one or both sides. In principle the board is produced as follows: the copper is covered initially by a layer of photosensitive material.

The circuit diagram is drawn out on paper (often by a computer), usually at twice full scale, and photographically reduced to the correct size. A transparency is then made with the circuit outline printed in black on it. The tracks which make the connections are formed by placing the transparency over the PCB and shining a strong ultra-violet light on it. The photosensitive layer reacts to the light everywhere except where the black lines of the circuit protect it. The board is then placed in a strong etching bath of ferric chloride solution, which dissolves away the copper everywhere except where it is protected by the unexposed photosensitive layer, leaving the track. Finally the board must be drilled so that the connecting wires of all the components can be pushed through and soldered. The transparency can be used to make as many copies as required. Double sided boards, with tracks on both sides, can be made in the same way. Multiple layer boards can also be produced, but the process is more complicated.

Home-made PCBs can be produced in the same way, but often the circuit diagram is drawn directly onto the board. For one-off circuits making a PCB may be impractical; instead a second option is to use a sheet of "vero-board", which has a series of parallel strips of straight copper track onto which the components can be mounted. The board comes ready drilled with holes at pre-set intervals. By a process of cutting the track and wiring other connections the circuit can be completed, although this is obviously less convenient than a proper PCB.

6.6.10 Integrated circuit (I.C. or Chip—*Figures 6.5* and *6.6*)

Integrated circuits are semiconductor devices which replace large numbers of other circuit components. A development of the transistor technology, ICs have made possible the development of modern electonics as we know it today. The IC allows us to miniturise circuits, since thousands of discrete components, each of which would be a few millimetres in size, can be reproduced or rather simulated on a single piece of silicon measuring no more than the size of any one of the components it replaces. Like the transistor, the IC starts life as a sheet of pure silicon material. To this p-type and n-type layers are added in some places. These are then subjected to various treatments which remove parts of the layers, or produce non-conducting areas. The result is a complex pattern of layers, from which it is possible to create regions which behave just like most of the components we have described earlier, but in a much more compact form. Modern ICs may have several layers bonded together, so that more detail can be included in the IC. The equivalent of several million conventional components can be placed on one chip.

Most of the black plastic chip that we see consists of a cover for the connecting wires from the silicon slice to the legs. The silicon slice itself is normally only a very small fraction of the total volume of the component, and the size of the component is determined by the fact that we have to be able to handle it and solder each leg to the PCB. Improved configurations are being introduced onto the market. The only way to distinguish different ICs with the same size and number of legs is by the code number printed on them.

Examples of ICs

There are a very large number of ICs on the market. These can be purchased cheaply and used in circuits very easily, providing the buyer knows which chip is required. The art of electronics lies in knowing what chips are available, what they will do, and how to build them into circuits. There is a good analogy here between the children's toy building set "Lego" and electronics; in Lego sets there are some simple basic general purpose bricks, which are used in nearly all the projects. Then there are several bricks which have a more specific purpose, such as roof or wheel components. Lastly, there are certain specialised blocks which perform one particular function only. These include the hull section in a boat kitset, or the steering axle in a car. In electronics resistors, relays and ICs would fall into each of these categories respectively. In both cases, the ability of the designer or builder is limited only by his or her knowledge of what is available and what the components can do.

The simpler electronic components are easy to identify and use. However all ICs look much the same, and they have to be identified by a code number. It is also impossible to tell what an IC does just by looking at it. For this

reason manufacturers put together data sheets for their ICs, which specify exactly what the chip will do. These data sheets can often be obtained when the chip is bought. Alternatively the sheets are collected together in books which are also available at a small charge. The data sheets usually contain circuit diagrams for specific applications, so quite often this is all that is needed to design a circuit. A large number of circuits can also be found in electronics magazines and books so the keen amateur can soon start making sophisticated circuits with relatively little experience. There is only one problem; what to do if it doesn't work! The answer to this problem is far from simple, since wiring mistakes, faulty components and even errors in the circuit diagram are not uncommon. The beginner should therefore proceed slowly, perhaps starting with simple kitsets from the local retailer, before getting into designing a computer!

The numbering of ICs is fairly complex, since different manufacturers have different numbering methods, and the same component could have a different number depending on the maker. Some of the expertise in electronics lies in the ability to identify the right company catalogue for a component. However there are some codes which are almost standards around the world, and a few examples will illustrate the point.

a. IC 741 (*Figure 6.6*)

This is a basic amplifier chip. When high quality is not too important, the 741 is a very good component to use. There are several variations around this chip. For example, in many circuits, several amplifiers are required, so a chip is available at about the same price, which contains four 741 amplifiers, all independant, but built into the same IC.

b. IC 555

This chip is a timer chip. It enables signals to be sent to other components after a set time interval which is determined by a resistor and condenser.

c. IC 2716

This chip is a memory store for a computer. The code has some meaning; the 16 means that the chip stores 16 k of data (1 k is 1024 pieces of information). A 2708 will store 8 k of data.

d. IC 7805

This chip is a power supply chip. It produces a stabilised 5 volts at its output, and is therefore used a great deal in circuits to power ICs. A 7812 produces a +12 volt supply, while a 7905 gives −5 volts.

e. ADC 803

This takes an analogue signal and converts it to a digital signal for use by a computer.

There are also some very well known specialised chips. For example the 6502 chip is the microprocessor chip which is at the heart of the older Apple, Commodore and BBC computers. On the other hand the early IBM PC used an 8088 microprocessor.

6.7 USING AND INTERFACING ELECTRONIC EQUIPMENT

So far we have been describing modern electronic components, and how circuits are produced. However, most users are unlikely to get into this area, but are more likely to want to use ready made electrical equipment, without worrying about the circuits inside. In the jargon this is the *Black Box* approach to electronics, and is what will be discussed here. We will consider any electrical thing as a box, the contents of which are quite unknown. In order to make it do anything useful, it must have some inputs and outputs, so that information can go in or come out. There are electrical and non-electrical types. The non-electrical interfaces will not be discussed further, other than to acknowledge that the subject of human/machine interfacing is a complex but exciting area of research. More relevant here is to consider electrical interfacing. It is often necessary to connect one piece of equipment up to another electrical box. Examples of this include connecting a computer to a printer, a microphone to an amplifier, one tape recorder to another, or a video camera to a player. In all cases the connections need to be made by wires, connected to whatever sockets are available on the two boxes. We can extend the idea of a black box a little further to include sensors and detectors which measure temperature, solar radiation, flow, or any other real thing of interest.

6.7.1 Electrical signals

So far in our discussion we have been

concerned with the effect of components on voltage and current levels which are produced by batteries or power supplies. There are many other sources of voltage which electrical circuits must deal with. Electrical sensors such as electrical temperature monitors, microphones, record player heads, fuel level gauges, flowmeters and speedometers all produce an electrical voltage or signal which is often quite small. This signal contains information in the form of the size of the voltage as a function of time. Many signals can be described as *Analogue* signals. The word "analogue" means "looks like" and an analogue circuit is one where the voltage "looks like" the signal it is trying to represent. For example, an analogue signal representing temperature could be produced by a sensor which generated 1 volt at 10°C, 5 volts at 50°C, and 10 volts at 100°C. The voltage varies according to the temperature. The other type of signal is digital, and this type will be discussed later.

These small, changing signals need to be processed (eg, amplified) so that we can use them to operate displays or drive loudspeakers, etc. We can represent the signal as a voltage on a single signal wire, measured relative to a second return wire, as shown, for example, in *Figure 6.9a*. Our electrical black

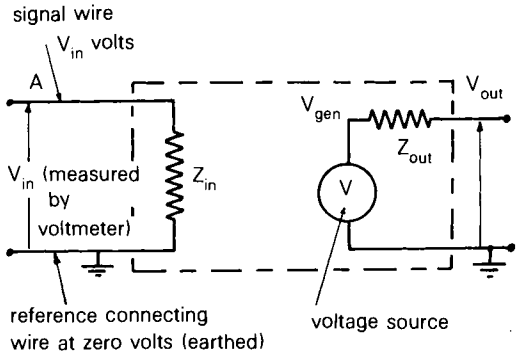


Figure 6.9(a) Diagram for a black box.

box must take this signal and improve it without distorting it or losing any important data which it contains. This is called *Signal Conditioning*. Every electrical connection must complete a full circuit, so that at least two wires will be needed. The return wire is usually earthed or grounded (ie, connected to the supply earthing system which is itself connected to the actual ground on which we stand), so the signal is simply the voltage on the signal wire at A relative to earth. This means that we only need to consider the voltage on the signal wire, and we can talk in terms of this as The Signal Voltage. Other voltages may be involved in the black boxes: for example virtually every box will require a power supply. However this can be considered as a quite separate issue and for our purposes we will ignore this need here.

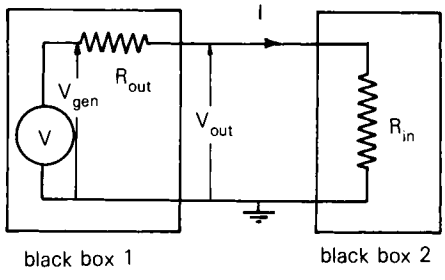


Figure 6.9(b) Connection of two black boxes.

6.7.2 Interfacing analogue circuits

Whenever we join two things together, say two electrical black boxes, in an electrical circuit with a voltage, a current will flow. The size of this current depends on the characteristics of the two boxes. If the current is too big then problems can arise, since the current can affect the internal operation of one of the boxes, and it may cease to perform properly. This is known as *Overloading*. It is possible to determine whether an overload will occur by studying the electrical characteristics of the inputs and outputs. This may sound difficult to do without knowing what exactly is in each box, but fortunately this is not necessary, thanks to a very useful model which works for all electrical systems. This is that when a signal is input into any black box, it behaves as if it were a single component with a single impedance Z_{in}. This is known as the *Input Impedance* of the device; whenever a piece of equipment is connected to the output of another, it will be just as if an impedance Z_{in} had been connected instead.

A similar thing happens at the output; this time the box behaves as if it were a voltage source producing a voltage, together with an *Output Impedance* Z_{out}. Any current produced by the voltage source must flow

through Z_{out} before it can flow into the external connections. This means that there will be a loss in voltage across Z_{out} whenever a current flows (by Ohm's law). An example of this is shown in *Figure 6.9a*. The box has an input and an output, each consisting of two wires. All the components inside each box can be treated as if there were only the equivalent single impedances labelled Z_{in} and Z_{out}.

A further simplification arises in most cases because we can ignore the capacitative and inductive components in the impedance, which leaves us with just resistances to consider. When two boxes are connected together the result is a circuit as in *Figure 6.9b*. It is really a very simple circuit to analyse, since it is just two resistances in series. We can apply Ohm's law to it and find the current. Using the notation of *Figure 6.9b*, for the whole circuit and using *Equations 6.1* and *6.2*:

$$I = \frac{V_{gen}}{R_{in} + R_{out}} \qquad \text{Equation 6.14}$$

For R_{in} only,

$$I = \frac{V_{out}}{R_{in}} \qquad \text{Equation 6.15}$$

Rearranging these and eliminating I gives:

$$\frac{V_{out}}{V_{gen}} = \frac{1}{1 + \frac{R_{out}}{R_{in}}} \qquad \text{Equation 6.16}$$

The meaning of this can be understood by putting in various values:

(a) $R_{out} >> R_{in}$

In this case the denominator in *Equation 6.16* is large and so $V_{out} << V_{gen}$. In fact V_{out} will be almost zero, which means that no voltage will be transmitted across the interface. In effect we are short-circuiting the output, which is bad, not only because there is no signal, but also because a high current will flow through R_{out} which could sometimes cause overheating and damage. This situation should be avoided.

(b) $R_{out} = R_{in}$

In this case, it can be shown that although V_{out} is less than V_{gen}, nevertheless the power transferred is a maximum. This is therefore the ideal situation where the power is of importance, eg, when loudspeakers are to be connected to an amplifier.

(c) $R_{out} << R_{in}$

This time there is hardly any voltage loss across R_{out}, and hence V_{out} is almost equal to V_{gen}. This is the best situation if the value of the voltage is important (for example if it represents the value of a measurement). In many situations this is the important factor, and so we can conclude that for transferring signals the best devices have a low output impedance and a high input impedance. These values are quoted in the specification of equipment, so it is not too difficult to check that condition (c) holds. Providing this is the case, then connecting the two together will not cause problems due to overloading the output. It is still possible to distort the signal, or damage the input of the second box if the voltage applied to it exceeds the maximum allowable, and this should also be avoided.

6.7.3 Analogue circuits in practice

In practice analogue circuits are the simplest to check. The signal looks like it should, and can be traced through a circuit with fairly simple equipment. The signal is measured with a voltmeter or oscilloscope connected between the earth (or return wire) and the signal wire (*Figure 6.9a*).

As the real world is analogue no complicated conversion of the signal is required when connecting to sensors. However because the information is carried in the form of the size of a voltage, serious problems can arise if there is any interference. Electrical noise is generated from many sources, including the mains power supply and many appliances (of which electric drills seem to be the worst), so it is essential to take steps to minimise the interference in delicate circuits. The interference is present in the form of electromagnetic fields generated by the source, which cause unwanted voltages to arise in any conductor in the vicinity, in much the same way as a radio aerial. Noise prevention requires that the wires carrying the signal are not subjected to these fields. This is done by various techniques, but the most basic is to shield the signal cable from the noise by screening it with a metal

covering as in a coaxial cable. The outer covering or screen is then earthed, and can even be used to complete the circuit. Effective earthing reduces the noise considerably, but care must be taken to avoid "earth loops", which can arise if a system is earthed independantly at different points.

Other techniques to remove noise include using filters to remove unwanted frequencies. Mains noise at a frequency of 50 Hertz (60 Hertz in the USA) is often a serious problem, and in some cases this frequency could be specifically removed. Often the required signal is one which changes only slowly with time, while the electrical noise will be at frequencies of at least a few hertz. As discussed in the examples earlier, in *Figure 6.7a* the condenser will remove high frequency noise from a slowly varying or constant voltage signal. Sometimes the problem will be to eliminate unwanted fixed or DC voltages from a fast changing signal. *Figure 6.7b* shows how an unwanted fixed voltage can be eliminated by a condenser. This is called a capacitive coupling and is often used in multi-stage audio amplifier systems, since it prevents any DC signal generated by the previous stage being amplified and causing voltage overloading of subsequent stages (eg capacitor C, in *Figure 6.6g* is for this purpose).

In the past it has been possible to use analogue circuits for logic operations. Although some controllers still work in this way digital systems are rapidly replacing them for cost and reliability reasons. Altering the function of an analogue system often requires a change of component in the circuit which makes them very inflexible compared to their digital counterparts, which can be reprogrammed for different functions fairly easily. The storage of information is also difficult in analogue systems.

6.8 DIGITAL CIRCUITS

In spite of the remarkable achievements in analogue systems brought about by the silicon chip, the really exciting developments in electronics have been achieved by applying the technology to digital systems. These are systems where the voltage on the wires no longer varies continuously over a wide range of values, but where the signal is specified only by the presence or absence of a fixed voltage (say five volts) on the wire. The concept is not particularly new: in the early days of electronic communication messages were sent out in Morse code, which consisted of pulses sent down the wires whenever a switch was closed. The pulses were either short (a dot) or long (a dash), and the alphabet was coded so that each letter was represented by a short sequence of dots and dashes. An "S" was three dots, while an "O" was three dashes, so to generations of boy scouts and girl guides the signal ... – – – ... stood for SOS (Save Our Souls), the International distress call. Modern systems use the same principles exactly except that the dot and dash are replaced by voltage on and voltage off.

The old Morse code method is a good example of a serial transmission system, which we will return to later. For now we will consider how digital systems work when all the information needed to specify one piece of data is to be generated at the same instant in time, since this is the way in which computers and other digital systems require their information. To start with then if we had a single wire the voltage could be on or off. We could define on as representing say "y" and off could be "n". Our data could then be only the letters n or y which is a little limited (hardly Shakespeare!). Of course if we used a "y" to mean "switch the fans in the greenhouse on", while "n" meant "switch them off", and we used this signal to control a greenhouse, it could well be all that is needed. However having only two choices is rather limiting. To give more options more wires are needed; with two wires four choices are possible (off/off, off/on, on/off, and on/on). Four wires allow 16 (2^4) different codes, while eight wires allows for 256 (2^8) combinations. The industry has chosen an eight wire system as standard, and the unit of data is called a *Byte*. The information on one wire is called a *Bit*, so eight bits make up one byte. In addition, 16 bits make up a *Word*, while four bits is called a *Nibble*. Devices with 16 or 32 bit systems are quite common.

6.8.1 Coding systems

On an eight bit system each byte of data can be any one of 256 possible combinations of voltages on or off in each of the eight wires. We can make each combination take whatever meaning we like, but as in Morse

Code, specific coding systems have been adopted. We will describe two. The first is to allocate a straight-forward numerical value to each bit. Thus we can define the right-most bit of a byte as having a value of one (if the voltage is on), the next 2, followed by 4, 8, 16, 32, 64, and 128 if the left-most bit is on. Any bit that is off counts as zero. The value of the byte is then found by adding the numbers. Thus the byte 11001010 (where 1 means on) would have a value of $128+64+0+0+8+0+2+0=202$. The left and right-most bits are called the most significant bit (MSB) and least significant bit (LSB) respectively.

The second coding system is called the ASCII (American Standard Code for Information Interchange) code. In this each alpha-numeric character is given a specific code. In addition some codes are used for other symbols such as #, %,), or >. Other codes are used to send special control instructions to equipment, so that there are 128 possible values of a byte. This leaves one bit which is not needed to form the code, and this is used to detect any transmission errors (see below). The full ASCII code is listed in *Table 6.3*, using the numerical decimal number to define the byte. Thus "A" is 65 or 01000001 while "a" is 97 or 01100001. Note that in ASCII the character three has a code of 51 or 00110011, and not 00000011. Other codes are used inside some computer chips to speed calculations, but these are not relevant here.

Characters 0 to 31 are used as control characters. Thus 13 is a carriage return command to a printer, while 10 is a line feed, and 8 is a back space.

Table 6.3 ASCII codes

Dec	Letter	Dec	Letter	Dec	Letter	Dec	Letter	Dec	Letter
65	A	78	N	97	a	110	n	48	0
66	B	79	O	98	b	111	o	49	1
67	C	80	P	99	c	112	p	50	2
68	D	81	Q	100	d	113	q	51	3
69	E	82	R	101	e	114	r	52	4
70	F	83	S	102	f	115	s	53	5
71	G	84	T	103	g	116	t	54	6
72	H	85	U	104	h	117	u	55	7
73	I	86	V	105	i	118	v	56	8
74	J	87	W	106	j	119	w	57	9
75	K	88	X	107	k	120	x		
76	L	89	Y	108	l	121	y		
77	M	90	Z	109	m	122	z		

Dec	Letter	Dec	Letter	Dec	Letter	Dec	Letter	Dec	Letter
32	(space)	40	(	58	:	91	[	123	{
33	!	41	)	59	;	92	\	124	|
34	"	42	*	60	<	93	]	125	}
35	# or £	43	+	61	=	94	^	126	~
36	$	44	,	62	>	95	_	127	DELETE
37	%	45	–	63	?	96	'		
38	&	46	.	64	@				
39	'	47	/						

0 null; 1 Start of heading; 2 Start of text; 3 End of text; 4 End of transmission; 5 Enquiry; 6 Acknowledge; 7 Bell (or other noise); 8 Backspace; 9 Horizontal tabulation; 10 Line feed; 11 Vertical tabulation; 12 Form feed; 13 Carriage return; 14 Shift out; 15 Shift in; 16 Data link escape; 17 Device control 1; 18 Device control 2; 19 Device control 3; 20 Device control 4 (stop); 21 Negative acknowledge; 22 Synchronous idle; 23 End of transmission block; 24 Cancel; 25 End of medium; 26 Substitute; 27 Escape; 28 File separator; 29 Group separator; 30 Record separator; 31 Unit separator; 127 Delete.

When one is using programmable computers, it is not uncommon to find strange looking instructions like 5E, 2A, or FE. These are written in *Hexadecimal* notation, which is not so much another code as a convenient way of writing a byte. A byte can be split into two nibbles of four bits each. A nibble can have one of 16 possible values, so if we had 16 symbols, we could write a byte with just two characters. Hexadecimal is just that; it begins with the ordinary numbers followed by the first six letters of the alphabet as follows: 0123456789ABCDEF. Some books use the symbol # before all hexadecimal numbers. Thus #A is 10, #B is 11 and so on. Thus #E is 14 or the nibble 1110, and so #EF represents the byte 1110 1111 (or 239 in decimal notation). A word of warning is necessary: in hexadecimal a numerical symbol such as #23 means 0010 0011 which is the number 35 in decimal. It is therefore important not to mix decimal and hexadecimal numbers. Fortunately this is rarely a problem for the user, since the situation is usually made quite clear in the instructions, and the user does not require to know anything about the codes.

Example

What is the decimal, binary, and hexadecimal (#) code for the letter M?

Solution: From the table the decimal code is 77. The binary code is found by finding the multiples of 2 which add up to 77. Thus:

$77 = 64 + 8 + 4 + 1 = 2^6 + 2^3 + 2^2 + 2^0 = 0100\ 1101$

In hexadecimal, 0100 = #4, while 1101 = #D, so 0100 1101 = #4D

6.8.2 Advantages of digital systems

When we discussed analogue systems, one of the main problems was noise. Digital systems overcome this difficulty because the information is no longer dependent upon the exact size of the voltage, but only requires that the voltage be identifiable as one of two values. Thus a voltage anywhere between 3.75 and 5 volts is recognised as on, while any value below 1.75 volts is taken as off. Providing any noise is less than 1 volt there will be no problems, and this is not difficult to do in practice. *Figure 6.10* illustrates how noisy a signal can be without loss of information. This signal would be recorded as 0, 1, 0, 1, despite the noise. Voltage spikes (sudden sharp pulses of relatively high voltage) can be produced on the power supply wires by components such as relays, and these can cause trouble, but they can be eliminated by using condensers connected across the power inputs to the components.

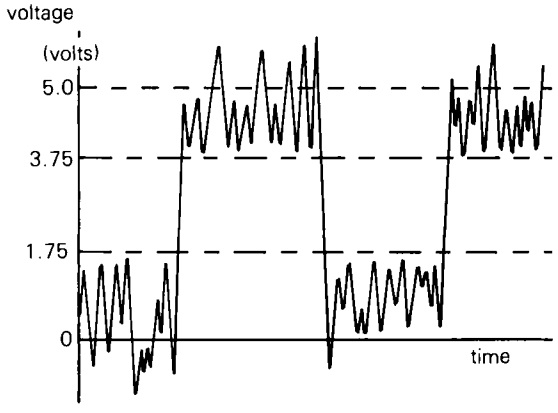


Figure 6.10 A noisy digital signal, still recognisable as 0101.

Digital data is very easy to store; instead of having to store the precise value of a voltage (which is very difficult), a memory only has to remember whether there was a voltage or not in a wire. This is similar to remembering the position of a switch, and is quite easy electronically. Of course, to remember one byte of data requires eight switch positions to be memorised. Memory chips able to store four million bytes suggest that this is of no great consequence! However the complexity of these chips is remarkable, even if they are still very poor in comparison to our own brain power.

With digital systems logic operations become possible, since the existence of a voltage on one wire can enable a voltage to be set up somewhere else. The ability to store data together with the ease of logical operations has made the development of computers possible, and in the next section we shall look briefly at what a computer consists of.

Before leaving this section the disadvantages of digital systems will be outlined. First the real world is essentially continuous and analogue in nature. Therefore before any digital system can be interfaced with any real thing (such as a device to measure milk temperature) the analogue value must be converted to a digital one. Some sensors do produce a digital output automatically. A

good example of this is a turbine flow meter, which generates a pulse each time the turbine blades rotate past a detector. The pulses are counted over a fixed time interval to give a digital number which is proportional to the flow rate. The value can then be displayed on a digital display.

Most sensors produce an analogue output, and the signal has to be converted to a digital form by an analogue to digital converter, or ADC for short. The information can then be processed. If the digital system is required to give an analogue output (for example if it is needed to drive a pointer on a dial) then the reverse conversion is needed using a digital to analogue converter (DAC).

A further problem arises in making these conversions; this is the problem of rounding. When an analogue signal is converted to a digital signal the resulting value must always be rounded to the nearest whole number, which is determined by the size of the least significant bit. Thus if an 8 bit data system is used there are only 256 different codes, so the rounding error will be 1 in 256, or an error of about 0.4% of the full scale reading. This may seem accurate enough for most farm applications, but if the reading is small compared to the full scale value the error in the reading can be large. For example if an instrument reading temperature in a greenhouse has a range of 0 to 200°C, then if the temperature is 10°C the error due to the ADC rounding alone will be about 1°C. Further measurement errors will serve to increase the error, and if tight control is needed for crop production, crop quality, or for fuel conservation, the error could easily be unacceptable. It is important to take these types of problems into account when selecting equipment.

An easy solution to the problem of rounding is to choose systems where the ADC works to at least 12 bits. The rounding error is then less than 1 in 4000, which is certainly more than adequate.

6.9 THE ELECTRONICS OF COMPUTERS

The electronics revolution in the 1980's was nowhere more apparent than in the way in which computers were introduced into all aspects of human life in the space of a decade. The change from a few (physically) large sized computers housed in dust free, purpose built computer halls, with operators in surgical clothing, to the desk-top computer of the same size (electronically) has occurred so quickly that it is almost a tribute to the adaptability of humankind. For example, most of this chapter has been written on a small lap computer on a flight at 35,000 feet over three continents!

While not exactly leading the field, the rural sector has not been slow in identifying areas where computers can assist the operation. In horticulture computer controlled greenhouses have been in operation for several years. In agriculture, obvious applications such as stock, financial, and production recording have been in use for some time, while pasture management programs have been developed in New Zealand and elsewhere. The first applications involved systems where the farmer input all the data manually using a keyboard. Subsequently, automatic identification systems were developed for stock, which meant that computers could be used to identify animals, then feed supplements, and record milk yield, cow weight and other parameters automatically. These applications, where the computer is connected directly without the need for a human interface, can be described as on-line systems.



Figure 6.11 A desk top computer, with hard and floppy disc drives.

But what is a computer, and how does it operate? *Figure 6.11* shows a typical desk top personal computer system. The most obvious components are the screen and the keyboard, but these are really not part of the computer at all! The real computer lies inside the box behind the keyboard and *Figure 6.12a* is an example, which shows that it is just a printed circuit board with a large number of ICs on it.

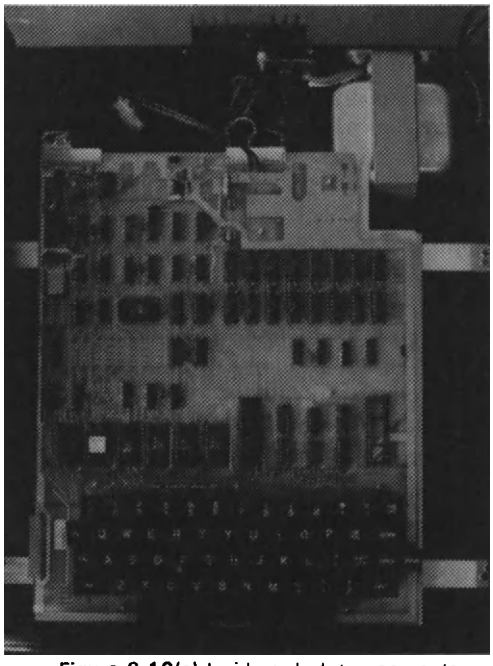


Figure 6.12(a) Inside a desk top computer.

In *Figure 6.12b* the main functional components which make up a computer are shown. It consists of two memory blocks (the ROM and the RAM), a Central Processor Unit, an Input and Output block, a clock, a reset button, and three sets of multiple wires called Buses. The computer shown is a small 8 bit system, similar in style and technology to the Apple II or the Commodore C64.

6.9.1 Central processing unit (CPU)

This is a microprocessor chip which does all the work of the computer. All calculations are performed here in locations in the chip called Registers. Registers can be 8, 16, or 32 bits in size. In addition the CPU sends out all commands to the other parts of the computer, and holds the key memory locations relating to the program being run.

6.9.2 Memory

Physically, the memory of the computer is a set of chips where data is stored. There are two types of memory in the computer, the ROM and the RAM. ROM stands for *Read Only Memory*, which means that information can only be obtained from the chip, and it is not possible for the computer to change the

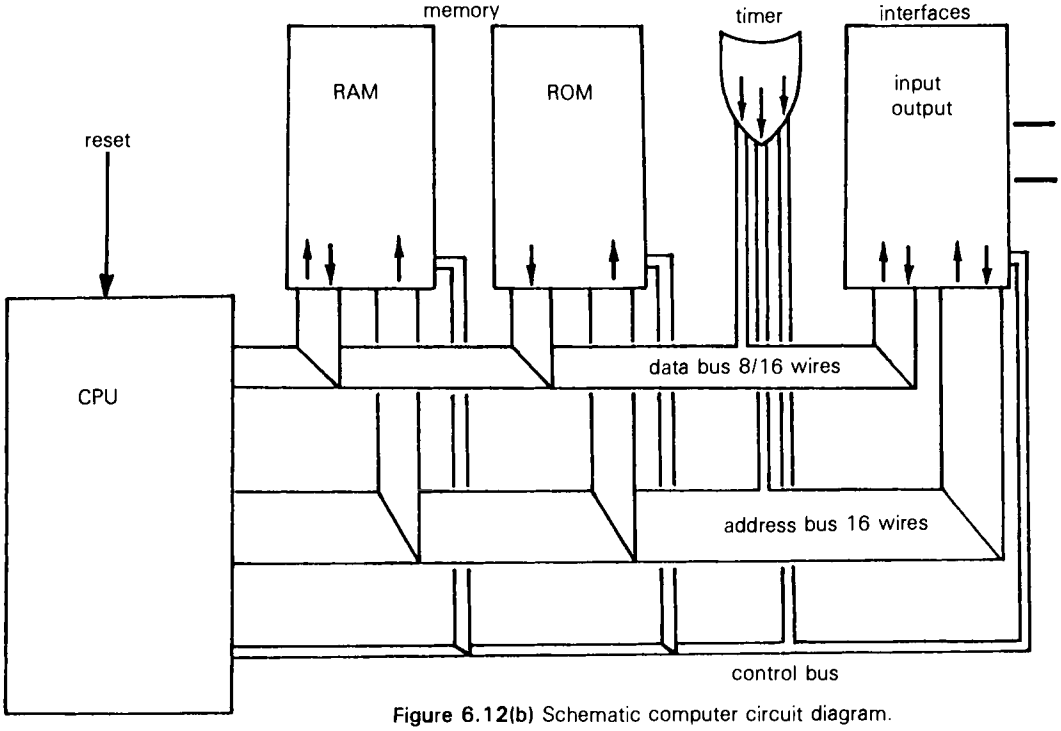


Figure 6.12(b) Schematic computer circuit diagram.

information in the ROM. The data in ROM is put there by the computer manufacturer, and contains all the important data the computer needs to run itself. This may include programs which operate the keyboard, control the screen, or allow the computer to interpret the instructions put in by the user, as well as any other details the computer needs for it to work properly. Data which could be placed in the ROM could be the year of manufacture of the computer, if this is to be displayed whenever the computer is switched on.

The RAM is the part of the memory where data can not only be obtained (a read), but fresh data can also be stored (a write). The initials originally meant Random Access Memory, but a better translation would be *Read And (write) Memory*. This part of the memory is available for the user to enter programs or instructions. It is also used by the computer for storing data used in programs, including the results of calculations, and information to be displayed on the screen or printed out on a printer. In most desk top computers all the data in the RAM is lost whenever the computer is switched off. In portable computers this may not happen, if there is an internal battery which maintains power on the RAM chips. This is called a battery backed RAM.

The size of the RAM is a measure of the capacity of the computer, since the larger the memory, the bigger the program that can be run. The unit of memory size is the k which stands for 1,024 (2^{10}) bytes (ie, just over 1,000 bytes). In 1965 a large business computer had typically 32k of RAM; by 1988 ordinary home computers were often 640k or bigger.

6.9.3 Input/Output interface

The computer is quite useless if we cannot get information into it or take information out. For this reason a screen or Visual Display Unit (VDU) and a keyboard are essential components of a complete computer system. However, they are really outside of the computer itself. Whatever appears on the screen must be passed to it through an I/O chip, as must any data from a keyboard. In addition, in view of the volatility of data stored in RAM, it is not a good idea to try to store useful information and programs only in the RAM, since a power failure or switching off would lose it all! In addition the RAM is not really that big if large quantities of data are to be stored. Other storage devices are therefore required, and the most common is the disc drive. A disc is a magnetic data storage device, and the disc drive can read or write data from or to it relatively quickly. The disc can store programs or data, and can be used during a program if necessary. Floppy discs are thin discs which can be removed from the disc drive and replaced by others. A floppy disc will store typically a few hundred kilobytes. Hard discs cannot be removed from the disc drive; however they will hold many megabytes of data. Cassette tape recorders were an alternative means of saving data but they are very slow and tedious to use, and are now obsolete.

6.9.4 Memory location

The memory can be considered as a large array of pigeon holes, each capable of storing one byte of data. Each pigeon hole is uniquely defined by its address, which is specified by a code number. If the code was 4 bits long then there could be 16 separate addresses, while with a one byte address code 256 separate pigeon holes could be distinguished. Even this is far too small a number, and it is more realistic to use a 16 bit code which gives 64k separate pigeon holes which can be addressed. Of course, the memory chips must have 64k pigeon holes before all of these addresses can be used, and on early machines some of the memory locations were in empty space! However as memory chips became able to hold more and more memory, it became easy enough to provide actual storage space for all the addressable locations. It should be added that the total addressable memory space includes ROM and RAM. Further developments have enabled even more memory to be addressed directly, by using ingenious programming, extended buses, and improved control methods.

6.9.5 Memory size

The size of the computer memory is a measure of the capacity of the computer. In the example we are using, an eight bit machine, the total memory is often set at 64k, since this is a very convenient size for the computer hardware to work with. It is far too small for programs which require a large

amount of data to be held in the memory, but it is quite adequate for many other programs used by farmers and home computer users. The value of 64k arises because most eight bit CPU chips are designed to be able to send and receive data from memory locations specified by a 16 bit code (ie, they have 16 connecting pins which are designated as the address lines).

6.9.6 The buses

The sets of wires which join the components together are called Buses. As shown in the diagram there are three major sets in a computer, known as the data, address and control buses. In the example shown of an eight bit computer the data bus consists of eight wires, while the address bus has 16, and the control bus varies in size. This means that one byte of information can be set up on the data bus if any one component generates the appropriate voltages on each wire at a given time, while on the address bus a number defined by two bytes can be set up. Thus the address bus can be used to specify the required address for any one of 64k addresses within the memory. Data and address buses of 16 and 32 bits are used in many larger computers.

6.9.8 Computer operation

The computer operates in a continuous series of steps. Each time the clock indicates the start of a cycle the computer performs whatever the next operation instruction calls for. In order to perform a job it must therefore be instructed what to do, and this is done by programming the computer. A program consists of a series of instructions put into the memory of the machine.

The machine has a very basic operating cycle which is indicated in *Figure 6.12c*. When the machine is switched on it is initialised to a known state. It is set so that it will look for the first instruction at a specific memory location defined by the value of a parameter called the program address. This is kept in a location in the CPU called the program address register (for example the program address may be set to zero). It then fetches

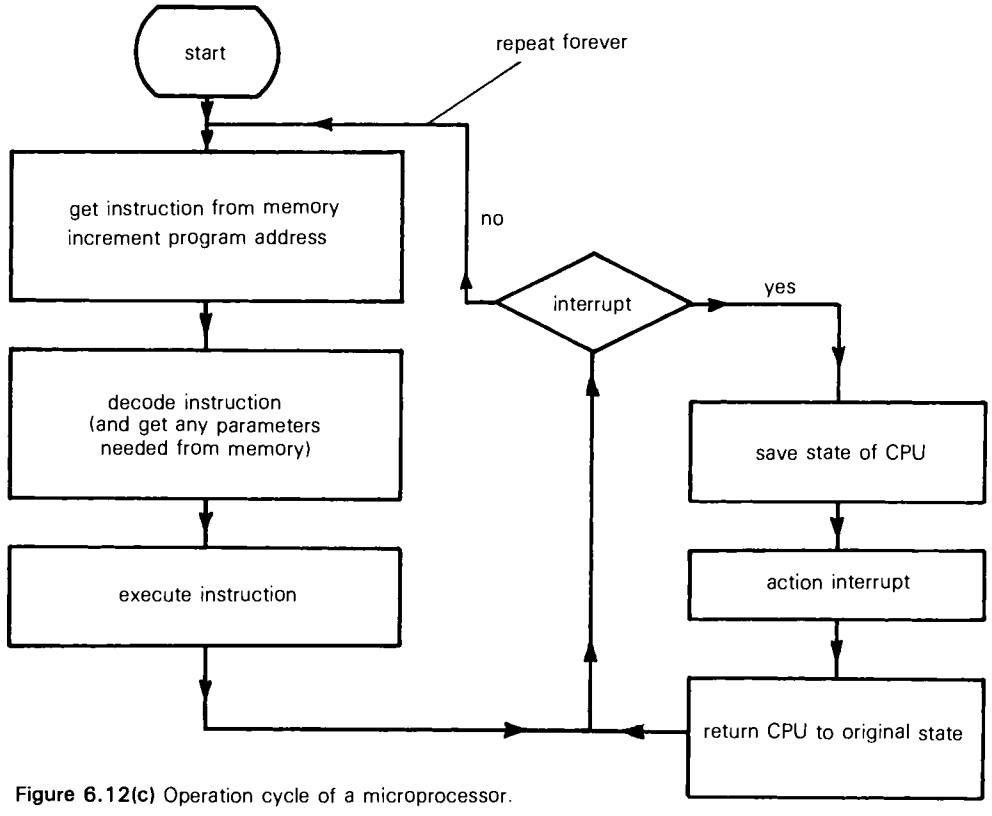


Figure 6.12(c) Operation cycle of a microprocessor.

an instruction from the memory address (whose address is equal to the program address), and then increments the program address register by one. The instruction is decoded (ie, the operation to be performed is determined), and the computer then proceeds to carry out that instruction. Quite often it may be necessary to clarify the meaning of the instruction by getting further codes from the memory, so that the complete instruction may occupy two or three locations in the computer memory. These latter parts of the command are termed the parameters of the instruction. Each time the memory is read the program address register is incremented by one so that it "points" to the address of the next command to be fetched. When the computer has completed carrying out the command it then gets the next instruction from the new program address and decodes that. The machine then repeats this operation until it is finally switched off.

When the clock puts out the pulse for a cycle the CPU puts out the address on the address bus, and the control code instructing the memory to put the contents of that address on the data bus. The memory chip reads these commands. The clock allows sufficient time for the voltages representing these numbers to become stable so that they are read without error, and then calls "time out" for a moment. Nothing happens except that the previous voltages on the buses are removed. Then the clock generates another pulse. The memory now obeys the instruction and the data appears on the data wires in the form of a one byte code. The CPU will read whatever appears on the data bus and treat it as all or part of an instruction code. In this way the computer carries out its function. The instruction may involve a mathematical operation, collecting data from a particular memory address where data has been stored, a transfer of data through the I/O devices, or some other operation.

As you can see from the above, each specific instruction involves reading the instruction and actioning it, and this may take several machine cycles to complete. In between each cycle there is a short break during which time the voltages on the wires are allowed to alter. Although each step seems trivial, each step occurs very quickly in practice (over one million clock cycles per second) and so the computer appears to us to be very fast.

The power of the computer lies in the fact that almost any computable task can be broken down into a series of a few very simple operations. These operations have such names as AND (logic), OR, NEGATE, ADD, LOAD, STORE, SHIFT LEFT (move each bit one place to the left), SHIFT RIGHT, TEST (is something true or false), and JUMP ON TRUE TEST RESULT. Of these the last is possibly the most important because it allows the machine to make decisions and to go to different parts of a program according to the results of these decisions.

In particular part of the computer cycle involves checking to see if there is an interrupt from an external device. Such interrupt requests can come from many sources, including the keyboard. Because we work so slowly relative to the computer, when we are typing in data the computer is idling away most of the time doing nothing and waiting for an input from the keyboard. On the other hand, if the computer is acting as an environmental controller the program would normally monitor the sensors continuously, taking action when necessary. An interrupt could be generated if a sensor breaks down or if the temperature goes out of control. In this case the interrupt causes the normal operation to be suspended as soon as the previous operation is completed (a matter of a few microseconds). The value in the program address register and any other data being worked on in the CPU are stored in memory. The program address register is then changed so that it directs the computer to get instructions from a different part of the overall program, and these are followed until the interrupt has been dealt with. Then the old address and data are replaced in the program address register and the CPU and the computer carries on where it left off.

6.9.9 Programming

The computer can only obey certain simple instructions like fetch a piece of data from memory. These instructions are written in single byte codes called machine code, and it is data which the computer can understand. Unfortunately it is a code which is very difficult for us to follow, and although some engineers will write programs directly in this code, it is much easier to write programs in

language which we can understand easily, and let the computer convert it to its language. We therefore use languages such as BASIC, PASCAL, FORTRAN, or COBOL which are meaningful to us. The computer then translates (compiles) the programs we write, and providing it has the translation program or Compiler for that language, it will generate a program of instructions which it can run. This procedure must take place before the program can be run, and a new program, called the compiled version, must be produced. Once this has been done the computer does not need the original program any more, but simply runs the compiled version. Commercial programs can therefore be sold in the compiled form, which makes them difficult if not impossible to alter. This need not be a hindrance if the program works as the user requires, but if the program is inadequate in some way, the user can do nothing about it, except hope that the producer will bring out a corrected version. In selecting software (the programs) the buyer should always ensure that the program works properly and that it does what is needed. It is most unwise to purchase on promises of future capabilities.

Most machines run a language called BASIC, (Beginners All-purpose Symbolic Instruction Code) which is one of the easiest computer languages for beginners to learn. It is very popular with home programmers and many programs are written in it both for business and hobby purposes. BASIC works differently to other languages in that the computer compiles the program as it runs it, on a line by line basis. BASIC programs therefore run very slowly compared to compiled programs (typically by a factor of 200) but they can be modified by the user, at least in principle. In practice this is still not recommended unless the user wrote the program initially.

6.9.10 Buying or writing software

If a reliable package is available, it is rarely worthwhile to write your own software, simply because the time needed can be enormous, even for an experienced programmer. Even if nothing is available it is a brave person (or someone with nothing else to do) who will undertake to develop a program which can be used to help in running a business.

Software packages are becoming better and easier to use as time goes on. For general purposes, three main types of software package are worth mentioning specifically. *Word-processor* software enables the operator to manipulate words in a file on the computer, so that changes and corrections can be made easily. These are now standard in most offices. Gradually, the ability to add drawings into the file is making it possible to produce quality illustrated reports ready for printing. *Spread-sheets* contain rows and columns of data which can be manipulated, sorted, plotted, and displayed in pie-charts, etc. Complex calculations can be performed on a row of the data, and repeated for every other row. Changes can be made to one figure, and the spread-sheet will automatically update all the calculations using the new data. The third type of package is the *Data-base*. This is a program which allows data to be stored in such a way that it is easy to sort, store and retrieve. The program allows searches to be made for particular key items. Some data-bases can be programmed so that the information is displayed in exactly the way the particular enterprise requires it. Some packages combine all three types. These are called integrated packages. In many cases one of these types of packages will be suitable as a basis for most applications, and only rarely would a completely original computer program need to be written for most companies.

6.10 INTERFACING DIGITAL CIRCUITS

When we consider digital systems as black boxes with inputs and outputs, the situation differs slightly from the analogue situation. As before the interface must involve electrical circuits where a voltage must be produced between the signal wire and a reference wire (the earth), and a finite current will inevitably flow. Now however the only data to be transferred will be whether the voltage is at the on or off level. Thus providing the input device has a high impedance, the signal will be transmitted without too much trouble, even if there is some noise present. In practice this is invariably the case unless we try to drive too many devices from one digital source. Problems can arise if the digital signal is used to drive an analogue system; digital devices have a relatively high output

impedance, which means that they are unable to drive devices which require an appreciable current. Normally a relay must be used. A further complication can arise if the noise on the signal could include high voltage spikes which could damage the digital electronic circuits. In this case input and output circuits are isolated electrically by using devices called opto-isolators. These convert the on or off input signal to an on or off light beam, which is picked up and converted back to an electrical signal but without the noise.

With these factors taken into account, digital interfaces appear to be relatively straightforward: as long as each wire from one device is connected to the corresponding wire in the other, then the connection should be simple. In practice such connections are indeed made in this way. However the exact details of the interface wiring can be quite complex, since large numbers of connections must be made. The interface must also include certain important control connections which allow the two devices to indicate to each other whether or not they can send or receive data. For example, details of a well-known standard, the Centronics Parallel Interface, are given in *Figure 6.13* and *Table 6.4*. This interface is a standard provided on most printers and numerous other digital systems. An alternative is the IEEE 488 standard (sometimes called the GPIB, or General Purpose Interface Bus). This interface often comes on scientific equipment. The two are not compatible without specific converters.

Table 6.4 Centronics parallel interface connections

PIN	SIGNAL	Source
1	Data strobe pulse	Comp
2	Data bit 1 (LSB)	Comp
3	Data bit 2	Comp
4	Data bit 3	Comp
5	Data bit 4	Comp
6	Data bit 5	Comp
7	Data bit 6	Comp
8	Data bit 7	Comp
9	Data bit 8 (MSB)	Comp
10	Acknowledge pulse	Prt
11	Busy	Prt
12	Paper Empty	Prt
13	Select	Prt
14	Signal ground	–
15	No connection	–
16	Signal ground	–
17	Chassis ground	–
18	+5 volts DC	Prt
19	Signal ground	–
20	Signal ground	–
21	Signal ground	–
22	Signal ground	–
23	Signal ground	–
24	Signal ground	–
25	Signal ground	–
26	Signal ground	–
27	Signal ground	–
28	Signal ground	–
29	Signal ground	–
30	Signal ground	–
31	Input prime	Comp
32	Fault	Prt
33	Signal ground	–
34	Ext prime	Comp
35	No connection	–
36	Input busy	Prt

Note Source of signal:
Comp = Computer;
Prt = Printer

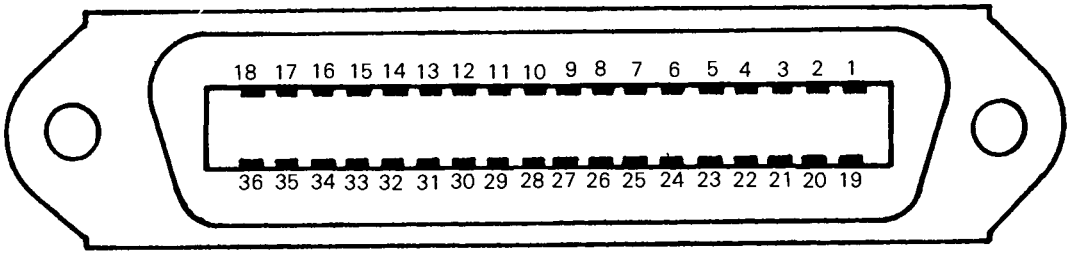


Figure 6.13 Centronics parallel interface. Thirty-six pin connector using flat contacts. View of front of socket (female—groove down middle).

As can be seen, there are two connections for each data line. That is, one signal line and one earth return wire (these earth wires will all be connected together at some point). In addition there are a large number of control

lines which are essential if the two devices are going to be able to transfer data without problems. Using the centronics interface as an example, a voltage on pin 10 indicates that the data has been accepted. The presence of a voltage on pin 11 indicates that the receiving device is busy and cannot receive more data. The sending device is prevented from sending any more data until the voltage disappears. This is very important if the receiving device is slow (eg a printer may be able to handle only 200 bytes per minute, while the computer is outputting data at 10,000 bytes per minute or more). The data will be lost if the receiving device cannot respond fast enough. Most slow devices have what is known as a buffer for receiving data. This is a store which will hold a few thousand bytes of data. Information is passed quickly until the buffer is full. Then the transmission is halted using the control on pin 11 until the buffer has been emptied (eg the data has been printed out). Then the transmission can be restarted with the next section of data and so on. This gets over the difficulties of sending one byte at a time and then waiting for a clear to send signal before sending the next byte.

6.10.1 Serial transmission

The interface described above is called a parallel interface, because the data is transferred along wires in parallel. All the bits making up the code are transmitted and received at the same instant, so the transfer is fast and efficient. However, there is a practical problem; for each bit a separate wire is needed. This is not difficult to do if the two devices are close together, since a ribbon or multiwire cable can be used to make the connection easily. Unfortunately, these cables are expensive compared to single wires, and they are bulky. For long distances the cabling costs would become very high and special cables would have to be laid. A system which could use existing telephone cables for communication would obviously be an advantage. This can be done by converting the data into a serial form, that is where the bits are fed one after the other along a single wire. This means that the data will be transmitted more slowly, since the machines will take at least eight times as long to transfer one byte of data (because each bit has to be sent in turn, one at a time). However this is not as bad as it sounds, because the receiving devices often take a lot of time to deal with the incoming data, and so transmission rarely occurs at maximum speed anyway.

In order to send data in serial form the sending and receiving devices must be programmed to use a common format for the signal. As the signal will now take the form of a sequence of high or low voltage pulses on a wire, the receiver must be able to identify the start and finish of each byte of data clearly. This is done by adding a start bit and a stop bit to the ends of the train of pulses. An example of this is shown in *Figure 6.14a*. This shows the signal produced using the so-called *RS232C* protocol, one of the most common standards for serial interfaces. In this diagram the start and stop bits are shown, with the data bits in between. The dotted lines in the Figure indicate that the bit may be on or off, depending on the data. The last data bit is in fact called a parity check bit. This is a check: if the device is set for even parity then the parity bit is chosen by the sending machine so that adding up all the bits that are "on" will give an even number. Thus for even parity, the letter A would be sent as 0100 0001 with the parity bit set at zero, while E would be 1100 0101 with the parity bit set at 1. The receiving device then checks that the received bits still add up to to an even number of "on" bits. If it does not then it flashes an error message. A transmission error affects hundreds of data bytes so on average half of them will fail the parity check, so the problem will be immediately apparent to the receiver operator.

Quite clearly the only difference between two "on" bits next to each other and one "on" bit alone will be the time the voltage is high for, and so the devices must be set to receive the data at a very specific rate. This is called the baud rate. It is almost the same as the number of characters transmitted per minute. Values range from a very slow 300 baud up to tens of thousands. As the speed increases so does the chance of errors, and often the baud rate can be set by the user, who can choose the fastest speed for reliable transmission.

The RS232C standard was developed by the telecommunications industry in the days before computers came into their own. It was used for long distance communications over telephone cables. In its fullest form it includes a set of control signals to check that the

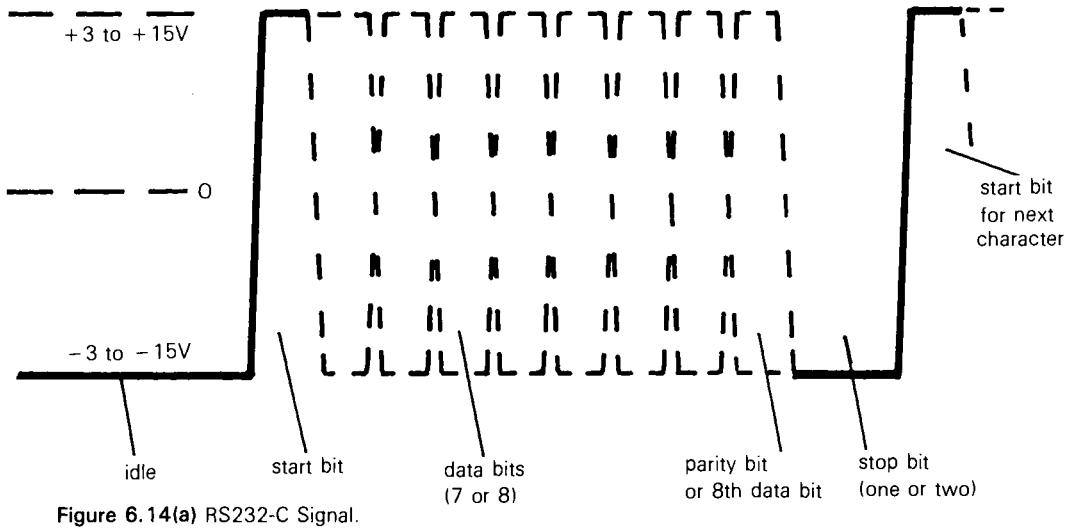


Figure 6.14(a) RS232-C Signal.

connection has been made before the data can be sent. For this reason a computer or printer with an RS232C interface does not have a connector with just two wires (a signal and earth), but instead normally has a socket with 25 connections! In practice not all of the pins are connected, but it is normal to use the 25 pin connector shown in *Figure 6.14b* as a standard. This is called a D shell, because of the shape of the outer part of the socket. The pins used are listed in *Table 6.5*.

It may seem very odd that we end up with a mass of wires coming out of what is meant to be a single wire system, but there is a very good explanation. In its original application the teleprinter was connected to a data transfer device called a modem. This received the output from the RS232C interface and converted it into a signal which was sent directly over the telephone wires. The RS232C was really the interface between the computer or teleprinter and the modem. This

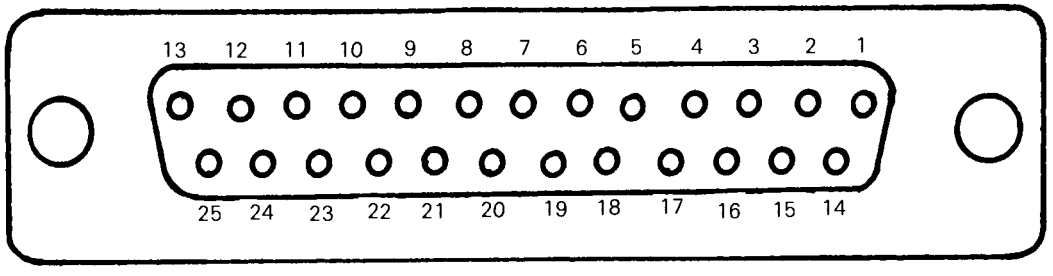


Figure 6.14(b) RS 232-C simplified. Twenty-five pin connector using round terminals. View of front of socket (female connector).

Table 6.5 RS 232C Serial interface

1	GND	Frame Ground
2	TxD	Data Transmit
3	RxD	Data Receive
4	RTS	Ready To Send
5	CTS	Clear To Send
6	DSR	Data Set Ready
7	GND	Signal Ground
8	DCD	Data Carrier Detect*
20	DTR	Data Terminal Ready*
21	SQD	Signal Quality Detect*
22	RI	Ring Indicator*
23	DRS	Data Rate Select*

* These are only required for communications between modems.

is shown in *Figure 6.15a*, which shows two devices and their modems in contact. Historically it was logical to keep the RS232C port on computers when they were developed, since they could then be used with modems, and having got an RS232C interface there was no reason why it should not be used for other purposes as well, such as for sending data to a printer, as shown in *Figure 6.15b*. There are a few problems; the computers are still expecting signals on certain pins before they will send or receive data. However this is done by carefully wiring certain pins to

others (not a job for amateurs), so that the computer is fooled into thinking that it is communicating to a modem! For example, pins four and five are often wired together and connected to pin 20 of the other device. In addition note that there are still two data lines

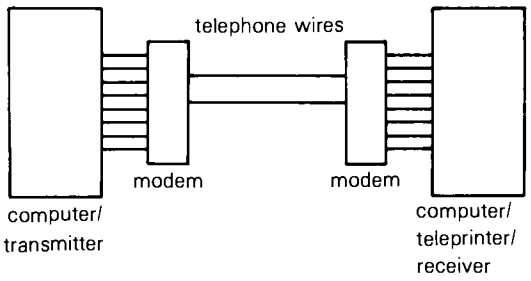


Figure 6.15(a) RS 232-C using modems for long distance communication.

in addition to the earth; one is for transmitting data, and the other is for receiving it. This means that the wires on pins two and three need to be crossed, since data sent by one device on pin two has to be received on pin three of the other. These cross-overs are done in the cable joining the devices, and for this reason the cable has to be specially made for the devices being connected. A cable with pins two and three crossed is called a reversed cable. If a modem is used then the cable needs no interconnections and is referred to as a normal RS232C cable.

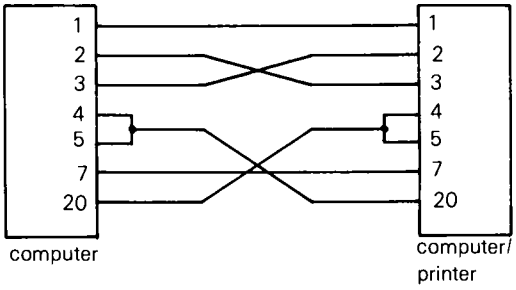


Figure 6.15(b) RS 232-C for very short distances (eg computer to printer).

Many computers only use a nine pin D shell interface. In some cases only the data and ground wires are needed.

RS232C means more than just the interconnections. The level of the signal voltages are defined, as are the electrical properties of the devices involved, and precise details of the pulses generated. However none of this affects the user, apart from mentioning that the voltage for an "on" is in fact any voltage from +3 to +15 Volts, while the "off" is defined by a voltage of −3 to −15 Volts. This last fact can cause problems, because some devices claim to supply an RS232C output when in fact an "off" is represented by 0 Volts. Some devices will not recognise this as "off", and so communication fails. This problem can be overcome by incorporating a relatively inexpensive electronic interface which converts the voltage levels (a line driver), but this can be irritating if it is not anticipated.

6.10.2 Electrical systems and equipment

Nowadays equipment is becoming increasingly based on solid state electronics. This means that as much as possible of the operation of the system occurs electrically in components which have no moving mechanical parts. This means that the devices can be much more reliable, since there is nothing to wear out.

Maintenance is also simplified. Instead of the service technician needing to spend hours or days trying to find a fault on site, she or he can simply remove the malfunctioning part or module from the system, and replace it with another. The faulty module can then be taken back to the workshop where there are adequate facilities for repair (or for discarding). In the meantime the equipment downtime is reduced to a minimum. This does assume that the servicing is up to this standard, and that spare modules are kept in stock, and these factors are important in the selection of equipment.

Most solid state systems require no more than 15 volts DC for their internal operation. They use very little power and require relatively little maintenance if any. For maximum life the temperature and more particularly humidity should be kept reasonably constant. High humidity and temperature should be avoided.

6.10.3 Control systems

An electrical or electronic control system is a device which receives inputs from one or more sensors or detectors, and which produces an output which can be used for control purposes. Usually the input involves a reference value or set point for the parameter to be controlled, and the control

action is dependant upon the difference between the set point and the actual value of the parameter to be controlled (*Figure 6.16*). For example temperature controllers require a temperature sensor, such as a thermocouple or other electrical thermometer, and the set point would be the desired temperature. The difference will be found by the comparator, and the output will be a control signal to switch on heaters if the temperature is too low, or fans if it is too high (the controller must also be able to switch the devices off again, of course, or do nothing if the temperature is correct).

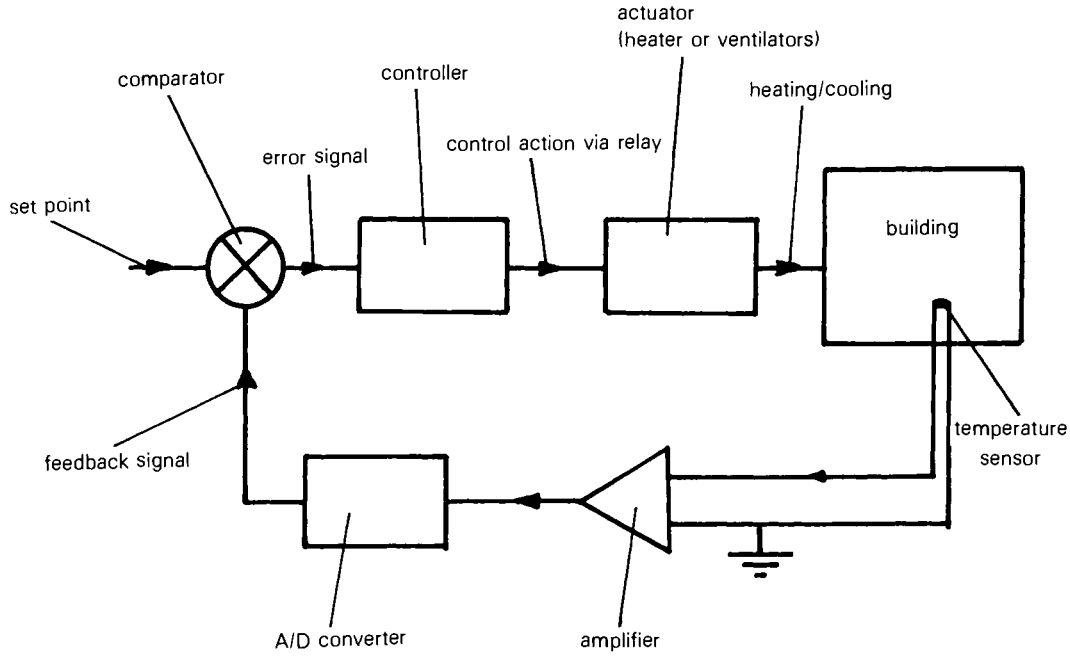


Figure 6.16 Feedback control circuit (digital system).

Controllers are required for environmental control, for electric motors, for the control of manufacturing processes, and for many other situations ranging from traffic lights to nuclear power plants.

In most cases the solid state controller (which operates on a few volts DC) will be required to switch on or off devices which require large voltages and currents. This is achieved through relays, as discussed earlier.

6.10.4 Security systems

A good security system is of vital importance to many industries, and is a fact of life in any developed country. Various types are available, ranging from relatively inexpensive infrared beam systems, which are designed to operate an alarm or switch on outside lights if there is a rapid change in the levels of radiation in the area under view, to very sophisticated video camera systems which scan an area and activate an alarm as well as record events whenever the image changes by a pre-determined amount. As an intruder gives off more infrared radiation than the surroundings, the difference can be detected. Unfortunately stray cats can have the same effect. Other systems involve trip wires or continous circuit monitors, which operate if the circuit is broken (for example if a door is opened or a window with a conducting strip deposited on it is broken).

Video camera systems are also available which will detect any movements, and record events using only the normal prevailing light conditions. More commonly the cameras are sensitive to infrared radiation, and infrared emitters are used to "illuminate" the area. Such emitters are invisible to humans. Film stars such as James Bond and McGyver can

of course penetrate anything, but most systems will deal with trivial attempts to inactivate them such as shorting out or cutting off the power supply.

Electric fence systems are effective ways of stopping most animals (with the exception of ants and elephants) but most determined human intruders can penetrate such fences relatively easily.

6.11 EXERCISES

1. Describe the following circuit components, outlining their importance in electronics: resistor, capacitor, transformer, PCB, integrated circuit, transistor, relay, diode.
2. Draw a block diagram to illustrate the main functional elements of a computer (ie ROM, RAM, CPU, buses, etc). For each block or bus describe its function.
3. Explain the terms: CPU, ROM, RAM, Bus, 64k, PROM, EPROM, byte, bit, word, data highway, interface, analogue, digital, microprocessor, hook up.
4. Explain the terms: impedance, resistance, AC, DC, farad, output impedance, input impedance.
5. Explain the terms: RS232C, IEEE 488, centronics, GPIB, serial, parallel.
6. Explain what is meant by an RS232C Interface. Draw diagrams to illustrate the signals produced on the data wires.
7. Discuss the differences between serial and parallel interfaces. When is serial communication preferable and why?
8. Suggest three applications of on-line microprocessor systems in agriculture or horticulture, which are or could be useful. In each case outline how the system would operate, and list the benefits to the user compared with existing or traditional methods.
9. Derive a relationship between the input and output impedances of two analogue devices, the voltage generated by the source, and the voltage received by the second device at its input terminals. Discuss the implications of this relationship in the selection of suitable analogue devices.
10. State the impedance of a capacitor as a function of its capacitance and the frequency of the signal. Discuss the use of capacitors in circuits as filtering devices. What does the j term in your equation imply ($j = \sqrt{-1}$).
11. Discuss noise problems in analogue circuits, and ways of reducing the problem.
12. Compare the advantages and disadvantages of analogue and digital systems.
13. Explain what is meant by a digital system.
14. A new electronic device has the following characteristics:

Inputs:

Number of channels	= 2, both analogue
Full scale	= 5 mV
Impedance	= 5×10^6 ohms

Outputs:

Output 1:

Output type	= analogue
Impedance	= 10 ohms
Signal	= product of input 1 and input 2 multiplied by 10^6.

Output 2:

Output type	= RS232C connector
Signal	= Each minute the device produces a sequence of signals representing the average values in the previous minute of: (1) The first input signal (2) The second input signal (3) The first output signal

Suggest two uses of such a device for an agricultural or horticultural enterprise. For each idea, draw a block diagram listing details of any associated equipment (eg meters, sensors, recorders, amplifiers, filters, etc.) and show the signal at each input and output.

15. Explain what is meant by a BUS.
16. How many different codes could a 12 wire BUS carry?

17. What is meant by a code in digital systems. Give examples.
18. Explain the meaning of the term ASCII.
19. Explain the signals on pins 2, 3 and 7 of an RS232-C interface. Indicate why the other signals are required, but do not attempt to explain them individually. In the case of Pin 2, draw the signal which would appear corresponding to a byte of data representing the letter E (=01000101).
20. Assuming the MSB is the left most bit, write out the 8 bit codes for the message HELLO No 14. Repeat this, but in hexadecimal code.

6.12 AIMS OF THIS CHAPTER

When you have read through this chapter, you should be able to achieve the following tasks.

1. Discuss the purchase of electronic equipment.
2. Explain the terms current, resistance, and voltage, using an analogy with water flow in pipes.
3. State and apply Ohm's law, for resistances either in series or in parallel. Explain why wire size is important.
4. Describe the various components which make up modern electrical circuits, including batteries, resistances, capacitors, inductances, transformers, relays, PCBs, and ICs.
5. Discuss and distinguish between analogue and digital circuits, and discuss interfacing methods for both types of circuit. Explain the meaning of the terms RS232C and centronics interfaces.
6. Describe two digital coding systems, including the ASCII system.
7. Explain the principle of operation of a simple computer.
8. Discuss the applications of electronics to horticulture and agriculture.

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Most good introductory text-books on Physics will give more information on the topics covered here.

Power systems and thermal systems

Chapter 7

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7.1 INTRODUCTION

The concepts of work, energy and power have been discussed in Chapter 3. In this chapter, we will describe equipment used throughout agriculture and horticulture to enable work to be done speedily, efficiently, and sometimes automatically. We will begin by describing the simplest types of equipment, which never the less play a vital role in enabling difficult operations to be carried out safely and easily.

7.1.1 Machines

A machine is a device to make life easier. The machines described here are mechanical systems which reduce the force which is required to move an object. Since work done is the product of force and distance, if the force is to be reduced then the distance the force moves must be increased. The simplest type of machine is a pulley and tackle, as in *Figure 7.1a*. Pulling on the rope lifts the weight. If we assume that everything is smooth (ie, no friction), then the tension in the rope (T) will be the same all along the rope. The minimum force required to lift the weight will be one which just balances the weight of the mass. Since the rope is wound around the tackle twice the weight is divided into four. This means that the tension in the rope is only one quarter of the weight of the object, and so the force required is also one quarter of the weight. However, in order to raise the mass by one metre, it is necessary to pull in four metres of rope. Since work done is force x distance, we are not really gaining anything. We are just pulling a smaller force over a greater distance.

Some definitions help to describe the performance of a machine. The *Effort* (F) is the force applied. The weight being lifted is called the *Load* (W). The *Mechanical Advantage* (MA) is defined as the ratio of the load to the effort.

$$\text{Thus MA} = \frac{W}{F} \qquad \textbf{Equation 7.1}$$

The *Velocity Ratio* (VR) is the ratio of the distance moved by the effort d_1 to the distance moved by the load d_2, or:

$$\text{VR} = \frac{d_1}{d_2} \qquad \textbf{Equation 7.2}$$

The velocity ratio can always be calculated from the geometry of the machine. Thus in the example above the VR will always be four.

The MA is less easy to calculate: in a perfect frictionless world the two would be perfectly matched, so that the mechanical advantage was exactly equal to the velocity ratio. In reality friction of the bearings reduces the MA, so that the effort is always more than in the ideal case. The efficiency is given by:

$$e = \frac{MA}{VR} \qquad \textbf{Equation 7.3}$$

Other examples of machines are shown in *Figure 7.1b* and *Figure 7.1c*.

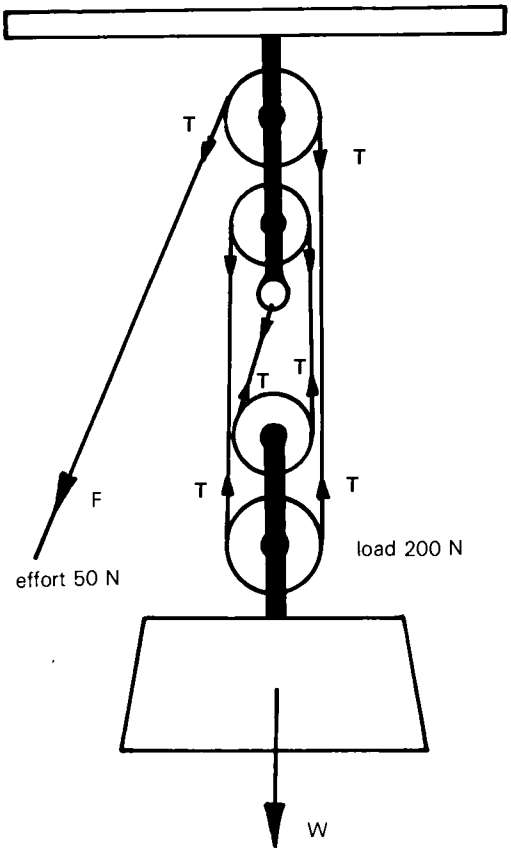


Figure 7.1(a) Pulley (VR = 4).

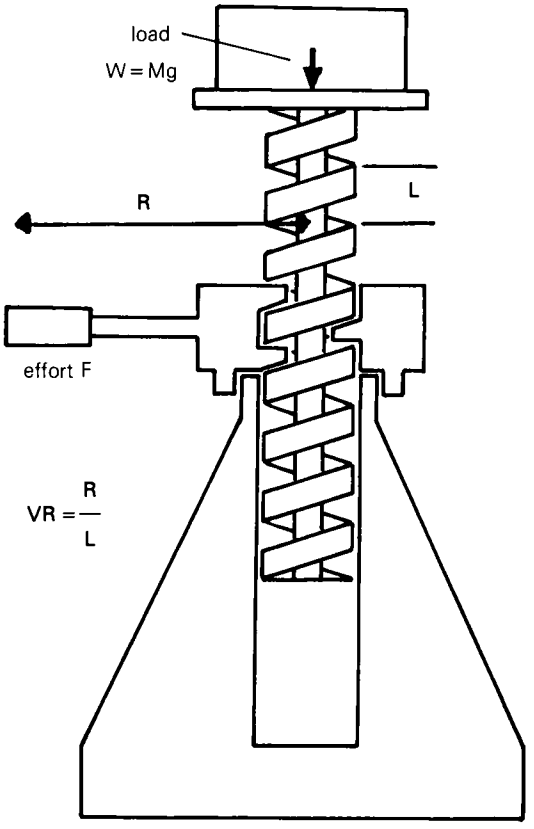


Figure 7.1(b) Screwjack.

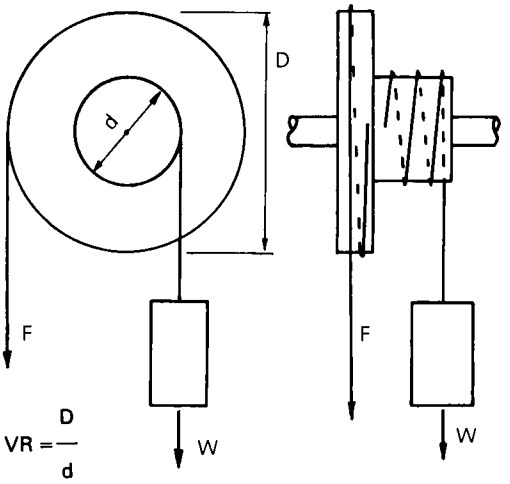


Figure 7.1(c) Differential axle.

7.1.2 Brake power

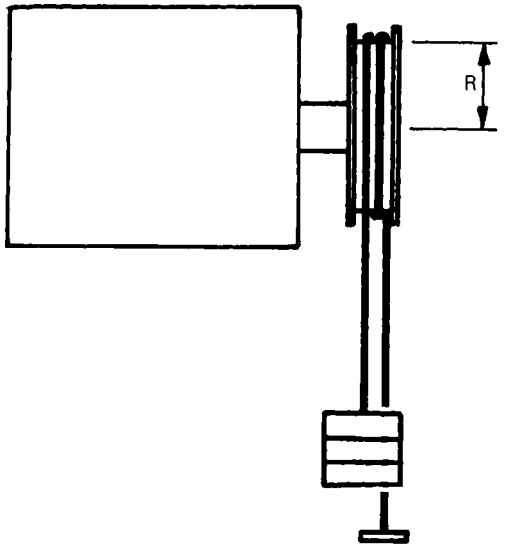
Before we leave this introductory section, we will define the power output from a motor or engine. This is called the brake power, because it is measured with a device called a *Prony Brake*. The prony brake is a system which generates a resistance to the movement of the engine so that the engine is under an artificially imposed load for test purposes. By monitoring the load and the speed of the engine, the power output can be measured. This can be shown as follows: *Figure 7.2* shows the configuration of a simple prony brake. The output shaft of the motor or engine under test is made to rotate

a large metal disc or drum. A cord is wrapped around the drum and weights are attached to each end. As the drum rotates, it tries to rotate the cord along with it, but it is possible to keep the cord stationary by adjusting the weights so that the difference in weight F – f just equals the sliding friction force produced by the motor on the cord. When the cord is stationary all the forces must just balance.

Thus, the force produced by the motor = F – f.

Now the work done is equal to the product of the force and the distance moved. In this case, in one revolution of the shaft, the distance the shaft moves is $2\pi R$, so the work done per revolution is given by:

$WD = 2\pi\ R\ (F - f)$ **Equation 7.4**



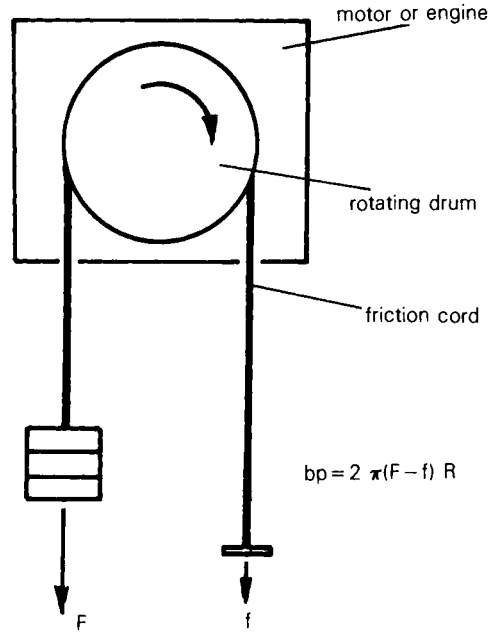


Figure 7.2 Prony brake.

But if the speed of the motor is S revolutions per second, then the work done per second (ie, the power output of the motor) is given by:

Brake power = bp = $2\ \pi\ (F - f)\ R\ S$ **Equation 7.5**

This can be written as:

$bp = 2\ \pi\ T\ S$ **Equation 7.6**

where T is the torque from the motor ($T = (F - f)R$).

Providing F and f are in newtons, and R and S are measured in metres and revolutions per second respectively, then the brake power will be measured in watts.

In passing it should be noted that the entire output from the motor is converted into heat by friction between the brake drum and the cord. These components will get very hot during the test and some method of cooling is essential. Quite often this involves spraying water onto the parts of the drum not in contact with the cord.

It should also be noted that it is quite difficult to get an exact balance using the two weights as shown. In practice the smaller weight f is usually replaced by a spring balance, which compensates for small variations in the friction force. In more sophisticated equipment the means of generating the forces may be quite different, but the principle remains the same.

7.2 ELECTRICAL POWER

7.2.1 Power and energy consumption

As discussed in the previous chapter, when a current flows through a resistance, work is done by the voltage. The rate of doing this work is the power (P), which is found by multiplying the voltage drop across the

resistance by the current, or as in *Equation 6.4*:

$$P = V\ I \qquad \textbf{Equation 7.7}$$

where P is in watts.

Power is measured in watts. The power output of many components is a very important value. Electric motors are described by their power output, normally in kilowatts. Older motors are still rated in horsepower, which is the old Imperial unit of power; one horsepower is equal to 746 watts. Some values of the wattage of a number of items of equipment are given in *Table 7.1*. For now take the values quoted as the wattage; we will discuss the correction due to the so-called power factor later.

For domestic appliances in New Zealand the voltage is 230 volts. The maximum socket current is 10 amps, so that the maximum apparent power input is $230 \times 10 = 2{,}300$ volt amps.

Energy use

The energy consumed by a piece of equipment is found by multiplying the power by the time for which it operates. Thus if a 25 watt light bulb is run for 60 seconds the

Table 7.1 Approximate power requirements of electrical equipment

Equipment	Input volt-amps	Equipment	Input volt-amps
Air conditioner, Central, electric	3000-9000	Knife, electric	100
Air conditioner, room	800-3000	Lamps, fluorescent	15-60
*Blanket, electric	150-200	*Lamps, incandescent	10-1000
Clock	2-3	Mixer, food	120-250
*Coffee maker	500-1000	Motors	1600 per kW
*Desk computer	100-500	Polisher, floor	250
*Corn popper	450-600	Projector, movie or slide	300-1000
Dishwasher	600-1000	Radio	40-150
Dryer, clothes	4000-5000	*Range, oven only	4000-5000
Dryer, hair	250	*Range, top only	4000-6000
Fan, 8 inch portable	30	Razor	8-12
Fan, 10 inch portable	35	Refrigerator, household	150-300
Fan, 12 inch portable	50	Rotisserie	1200-1650
Fan, kitchen vent	75	Scissors, electric	12
Freezer, household	300-500	Sewing machine	60-90
*Fryer, deep fat	1200-1650	*Soldering iron	200-250
*Frying pan	1000-1200	Television	200-400
Furnace, oil (fan & burner)	500-600	*Toaster	500-1200
Waste disposal Unit	200-400	Toothbrush, electric	15
*Heater, permanent wall type	1000-300	Vacuum cleaner	250-800
*Heater, portable household	1000-1500	*Waffle iron	600-1000
*Heater, water	2000-5000	Washer, automatic	600-800
*Hot plate (per burner)	600-1000	Washing machine	350-550
*Iron, hand	660-1200	Welder, transformer 180 amp output	8620
*Jug	1500-2000	225 amp output	11500
Juicer	100		

* These devices operate at a Power Factor (PF) close to 1.0 (discussed later), so the volt-amps gives the true power input. Most of the other devices involve motors, so that the PF varies from 0.5 – 1.0. The true wattage used is less than the volt-amps, since as we shall see, the actual input power is given by watts = volts × amps × power factor.

energy consumed will be:

Energy used = $25 \times 60 = 1500$ joules

This may seem a lot but really the joule is just a very small unit. In practice the unit of measurement of energy consumption is the kilowatt-hour, (kW h) which is the power in kW multiplied by the number of hours of operation. It is thus the amount of energy used when something (eg a light bulb) of say 1 kW runs for 1 hour. Since watts are the rate of doing work, and the units of work are joules:

1 joule/sec = 1 watt; so
1 joule = 1 watt going for 1 second; ie
3,600 joules = 1 watt going for 1 hour
3,600,000 joules (= 3.6 MJ) = 1 kW hour = 1 kW h

Thus 1 kW h = 3.6 MJ (= 3,600,000 joules) **Equation 7.8**

Electricity is normally priced as the cost per kW h used.

Example

Find the cost of running a 24 watt light bulb for two days, at a charge of 15 cents per unit (ie per kW h).

Solution: energy used = power (kW) × time (hours)
Power used = 24 watts = 0.024 kW
Time = two days = 48 hours
Thus energy used = $0.024 \times 48 = 1.152$ kW h
At 15 cents per kW h the cost will therefore be: $15 \times 1.152 = 17.3$ cents

This is not very much. Note that the calculation could have been done using watts and seconds to give joules, but the numbers would have been very large and the calculation would have been more tedious.

7.2.2 Line losses

Combining Ohm's law and the power law leads to an important practical result. Since $P = V\ I$ and $V = I\ R$ (*Equations 6.4* and *6.1*, where P is in watts, V is in volts, R is in ohms and I is in amps), substituting gives:

$W = (I\ R) \times I = I^2R$ **Equation 7.9**

In other words as the current through a fixed resistance increases, the power goes up as its square. Thus, when we transmit power along cables, the cable has a resistance and power is lost. The losses are proportional to the current squared. These losses are turned into heat, and we often call these heating losses in conductors the "I^2 R losses". Thus, for transferring power in cables, it is best to keep the current as low as possible and the voltage as high as possible. This explains why the national grid electricity cables and lines are at high voltage (up to 500,000 volts!).

7.2.3 Water heaters

If we connect a suitable resistance wire across the power supply, put it in a hot water tank and switch it on, we get heating. The heat produced is given by *Equation 6.4*. Hot water elements are usually rated in kW. For example, you may have a 1.5 kW element. This means that when it is connected to the mains (230 volts*) the element delivers energy at the rate of 1.5 kW (or 1500 joules per second).

Example

What will the resistance be, and what is the current which flows through the wires?

Solution: Its resistance will be given by:

$$R = \frac{V}{I} = \frac{V^2}{W} = \frac{230 \times 230}{1500} = 35.3 \text{ ohm}$$

The current flowing will be:

$$I = \frac{V}{R} = \frac{230}{35.3} = 6.52 \text{ amps}$$

Example

A dairy farmer receives a bill for two months water heating of $1418.25. What information would you need and how would you decide if the heating charge was reasonable? The cost of electricity was $0.25 per unit.

Solution: The farm used 1418.25/0.25 = 5673 kW h of energy for heating water over two months. This is about 5673/61 = 93 kW h per day. Is this satisfactory? To answer this we need to know how much energy is required to heat the water in the first place. We need to know how much water is heated, how often, to what temperature, and from what temperature.

On the farm they clean once a day with 60 gallons (273 litres of water at 95°C). This is the only hot water used. The cold water comes in at 16°C.

From *Equation 3.54*, the energy required is given by:

$$Q = M\ S\ \delta T \qquad \textbf{Equation 7.10}$$

where Q is the energy in joules, M is the mass in kg, (ie, 273 kg since 1 litre has a mass of 1 kg), S is the Specific heat (4,200 J kg^{-1} $°C^{-1}$), and δT is the temperature difference. Thus:

$$Q = 273 \times 4200 \times (95 - 16) = 9.06 \times 10^7 \text{ J}$$

We now need to get this into kW h.

$$Q = \frac{9.06 \times 10^7}{3.6 \times 10^6} = 25.2 \text{ kW h per day}$$

So in 61 days this will be $61 \times 25.2 = 1537$ kW h.

Now the power bill said 5673 units. Would you check the meter reading?

I hope your answer is yes! You check the meter reading shown on the bill against the reading on the electricity meter. The reading tallies. Somehow the water heater is using $93 - 25 = 68$ kW h too much electricity per day. Can you suggest where?

Some heat is inevitably lost by heat transfer through the cylinder walls. As a rough guide an old 273 litre cylinder will lose heat at the rate of about 0.3 kW. Thus, if it is left on 24 hours a day this will only amount to 8 kW h. By itself this would not be enough. Other possibilities include leaky valves, a thermostat set at 103°C (think about it!), wet insulation, cylinder in a drafty position, etc. By checking the system you could save this farmer $5,475 a year!

* In fact the mains voltage does not have a constant value. We will discuss what happens shortly. Here our model of the system is perfectly adequate if we do take the voltage as constant at a value which represents the effect of the voltage called the RMS value. This is an example of a model which is very good for its one purpose of calculating the power, even though it is a very poor description of reality.

7.3 ALTERNATING VOLTAGE SUPPLIES

Unfortunately we have so far only considered the situation where the current stays constant. We refer to these by the letters DC (Direct Current). Unfortunately for power applications DC is rarely used. Nearly all electrical power on farms and in buildings is in the form of voltages and currents which vary with time. We will first describe the nature of the mains power supply (ie, the power supplied by the Electricity Authority). Then we will examine how the power is calculated, and show why Ohm's Law is still a good model, even for varying voltages.

Alternating current is a flow of electricity which changes its direction of flow at certain regular intervals. Suppose we get a voltmeter that has zero in the centre of its movement (*Figure 7.3*) so that it can register a voltage regardless of which way we connect the positive or negative terminal. When we

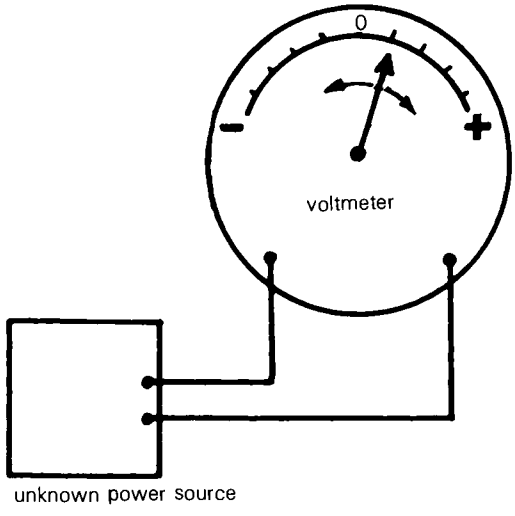


Figure 7.3 Illustration of voltmeter measuring a regularly changing voltage.

connect this to a source of electricity unknown to us we observe that the needle keeps swinging from one end of the scale to the other with great regularity. As we watch the pointer, starting at zero, we observe it moves to the right, first rapidly, then more slowly, until it reaches a maximum of 100 volts in exactly 15 seconds. Then it starts dropping back toward zero, first slowly, then rapidly until in 15 seconds it is back at zero. It repeats this same operation toward the left side until, in 30 seconds, it is back at zero again. It repeats this same procedure every minute. This is known as an alternating voltage or current source, and is described as an AC voltage. If the voltage were plotted against time it would produce a graph as in *Figure 7.4*. This illustrates one cycle of alternating current.

The equation for this voltage is:

$V = V_o \sin 2\pi ft$ **Equation 7.11**

where V_o is the peak voltage, f is the frequency in hertz, and t is the time in seconds.

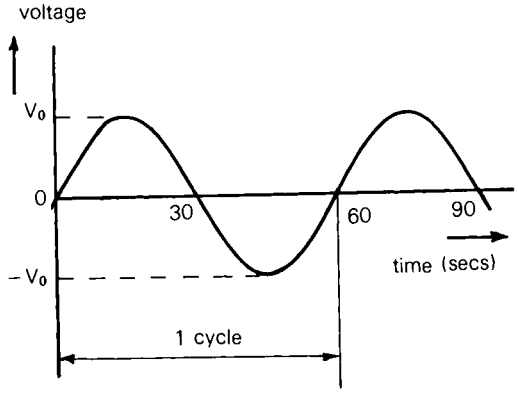


Figure 7.4 Alternating voltage (AC). The frequency here is one cycle per minute (0.01667 Hz).

Alternating voltage that takes a full minute to complete an entire cycle has a frequency of one cycle per minute. In New Zealand the mains voltage operates at 50 cycles per second (50 hertz or just 50Hz). In the USA 60 Hz is used. In the laboratory we have to observe these time dependant variations of voltage with an oscilloscope rather than a voltmeter. Now how do we work out the power in this situation? Let us consider the power produced by an electric heater element connected to the mains supply. The element is just a length of special wire which has a resistance of around 30 ohms.

Ohm's law still applies at every instant in time. Therefore the current will follow the voltage, peaking whenever the voltage peaks. In *Figure 7.5a* and *b* the voltage and current are shown for a circuit with a peak voltage (V_o) of 325 volts and a peak current (I_o) of 10 amps. The current flows first in one direction, and then back the other way as the voltage reverses. Not only does Ohm's law apply at every instant, but so does the power law. Thus if we multiplied the voltage by the current at every instant, we would get the instantaneous power P. This is done in *Figure 7.5c*. Note that where both voltage and current are negative, the power is still positive since two minuses multiplied together give a plus.

Note that wherever V and I are zero, so is P, and wherever V and I reach maximum values ($V_o = 325$ V, $I_o = 10$ amps) the instantaneous power is 3250 watts (ie V × I). You can check *Figure 7.5* by putting in values at the point marked X – X. Does the product of the voltage and the current equal the value of the wattage? You should get (roughly) V = 210 V, I = 6.5 amps, so P = 1365 W.

Mathematical derivation

The mathematical calculations are as follows (it is not essential to understand them to be able to follow this section):

If the peak value of current is I_o then the instantaneous power is given by

$P = V_o \sin 2\pi ft \times I_o \sin 2\pi ft$

$= V_o I_o (\sin^2 2\pi ft)$ **Equation 7.12**

where t is the time in seconds, and f the frequency in hertz (cycles per second).

From trigonometry, for any angle A:

$\sin^2 A = 1/2\ (1 - \cos 2A)$ so

$P = 1/2\ V_o I_o\ (1 - \cos 4\pi ft)$

Equation 7.13

ie, a cosine wave with twice the frequency and displaced zero, as shown in *Figure 7.5c*.

The power from the heater resistance thus comes out in a series of short bursts of power each lasting half a cycle. In practice we do not notice this variation in power since it happens too quickly to give any detectable variation in the temperature of the heater element. Instead what we measure or detect is the average power output over many cycles.

If this seems hard to understand, it is helpful to realise that the power in electricity arises because of the flow of current (or electrons) *through* a resistance. It does not matter which way the electrons flow, as long as they are driven through the resistance by the voltage. The best analogy is to consider a simple water turbine (*Figure 6.1*). Power will be extracted as the water flows through the turbine, pushing against the sides of the blades. If the water flow is then reversed, the turbine can be forced to turn as the water now pushes against the opposite face of the blades. This principle is used in tidal power stations, where power is extracted both as the tide comes in and as it goes out.

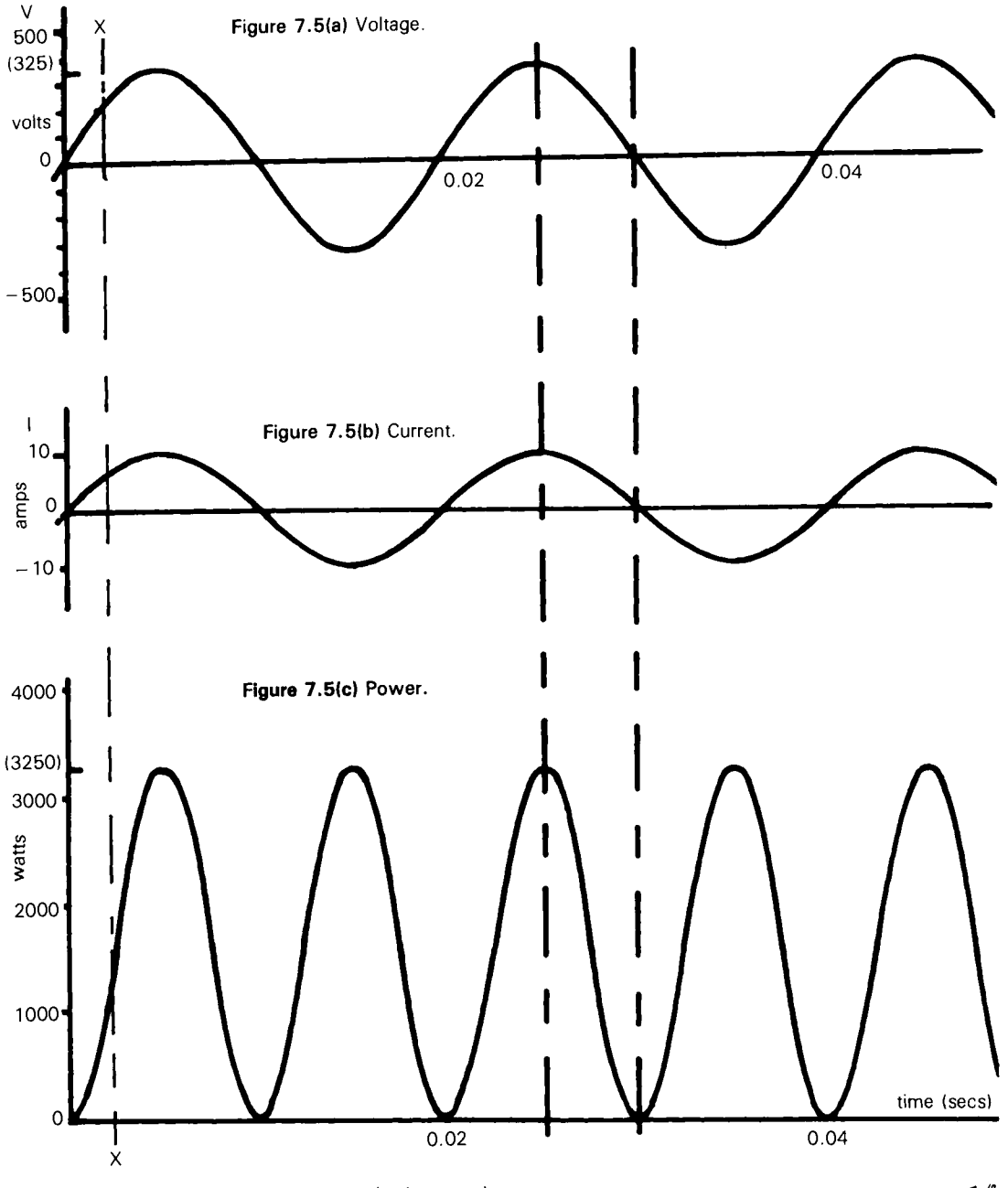


Figure 7.5(a) Voltage.

Figure 7.5(b) Current.

Figure 7.5(c) Power.

Figure 7.5 Alternating voltage and current in phase, and power generated.

The average value of the power is found by summing all the bursts and dividing by the time for one cycle (1/f).

Thus, integrating over the cycle gives:

$$\text{Power} = f \int_{t=0}^{t=1/f} 1/2\ V_o\ I_o\ (1-\cos 4\pi ft)\ dt$$

$$= 1/2\ V_o\ I_o\ f\ t - \left[\frac{\sin 4\pi ft}{4\pi f}\right]_0^{1/f}$$

$$= 1/2\ V_o\ I_o$$

Equation 7.14

We can write this as:

$$P = \frac{V_o}{\sqrt{2}} \times \frac{I_o}{\sqrt{2}}$$

Equation 7.15

or $P = V_{RMS} \times I_{RMS}$ **Equation 7.16**

where $V_{RMS} = \frac{V_o}{\sqrt{2}}$ **Equation 7.17**

and $I_{RMS} = \frac{I_o}{\sqrt{2}}$ **Equation 7.18**

V_{RMS} and I_{RMS} are called the Root Mean Square values (or RMS values) of the voltage and current respectively.

Example:

What are the values of the RMS voltage and current for the example in *Figure 7.5*?

Solution:

$$V = \frac{325}{\sqrt{2}} = 230 \text{ volts}$$

$$I = \frac{10}{\sqrt{2}} = 7.07 \text{ amps}$$

We write it this way (*Equations 7.16-7.18*) because $V_o/\sqrt{2}$ and $I_o/\sqrt{2}$ represent the effective values of the voltage and current respectively.

Thus if we use the RMS values *Equation 7.16* just says:

Power = volts × amps ($= V_{RMS} \times I_{RMS}$)

which is identical to the power law for constant currents.

What this means is that for purely resistive AC circuits we can forget that the voltage and current are varying and simply use our old laws: thus as in *Equations 6.1* and *6.4*, V = I R and P = V I where V and I are in fact the RMS values. We will therefore drop the subscripts after the next example.

Example

What is the power output for the situation in *Figure 7.5*?

Solution: $P = V_{RMS} \times I_{RMS} = 230 \times 7.07 = 1630$ watts

When we describe a mains supply as 230 volts, the value is indeed the RMS value. The peak voltage is in fact $230 \times \sqrt{(2)} = 325$ volts.

The peak to peak voltage (total swing of the voltage) is in fact 650 volts (*Figure 7.5a*).

Many electrical devices, such as heaters or lamps, work equally well in theory on AC or DC supplies. Other devices, such as motors, must be designed for one source or the other.

The main reasons for supplying AC throughout the country are that electricity can be generated in the form of AC conveniently, and that AC voltage can be stepped up or down by transformers, devices which are relatively cheap, and are highly reliable (since they do not have any moving parts).

7.3.1 Power factor

Earlier we said that resistance was one form of impedance (ie, something which tries to prevent or reduce the flow of current). There are two other forms of impedance, which we met in the previous chapter. These are Inductors and Capacitors. In practice electric motors and electromagnets are examples of devices which behave like inductors. In particular, a motor consists of coils of wire (windings) which create varying magnetic fields from which the required torque is generated, and these coils act like inductances. One of the features of an inductance is that it makes the current "lag" behind the applied voltage. This means that in a real AC circuit with a motor, the current reaches its peak after the voltage (*Figures 7.6a* and *b*). There is a time delay before the current catches up to the point in the cycle that the voltage has reached. For example, when alternating current is applied to an induction motor, due to the inductive load of the motor windings, the current is not in step with the voltage but lags behind by about 86° when the motor has no load, to about 25° when it is fully loaded, as shown in *Figure 7.6*. At time t = 0.005 seconds the voltage has reached its peak value. The current does not reach the same point in its cycle until time t = 0.0098 seconds in curve b and t = 0.0064 seconds in curve c.

Power produced in one cycle

It turns out that the useful power produced when the current lags by more than 20° is significantly less than the potential power if the same current is in phase with the voltage. We can see this by the following argument.

The power produced in a device at any instant in Watts is always the product of the voltage across it and the current at that instant (this was discussed earlier). Suppose we now consider the product of voltage and current in an electric motor, where the current lags

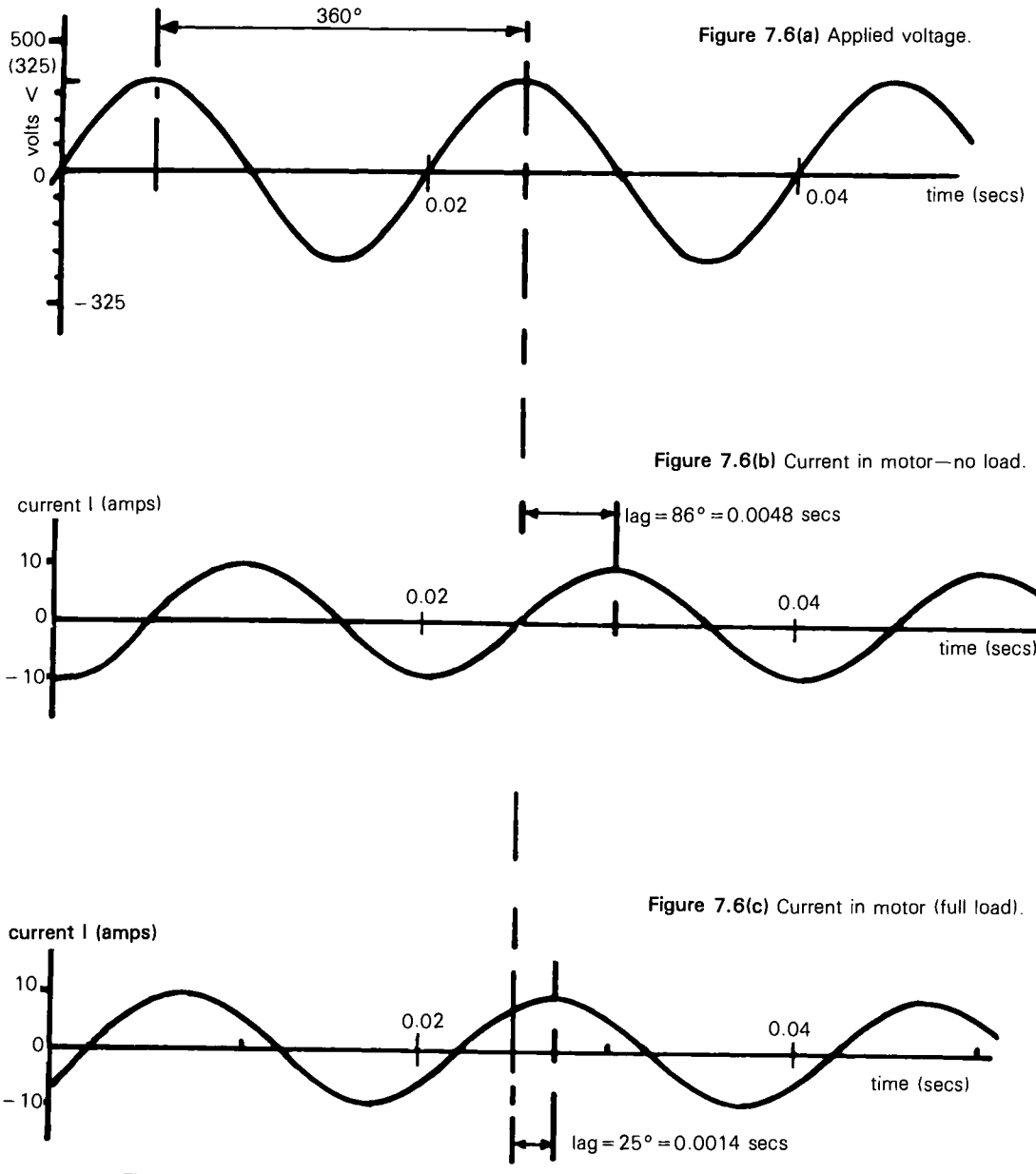


Figure 7.6(a) Applied voltage.

Figure 7.6(b) Current in motor—no load.

Figure 7.6(c) Current in motor (full load).

Figure 7.6 Current lag in motor.

behind the voltage. *Figure 7.5c* showed the situation when the current and voltage were in phase (ie, no lag). Using the same scales, *Figure 7.7c* shows the resultant curve which represents the instantaneous power at every moment in time. Again, the result is a sine wave with twice the frequency, but in comparison with *Figure 7.5c* the curve drops below the axis at some points. This means that the power is actually negative for short periods of time. You can check this by taking some readings off curves 7.7a and b. At every point you should find that $P = V \times I$ (*Equation 6.4*).

Mathematically, if $\emptyset$ is the angle of lag of the current behind the voltage it can be shown that:

$$P = 1/2\ V_o\ I_o\ ((\cos^2 \emptyset/2) - \cos 4\pi ft)$$

Equation 7.19

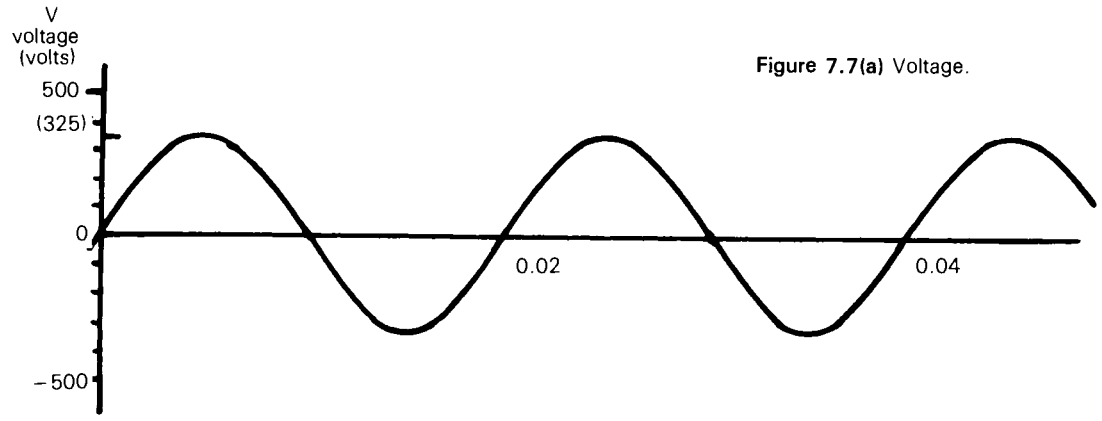


Figure 7.7(a) Voltage.

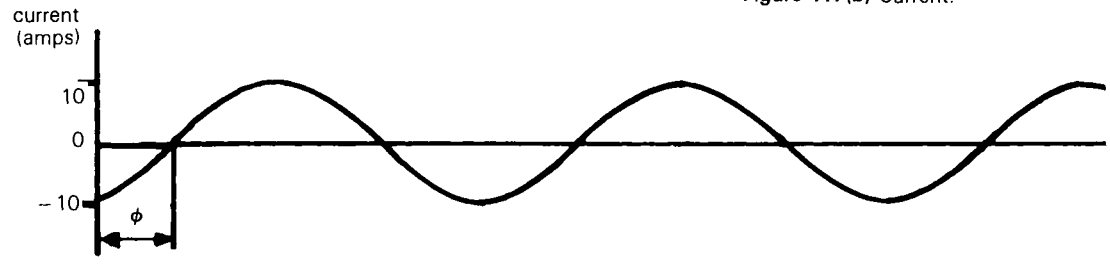


Figure 7.7(b) Current.

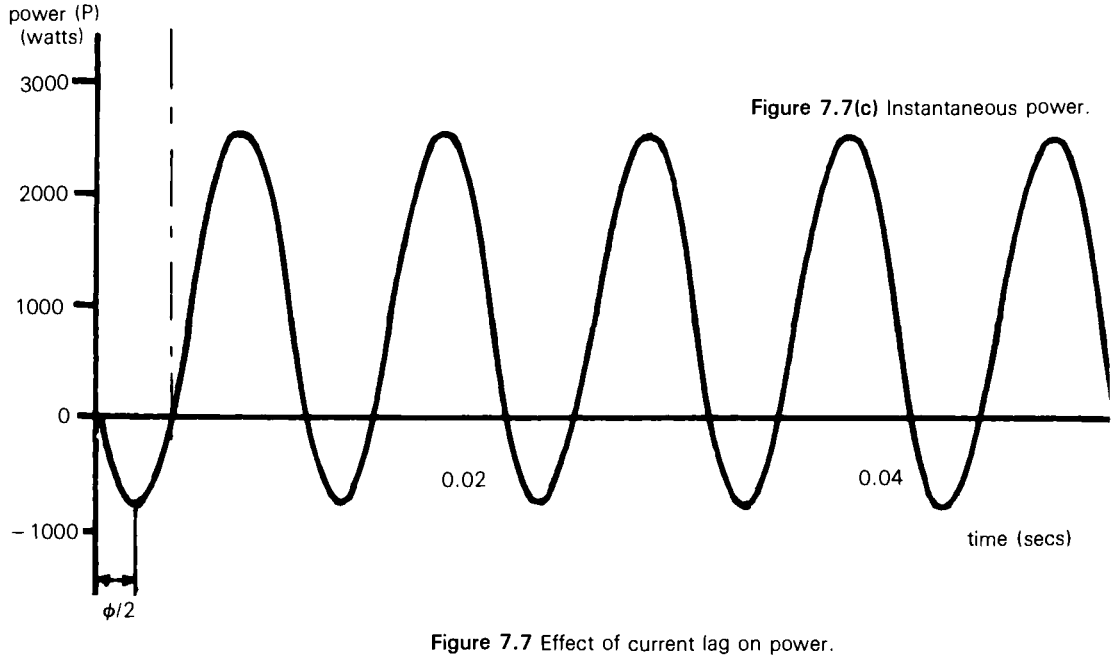


Figure 7.7(c) Instantaneous power.

Figure 7.7 Effect of current lag on power.

The curve is the same shape as before, except that the sine wave peaks half way between the voltage and current peaks, and is displaced downwards.

When we work out the average power it will clearly be less than the power obtained in the pure resistance, since we must add up all the positive areas under the curve and subtract the negative areas (ie the parts below the axis). Mathematically it can be shown that:

$$\text{Power} = V \times I \times \cos \emptyset = V \times I \times PF$$

Equation 7.20

where V is the root mean square voltage and I is the root mean square current. The cosine of the angle of lag of the current (cos Ø) has a value between 0 and 1. This term is called the Power Factor or PF. If we measure the input current and voltage to a motor, and we also measure the input power, then we can calculate the power factor.

Example

What is the value of the power factor for a pure resistance?

Solution: PF = 1.0

(You can confirm this from several viewpoints: the angle of lag Ø is zero so cos Ø = 1.0: alternatively *Equation 7.20* requires P = 1.0 since P = V × I).

The product of V and I is referred to as the apparent power, since it is what we would have expected.

$$\text{Thus Apparent Power} = V \times I$$

Equation 7.21

The power factor can be expressed as:

$$\text{Power factor} = \frac{\text{true power in}}{\text{apparent power}} = \frac{\text{watts}}{\text{volts} \times \text{amps}} = \frac{P}{V \times I}$$

Equation 7.22

Power factor is important because, for low power factors, an excessive amount of current must be carried through the conductors in order to develop a specified power rating. This can cause over-heating of the connecting wires (because the wires always have some resistance and the heat generated will be equal to I^2 R). There will also be a greater voltage drop in the supply lines, because the product IR will be higher. These are of concern to the power supply authorities, who are paid for the watts used and not the current, but whose costs are dependent on current (since the line losses and the size of the wires are dependent on current).

The ideal power factor is 1.0, which means that Ø = 0 (ie voltage and current in phase). In induction motors (inductors) the current always lags the voltage. The power factor therefore always falls below 1.0.

In a condenser the current always leads the voltage (ie the current peaks before the voltage peaks). This means that a correctly sized condenser connected across each phase of a motor will correct the motor's lag, so that the current and voltage are again in phase. In order to get a power factor near to unity, the power board usually specifies that a condenser must be installed on all electric motors. The board specifies the size, and the electrician will install it. The condenser brings the current more in phase with the voltage, and the power factor comes closer to 1.0. For example, in New Zealand, the consumer must arrange to fit a suitably sized condenser to each motor to give an average power factor of 0.95 to 0.97 at between 33% to 125% of the rated motor power. By connecting a capacitor of the correct size across each phase of an electric motor a low power factor of, say, 0.4 may be corrected to 0.96 with a large drop in the current drawn by the motor. At the same time there will be no change in the true power which the motor uses. Power board engineers will supply tables of recommended condenser sizes for all motors up to 200 kW on request.

7.3.2 Implications for the consumer

While the requirement to correct the power factor to unity is very important for the Supply Authority, it is of less importance to the consumer. There could be problems with voltage losses on wiring around the farm, but in general these effects are rarely noticeable. In order to force large consumers to attend to their power factor, the supply authorities have developed different scales of charges, which are based on a maximum KVA (kilo volt-amp) rating. A company buying power on such a tariff must take all possible steps to reduce its peak KVA demand. In practice many factories install automatic correction units which switch banks of condensers in and out as required to maintain an optimum power factor at all times.

7.4 ELECTRICAL POWER GENERATION AND DISTRIBUTION

7.4.1 Sources

Electrical power comes from various large power stations distributed around the

country. The power is distributed via overhead transmission lines. In many places different land masses are connected by high voltage cables on the ocean floor. The power stations derive their power from one of the following:

(a) Hydroelectricity

A river is dammed, and the water is allowed to flow through a turbine, converting potential energy of the water into electricity. The water can be fed through a series of stations on its way to the sea (*Figure 7.8a*). About 85% of New Zealand's electricity is produced in this way. The Netherlands and the UK have almost no hydroelectric resources.

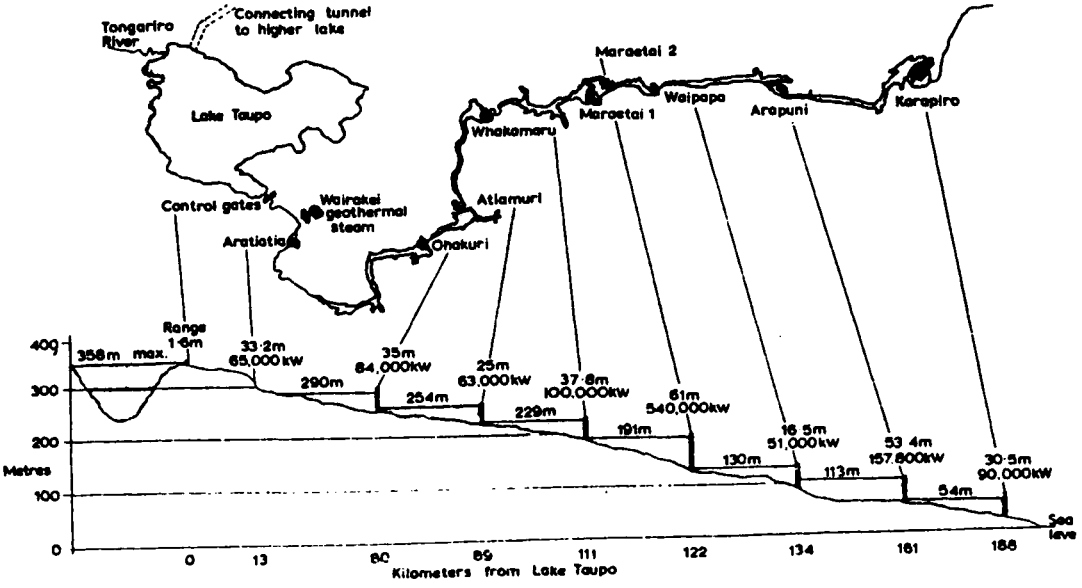


Figure 7.8(a) Hydro-electric stations on the Waikato River, New Zealand (New Zealand Technical Institute).

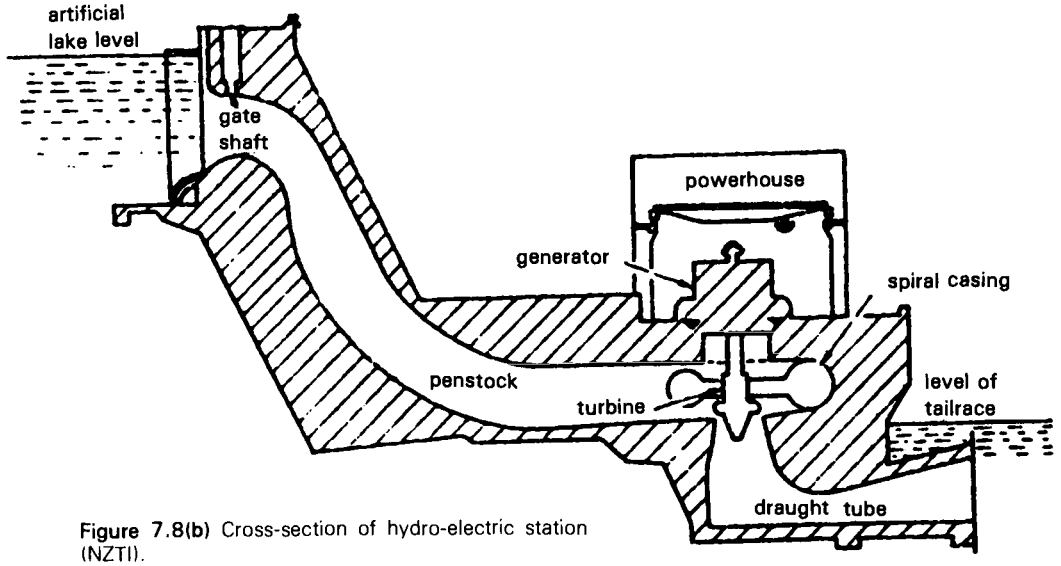


Figure 7.8(b) Cross-section of hydro-electric station (NZTI).

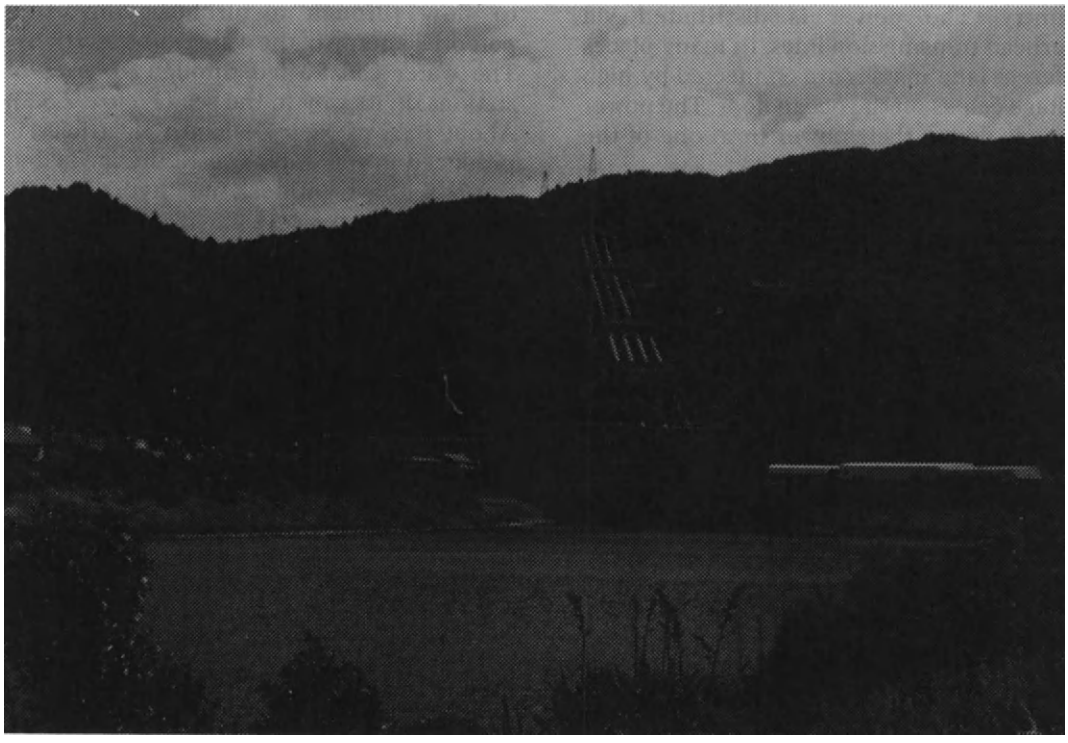


Figure 7.8(c) Hydro-electric station at Tokaanu, New Zealand.

(b) Geothermal

A bore hole is drilled in a thermally active region, (eg Rotorua in New Zealand) and subterranean steam is drawn off. This is then passed through turbines to produce electricity. The steam is heated by the heat from radioactive reactions taking place inside the earth.

(c) Thermal

Conventional fuels (gas, oil, coal) are burnt to generate steam which is passed through turbines. Nuclear power is also used to generate heat. In many countries these are the only sources of power.

(d) Alternative sources of power (eg wind, solar energy)

These currently represent only very minor sources of power with limited applications. They are discussed later in this chapter.

7.4.2 Method of generation

Apart from the last, all these systems rely on the source of power causing a turbine to rotate (*Figure 7.8b*). This rotation gives rise to electricity, because of a key natural phenominum. If a permanent magnet is rotated past a coil of wire, an alternating current will be induced in the coil. If the magnet is rotated at 50 revolutions per second, ie, 3000 rpm (revolutions per minute), the frequency will coincide with the mains frequency of 50 hertz. This, in principle, is the way alternating current is produced. In practice an electro-magnet is used instead of a permanent magnet. This is powered by an external DC generator (called an exciter), fed through slip rings and brushes.

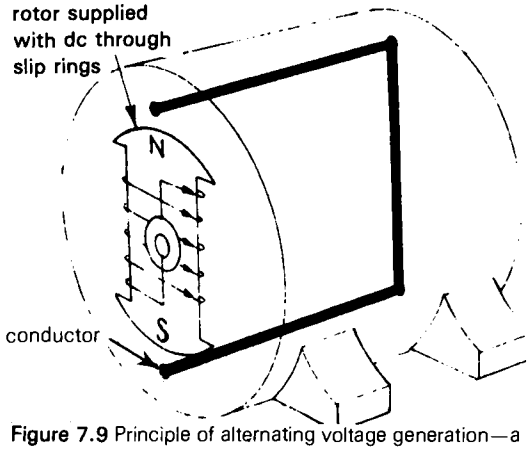


Figure 7.9 Principle of alternating voltage generation—a single phase two-pole alternator (NZTI).

There is one other important difference. To make greater use of the circumference of the generator, three sets of coils are used (*Figure 7.10*). The current is transmitted through three different sets of wires. One end from each set of coils is joined together to form the *Neutral Wire*. The other end becomes the phase wire. Thus there are three separate phase or line wires and one neutral wire. In addition, for safety reasons, at the power station the neutral wire is connected to a large mesh of metal conductors which are buried into the ground. This forms the earth connection. Note that we have labelled the phases red, blue, and yellow. This is purely as a label and does not imply any sort of actual colour code for wiring!

The relationship between the voltages on the phase wires is shown in *Figure 7.11a*. These represent the voltage between each phase wire and the neutral wire. They are all the same magnitude, but the peaks are one third (or 120°) of a cycle apart in time. The voltage between the phase and the neutral is called the *Phase Voltage*.

7.4.3 Three phase power distribution

The power produced at the power station is transmitted at high voltage (eg 500,000 volts) to substations which reduce the voltage to 11 kV. Local authority transformers reduce the phase voltage to 230 V, and it is distributed to consumers at this voltage. In the USA, the distribution voltage is 110 volts, while in the UK it is 240 volts. These transformers may

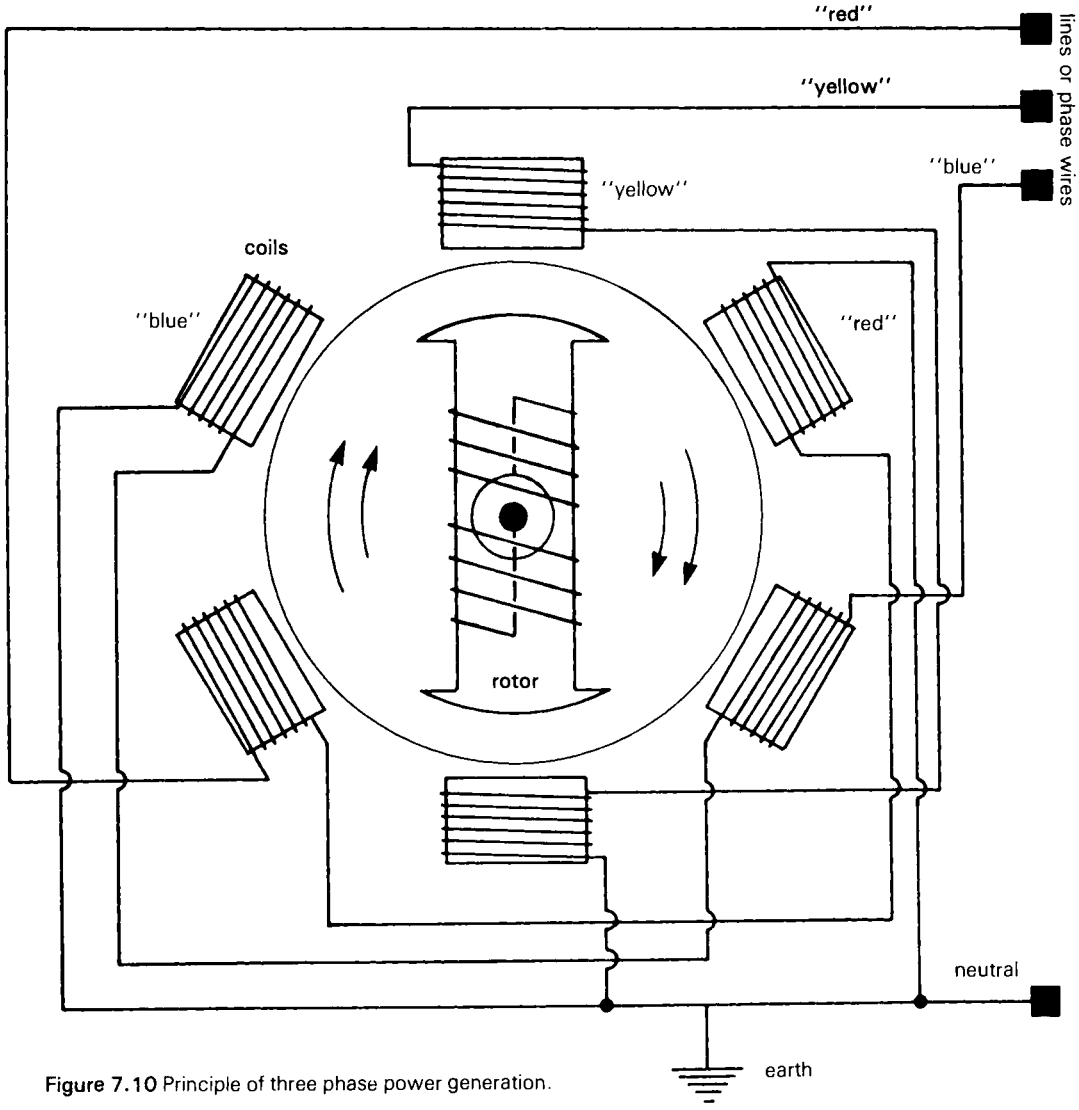


Figure 7.10 Principle of three phase power generation.

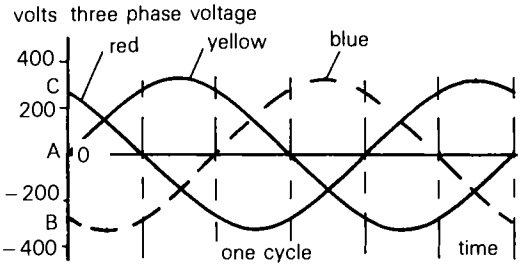


Figure 7.11(a) Phase-neutral voltages.

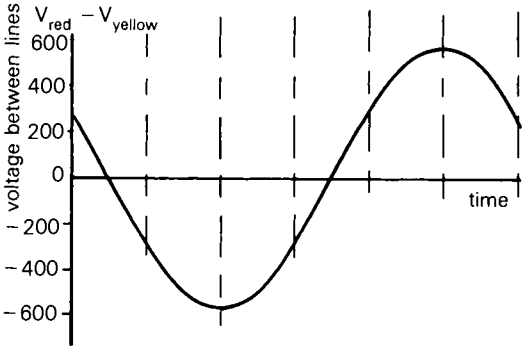


Figure 7.11(b) Phase-phase voltage.

be seen mounted on poles or at street level in the town and country. From the transformer the power is distributed through three phase wires and a neutral which is at earth potential.

In *Figure 7.12* consumers A, B, and C could be households in any street. Each is connected to one phase and hence has a 230 volt supply. Consumer D has all three phases connected, and is able to drive more powerful equipment. This consumer could be a factory or farm. Consumer D can use equipment which is connected between any two phase lines as well as equipment run off one phase (ie between phase and neutral). If we measure the voltage between two phase wires (say the "red" and "yellow" phases in *Figure 7.12*) we obtain what is known as the line voltage. We would discover that the voltage is about 400 volts—ie 1.7 times greater than the phase voltage between any phase and the neutral! This may seem strange, but studying *Figure 7.11a* and *b* will explain this. The voltage between the red and yellow phases will be found by measuring the difference between them at every point on their cycle.

The result of plotting $V_{red} - V_{yellow}$ is shown in *Figure 7.11b*. A larger sine wave results, and it can be shown to be given by:

$$V_L = \sqrt{(3)}\ V_p = 1.732\ V_p$$

Equation 7.23

where V_L is the line voltage and V_p is the

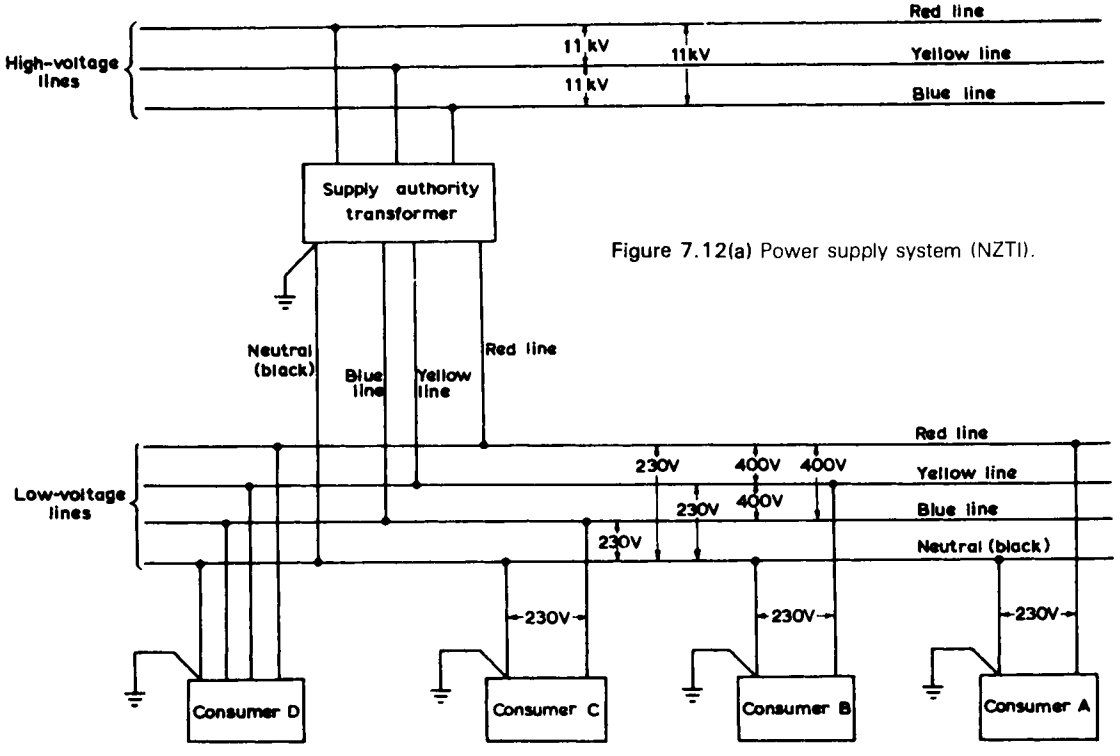


Figure 7.12(a) Power supply system (NZTI).



Figure 7.12(b) A local step down transformer producing domestic supply at 230/400 volts.

phase voltage (all RMS values of course).

In practice this means that a consumer with a three phase supply can use either the line voltage of 400 volts or the phase voltage of 230 volts. Different types of equipment require one or other type of supply. Consumers A, B, and C (*Figure 7.12*) could only use equipment which will run on a single phase power supply.

Example

What is the peak voltage in *Figure 7.11b*. Using this value, what is the RMS voltage?

Solution: $V_o = 565$ volts.
Therefore, $V_{RMS} = 565/\sqrt{2} = 400$ volts.

7.4.4 Domestic supplies

In practice alternative properties are connected to alternate phases in sequence. This spreads the domestic load equally between the three phases. The consumers A, B, and C in *Figure 7.12* are likely to be next door neighbours. Occasionally a line fuse blows so that one in three houses in a street is without power. The domestic supply is the 230 volts (RMS) and each house is connected between one phase and the neutral wire.

Earthing

In New Zealand the multiple earth neutral system is used. This simply means that the neutral is connected to earth at each property, thus ensuring that it is always at earth potential. In other countries a slightly different system is used.

An earthed wire is connected to the frame of each appliance. In the event of a fault which results in metal parts of the appliance becoming live, the current will flow down the earthed wire and not through any person who touches these metal parts. The result will often be that a large current flows, so that the fuse blows, thus protecting the user completely. It is therefore important to establish the cause of a fuse blowing before re-using the electrical equipment.

Wiring

The three wires in a domestic appliance comprise the phase (the insulation around the wire is coloured red or brown), the neutral (black or blue) and the earth (green or green/yellow stripes). If wiring an appliance plug it is most important that these wires be correctly identified and connected to the correct terminal which will be marked P, N or E.

It may be thought that because the neutral and earth are at the same potential an interchange of the wires is not critical. This is definitely not so. An appliance will still operate, although it will be unsafe, with the phase and neutral exchanged. A combination of these two errors is lethal as it causes the frame to come alive. While the law permits appliances to be wired by the householder, in New Zealand it is illegal to modify or interfere in any way with permanent wiring or wall plugs. This work must be undertaken by a registered electrician.

7.4.5 Controlled power supplies

Two key facts about electrical power generation are–

(1) power stations operate most efficiently if they operate continuously, and are not stopping and starting;

(2) you cannot store electricity once you have made it.

This means that ideally, a continuous constant demand for power is required, 24

hours a day. Unfortunately people like to sleep at night, wake up during the day, cook meals at 5.00 pm, and have Saturdays and Sundays off from work. This means that the power demand fluctuates wildly. The supply authorities have to build enough stations to match the peak demand, so during off peak periods, they will have surplus generating capacity, which is a waste of expensive resources.

To try and even out the demand (ie reduce the peak load, and spread the load throughout the day), power boards have introduced the controlled power supply. This means that it is controlled by them, and they can switch the supply off to an appliance (such as a water heater) when the nationwide demand starts to climb. This is done by sending an electrical pulse through the cable which triggers the meter. This controlled supply is then sold at a reduced rate: the price you pay is not being able to have the power available 24 hours per day. For water heaters this is not too important (unless you like showers at 5.00 pm, in which case the tank will stay cold until the power comes back on later in the evening). Usually the power is only off for one or two hours in any day.

In some countries charges are worked out according to the time of use. Thus electricity used at night or off-peak is at a reduced price.

7.5 ELECTRIC MOTORS

An electric motor is a machine to convert electrical energy to mechanical energy. This is achieved by converting the electrical power to magnetic power. This exerts a constant twist on the revolving rotor of the motor which in turn overcomes the resistance of the motor load. Compared with an internal combustion engine the efficiency of an electric motor is very high, varying from 65% for a small motor to over 80% for large motors. The main losses are due to heating of the electrical windings, power to drive the cooling fan, and friction in the bearings.

In addition, the good points about an electric motor are the ease of starting (even under a moderate load), the low first cost, low operating cost, long life, simplicity and quietness in operation, its ability to withstand temporary overloads, it can be automatically and remotely controlled, and it is compact and safe.

There are several different types of motor, depending on the size, starting system and the type of power supply. We will describe the main types.

7.5.1 Three phase induction motor

The induction motor has two main parts, the stator and the rotor. The stator (or stationary part) is made from circular steel ring laminations with slots punched on the inside diameter. Coils of wire are wound into these slots and wired in three sets so that each set can be connected to a separate phase of the three phase supply (*Figure 7.13*). Each coil of wire is called a Pole, and the number of poles per phase is an important design feature which determines the speed of the motor, as discussed later. The stator shown has four poles per phase. Motors with two and six poles per phase are also common.

Magnetic field due to stator

In order to understand the operation of the induction motor it is necessary to accept one or two experimental facts about coils, magnetic fields, and currents. First, if a coil has a current flowing through it, a magnetic field, whose strength varies with the size of the current, is created along the axis of the coil. Thus if we put an alternating voltage onto a coil, a pulsating magnetic field is produced. Because of the way in which the coil is orientated this field runs in a radial direction towards the centre of the stator.

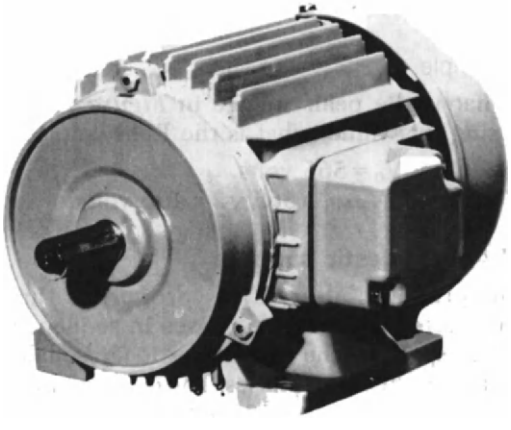


Figure 7.13(a) Three phase induction motor, fully enclosed (Farm Electric Handbook).

Suppose the field due to a coil connected to the red phase is just at its maximum value (*Figure 7.13*). The coils on either side will not

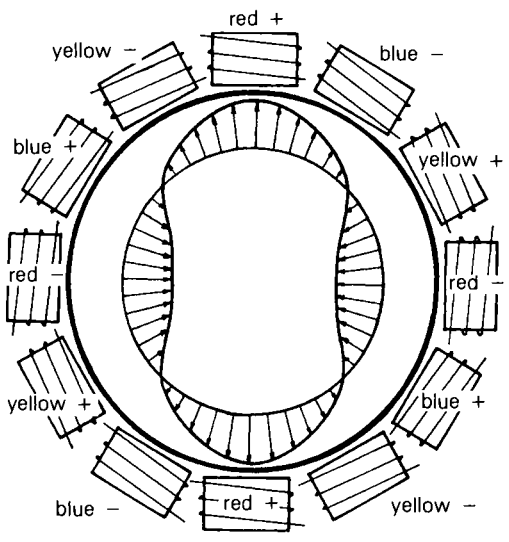


Figure 7.13(b) Stator showing model of magnetic field strength.

be at their maximum since they are connected to the other phases. In fact one will be dropping (say the coil on the right), while the other will be starting to increase. The net result will be a magnetic field which is strongest near to the coil and dropping away sharply on either side. It will be a maximum in the oppposite direction next to the next red coil.

However only one sixth of a cycle later (ie 0.00333 seconds) the yellow coil on the left reaches its peak, while the coil connected to the red phase has dropped. The coil is wired so that the field is in the same sense as the field in the red coil. The effect is that the previous magnetic field pattern has rotated so that it is now strongest next to the yellow phase coil. This process is repeated for each coil in turn, so that in effect there is a rotating magnetic field. In this example the speed of rotation of this field is 25 Hz, or 1500 rpm. This is called the *Synchronous Speed.* It depends on the number of poles (coils) connected to each of the three phases, as given in *Table 7.2.*

The rotor

The rotor (or rotating part) consists of two rings to which are welded a series of copper bars to make a "squirrel cage" (*Figure 7.14*). The bars are let into slots in a series of steel laminations which form the centre of the cage. The rotor shaft runs through the middle of the assembly. The laminated core creates highly inductive properties. Alternatively the squirrel cage may take the form of an aluminium casting. In effect the rotor can be taken as a series of conductors running parallel to the axis of the rotor.

Operation

When the rotor is placed inside the stator it is subjected to the rotating magnetic field. When stationary, the conducting bars in the rotor therefore experience a changing magnetic field. The laws of electromagnetism show that in this situation a current is induced in the conductor (hence the term induction motor). This current is generated solely because the rotating magnetic field pattern passes through the conductors.

We now have a radial magnetic field pointing towards the centre of the rotor, and an induced current flowing parallel to the axis of the rotor (*Figure 7.15*). Again the laws of electromagnetism state that in this situation a force is produced. This force will be at right angles to the directions of current and magnetic field, which will therefore be along the circumference of the rotor (Fleming's left hand rule gives the direction if you are a physicist). This force makes the rotor move, and it rotates so that it tries to catch up with the rotating magnetic field.

An alternative explanation is to say that the induced current has an associated magnetic field which tries to hold onto the rotating stator field and is therefore drawn around with it, thus turning the rotor (rather like the attraction between two magnets).

Because of the turning force the rotor

Table 7.2 Motor synchronous speeds

			Synchronous speed
Two pole motor	–	Two poles per phase	– 3000 rpm
Four pole motor	–	Four poles per phase	– 1500 rpm
Six pole motor	–	Six poles per phase	– 1000 rpm

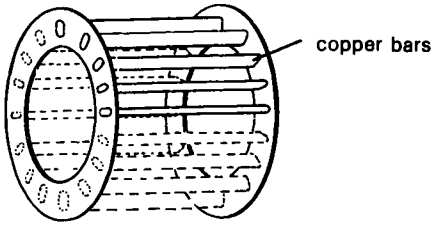


Figure 7.14(a) Squirrel cage rotor: schematic (NZTI).

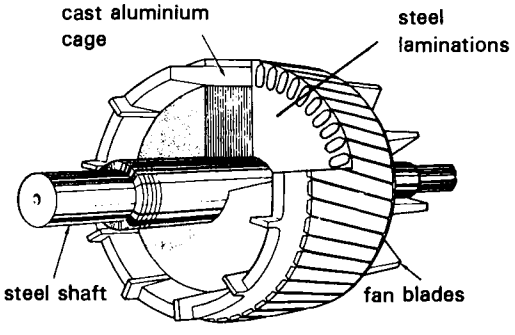


Figure 7.14(b) Practical rotor (NZTI).

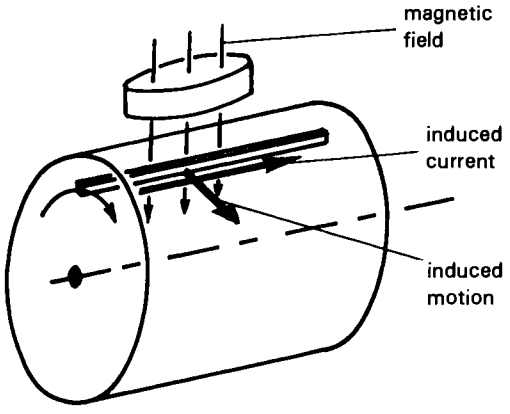


Figure 7.15 Principle of induction motor operation.

rotor always moves a little slower than the field. The percentage difference in speed is called the *Slip*.

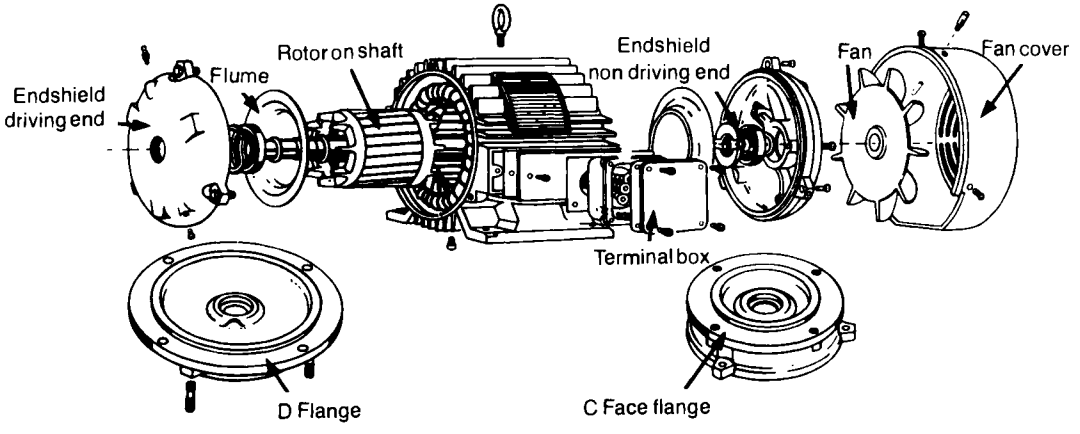


Figure 7.14(c) Exploded view of induction motor (Farm Electric Handbook).

accelerates until it is moving almost as fast as the rotating magnetic field (ie the synchronous speed). However as it speeds up the rate of change of magnetic field in the rotor starts to fall, since the rotor conductor bars are almost keeping up with the field. If the rotor reached the synchronous speed then there would be no change in magnetic field around the conductors (since the conductor would then be travelling around exactly in pace with the rotating field). Unfortunately as a result the induced current would fall to zero, and hence there would be no force! Friction and the need to draw power from the motor mean that in practice the

Example

If a four pole three phase induction motor turns at 1425 rpm, what is the slip? If the rotor is 150 mm in diameter (ie R = 0.075 m) how fast is the circumference moving?

Solution: From *Table 7.2* the synchronous speed is 1500 rpm.

$$\text{Hence: Slip} = \frac{(1500 - 1425)}{1500} \times 100 = 5\%$$

Equation 7.24

In one revolution it turns $2\pi R$ metres (since the circumference of a circle is $2\pi R$). In one

second the rotor turns 1425/60 times, so the speed is:

$$S = \frac{1425 \times 2\pi \times 0.075}{60} = 11.2 \text{ m/s}$$

Operating characteristics

The operating characteristics of an induction motor are shown in *Figure 7.16a*. As the load on the motor increases the speed falls and the current increases leading to overheating if the overload is maintained. The efficiency is a maximum at the design load, and falls off above and below that load. Note the different horizontal axis in *Figure 7.16b*. This covers only a small part of the range covered in *Figure 7.16a* (from the synchronous speed to about 4% slip).

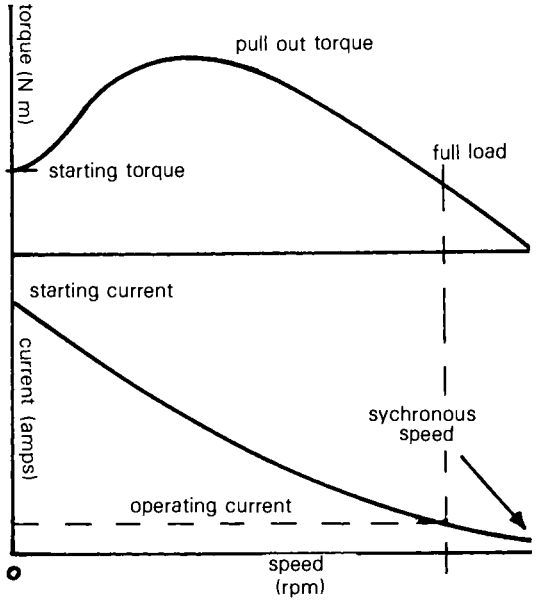


Figure 7.16(a) Typical motor torque and current over range of speeds from zero to synchronous speed.

Starting three phase induction motors

On starting, when the rotor is initially stationary, the impedance to current flow is very low. However, as the rotor reaches operating speed, the impedance will increase substantially. From Ohm's law this means that, if at normal operating speed the current is kept to acceptable limits, then during starting a heavy current will be drawn while the rotor is accelerating up to its operating speed. On rural properties, large motors can therefore cause unacceptably large voltage drops in supply lines. In addition, a motor

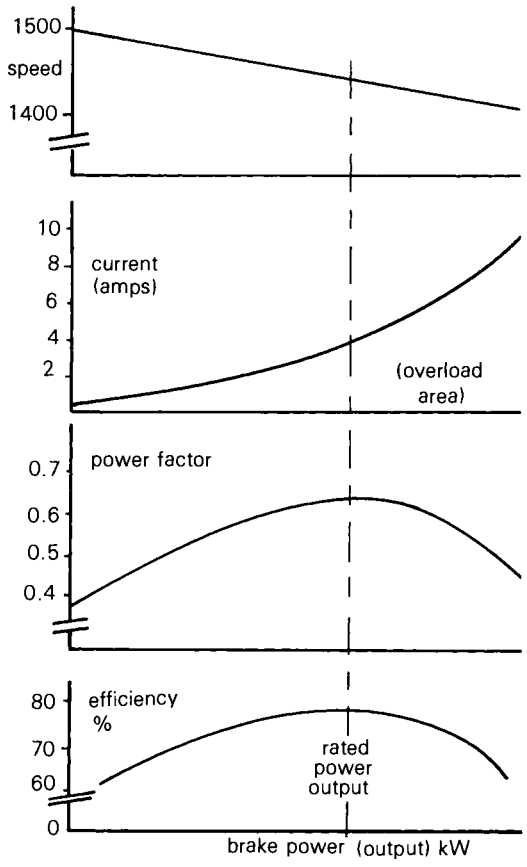


Figure 7.16(b) Motor curves as functions of brake power.

which is frequently stopping and starting could overheat and burn out.

Two methods can be used to start motors:

(a) Direct on Line (DOL): Small motors up to 20 kW (depending on their closeness to the nearest transformer) may be started by simply switching them on.

(b) Star-Delta starting: Where DOL starting is not acceptable, the applied voltage and hence the current may be limited by starting with the stator phases connected in "star" and then switching to "delta" for running. This is explained in *Figure 7.17*. In star connection the coils are connected between the phase wires and the neutral wire, so that the voltage is only 230 volts on starting, and hence the current is smaller (from Ohm's law). In delta the coils are connected between pairs of phase wires, and so the voltage is the between lines voltage of 400 volts. Hence the current (and hence power) will

be greater. Modern star/delta starters change over automatically and manual operation is not required.

In *Figure 7.17a* the star configuration is shown, first with all the connections, and second in the schematic way which explains why it is called a star. In *Figure 7.17b* the delta configuration is shown in a similar way. Note that the neutral connection is not even needed! You may like to follow the wiring around to confirm that the two diagrams for each configuration are the same.

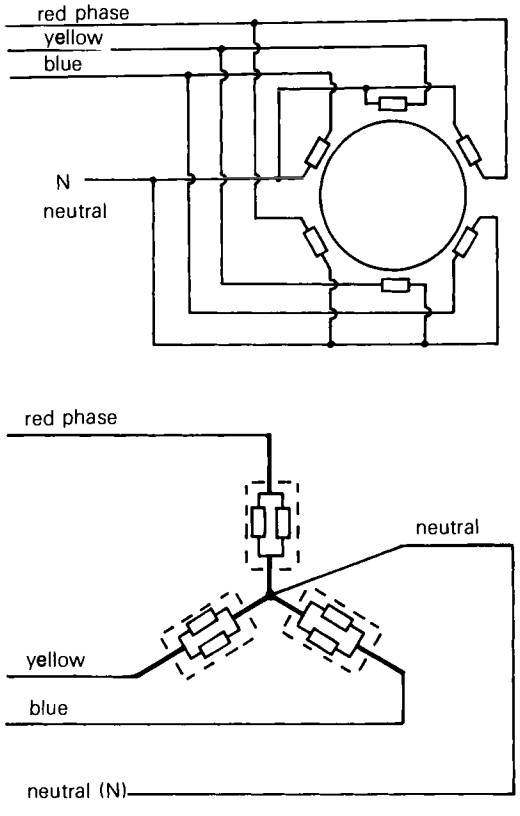


Figure 7.17(a) Star configuration.

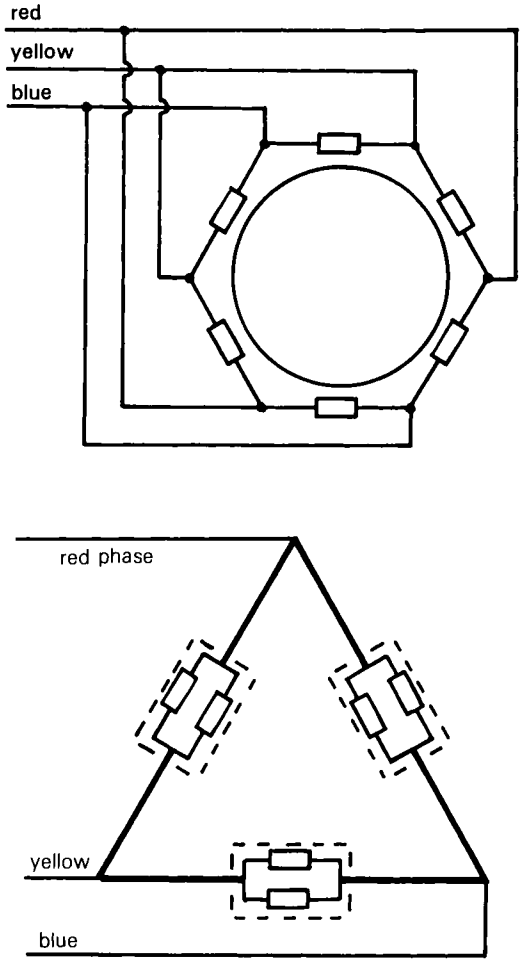


Figure 7.17(b) Delta configuration.

Three phase synchronous motors

In some applications it is important for the motor to turn at a specific speed. Synchronous motors are designed so that they will operate at the synchronous speed of the rotating magnetic field. This is usually done by designing coils in the rotor so that once it is up to speed the rotor develops a fixed orientation relative to the stator field. In order to maintain this position as the magnetic field rotates, the rotor must turn at the synchronous speed. In the salient pole and slip ring sychronous motors the rotor is fed a DC current through slip rings. On the other hand a reluctance motor has a special rotor which enables it to operate without requiring to be energised through slip rings. The torque is maintained only at the synchronous speed, and so special windings are required for starting. Some motors have a rotor which operates like an induction motor for starting, but which changes over to synchronous operation once sufficient speed is developed. Reluctance motors are used in computer disc drives and nuclear reactor control rods.

7.5.2 Single phase motors

Single phase and three phase motors are similar in construction except that the stator of the single phase motor is connected to one phase only. As in three phase the stator may be two, four or six pole and the synchronous

speeds are the same, namely, 3000, 1500 and 1000 Rpm. However, because one phase only is present the field oscillates and does not rotate. Once started there is no problem, but without special starting provisions the motor will only run if the rotor is given a twist to start it in the desired direction. It is necessary to provide a means of starting a single phase motor and these motors are often named after the starting method used.

Split phase motor

This is one of the commonest types of single phase motor. The stator is supplied with an additional set of starting poles interspersed between the main poles. In contrast to the main poles which are highly inductive, but of low resistance, the starting poles are arranged to be less inductive and have higher resistance. The effect of this is to make the current in the starter windings lead the current in the main windings slightly and create an approximation to a rotating magnetic field (ie the starter current peaks a little before the current in the main windings). This is sufficient to start the motor. After starting, the starter windings (which are short time rated and would soon burn out) are disconnected by a centrifugal switch.

Capacitor start motors

This is a modified form of the split phase motor. The currents in the main and starter windings are displaced further by placing a capacitor in the starter windings circuit. The effect of this is to cause the starter pole current to lead the voltage and to create a stronger rotating field for better starting torque. As with the split phase the starting circuit is disconnected by a centrifugal switch.

Shaded pole motors

These are very small motors (less than 40 watts) used where efficiency and starting torque are not important. The poles are shaded on one side by a copper band, which has a similar effect to the starting coils in a split phase motor. These motors are quite inexpensive to produce. They are very common in small appliances such as small domestic heating fans. They have poor starting characteristics (ie a small starting torque).

Series wound motors (universal motors)

In these motors the current in the rotor is supplied via a commutator and brushes from the mains power, rather than by induction. They have good starting characteristics, and are used in hand tools and kitchen appliances. Series wound motors are available which operate off either AC or DC power sources.

Direct current motors

Direct current motors require a DC voltage supply. They have good starting characteristics and have been used in lifts and other heavy duty situations involving many starts and stops. The voltage is applied to both the stator and the rotor, which may be connected in series or in parallel. A commutator (a cylinder made up from thin radial segments of copper insulated from one another) is required so that spring loaded carbon/copper brushes can transfer the current to the rotor. The main advantages of DC motors are that they can be operated at a range of speeds which can be adjusted using relatively straight-forward controllers, and they can produce very high torques for short periods of time without damage. They can also produce a braking torque to stop movement efficiently. On starting the motor has a very low impedance to current and some form of voltage regulation is required to prevent overloading. DC motors are tending to be superceded by AC motors in most applications, as controllers for the latter improve.

Stepping motors

A stepping motor is one which translates digital electrical signals into fixed mechanical movements. While conventional motors rotate continuously when energized, a stepping motor rotates in fixed angular increments. Its rotor position is closely controlled by the energisation of the stator windings. The stepping motor has a number of attractive features that can provide advantages when the device is applied in a motion-control system. Among these are its digital nature which permits easy interfacing with digital controllers and the accurate positioning capability of the motor which leads to precise control of velocity and acceleration without the need for sensors to measure these parameters. A stepping motor

would be a logical choice for greenhouse ventilation systems.

Stepping motors are manufactured in a wide range of sizes, step angles and power capabilities. The size may range from a 25 mm diameter, pancake motor, to units weighing 30 kg which are capable of producing more than 2 kW of usable shaft output power. Typical step angles vary from 0.72° to 90°, with 1.8°, 7.5°, and 15° being the most popular.

Other types of single phase motor

Other types of single phase motors include reluctance motors, hysteresis motors and repulsion start motors. The first two are motors which will operate at the sychronous speed, and can be used where constant speed is important (eg record player turntables).

7.5.3 Linear motors

If one imagines that the stator of a conventional induction motor were to be cut along one side and rolled out flat (*Figure 7.18*), then the result is very similar to the stator or primary of a linear motor. The rotating magnetic field now becomes a moving field which sweeps along the primary. Currents induced in the rotor (now called a secondary) cause the rotor to move after the field producing linear movement. The linear motor has considerable applications for conveyor belts, overhead cranes and the propulsion of high speed trains. The secondary (the "rotor") can be nothing more than a flat plate in simple applications. In the case of long distance transport the primary (the "stator") can be the moving part, since it would be uneconomic to wind a three phase power supply along the entire track. Instead the power to energise the primary is fed to the train as it moves.

7.5.4 Motor overload protection and motor selection

As discussed, all AC motors draw heavy starting currents and this tends to make the use of fuses inappropriate as they would only blow on starting. A method known as thermal overload protection is used instead. The incoming phase wires are wound onto coils around bi-metallic strips at the end of which are contacts. In the event of a sustained overload the coils will heat the bi-metallic strips which bend and open the contacts. In addition to overload protection, safety equipment in the form of heavy duty fuses or circuit breakers is fitted to all but the smallest motors.

In this connection it should be noted that modern electric motors are of the CMR type, that is, they are of Continuous Maximum Rating. They have no continuous or even short period overload capacity. At best, they

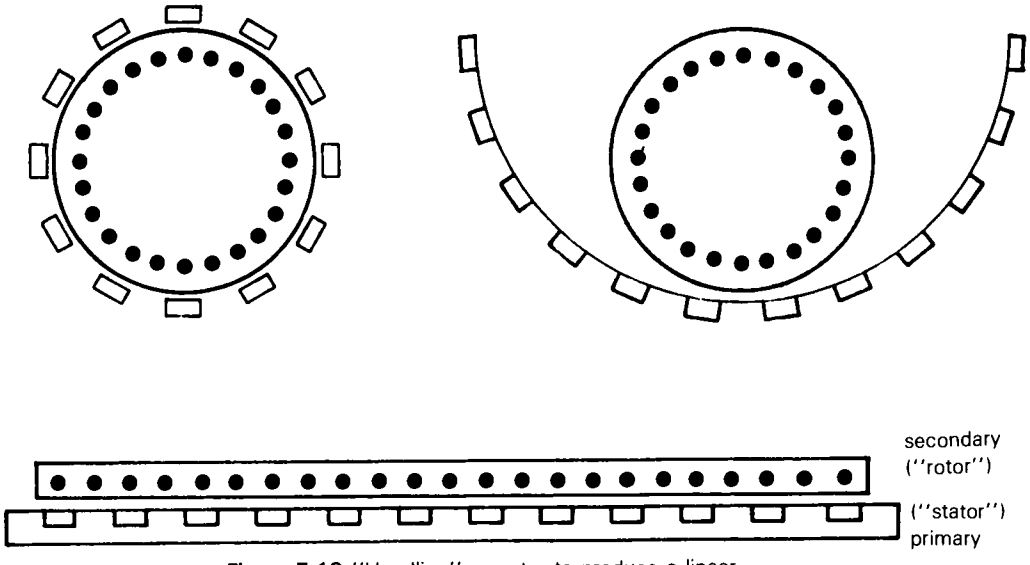


Figure 7.18 "Unrolling" a motor to produce a linear motor.

will withstand 100% excess torque for a few seconds only, before they overheat. Hence, it is always important to select a size of motor which has adequate power for the particular task.

7.5.5 Selection of motors

The selection of the proper motor for a particular job is important. Normally the specifications should include a description of the available power supply, its intended use, type and size of load, conditions under which the motor operates, and any space limitations. Often by specifying a standard type of motor one can take advantage of early delivery and minimum cost.

In actual use the motor must play the role of a servant, supplying the energy required by the load. By plotting the load requirements along with the performance characteristics of a motor on the same graph, one can determine the actual conditions under which the motor is operating.

7.6 ELECTRICAL SAFETY

Mains voltage is sufficiently high to kill any person who makes contact with a phase wire, particularly if they are earthed by contact with damp ground or concrete. People are electrocuted every year in industry, on the farm and in the home, and the greatest care must be exercised by anyone using electricity. The safest rule is "if in doubt–don't". All electrical installation work in New Zealand must comply with the New Zealand Electrical Wiring Regulations, which set down minimum safety requirements for the protection of life and property.

An electric shock occurs when an electric current (in excess of about 0.04 ampere) passes through the human body.

A person can receive a shock in many different ways, but in each case they must complete a circuit and cause a current to flow. To form such a path, the body must simultaneously touch a live wire and an earthed wire or component, (or another live wire from a different phase).

Shocks resulting from contact with "live" conductors are more likely to happen if you work on current-carrying parts of apparatus. Don't do it!

When working around electrical equipment, keep alert, move slowly, and think about what you are going to do. Refuse to use electrical equipment known to be faulty. Be sure the power is off before making connections. Be aware of factors which will decrease your body resistance, like wet hands, standing on a wet floor, or resting your head against a water pipe.

7.6.1 Effects of electrical shock on humans

When a person becomes part of a closed, energized electrical circuit, a current will flow through their body between the two points which connect them in the circuit. The magnitude of the current is the proper criterion of shock intensity. The voltage present is not by itself dangerous: the danger arises if the voltage is sufficiently high and the resistance sufficiently low, so that a dangerous current results. The duration of the current (ie how long it flows) is also important. A current of one milliamp is barely perceptible. More than ten milliamps is painful, and voluntary control of the muscles can be lost: a person may be unable to let go or to free themselves. Sweat and the continuous flow of current can also reduce their skin resistance, so that the current will increase. A current of 100 to 200 mA causes uncoordinated twitching of the walls of the heart's ventricles (ventricular fibrillation), and the shock is fatal if the current duration is one second or more. A 230 volt shock often causes this level of current. At greater current levels the chest muscles can stop the heart without causing fibrillation. Survival is possible if artificial respiration is given. Severe burns are also possible. The victim may be thrown clear of contact, thus increasing the chances of survival.

7.6.2 Factors affecting severity of shock

Since the person receiving a shock is really just part of an electrical circuit, we can analyse the circuit, considering the person as a series of resistances. Resistance to current flow is to be found mainly in the skin surfaces. Dry skin has a resistance of 1000 ohms or more, but a sharp decrease in resistance takes place when the skin is moist. If the current flows for any length of time (say, five seconds or longer), however, even dry skin will lose much of its normal resistance. The internal resistance is only a few hundred ohms at most.

Under certain conditions, a voltage as low as 22.5 volts could cause a dangerous shock! Records show that electric shocks have been fatal when the AC voltage has been as low as 40 volts.

7.6.3 Help for victims

If a person is being shocked, the first thing to do is to stop the current flow as quickly as possible. Time is important because the body resistance will go down with time, permitting the current to increase. The best way to stop the current flow is to de-energize the circuit by throwing a switch or pulling the appliance cord from the receptacle. If this is not possible, the victim must be removed from the circuit.

Before touching the victim of an electric shock, the rescuer must check that it is safe to do so. If the victim is still in contact with a live conductor, and if the supply cannot be disconnected quickly, the victim can be pulled clear using a dry piece of wood, or any dry non-conducting material, or by dragging him/her clear by loose clothing. On no account should the bare skin or wet clothing be touched. Many people have been electrocuted by making themselves a part of the circuit as they attempted to rescue another person. If breathing has stopped, is intermittent, or very weak, resuscitation (rescue breathing) should be started immediately. Only a short time without oxygen can cause serious damage to the brain. If the heart is not beating then full CPR (cardio-pulmonary resuscitation) treatment is needed. Resuscitation may take a long time (possibly eight hours) and should be continued until a medical authority pronounces the victim beyond help. If you have never taken a course in CPR then take one now!

7.6.4 Safety of portable appliances

The safety of an earthed appliance depends upon the low resistance of the earth-continuity conductors and their connections. Unfortunately, portable tools are usually subjected to a great deal of abuse, and the earth-continuity conductors are often broken or develop a high resistance because of corrosion or looseness of the earthing connections. Portable appliances with faulty earth-continuity conductors have caused many fatal accidents, particularly when the appliances were used in wet situations.

There are various types of earthing for portable appliances. Direct earthing is used on appliances with exposed metal frames used in dry indoor situations. The metal frames and all other metal that may become alive are earthed by connecting them to the earth lead in a flexible cable. Double-insulated appliances are ones which usually have accessible metal parts (for example, an outer case), but additional protective insulation is provided. This consists of high-grade insulation enclosed within an outer casing of more high-grade insulation. The quality, strength, and thickness of the insulation is such that breakdown is considered to be virtually impossible. Such power tools comply with the regulations for use outdoors under wet conditions.

An isolating transformer is an alternative and effective safe-guard, which is exactly the opposite to direct earthing. It isolates the supply from the earth. Should a person make contact with any part of the appliance circuit there will be no return path through the person, and so no electrical hazard exists. When isolating transformers are used only one appliance should be used from a single secondary winding, unless the transformer is designed to take more than one plug. Certainly stacking plugs and multiple plug boxes should never be used on the output of an isolating transformer, because the different pieces of equipment will all be connected to the same windings, and anyone grasping two tools could be "connecting" themselves across the power supply. The isolating transformer is itself regarded as a portable appliance. The transformer must therefore be placed in a dry indoor situation, preferably adjacent to its point of supply and connected with a short flexible cord. It should not be placed on a metal floor, since there is a risk of earthing back to the casing. While isolating transformers are a valuable safety aid, even they are not fool-proof.

Great care should be exercised when operating large items of equipment such as headers, stackers or cranes in the vicinity of power lines. If there is any risk of contact the Power Board should be asked to turn the power off. A common cause of fatal electrical accidents is created by fencers drawing wires

across gullies which are traversed by power lines.

Fuses protecting single phase domestic equipment are rated at 5, 10 or 15 amps. If the fuse blows make sure you have identified the fault before attempting to replace the fuse. It should be rewired with the correct grade of fuse wire. The capacity of the fuse is stamped on the fuse holder.

Extension cables

Extension cords receive a great deal of abuse, especially in workshops and on building sites. Freyed or damaged cords should be discarded as they are dangerous. It is particularly dangerous to plug one extension cord into the outlet of another. Even though, on their own, each cord will operate perfectly normally and safely, incorrect internal wiring can mean that the earth wire can become connected to the live mains supply. This means that the casing of any appliance becomes live, giving anyone touching it a bad shock.

7.7 INTERNAL COMBUSTION ENGINES

An engine is a device which turns one form of energy into mechanical energy. In the Internal Combustion (IC) engine, the source of energy is chemical. The fuel (such as petrol or diesel fuel oil), is burnt inside the engine generating heat, which causes a rapid expansion of the gases. This expansion drives a piston which produces the mechanical power. There are two main types of IC engine, the difference arising from the way in which the fuel is ignited. In the spark ignition engine, the fuel is ignited by an electrically generated spark. In the Compression Ignition engine (often called a Diesel engine), the fuel is ignited without the need for a spark. We will describe the spark ignition system first, and then describe how the compression ignition engine differs. We will also start with a four stroke engine, as distinct from a two stroke: in the four stroke engine the piston makes four strokes (traverses of the cylinder) to complete one cycle.

7.7.1 Basic components of a four stroke IC engine

The basic parts of an engine are shown in *Figure 7.19*. The engine consists of a circular cylinder, within which a piston can move. The piston fits closely into the cylinder, and the fit is made almost completely airtight by the piston rings, which are soft metal rings fitted into slots in the piston head. These slide on the surface of the cylinder, and are kept lubricated with a thin film of oil to minimise wear. The diameter of the cylinder is called the *Bore*. The piston is connected to the crankshaft at the bottom by the connecting rod. The connecting rod converts the up and down motion of the piston into a circular motion of the crankshaft. There are bearings at both ends of the crankshaft (the little end and big end bearings as shown), and the crankshaft rotates on large bearings. In a motor car the crankshaft drives the wheels via the gear box. At the top of the engine there are two valves which control the inlet fuel from the inlet port, and the outlet of waste gases through the exhaust port. There is also a spark plug which produces the spark to ignite the fuel. Some other terms help in the description of the engine's operation. The piston moves up and down the cylinder. When it is at the top, this position is called *Top Dead Centre* or TDC. The big end is at the top of its circular path. The volume left at the top of the cylinder above the piston is called the *Clearance Volume*. At the bottom the position is called *Bottom Dead Centre* (BDC). The distance between TDC and BDC is called the *Stroke*. The swept volume is thus given by:

Swept volume = stroke × cross-sectional area of cylinder **Equation 7.25**

The clearance volume is the volume left above the piston when the piston is at TDC. In this position any fuel-air mixture will be compressed into the smallest possible space.

Compression ratio (CR)

The compression ratio is an important design feature of an engine. It is the ratio of the maximum volume of the cylinder to the minimum volume, or:

$$CR = \frac{\text{volume at BDC}}{\text{clearance volume}}$$

Equation 7.26

Operation

The operation of the engine is in four parts as follows (*Figure 7.20*):

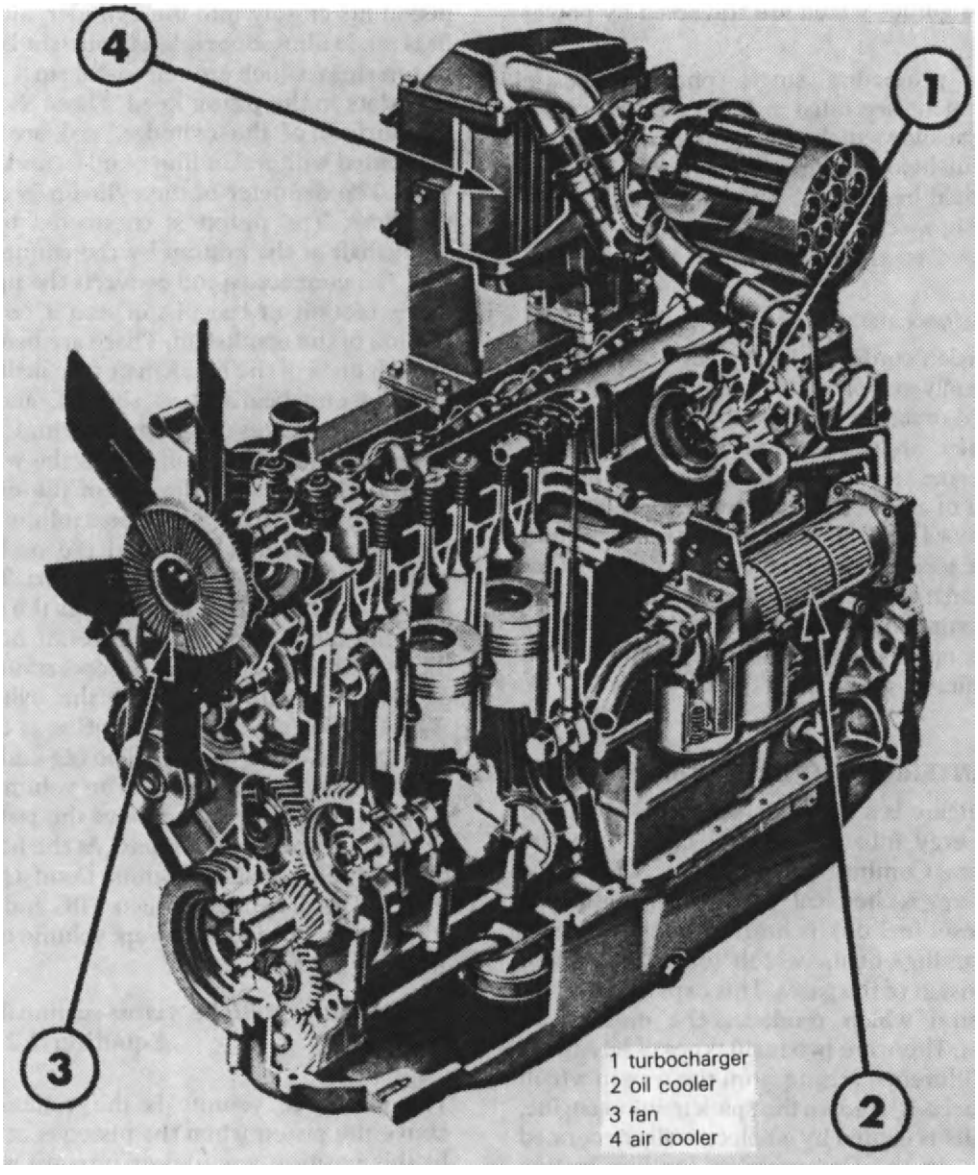


Figure 7.19(a) Diesel tractor engine (Culpin, Ford).

a. Induction stroke

We start our description with the piston at TDC. As the piston starts to descend, the inlet valve opens. The piston then sucks a fresh gaseous mixture of air and petrol into the cylinder.

b. Compression

After the piston has reached BDC the inlet valve closes. The piston now returns to TDC and the mixture is compressed. Just before the piston reaches TDC again the spark plug fires a spark which ignites the fuel.

c. Power stroke

The mixture continues to burn, expanding rapidly, and forcing the piston downwards.

d. Exhaust stroke

The exhaust valve opens and the piston returns to TDC, forcing the burnt gases out through the exhaust. The piston is now back at TDC, ready for the next inlet stroke.

Operation of the valves

Each valve opens and closes once every two cycles of the engine. Obviously the opening

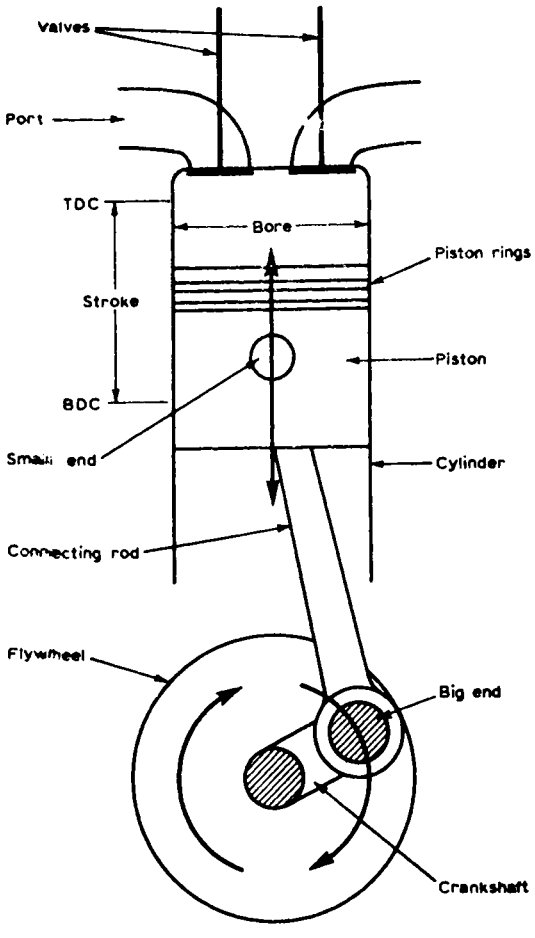


Figure 7.19(b) Reciprocating to rotary movement (Sully).

and closing of these valves must be exactly timed to coincide with the right position of the piston. This is achieved by operating the valves by a push rod driven off another shaft called the camshaft, which is turning at exactly half the speed of the engine (*Figure 7.21*).

At first it looks as though the valves open and close at TDC and BDC. In practice this is not the case: if we consider the crankshaft as indicating the position of the piston, then the inlet valve is usually set to open at 5° before TDC and to close 40° after BDC. This is to maximise the volume of fuel which is

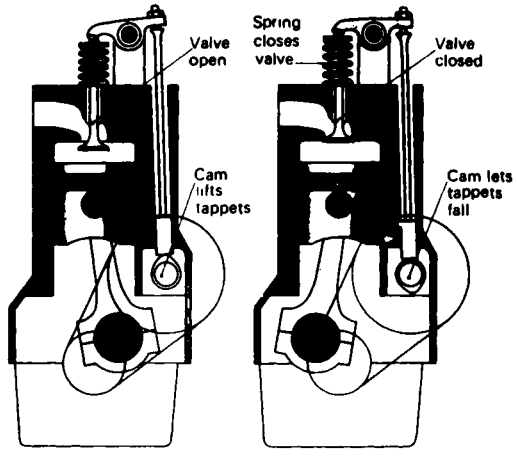


Figure 7.21 Valve operation (Drive Publications).

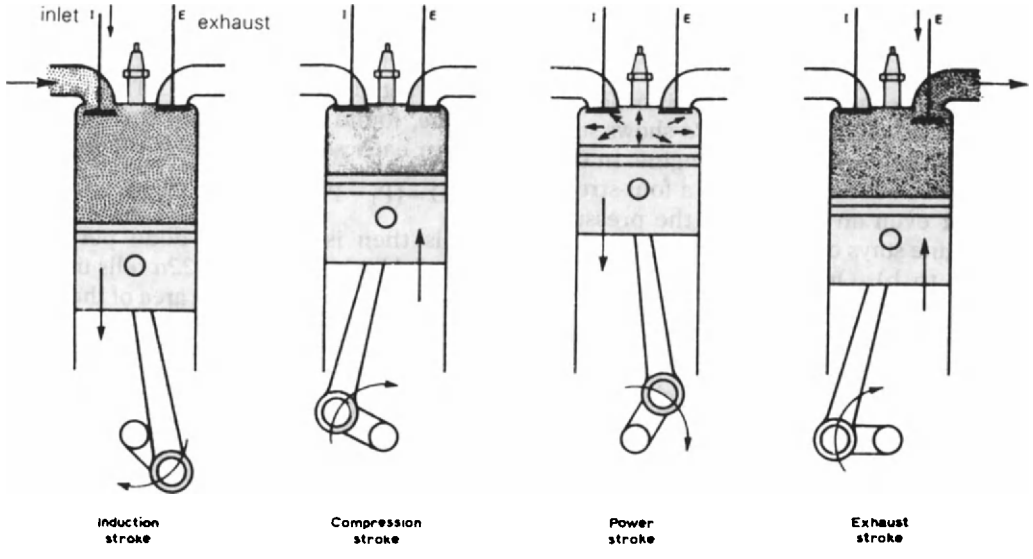


Figure 7.20 Four-stroke cycle (Sully).

admitted to the cylinder. Even though the piston is moving in the wrong direction, the pressures and flow patterns around the valves enable fresh mixture to be admitted all the time the valve is open. Similarly the exhaust valve opens at 40° before BDC and closes 5° after TDC to maximise the removal or purging of the waste gases. Yes, at one point both valves are open at the same time! However the cylinder head is designed to prevent fresh mixture going straight out of the exhaust.

The timing of the instant at which the spark is set off to ignite the fuel is also critical. In most engines the timing is allowed to vary slightly depending on the speed and load on the engine. It is typically set at around 15° before TDC. It is set by altering the setting of the points in the contact breakers, or by the electronic ignition system in many vehicles. These will be discussed later.

7.7.2 Power output from an engine

The power that an engine produces can be calculated by considering what is going on inside the engine during a cycle. If a pressure tapping is made into the cylinder so that a pressure gauge can be connected, the pressure in the cylinder at any instant can be recorded. If at the same time a linear transducer is used to record the position of the piston at any instant, then it is possible to plot these two against each other on a graph. Furthermore the piston position is a direct measure of the volume of the fuel-air mixture. The graph thus indicates the relationship between pressure and volume throughout the engine cycle, and is called an *Indicator Diagram*. *Figure 7.22a* shows such a diagram for a rather special engine. In this engine (which is definitely not a four-stroke engine, or even an IC engine) the pressure in the engine stays constant during the power stroke (a to b). Once the power stroke is finished the pressure is dropped instantaneously (b to c) so that the exhaust gases can be purged at constant pressure. This is done by opening an exhaust valve. When the piston has reached TDC again the exhaust valve is shut and the pressure is forced up to the higher pressure again by whatever is being used as a source of power, so that the cycle can repeat. This is a good model of what a steam engine does. An inlet valve admits steam to the cylinder at TDC and continues to admit steam, pushing the piston down at the pressure of the steam in the boiler.

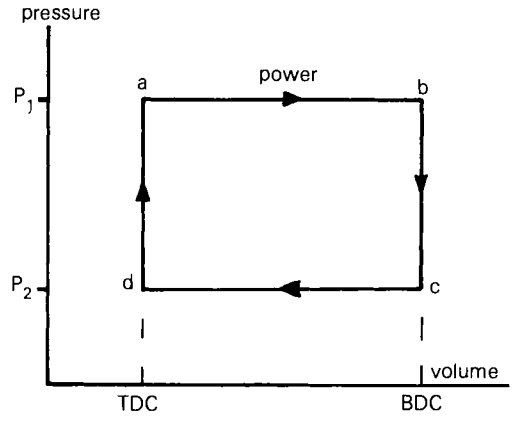


Figure 7.22(a) Pressure—volume curve for an idealised (steam) engine.

Now, let us consider the work done by the engine in one cycle. Since work is equal to the product of force times the distance moved, the work done as the piston is forced down the cylinder under the constant pressure P_1 (ie, from a to b) is given by:

$$WD = P_1 \text{ A L joules} \qquad \textbf{Equation 7.27}$$

where A is the cross-sectional area of the cylinder, and L is the stroke. The product P_1A gives the resulting force on the piston. No work is done between b and c, or between d and a, since no distance is moved even though the force still acts. Between c and d the piston is forced back up the cylinder against the action of the pressure of the gas P_2. Thus work has to be done on the gas rather than by it. This means that this work has to be subtracted from the total. The total work done, found by adding up the components from each section of the curve is just:

$$WD = (P_1 - P_2) \text{ A L} \qquad \textbf{Equation 7.28}$$

This then is the work done per cycle. A careful look at *Figure 7.22a* tells us that this is exactly the same as the area of the indicator diagram enclosed by the curve, since the product L A is just the swept volume. Thus if we measure this area we can determine the indicated power directly. We can also simplify *Equation 7.28* by substituting the pressure difference $P = P_1 - P_2$ into the equation.

If the engine completes S revolutions per second, then the rate of doing work (ie, the power) is simply the work done in one cycle times the number of cycles completed per

second or:

ip = P A L S **Equation 7.29**

where ip is the *Indicated Power*, which means the power output as estimated from the indicator diagram.

This equation tells us the power output from a very simplified single cylinder engine. Now, what about a real four stroke engine? What will its indicator diagram look like? Ideally, the answer is shown in *Figure 7.22b*. The engine cycles as follows:

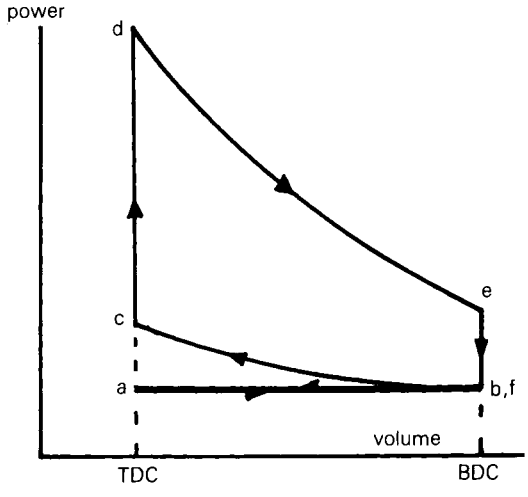


Figure 7.22(b) Ideal curve for IC engine.

a-b: Induction, with no increase in pressure.

b-c: Compression of the new mixture. This is an adiabatic process, which means that there is no heat flow out of the gas through the walls of the cylinder.

c-d: Combustion. Ideally this occurs at constant volume while the piston is at TDC.

d-e: Power stroke. This is also adiabatic in the ideal cycle.

e-f: At BDC the exhaust valve opens and the pressure drops immediately to the lowest value.

f-a: Exhaust stroke. Again in the ideal engine this would be at constant pressure which is the same as the pressure in the induction stroke.

The work done in one complete cycle is given by the volume enclosed by the curve *bcde*. Note that the engine takes two revolutions to complete one cycle. No work is done or required as a result of the induction and exhaust strokes, as the curves *ab* and *fa* overlap and cancel out. This ideal cycle is called an Otto cycle. Its efficiency can be worked out theoretically and is given by:

$$\text{Efficiency} = 1 - \frac{1}{CR^{0.4}}$$

Equation 7.30

where CR is the compression ratio. By efficiency we mean the ratio of the power output by the engine to the power input in the form of the power extractable from the fuel. Note that the higher the CR the higher is the theoretical efficiency. For a typical engine with a CR of 9, the efficiency is thus about 58%. This is the ideal maximum possible efficiency which an engine with this CR can attain. So, what happened to the other 42%? After all you paid for it when you bought the petrol! The answer is that this power is wasted and given off as heat in the engine exhaust, or through the walls of the engine cylinder. It is a basic rule of nature which says that whenever you convert heat into mechanical power you lose some of your energy in the form of waste heat. This is unfortunate for us, and it would be nice if there were exceptions to this rule. Regretfully this model of how nature behaves is one of the most well tested and proven rules of the lot. It is called the second law of thermodynamics.

On the bright side we are at least getting over half our power out in this ideal engine. Unfortunately when we consider a real engine things get even worse! *Figure 7.22c* shows an indicator diagram for a real engine. Now we

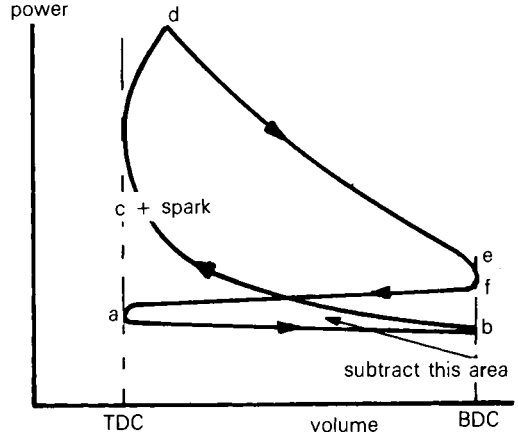


Figure 7.22(c) Real curve for IC engine.

can see how at every point the curve seems to contrive to reduce that vital area inside the curve. Worse still, we actually have an area to deal with between the induction and exhaust stroke curves. The problem here is that this is work done on the gas and so the area has to be subtracted! The effect of all this is to reduce our efficiency down to around 35% or less.

The next question to ask is how do we modify *Equation 7.29* to deal with this complex curve? The answer is that we use a term called the *Mean Effective Pressure* P_{me}, which represents the average constant pressure which would have the same effect as the real pressure has over one cycle. Thus we use the model:

$$ip = P_{me}\ A\ L\ S \qquad \textbf{Equation 7.31}$$

where in effect:

$$P_{me} = \frac{\text{Area enclosed by curve}}{L\ A} \qquad \textbf{Equation 7.32}$$

P_{me} can never be measured directly: it is an imaginary pressure value which is used to fit the model. The reason for doing this is that the model is useful for determining engine performance.

Next we deal with the problem of having the four stroke engine which has only one power stroke every two revolutions. At the same time we can include the effect of having more than one cylinder in the engine. If there are N firing strokes per revolution of the whole engine, then the indicated power is given by:

$$ip = P_{me}\ L\ A\ N\ S \text{ Watts} \qquad \textbf{Equation 7.33}$$

This is the true indicated power for a real engine.

Lastly we have to relate the indicated power to the brake power that actually comes out of the engine and is measured by the prony brake. This is less than the indicated power, because there will inevitably be friction and other losses in the engine which reduce the power output. These can be included by defining the *Brake Mean Effective Pressure* P_b, which fits the model so that the brake power bp is given by:

$$bp = P_b\ L\ A\ N\ S \text{ watts} \qquad \textbf{Equation 7.34}$$

Again, P_b can never be measured directly: it is just a model to represent reality.

The mechanical efficiency of the engine is given by:

$$\text{mechanical efficiency} = \frac{bp}{ip} \qquad \textbf{Equation 7.35}$$

Mechanical efficiencies of up to 80% are possible with modern engines. The value depends on the speed and load on the engine, being greatest at high speed and low load.

Example

A six cylinder four stroke engine has a total swept volume of 2000 cc and an output of 65 kW at 4500 rpm. Calculate P_b.

Solution: For this engine there will be three power strokes per revolution (since it has six cylinders each firing once every two revolutions). Thus N = 3. The volume of one cylinder (L A) will be equal to the total volume divided by the number of cylinders. Thus:

$$L\ A = \frac{2000 \times 10^{-6}}{6} = 333.3 \times 10^{-6}$$

Thus rearranging *Equation 7.34*:

$$P_b = \frac{bp}{LANS} = \frac{60 \times 65 \times 10^3}{333.3 \times 10^{-6} \times 3 \times 4500}$$

$$= 860 \text{ kPa}$$

7.7.3 Overall engine efficiency

The overall efficiency of an engine is described by either of two parameters. The first is the *Brake Thermal Efficiency*, so called because it takes account of the thermal losses and the overall mechanical losses. It is given by:

$$BTE = \frac{\text{brake power (bp)}}{\text{Energy value of fuel used in one second}} \qquad \textbf{Equation 7.36}$$

The energy value of petrol and diesel fuels is around 46 MJ/kg.

The alternative measure is called the *Specific Fuel Consumption* (SFC). This is a measure of how much fuel is used to produce the power. Thus:

$$SFC = \frac{\text{Fuel used in kg per hour}}{\text{brake power in kW}} \qquad \textbf{Equation 7.37}$$

Note the specific units of both terms. They are not the standard SI units.

The relationship between SFC and BTE is:

$$SFC = \frac{3.6}{Q \times BTE} \text{ kg/kW h}$$

Equation 7.38

where Q is the energy value of the fuel in MJ/kg.

Example

Calculate the bp, ip, mechanical efficiency, BTE, and SFC for a four stroke, four cylinder, 2000 cc engine operating at 4000 rpm and producing a torque of 60 N m, if the fuel consumption is 11 kg/hour, P_{me} is calculated from the indicator diagram to be 498 kN m^{-2}, and the energy value of the fuel is 46 MJ/kg.

Solution: For this engine N = 2 and the swept volume L A is:

$$L\,A = \frac{2000 \times 10^{-6}}{4} = 5 \times 10^{-4} \text{ m}^3$$

a. From *Equation 7.6*, bp = 2 π T S

$$= \frac{2 \times 60 \times \pi \times 4000}{60} = 25.1 \text{ kW}$$

b. $ip = P_{me} LANS$
$= 498 \times 10^3 \times 5 \times 10^{-4} \times 2 \times 4000/60$
$= 33.2$ kW

c. Mechanical efficiency

$$= \frac{bp}{ip} = \frac{25.1}{33.2} = 75.6\%$$

d. $$BTE = \frac{bp}{\text{Fuel energy per second}}$$

Fuel energy per second

$$= \frac{11 \times 46 \times 10^6}{3600} = 1.406 \times 10^5 \text{ J/s (or watts)}$$

Hence: $$BTE = \frac{25.1 \times 10^3}{1.406 \times 10^5} = 17.9\%$$

e. SFC

$$= \frac{\text{Fuel used per hour (in kg per hour)}}{\text{bp (in kW)}}$$

$$= \frac{11}{25.1} = 0.438 \text{ kg/kW h}$$

In practice the value of the BTE varies according to the operating conditions of the engine. In most cases for any given engine speed there will be an optimum power output where the BTE is a maximum, of the order of 22%. Similarly, at full throttle, there will be an optimum speed at which the BTE is a maximum. Maximum power is usually obtained at a higher speed, with a slight loss in efficiency. Fuel costs can therefore be kept to a minimum by selecting speed and power output.

7.7.4 Two stroke engines

So far only the four stroke engine has been described. A two stroke engine works in a similar way to a four stroke, except that there is a power stroke on every engine revolution. This is achieved by using the space under the piston to suck the air/fuel mixture into the engine (*Figure 7.23*), and by a very different valve arrangement. Following the path of the fuel, as the piston ascends upwards, the mixture is sucked into the crankcase area through the valve on the side, with the transfer port closed by the piston. When the piston descends the valve shuts and the mixture is compressed until the transfer port opens. The mixture then passes into the chamber above the piston where it is compressed further on the next upstroke and then ignited. As soon as the power downstroke takes the piston past the exhaust valve, the spent gases are allowed to escape. The fresh mixture coming in assists this by causing a swirling flow of gases.

The two stroke engine has the advantage of lightness over the four stroke engine—about half the weight for the same power output. This makes it attractive for applications such as chain saws where weight is important. It can also be operated at an angle or even upside down, since there is no oil in the crankcase. However the disadvantages are that it is less efficient than a four stroke, it requires that lubricating oil be added to the fuel for lubrication, it tends to run more unevenly, and as the bearings wear, the seals will allow air to be admitted into the crankcase all the time so that the engine seems to run only at full throttle.

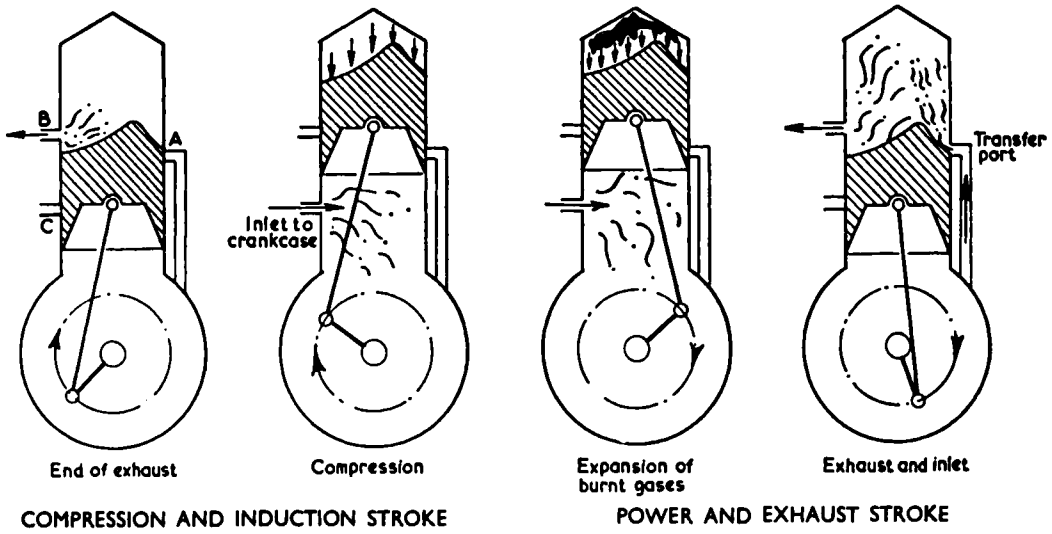


Figure 7.23 Two stroke engine (Hannah and Hillier).

7.7.5 Carburettors

The function of the carburettor in an engine is twofold: it must mix the vapourised petrol with the air in the correct proportions for proper ignition, and must adjust the flow rate to match the requirements placed upon the engine. The correct ratio of fuel and air depends on what you want. In a laboratory test the right ratio to burn all the fuel would be 15 parts of air to one part of fuel (by weight). This is called the Stochiometric ratio. For maximum power a mixture with excess fuel in it is required, say 12:1. This is called a rich mixture. The engine then produces carbon monoxide in the exhaust (a poisonous gas). For maximum efficiency, a lean mixture of say 16:1 air:fuel is required. Then all the fuel is burnt and only carbon dioxide is emitted, as well as the excess oxygen. The mixture burns more slowly, so that some gas can still be burning as the exhaust valve opens. As a result a lean mixture is likely to cause exhaust valves to wear out faster. The air/fuel ratio also affects the production of other exhaust gases which are considered dangerous, such as the nitrogen oxides. *Figure 7.24* shows the effects of the ratio on the levels of emission of pollutants.

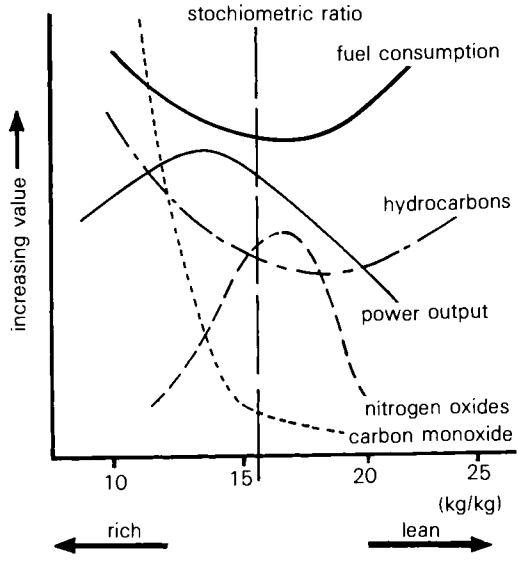


Figure 7.24 Effect of air/fuel ratio on emission levels of various gases.

Two of the main types of carburettor are shown in *Figures 7.25a* and *b*. In the downdraft carburettor, when the piston descends on the inlet stroke a vacuum is created and air is sucked down through the body of the carburettor, and thus through the constriction or Venturi (refer to the chapter on fluids). The venturi causes an increase in velocity at the neck with a corresponding drop in pressure. A small tube leading from a float chamber at the side of the carburettor contains the fuel, which is sucked out by the flow of air. Careful sizing of the tube enables the right mixture to be produced. The butterfly throttle valve at the bottom controls the flow of air: if it is closed across the tube, then the air flow is limited, and so less fuel

is sucked out of the tube. The upper butterfly valve is the choke. If this is closed it reduces the air flow, but the end of the fuel tube experiences the full vacuum of the engine. The result is a rich mixture for starting the engine.

the engine cylinder side of the carburettor and the pressure above the carburettor piston are always the same (P_2). As P_1 is atmospheric and P_2 is controlled by the butterfly valve, the degree of opening (and hence the fuel admitted) depends on the throttle setting and

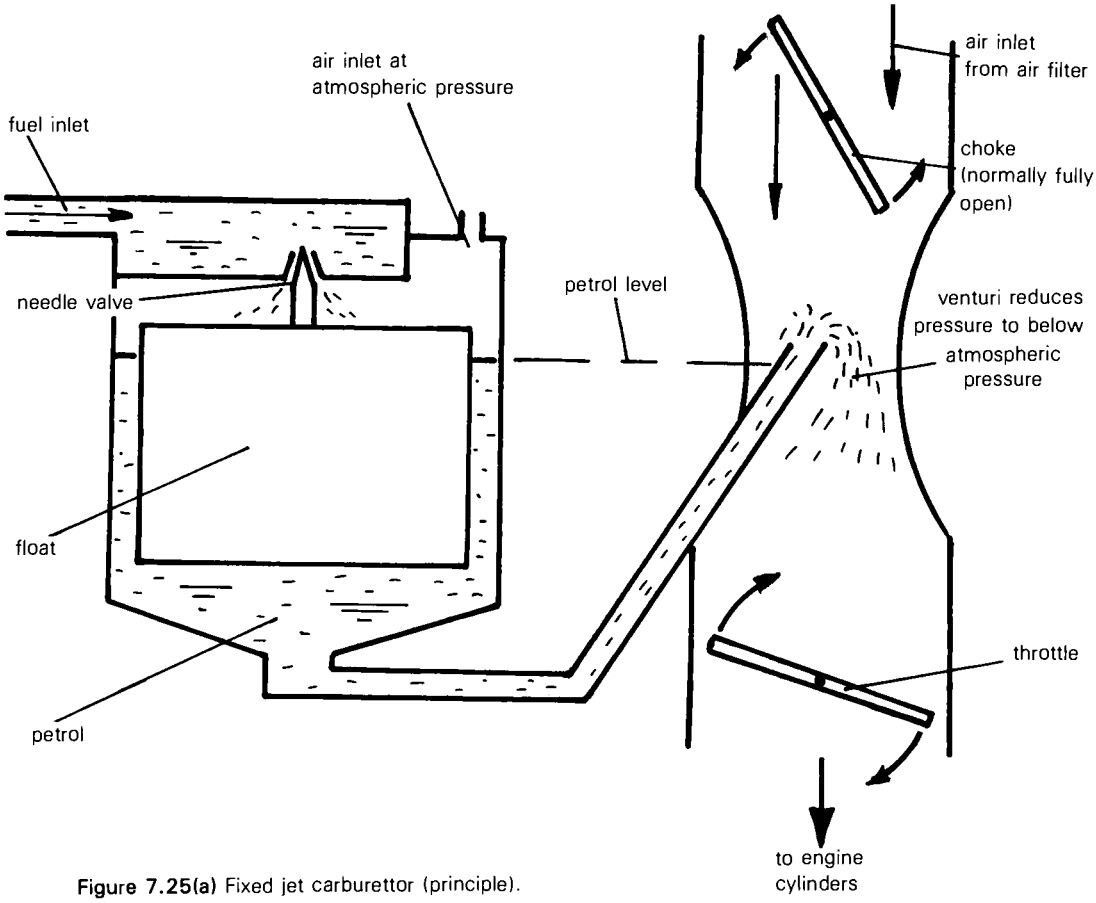


Figure 7.25(a) Fixed jet carburettor (principle).

In practice extra tubes are required to compensate for viscosity effects and surface tension. These vary in magnitude over the range of flows that the carburettor must deal with. An idling flow tube with an adjustment screw is also needed to allow the engine to run smoothly at low speed under no load conditions. Thus a real carburettor is a fairly complex device.

The alternative type of carburettor is shown in *Figure 7.25b*. Here the fuel is admitted into the airstream through a small hole which is blocked by a tapered needle. The needle sits on a piston, which moves up and down according to the difference in pressure between P_1 and P_2. Note that the duct at the side of the piston means that the pressure on the particular shape of the taper of the needle. Different needles can therefore give different performance characteristics of an engine.

7.7.6 Electronic fuel injection

In electronic fuel injection systems the petrol is injected into the inlet to the engine through solenoid valves. These are controlled by an electronic processor which senses the state of the engine at every instant.

7.7.7 Fuels

There are several fuels which can be used in internal combustion engines. The most common are the so called petrol and diesel fuels, which are obtained from oil deposits in the earth. These are both effectively non-

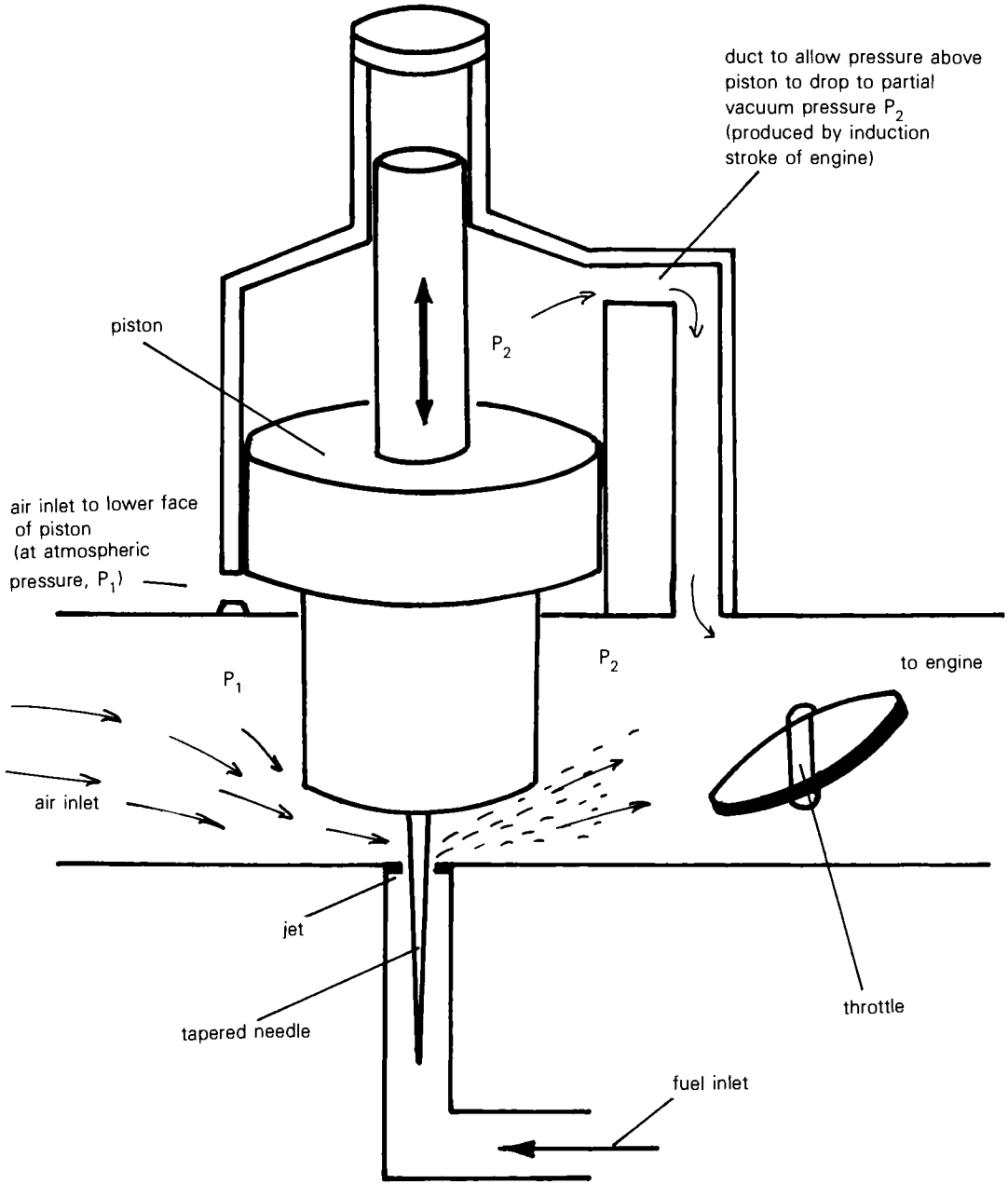


Figure 7.25(b) Variable jet (SU) carburettor.

renewable, since the deposits were formed 500 million years ago from decaying forest residues. In New Zealand synthetic petroleum has been manufactured from methanol since 1984. The methanol feedstock comes from the conversion of natural gas, which itself is non-renewable. In South America, ethanol (C_2H_5OH, or ethyl alcohol)) is used as a fuel. This is obtained from sugar cane and other crops, and is therefore a renewable source of liquid fuel. Methanol, compressed natural gas (CNG) and liquefied petroleum gas (LPG) are also used. Methanol (CH_3OH), or wood alcohol, has about half the energy value per kg of petrol. CNG consists mainly of methane (CH_4) compressed to 20 MPa. A similar fuel can be manufactured from the anaerobic digestion of crops and manures, but this gas

contains about one third carbon dioxide, which will not burn and is therefore of little use. LPG is mainly propane (C_3H_8) at a pressure of 1 MPa. It is heavier than air in the gaseous form, and therefore can be more dangerous than other lighter gases if there is a leak.

These fuels exhibit different degrees of flammability and different burning characteristics. Two parameters are used to describe how easily the fuel can be ignited. The *Flash Point Temperature* (FP) is the temperature at which the fuel will ignite when exposed to a naked flame under controlled conditions. The *Auto-Ignition Temperature* (AIT) is the temperature at which the fuel will ignite spontaneously without the need for a flame to start it. Values for various fuels are indicated in *Table 7.3*.

Table 7.3 Fuel Properties

	FP°C	AIT°C
Petrol (low octane)	−51	288
Petrol (high octane)	−51	343
Diesel fuel	+93	232
Ether (easy-starter)	−29	132

The implications of these values are as follows: a fuel with a low flash point is a dangerous fuel to use. Considerable care is needed when filling tanks, and no naked flames should be allowed in the vicinity. They will ignite easily in an engine as soon as a spark is introduced. Fuels with higher flash points are safer to handle. Fuels with high AITs cannot be ignited easily just by heating them, so petrol is harder than diesel to ignite in this way. However diesel and ether can be ignited just by heating them to a moderate temperature.

This may not seem to be very relevant to a discussion on ignition, until we consider what happens to the gas inside a cylinder when it is compressed. We know that work is done on the gas. We also know that in an engine the compression is very fast, so that not much heat can leave the gas during the compression. This means that the temperature of the gas must rise. In fact it reaches 200 to 500°C, depending on the compression ratio.

It is at this point that the difference between petrol and diesel engines becomes apparent. The petrol engine uses a fuel with a low flash point and a high AIT. The fuel is allowed to enter the cylinder with the air and is compressed with it. It is ignited by a spark at the exact moment when it is required to burn, and not before. If the mixture heats up above the AIT, it is likely to ignite spontaneously, and at the wrong time. This results in poor performance, and irregular firing. It is referred to as "knocking" or "pinking". As the compression ratio increases the temperature of the mixture increases and so the greater is the likelihood of pinking. This sets a limit to the CR which can be used in a petrol engine, and few exceed a CR of nine. Over the decades fuel technologists have improved the properties of petrol by adding various chemicals, such as tetra-ethyl lead, which reduces the chance of pinking considerably. However the lead is emitted in the exhaust as lead bromide gas, which is a serious pollutant. Many countries are banning the use of leaded petrols, or restricting the allowable levels.

The octane rating of a fuel is often used to describe its resistance to spontaneous detonation. Top-grade petrol has an octane rating of around 99, and will work in engines with a CR of nine. Lower-grade petrol, at 93 octane can only be used in engines with CRs of around six.

Diesel engines use fuels with low AIT values. The engine works at a high compression ratio and the aim is to cause spontaneous ignition of the fuel at the right moment. We will see how this is done after we have considered how the spark is generated which ignites the fuel in a petrol engine.

7.7.8 Ignition systems

Nowadays there are three main types of petrol engine ignition system. These are the magneto, the coil ignition, and electronic systems. The first two types, which will be described briefly, are essentially electro-mechanical devices, while electronic ignition systems produce the same effect by purely electronic means.

Magneto ignition systems are used mainly in small engines such as chain saws, mower engines and some motor cycles. The main advantage of a magneto system is that no

battery is required. It is therefore well suited to small, compact power plants. It works by generating a low voltage in a coil through electromagnetic induction as the engine crankshaft rotates. This low voltage is transformed to a high voltage pulse which is fed to the spark plug at the correct point in the engine cycle. The spark then ignites the petrol vapour in the cylinder.

Figure 7.26 shows a schematic layout of a coil ignition system. There are two separate electrical circuits, the primary and the

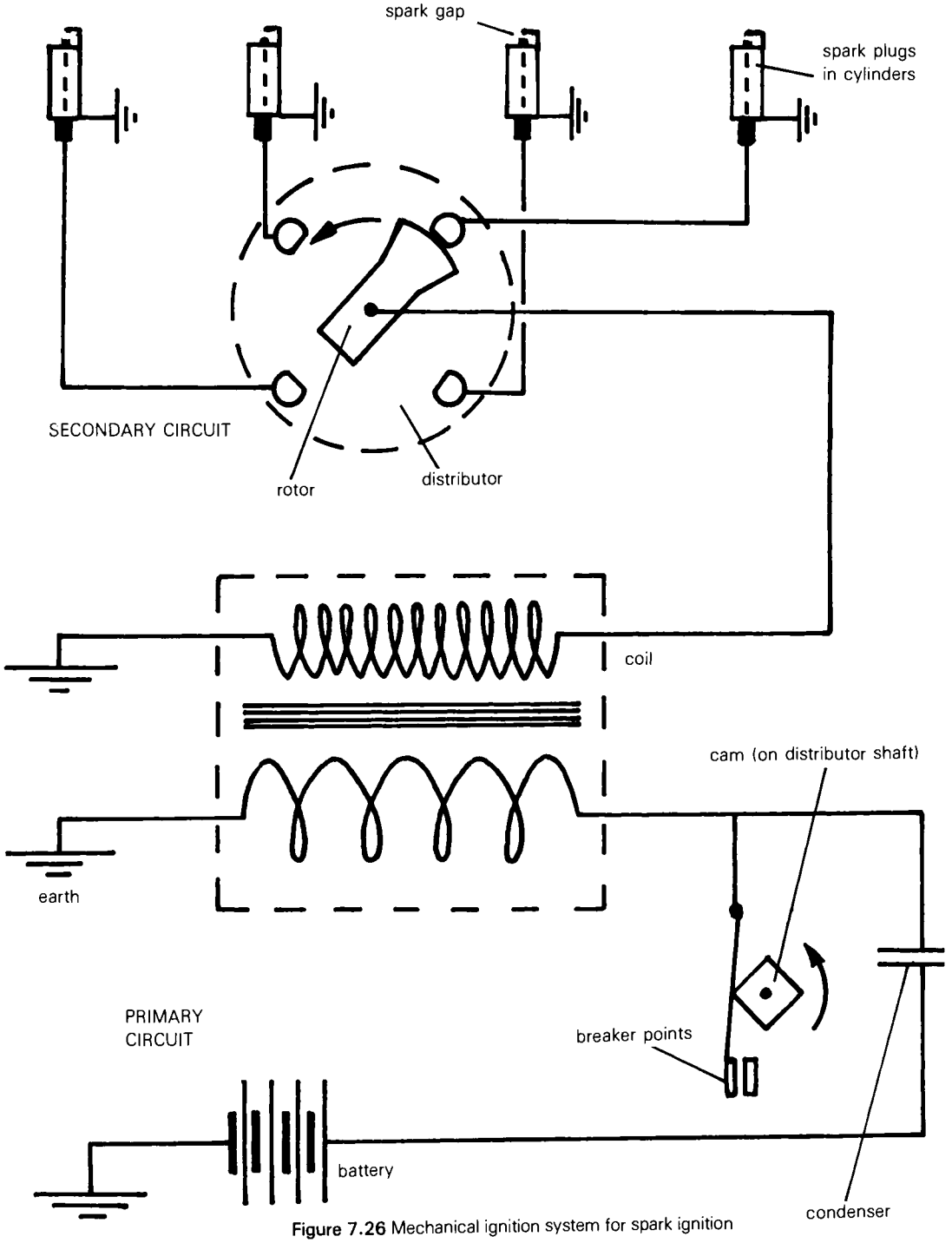


Figure 7.26 Mechanical ignition system for spark ignition engines.

secondary. Both pass into the coil, which is essentially a transformer. The primary circuit includes the contact points and a condenser connected in parallel across them. These are all normally located inside the distributor housing. The circuit also includes the battery, and a winding inside the coil which has a small number of turns of relatively heavy wire. The secondary circuit includes the secondary winding of the coil which has a large number of turns of fine wire wound around the primary. Inside the two windings of the coil, a laminated iron core acts to increase the intensity of the magnetic field inside the coil. One end of the secondary winding is connected to the frame of the engine (ie the "earth" return) while the other is connected to the centre shaft of the distributor. The rotor arm rotates around inside the distributor cap, sweeping past a series of metal contacts which carry the voltage to the spark plugs in each cylinder in turn.

When the ignition is switched on and the contact points are closed, a current flows in the primary circuit, and a magnetic field is built up in the coil. When a spark is required the contact points are opened by a cam on the distributor shaft. The current stops immediately and the magnetic field in the coil suddenly collapses. This rapid change induces a very high voltage in the secondary (around 30,000 volts). The rotor arm will at this instant be passing one of the metal contacts in the distributor cap, and so the voltage is transferred to the spark plug, causing a spark and burning of the fuel. The condenser in the primary circuit acts as a buffer to absorb some of the stored energy in the coil, and acts to increase the size of the voltage, as well as to reduce arcing across the contact points.

As the time required to burn the fuel does not depend upon the speed of the engine, it follows that in order to get complete combustion at the right instant, the spark must be advanced a little at high engine speeds. A centrifugally operated automatic advance mechanism achieves this on most tractor and car engines. Most car engines also have a vacuum advance, which also advances the spark as a result of the vacuum in the carburettor during normal steady running. When the engine is suddenly accelerated by opening the throttle, the vacuum drops and the effect of the advance is reduced. The spark is therefore retarded while the engine picks up speed. This prevents "pinking" or uneven behaviour of the engine during rapid acceleration.

7.7.9 Compression ignition engines (Diesel engines)

Diesel engines operate at compression ratios in the region of 14 to 25. Air only is compressed in the compression stroke. It is heated adiabatically so that the temperature rises to well over the AIT of the fuel. Instead of a spark being delivered, the diesel fuel is sprayed into the cylinder at the required instant through an *Injector*, and it ignites automatically. In other respects the diesel is very similar to the petrol engine. However there are some notable differences. First, because of the higher CR, the efficiency of the diesel is higher (eg, up to 35% for a diesel compared to 25% for a petrol engine). Next the engine pressures are much higher in the diesel (around 4 MPa). This means that the diesel has to be built more strongly, making it heavier and more bulky. Instead of the electrical ignition system, the diesel requires a special injector pump which is capable of injecting the fuel into the cylinder when the air is already at 4 MPa. The fuel must be pumped to pressures of 40 MPa to achieve this. This is achieved with a special high pressure positive displacement pump called the *Injection Pump*. The injector and the pump must be manufactured very carefully with very fine tolerances, so that owner maintenance and repair is not possible. Fortunately the systems available are so well designed and made that little maintenance is required, and in practice the diesel system is much more reliable than the coil-ignition systems on petrol engines.

The injector is located at the top of the cylinder, and looks similar to a spark plug. It takes the form of a spring loaded valve which sprays the fuel through a small hole (around ten micrometres in diameter) when the injector pump applies pressure at the required instant in the engine cycle (*Figure 7.27*).

The injection pump can take different forms. The most common are the in-line pump and the rotary pump. In the in-line pump the fuel is pumped into each injector by a separate pump, while in the rotary pump the fuel is distributed from a single pump to each

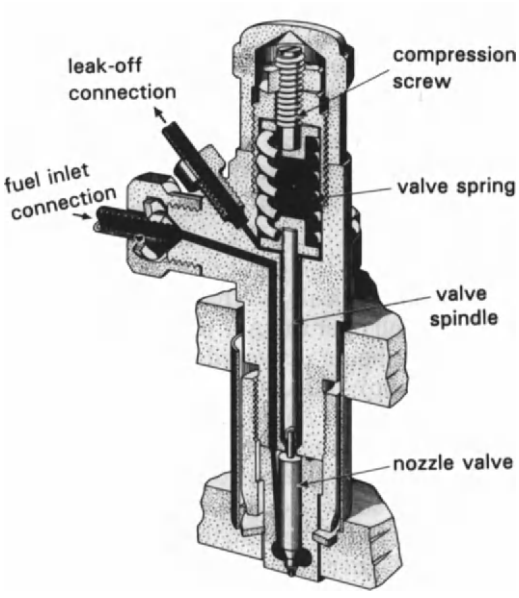


Figure 7.27(a) Separate injector ('closed' type nozzle) (CAV, Shell).

cylinder in turn (*Figure 7.27b*). The pump must not only supply the pressure to force the fuel into the engine, but it must also meter the amount of fuel supplied so that the engine can be controlled. A sliding mechanism called the Rack is used to achieve this. In effect the rack limits the length of the high pressure stroke of the pump. The rack is controlled by the setting of the throttle and the governer, as described below.

Some practical notes: good filters are essential, as only perfectly clean fuel should ever be allowed to reach the injection system. It is also a good idea to make sure that the engine does not run out of fuel. If air gets into the fuel lines it must be bled out, and this takes quite a few minutes to do! Lastly, the high pressure of the fuel emerging from an injector means that it can easily penetrate human skin. One should never allow an injector to spray fuel onto a person.

To list the advantages of a diesel engine, it is more efficient, it burns a fuel which is usually less expensive than petrol and is safer to handle, it is more reliable since there is no electrical ignition system, and it is well suited to remote starting and automatic operation. The disadvantages are that it is heavier on a power output per unit mass basis, and the robust construction also means that diesel engines are generally more expensive to buy initially. They are a good choice for most stationary engine situations.

7.7.10 Engine speed control

The speed of an engine can be controlled in

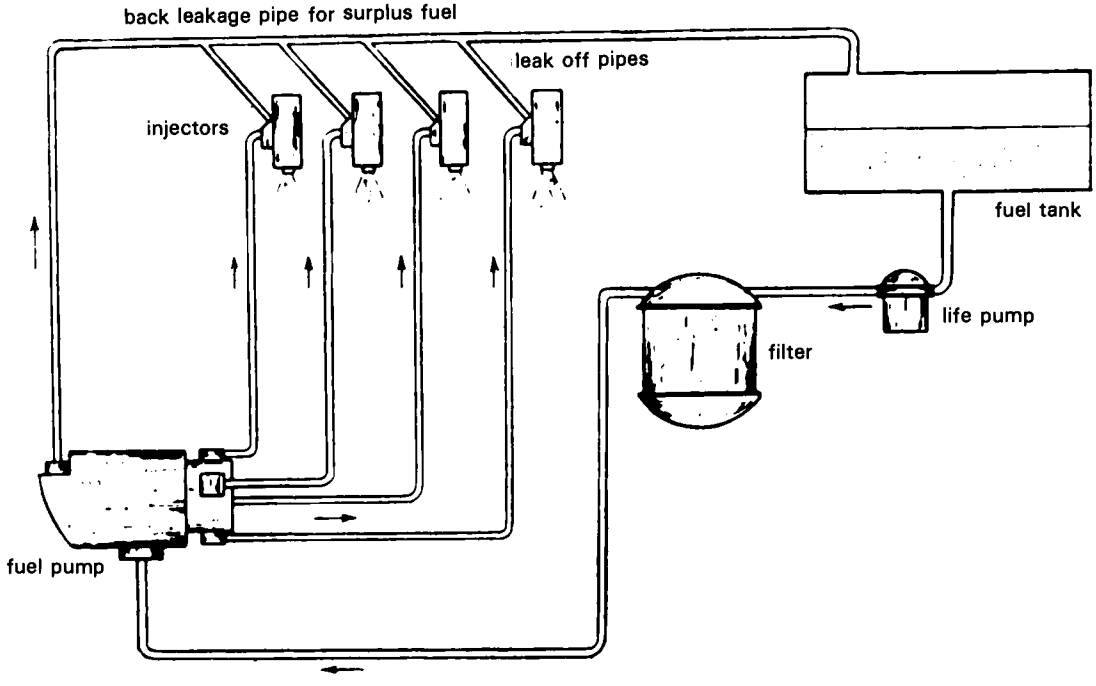


Figure 7.27(b) Fuel supply system (source unknown).

two ways. The most common is to use the throttle control as on a car engine. The throttle is adjusted by the driver manually and the engine power output varies immediately according to the setting. On stationary engines and on tractors this form of control is not always the most convenient. It is preferable to have a controller which automatically adjusts the flow of fuel so that the engine speed is kept constant. This form of controller is called a *Governer*. The governer can be a mechanical system, which relies on the centrifugal force generated by rotating weights, or pneumatic, where a diaphragm linked to the vacuum inside the air inlet manifold adjusts the fuel flow.

7.7.11 Engine cooling

Due to the second law of thermodynamics, over 65% of the energy supplied in the fuel is wasted as surplus heat. It is not surprising that engines get very hot and must be cooled continuously. Air and water are the two main alternatives. Air cooled systems are simple and reliable, and there are no problems with leaks, frost, corrosion, or perishing of rubber hoses. However air cooling is less efficient than water because the air has a lower heat capacity, and a large volume of air is therefore needed to produce the same effect. Fins and ducting are essential. Water systems can be more effective in keeping temperatures down, and this increases the efficiency of the engine. They are also quieter. The water is passed through channels in the engine block, where it is heated, and then circulated through the radiator where it is cooled.

7.7.12 Engine lubrication

All moving parts in an engine require lubrication. In nearly all modern engines oil is forced around the entire engine by a pump, and recirculated back to the sump through a filter. The oil not only lubricates, but in the cylinder it provides an effective seal between the piston rings and the cylinder itself. It also dislodges sludge and other deposits such as carbon and holds them in suspension, and cools any hot spots. The oil also carries any other larger deposits away to the filter. Thus the oil works hard all the time and regular oil changes are an essential part of the regular maintenance of any engine.

7.8 REFRIGERATION

Cooling is necessary in agriculture and horticulture in a number of areas. Most biological products (such as meat, fruit, milk, flowers and vegetables) decay with time, but the rate of decay can be greatly reduced if the temperature of the product is lowered as soon as possible after harvest. Heat must also be removed from animal houses and greenhouses. In many countries domestic houses also need cooling in summer. Industries require cooling systems for the production of liquefied gases and chemical products such as enzymes. Lastly every home should ideally have a refrigerator to keep perishable foods, and to cool the soft drinks, together with a freezer to store meat and vegetables for long periods, as well as keeping the ice-cream frozen!

Refrigeration can be achieved by a number of methods. A cold substance can be obtained and used for cooling by absorbing heat. In olden days ice was collected in winter and stored for use in summer, or shipped from a cooler part of the country to the hotter parts. Ice was deemed an expensive luxury, and only for the rich. Nowadays the ice can be produced by refrigerators but ice banks are still used, particularly in some dairy sheds where the heat load is very intermittent.

An alternative method of cooling is by forcing a liquid to evaporate. If relatively dry air is blown over a wet surface, this makes moisture evaporate. In order to evaporate, the latent heat of evaporation of the water molecules is needed. This heat is obtained by cooling the remaining moisture and hence the surface. Evaporation is distinct from boiling in that it takes place at almost any temperature, but it can only occur at the surface of the liquid. A useful model is to picture the liquid as a mass of molecules all moving about at various speeds and colliding all the time. Occasionally a faster moving molecule reaches the surface and there is nothing to stop it escaping. The liquid thus loses the faster molecules so the average velocity of those remaining drops, thereby reducing the temperature. A few molecules which escape may eventually find their way back to the liquid and be re-absorbed (thereby raising the temperature a little), but the net effect will be a cooling as long as more are emitted than absorbed. As the temperature rises the evaporation rate

increases. The temperature drop from this method is limited to the wet bulb depression (a few degrees only), because if there are a lot of water molecules in the air, the rate at which molecules from the air collide with the liquid surface and are absorbed increases until it matches the rate of loss. At this point no further cooling is possible. A volatile liquid (ie, one which evaporates more easily than water) can be used instead of water. However the liquid must always be replaced once it has gone.

It is also possible to produce cooling by the rapid expansion of a gas. This is achieved by allowing the gas at high pressure to escape through a nozzle. The gas is cooled providing there is no time for heat to flow by conduction from the surroundings into the gas. In other words the process is adiabatic.

The most important practical method of cooling is that used in a refrigerator. Before describing it however, we need to consider the strange way in which our world actually behaves. Of all the models and laws which govern our world, none is more mysterious and far reaching in its implications than the so-called second law of thermodynamics, which we must now discuss.

7.8.1 The second law of thermodynamics

So far we have seen how things are heated up by applying heat. To cool things heat must be removed. This does not seem too difficult at first, since we know that any hot body, like a cup of coffee, cools down until eventually it reaches the temperature of the room. However, equally well, we know that the coffee never cools down to a temperature below the room temperature. The natural flow of heat is always one way, ie, from the hotter body to the cooler one. The more you think about it the more this one way flow of heat is at once obvious but also a little perplexing. For example, if you watched a film which showed a cup of coffee getting hotter, and there was no heating source, sooner or later you would have to come to the inevitable conclusion that in fact the film was being shown in reverse! You see our world has a one way sign on it as far as time and heat flows go. Strange as it may seem, the following statements all come from the same law of nature, and follow from one another. The law is called the second law of thermodynamics, and it is one of the most thoroughly proven models of nature there is.

a. Heat never flows up a temperature gradient.
b. Although it is possible to convert mechanical energy into heat completely, it is impossible to convert heat completely into mechanical energy: there is always some loss of efficiency.
c. The state of disorder of the universe is always increasing.
d. A refrigerator must always discharge more waste heat than it removes from the region it is cooling. The extra heat must come from another power source.

The statements above do not seem to have too much to do with one another and yet they all come from the second law. They have been given in a very "loose" form, and would be criticised (quite correctly) by pure scientists.* However they do indicate the diversity of the second law, and may help the student to realise that what we are dealing with here is not just another hard and fast rule about the way things behave, but a law which is at the heart of nature itself, which even has profound philosophical implications. The law has indeed caused great minds to reflect at length on the nature and future of our universe, and the reader is encouraged to take the matter further by reading some of the references. However here we can only pause before moving back to the subject in hand, how to cool things down below room temperature.

It is worth noting that the law does not prevent cooling below room temperature; it only restricts the direction in which heat can flow. We cannot therefore cool a body by causing heat to flow out of the body and into something warmer: however if we can make something cool itself without there being any heat flow, then this is quite acceptable. This is not hard to do if we go back to a little basic science.

* The Second Law states that when any isolated system undergoes a natural spontaneous change the Entropy of the system will increase, where the entropy is given by:

$$S = K \ln Z$$

where Z is the number of possible configurations of the system, K is Boltzmann's constant, and S is the entropy.

7.8.2 Boiling

Unlike evaporation, boiling takes place at a specific temperature. When a liquid boils, it does so by taking in a lot of heat which causes molecules to break out of the liquid and escape as free molecules. The energy required to do this is quite large compared to the energy normally needed to raise the temperature of the liquid by one degree and is called the latent heat of evaporation, since it is the "hidden" energy which must be provided to change the state of the fluid from a liquid to a vapour. This change takes place at a constant temperature and the liquid (and vapour) do not get any hotter until the change is completed. Thus boiling an egg is really a simple way of maintaining the egg at 100°C while it cooks by putting it into boiling water. The water temperature (and therefore the egg temperature) will not alter until all the water has boiled away, and this takes a long time. If the latent heat of water was zero, then all eggs would have to be fried or baked, since the water would vanish into steam as soon as it reached 100°C!

The temperature at which boiling occurs is dependent upon the pressure. At normal atmospheric pressure the boiling point of water is 100°C, but at two bars the boiling point is 120°C. Conversely, at 0.5 bars (on top of Mount Everest for example), the boiling point is a miserable 80°C. This is why no mountaineer should take tea (you cannot boil water hot enough to get a decent brew!). The boiling curve for water is shown in *Figure 7.28*. The graph indicates how the boiling point changes as the pressure alters. Everywhere below the curve the water will be in its gaseous state (ie, steam), while above the curve it is a liquid. If for any reason the pressure in the fluid changes in such a way that the fluid crosses the boiling curve, a very unstable situation arises: the fluid is suddenly in the wrong state. In order to get back to equilibrium the fluid must now change its state. However this requires that latent heat must flow into or out of the fluid in order for the change to occur. In the case of a sudden drop in pressure (from A to B in *Figure 7.28*), the fluid must boil, which requires heat to be taken in. The problem then is where from. There are two sources; itself and its surroundings. By extracting heat from itself (ie, by cooling down from T_a to T_c, and therefore making available an amount of heat equal to $MS(T_a - T_c)$), some boiling is possible (*Equation 3.54*). This brings the liquid back to equilibrium, but now the temperature of the fluid will probably be below that of its surroundings. Further heat can therefore flow into the fluid from the surroundings, causing further boiling, but also cooling the surroundings. The latent heat of evaporation of water is 2260 kJ/kg at 100°C and one bar absolute pressure.

A similar effect occurs when solids melt to form liquids; extra heat must be supplied to the solid before the change will occur, and this occurs at a fixed temperature. The value of the latent heat of fusion for water is 333.5 kJ/kg. To freeze meat and vegetables at −1°C the latent heats are about 226 kJ/kg and 300 kJ/kg respectively.

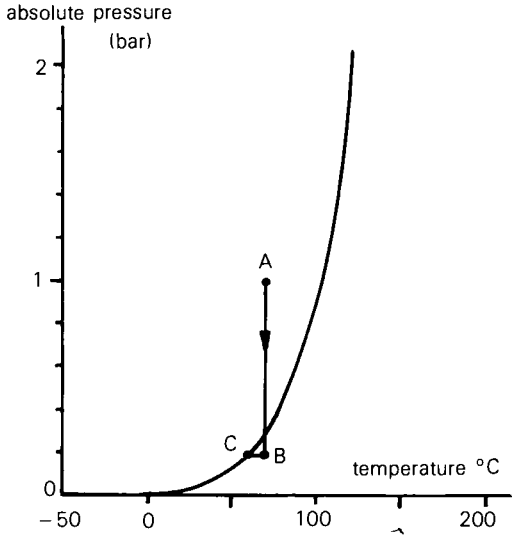


Figure 7.28 Boiling curve for water.

7.8.3 Refrigeration cycle

The device for achieving low temperature is of course the refrigerator. Most of us will be very familiar with the domestic version, and may even be able to identify the different components. However, now that we have stated the second law of thermodynamics, it is obvious that one cannot simply take heat out of a body; the heat has to flow somewhere and that somewhere must be cooler than the place that the heat came from. Therefore it appears to be quite impossible to cool anything below room temperature. The answer is to build a device containing a fluid

which transfers the heat in two stages. First the fluid is subjected to a sudden pressure drop, which forces it to boil. It obtains some latent heat from itself by cooling itself, and the rest is obtained by natural heat flow from the immediate surroundings. Second the boiled vapour is now compressed, which causes an unavoidable temperature rise, so that when it comes in contact with a region designed to receive heat, the fluid is much hotter than the surroundings, and so the fluid is cooled by natural heat transfer out of the fluid. Once the fluid has dropped back across the boiling curve, it now needs to condense, and this is achieved by a further transfer of latent heat, this time out of the fluid.

The basic components are the same in all refrigerators, and consist of four key components. These are shown in *Figure 7.29a*. Fundamental to the operation of the refrigerator is the fluid which is pumped around a piped circuit. The fluid, or refrigerant, is a very carefully chosen fluid with just the right properties. It must be a fluid which boils at a low temperature at atmospheric pressure. For example the very common refrigerant freon R12 ($C Cl_2F_2$) boils at $-30°C$ at normal pressure. Its latent heat of evaporation is 165 kJ/kg at $-30°C$ at one bar absolute pressure. The boiling curve for R12 is shown in *Figure 7.29b*, with a refrigeration cycle shown on it.

Starting at point A (*Figures 7.29a* and *b*) the refrigerant leaves the reservoir, and passes through the expansion valve. This valve restricts the flow of refrigerant, and causes a large pressure drop as the fluid passes through. Hence the fluid is in a state where it must boil (B). The fluid flows into the evaporator. Here is where the area to be cooled is located, and where most of the boiling occurs. The ice box in the domestic refrigerator contains both the expansion valve and the evaporator. Heat is removed from the evaporator and passes into the refrigerant. The refrigerant boils, and the system is so designed that the refrigerant is completely converted to a vapour. Further heating of the vapour will also occur, so the vapour emerges from the evaporator as a super-heated vapour, ie, one that is heated above the boiling temperature (C).

At this point the refrigerant could be discharged to the atmosphere as a waste

Figure 7.29 Refrigeration cycle.

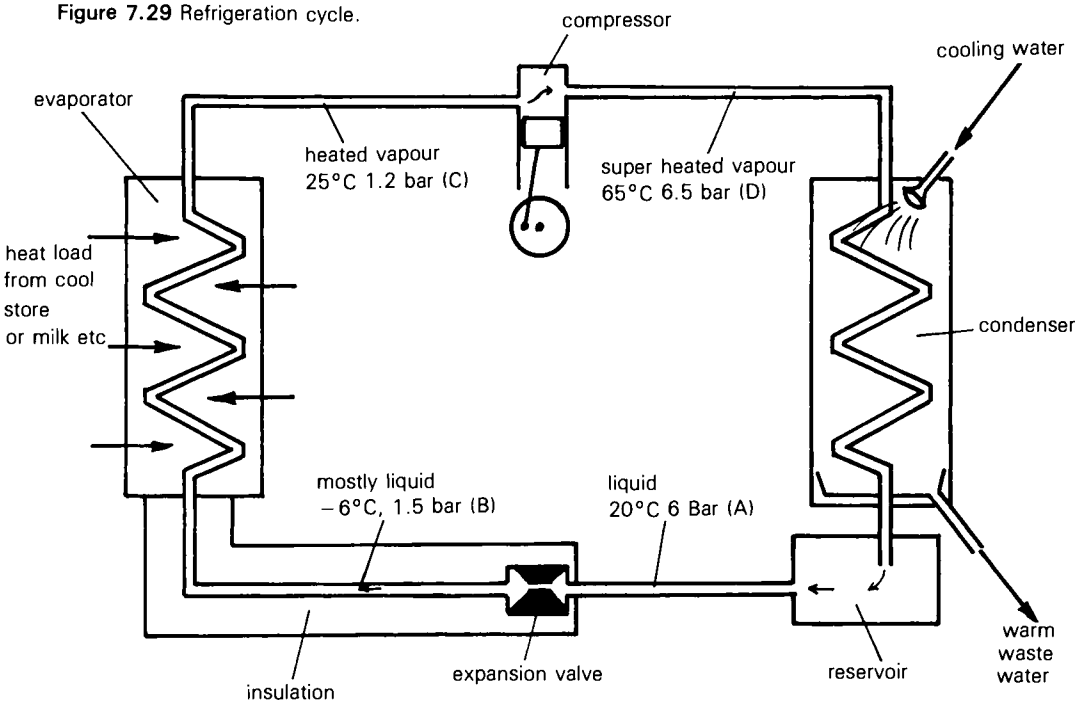


Figure 7.29(a) Schematic outline.

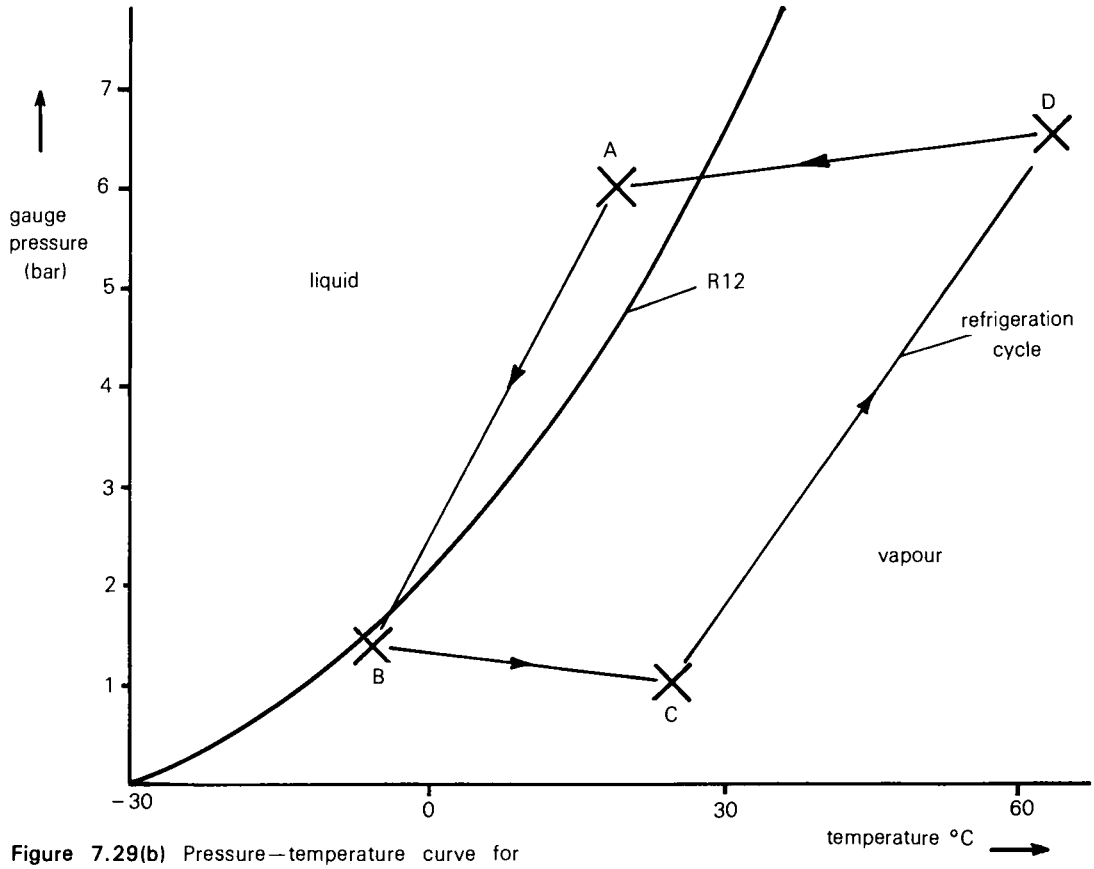


Figure 7.29(b) Pressure–temperature curve for refrigerant R 12, with refrigeration cycle superimposed.

product: it has completed its task of producing cooling of the evaporator. Unfortunately this is not acceptable practice – the refrigerant is quite expensive, and the cost would be quite prohibitive, but even more important nowadays would be the consequences for the environment. From laboratory trials, freon is suspected of being a catalyst which could cause great damage to the ozone layer surrounding the earth's atmosphere. Since it is also relatively inert its effects could be long lasting. Instead we must now recover the refrigerant and return it to its original state in the reservoir.

This is done in two stages: the first involves the compressor. This is just a positive displacement pump, and it compresses the refrigerant, returning it to the high pressure again. This also causes the gas to heat up as well, because the pump is doing work on the gas (D). It is important in the design of the refrigerator that the gas does not condense in the compressor, since this would cause problems, and possible damage to the compressor. From the compressor the gas flows into the condenser. This is just another heat exchanger. Here both the latent heat and the sensible heat of the gas is extracted from the refrigerant, and it condenses back to a liquid. The heat must be dumped into something. If a source of cold water is available, this can be used, and produces an efficient result. However often this is not convenient, and air is used instead. The air is blown over fins which make up the condenser, using fans. In the domestic refrigerator, the condenser consists of a metal pipe network at the back of the refrigerator, and it relies upon a steady flow of air created by the convection effect as the heated air rises to carry the heat away. This flow is quite adequate as long as there is an unobstructed circulation of air around the rear of the machine. Once cooled the liquid refrigerant flows back into the reservoir (A). The slight drop in pressure is due to head loss in the pipes.

The net effect of this is that as a result of

supplying power (W) to the motor driving the compressor, a quantity of heat (Q_{evap}) is extracted from the evaporator and heat is delivered to the condenser (Q_{cond}). Since energy must be conserved, what comes out at the condenser per second must be the sum of the energy entering the refrigerator plus the heat absorbed in the evaporator. Ignoring losses due to friction and heat losses, the heat transfer can be written as:

$$Q_{evap} + W = Q_{cond} \qquad \textbf{Equation 7.39}$$

The performance of a refrigerator is measured in terms of the *Coefficient of Performance* (COP), which is defined at the useful heat removed from the evaporator divided by the work put in (it is thus the equivalent of the efficiency of an engine). Thus:

$$COP = \frac{Q_{evap}}{W} \qquad \textbf{Equation 7.40}$$

Unlike the efficiency of an engine, the COP can be (and usually is) greater than one. Its value depends upon the temperature of the evaporator and the condenser, being greatest if the difference is small. Values of two to three are quite normal.

Example

A refrigeration plant must cool water flowing at 250 litres per minute from 15°C to 5°C. If the compressor uses 30 kW of power, and 3 kW of heat is lost through friction and radiation losses, calculate the plant capacity, the COP and the heat rejected at the condenser.

Solution: a. The heat absorbed is given by *Equation 3.54*, and is:

$$Q_{evap} = M\ S(T_2 - T_1)$$

$$= \frac{250 \times 4200 \times (15-5)}{60} = 175 \text{ kW}$$

b. $$COP = \frac{175{,}000}{30{,}000} = 5.83$$

c. The heat rejected at the condenser will be given by:

$$Q_{cond} = 175 + 30 - 3 = 202 \text{ kW}$$

In practical situations the evaporator should be placed within the region to be cooled. The expansion valve should be located close to the evaporator. Refrigerated milk storage vats achieve this, but in large cool stores it is often impractical to run pipes containing refrigerant over the long distances involved. Instead the refrigeration plant cools a fluid such as brine, which is then circulated around the cool stores.

7.8.4. Heat pumps

It is very worthwhile observing that the refrigerator in the above example uses only 30 kW of electrical power to produce 202 kW of heat at the condenser. If we needed to heat the coolant by this amount for some purpose (such as heating a greenhouse, a house, or to warm water), then the refrigerator is in fact a super efficient means of doing just that. In fact in the example above, it produces 6.7 times more heating than an electric heater would using the same electrical power. Strange as it seems this happens in reality. It is a case where our model correctly predicts the behaviour of our world in a way we would not have expected. Of course, heat is not being created: it is being extracted from the water being cooled in the evaporator. This "refrigerator in reverse" is called a heat pump, and it is a most economical means of heating houses and offices. The outside air is used as the source of heat, so that the heat pump cools the air outside and delivers the heat to the inside air of the building. The only reason why heat pumps are not used much in domestic situations is that they cost much more than ordinary electrical heaters to buy.

The COP of a heat pump is defined as:

$$COP_{heat\ pump} = \frac{Q_{cond}}{W} \qquad \textbf{Equation 7.41}$$

This will always be higher than the COP when used as a refrigerator. Even small heat pumps have COPs of three or four, depending upon the temperature difference. The hotter the source of heat, the greater the COP.

7.8.5. Vacuum cooling

Vacuum cooling is a form of evaporative cooling which is particularly valuable to horticulturalists. Evaporation rates can be increased by reducing the pressure. If a vegetable crop is sprinkled with water, and then placed in a chamber which can then be evacuated with a vacuum pump, the water can be made to boil and as it does so it removes heat from the crop. In this way it is

possible to cool crops such as lettuce down to only a degree or so above freezing point in the field. This is an effective way of preserving the freshness of the crop. Such systems are only suitable on crops which have a small heat content. From *Figure 7.28* a pressure of 0.6 kPa absolute (ie 99.4 kPa below atmospheric) will cause water to boil at 0°C.

7.9 HEAT TRANSFER

The three forms of heat transfer were described briefly in Chapter 3. We will now describe practical models of the processes.

7.9.1 Conduction

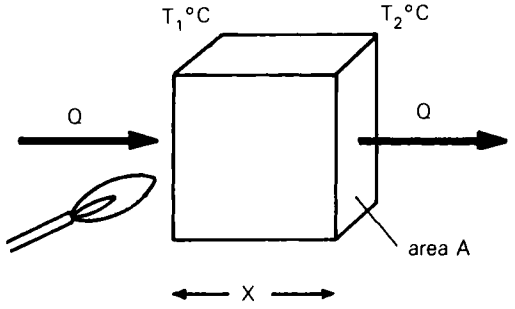
Conduction is the transfer of heat between molecules without gross molecular movement. In essence, the molecules in the hotter body vibrate close to those in the cooler body, and the kinetic energy is transferred. If we consider a block of material with one end being heated in a flame (*Figure 7.30a*), the model of conduction through the material when the steady state has been reached is as follows:

$$Q = -k\,A\,\frac{T_1 - T_2}{x} \qquad \textbf{Equation 7.42}$$

Table 7.4 Density and thermal conductivity values

Material	Density kg m^{-3}	Thermal conductivity (k) $Wm^{-1}{}^{\circ}C^{-1}$	Typical thickness mm
Gypsum plasterboard (paper faced with fibrous plasterboard)	800	0.22	7, 9, 12, 15
Hardboard	950	0.14	4.75, 6
Particle board (medium density)	600	10.11	9, 12, 15, 18, 25
Calcium silicate (insulation)	–	0.05	
Foamed vinyl	–	0.036	
Glass fibre blanket	16	0.04	50, 75
Glass fibre building batts	9	0.05	50, 65, 80, 95
Polystyrene foam (and Ureaformaldehyde foam)	25	0.035	12, 25, 38, 50, 75, 100
Polyurethane foam	30	0.025	12, 25, 38, 50
Polyethylene	35	0.040	15
Cement plaster	1860	0.8	10
Structural concrete	2300	1.6	100, 150, 200
Foamed concrete	900	0.3	100
Timber (softwood)	550	0.13	12, 18
Timber (parallel grain hardwood)	800	0.39	25, 38, 50
Weatherboard exterior cladding	550	0.13	–
Still air (10°C)	1.21	0.024	
Still air (50°C)	–	0.028	
Still air (100°C)	–	0.032	
Glass	2480	1.050	3, 4, 5
Aluminium	2660	230	–
Steel	7850	40	–
Stainless steel	7820	17	–
Copper	8890	380	–
Water (ice)	–	2.44	–
Water (0°C)	1000	0.569	–
Water (50°C)	–	0.643	–
Water (100°C)	–	0.681	–

Figure 7.30(a) Conduction



where Q is the rate of heat flow in watts, k is a constant for the material called the *Thermal Conductivity* in W m^{-1} $°C^{-1}$, A is the cross-sectional area (m^2), T_1 and T_2 are the temperatures of the hot and cold ends in °C, and x is the thickness of the material in m. This model applies strictly only when there is no change in conditions, ie, the temperatures at the ends are constant. More complex equations can be used to model non-steady state situations. Values of k are given in *Table 7.4*.

For most materials k is constant over the range from −5 to 50°C. In many cases we are interested in the performance of particular components rather than the material itself. For example we may be concerned with heat flow through a wall in a cool store consisting of plaster, fibreglass insulation, a paint layer, and an exterior cement block. We can deal simply with this situation by defining the *Thermal Conductance* for a material as:

$$C = \frac{k}{x} \qquad \textbf{Equation 7.43}$$

so that *Equation 7.41* becomes simply:

$$Q = C\ A\ (T_1 - T_2) \qquad \textbf{Equation 7.44}$$

If we have a composite wall with more than one material, it is a matter of algebra to show that we can write:

$$Q = U\ A\ (T_1 - T_2)$$

$$\text{where } U = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \qquad \textbf{Equation 7.45}$$

where C_1 and C_2 are the thermal conductances for the two materials in question, and U is called the *Overall Thermal Conductance*. For standard building materials values of C have been measured and can be found in reference books. Some values are listed in *Table 7.5*.

Table 7.5 Thermal Conductance

Material	Thermal conductance C W m^{-2} $°C^{-1}$
Solid concrete block 100 mm thick	12.5
Hollow concrete block 100 mm thick	9.09
Hollow concrete block 150 mm thick	6.25
Hollow concrete block 200 mm thick	5.26
Building paper	18.9

In some situations we have to consider heat flows in parallel. For example, the materials in the ceiling and floor of a cool store are likely to differ from those in the walls. In these cases it is necessary to consider the heat flows through each component separately, and add to get the total.

7.9.2 Convection

Convection is the transfer of heat by the movement of molecules within a fluid such as water or air. Convection may be free or forced. Free convection occurs because a heated fluid expands and therefore becomes less dense. It therefore becomes more buoyant, and tends to rise, while cooler parts of the fluid fall. In this way a circulation can be easily built up above a hot surface. The hot surface heats the air above it, and this air rises, allowing cooler air to move in from the side. A similar effect can be seen in a saucepan of water on a hot stove. Forced convection describes the cooling process when the fluid is forced across the hot (or cold) surface by a fan, a pump, or the earth's winds.

A complete model of convection is hard to produce. However the main practical effect of convection arises in its importance in the removal of heat from a hot surface exposed to a fluid. The main resistance to heat flow arises from a narrow surface film of fluid which covers the surface and reduces the flow

of heat (an example is shown in *Figure 7.30b*). This is referred to as the lamina boundary layer, and we can describe the behaviour of it by the equation:

$$Q = h\ A\ (T_s - T_f) \qquad \textbf{Equation 7.46}$$

where Q is the heat flow (W), A is the area (m^2), T_s and T_f are the surface and fluid temperatures respectively, and h is the Convective Heat Transfer Coefficient in W m^{-2} $°C^{-1}$. It is also referred to as the film coefficient or the surface conductance. The value of h depends on a number of factors, including the conductivity of the fluid, the velocity of the flow, and the geometry. Condensation and evaporation can also affect the value. The range of typical values for various conditions are listed in *Tables 7.6* and *7.7*.

Table 7.6 Range of values for convective heat transfer coefficients in fluids

Type of flow	h (W $^{-2}$ $°C^{-1}$)
Free convection, air	5 – 25
Forced convection, air	10 – 500
Forced convection, water	100 – 15,000
Boiling water	2,500 – 25,000

Table 7.7 Surface conductance values for air-glass interfaces

Air velocity (m/s)	Surface conductance (W m^{-2} $°C^{-1}$)
0	9
5	22
10	35
15	47.5

Values for practical situations can be determined by experiment and these are published in various design tables.

The effect of the lamina boundary layer is to reduce heat transfer substantially. In heat exchangers every effort has to be made to reduce the effect of it in order to improve the performance. The effect can be modelled by using a modified value of U, as is shown in the following examples.

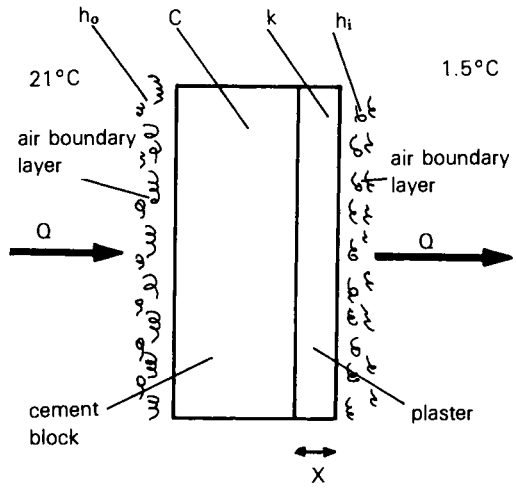


Figure 7.30(b) Boundary layer and composite wall (see example).

Example

a. A cool store wall measuring 10 m × 4 m is built from concrete blocks with a 15 mm cement plaster on the inside (*Figure 7.30b*). If the inside temperature is 1.5°C and the outside 21°C, calculate the heat flow given that the conductance (C) for the blocks is 4.0 W m^{-2} $°C^{-1}$, the conductivity of the cement is 0.58 W m^{-1} $°C^{-1}$, and the internal and external surface film coefficients are h_i = 8.13 W m^{-2} $°C^{-1}$ and h_o = 18.87 W m^{-2} $°C^{-1}$ repectively.

Solution: The heat flow is given by:

$$Q = U\ A\ (T_{outside} - T_{inside})$$

Only U needs to be calculated. This is given by:

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x}{k} + \frac{1}{C} + \frac{1}{h_i} \qquad \textbf{Equation 7.47}$$

$$= 0.053 + 0.026 + 0.25 + 0.123 = 0.452$$

Thus U = 2.21 W m^{-2} $°C^{-1}$

Thus Q = 2.21 × 40 × (21 − 1.5) = 1.72 kW

b. Calculate the heat transfer through a coolstore wall measuring 4 × 10 m, and made of structural concrete 100 mm thick, if the surface temperatures inside and out are 0° and 25°, with and without a layer of polyurethane foam 25 mm thick.



Figure 7.30(c) Cool store for kiwifruit showing refrigeration plant and pipes.

Solution: a. Without the foam, from *Table 7.4*, $k = 1.6$, so $C = 1.6/0.1 = 16$

Hence: $$Q = \frac{1.6 \times 4 \times 10 \times (25 - 0)}{0.1}$$
$$= 16{,}000 \text{ W}$$

Equation 7.48

b. With the foam,

$$C_{foam} = \frac{0.025}{0.025} = 1 \text{ W m}^{-2} \text{ °C}^{-1}$$

Thus $$\frac{1}{U} = \frac{1}{16} + \frac{1}{1}$$

So $U = 0.941 \text{ Wm}^{-2} \text{ °C}^{-1}$

Hence $Q = 0.941 \times 40 \times 25 = 941$ W

It is worth comparing these two results to see the effect of the foam.

7.9.3 Radiation

Electromagnetic radiation has been discussed earlier in Chapter 3. Here we will develop some further concepts in relation to heat transfer. Radiation is the transfer of heat through electromagnetic waves. It takes place without the need for a conducting or convecting material, so that radiation transfer can take place through a vacuum. We now need to consider how much energy is associated with the radiation. Again we have to resort to models which describe the amount and nature of the radiation.

First there are a few principles which need to be established. The first is that all matter is continuously radiating energy in the form of electromagnetic radiation. That includes the sun, the stars, the earth, you, the chair you are sitting on, this book, the clouds, the ground, a crop of cucumbers, and even the polar ice caps. Everything which is not at absolute zero temperature (−273.15°C) is radiating heat. Of course not everything radiates the same amount or type! These are determined largely by how hot the surface of the radiating body is. Thus the sun has an apparent surface temperature of around 6000°K, and radiates accordingly, while the radiation from the earth, at 293°K (20°C) is much more moderate. Three mathematical models govern the emission of radiation. The radiation is distributed over a range of wavelengths as shown in *Figure 7.31*. This represents the maximum amount of radiation power which can be emitted at any

wavelength. The shape of this curve is given by:

$$R\,d\lambda = \frac{A\,d\lambda}{\lambda^5\,(e^{B/\lambda T}-1)}$$

Equation 7.49

where R $d\lambda$ is the power emitted per square metre in the wavelength range from λ to $(\lambda + d\lambda)$ in W m^{-2} (and where $d\lambda$ is very small), T is the absolute temperature (°K), λ is the wavelength (m), $A = 3.74 \times 10^{-16}$ W m^2, and $B = 1.44 \times 10^{-2}$ m °K. The term R is called the *Spectral Radiancy.*

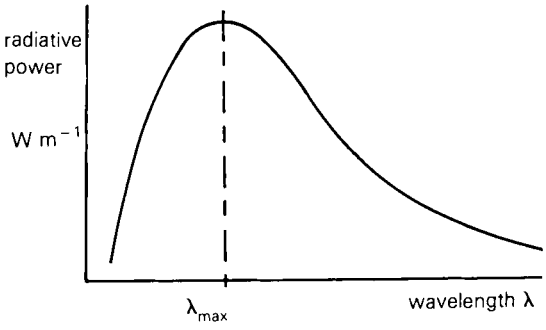


Figure 7.31 Radiative power distribution for a perfect black body radiator.

A graph of this relationship between E and λ looks the same at all values of T. However the value of λ when the maximum power is emitted differs substantially. The peak is given by:

$$\lambda_{max} = \frac{2.88 \times 10^{-3}}{T}$$

Equation 7.50

For the sun, the value of T is around 6,000 °K, so that λ_{max} should be around 0.48 μm. In fact, λ_{max} is about 0.58 μm. The difference arises because the sun does not behave exactly as our model predicts. This wavelength corresponds to the middle of the visible part of the electromagnetic spectrum (*Figure 3.28*), so our eyes are well adapted to the light from the sun. On the other hand radiation from the earth at 300 °K peaks at around 10 μm, which is in the infra-red part of the spectrum and quite invisible to our eyes, even though our bodies can sense this radiation in the form of heat. For example, an electric heater will radiate heat with a peak at around 4 μm, which we can feel quite easily.

Equation 7.49 gives the radiation for a perfect radiator of heat. A body which emits the amounts shown is called a *Black Body.* This is because it will not only emit all the radiation which falls on it, but it will also absorb all the radiation which strikes it too. Thus nothing would be reflected and so it would appear black! In practice many objects emit (and therefore also absorb) less radiation than the maximum, especially at short wavelengths. The *Emissivity* of a surface is defined as the fraction of the radiation emitted to that of a perfect black body in that wavelength. Thus when light falls on an object on the earth it reflects some of the light so that we can see it. The colour of an object is determined by the fraction of visible light which is scattered. Green leaves are green because when they are irradiated with sunshine, they absorb red and blue wavelengths strongly, but do not absorb the green wavelengths in the light. We see the green that is left unabsorbed.

Fortunately, when we consider the total amount of radiation we do not have to concern ourselves unduly with the wavelength distribution. Instead we can use a mathematical model which describes the total amount of heat which is radiated from a hot body. This is given by the Stefan-Boltzmann law which says that the heat radiated from a body is given by:

$$Q = \sigma\, e\, A\, T^4$$

Equation 7.51

where Q is the total emissive power in watts, e is the emissivity of the object as a fraction of that of a black body at the same temperature, A is the area of the emitting surface, T is the absolute temperature, and σ is a constant equal to 5.67×10^{-8} W m^{-2} °K^{-4}.

If everything is continuously radiating heat, why do they not get cooler? The answer is, of course, that they are also absorbing radiation. If a hot object is placed in a vacuum, it will radiate heat and its temperature will drop. As the temperature falls it will radiate less heat until the incoming and outgoing radiation flows are the same. Thus the temperature is ultimately determined by the balance of radiation flows.

The radiation exchange between two surfaces is given by the formula:

$$Q_{12} = A_1\,\beta_{12}\,\sigma\,(T_1^4 - T_2^4) = A_2\,\beta_{21}\,\sigma\,(T_1^4 - T_2^4)$$

where

$$\frac{1}{\beta_{12}} = \frac{1}{F_{12}} + \frac{1-e_1}{e_1} + \frac{A_1\,(1-e_2)}{A_2\,e_2}$$

Equation 7.52

where e_1 and e_2 are the emissivities of the surfaces one and two respectively, and F_{12} is the view factor, or the fraction of radiation emitted by surface one which is actually received on surface two. β_{21} is similar with the one's and two's reversed.

This is quite complicated to use. However for a small object in a large enclosure, (such as a pipe in a greenhouse, or an object exchanging radiation with the sky), it simplifies to:

$$Q_{12} = e_1\,A_1\,\sigma\,(T_1^4 - T_2^4)$$

Equation 7.53

and for two small objects:

$$Q_{12} = e_1\,e_2\,F_{12}\,A_1\,\sigma\,(T_1^4 - T_2^4)$$

Equation 7.54

7.9.4 Transmission, absorption and emission coefficients

A body exposed to electromagnetic radiation may either reflect, absorb, or transmit the radiation. If the fractions reflected, absorbed and transmitted are r, α, and τ respectively, then since all the energy must be accounted for, it follows that:

$$r + \alpha + \tau = 1$$

Equation 7.55

For an opaque body, $\tau = 0$, so:

$$\alpha = 1 - r$$

Equation 7.56

A very important finding for materials is that for any particular wavelength the absorption and emission coefficients are identical. Thus:

$$\alpha_\lambda = e_\lambda$$

Equation 7.57

Note that this only applies for a particular wavelength λ. In particular the values of e and α for short wave solar radiation and long wave terrestial re-radiation can be very different, so that a surface can be coated with special materials which are good absorbers (of solar energy) and poor emitters (of long wave thermal radiation in the far infra-red wavebands). Values of these coefficients are given in *Table 7.8.*

Example

Calculate the convection and radiation heat loss per m length from a 25 mm diameter

Table 7.8 Reflectivity and emissivity values at room temperatures
(for long wave and solar radiation)

Material	Reflectivity (r) (for long wave radiation)	Average emissivity (e)	Average absorbtivity (α) (for solar radiation)
Aluminium foil (bright)	0.95	0.05	0.15
Aluminium sheet, mill finish	0.80	0.20	–
Steel, galvanised, bright	0.70	0.30	0.37
Steel, galvanised, dull	0.10	0.90	–
Copper, bright	0.95	0.05	0.18
Copper, dull	0.34	0.66	0.65
Asbestos board	0.04	0.96	–
Asphalt	0.15	0.90	0.90
Brick	0.07	0.93	0.75
Clay tiles, red	0.29	0.71	–
Concrete, rough	0.06	0.94	–
Concrete, uncoloured tiles	0.35	0.65	–
Glass, wood, and other building materials (approx)	0.10	0.90	–
Snow	0.82	0.18	–
Paper (white)	0.95	0.05	–
Paint (oil base all colours)	0.94	0.06	–
Matt black paint	0.97	0.03	0.96
White paint	0.95	0.05	0.14

heat pipe in a greenhouse, if the surface temperature is 90°C and the air temperature is 10°C. The pipe has an emissivity of 0.9.

Solution: a. Convection losses can be calculated by using the free convection figure of 10 W m^{-2} $°C^{-1}$.

The surface area of 1 metre of pipe is given by:

$A = 2\ \pi\ R\ L = 0.0785\ m^2$

Thus the loss per metre of pipe is:

$Q = 10 \times 0.0785 \times (90 - 10) = 62.8\ W$

b. Radiation losses

The absolute temperature of the pipe is $273.15 + 90 = 363.15°K$

Hence from *Equation 7.53* the emitted radiation per m is:

$Q = 0.9 \times 0.0785 \times 5.67 \times 10^{-8} \times (363.15)^4$
$= 69.7\ W$

7.10 HEAT EXCHANGERS

Heat exchangers are used to cool or heat fluids. Most often they are required in horticulture and agriculture for cooling, eg, milk, the air in a cool store, or the refrigerant. The basic principle is shown in *Figure 7.32*. A hot fluid enters and is cooled from T_{1h} to T_{1c}, while the other fluid heats up from T_{2c} to T_{2h}. At all points the two fluids are separated by the walls of the heat exchanger and so all heat must flow by conduction through the walls. Thus the quantity of heat depends on the material conductivity, the film transfer coefficients on both sides, and the temperature gradient at any point. The last term is very difficult to calculate because it changes as the fluids heat or cool. However the greater the temperature difference and the more turbulent the flow in the fluids the greater will be the heat transfer.

Heat exchangers can be designed to be parallel flow, counter flow or cross flow designs (*Figure 7.32*). The curves indicate the temperature profile through the heat exchanger. As the temperature curves suggest, the parallel flow design is not very efficient in cooling the hot liquid, and in practice most heat exchangers are either counter or cross flow designs. The performance of a heat exchanger is measured in terms of its *Effectiveness Ratio* given by:

$$E_c = \frac{\text{Actual temperature drop}}{\text{Ideal temperature drop}} = \frac{T_{1h} - T_{1c}}{T_{1h} - T_{2c}}$$

Equation 7.58

A good example of a heat exchanger used in agriculture is the plate heat exchanger (Chapter 10, *Figure 10.8*), which consists of a set of stainless steel plates clamped together. The plates are stamped to make a series of small channels between each pair of sheets. Milk is cooled hygienically as it flows between one pair of sheets, while cooling water flows in the opposite direction through the channels between these sheets and the next on both sides. In this way the exchanger has alternate layers of milk and water flowing in opposite directions.

7.11 FANS

Fans are used to drive air and other gases through buildings and pipes. In many respects the performance curve of a fan is similar to that of a centrifugal water pump eg, as in *Figure 5.36* (Chapter 5). The volume of air moved per second drops off as the pressure across the fan increases.

Fans can be a centrifugal, axial flow, or propeller design. Centrifugal fans have a relatively poor efficiency (from 45 to 75%), but they can deliver air at relatively high pressures. They are common in drying systems where it is necessary to blow air through the crop. They are used where small volumes of air are required at higher pressures, such as hot air driers. Axial flow fans work at an efficiency of around 80%, due to the cowling and the number and design of the blades. They work at air pressures up to 500 Pa, and can be used in grain and potato stores. They are more suited to high flow rate and low pressure applications such as ventilation systems for greenhouses and stock housing. Propeller fans are simple and inexpensive. They will not work at pressures beyond 125 Pa, and so can only be used where there is little obstruction to the air flow, such as in properly designed greenhouses with automatic vents.

Fans are normally driven by an electric motor, which may be on a separate shaft so that the drive is via a belt, or the motor and fan may share the same shaft. In horticulture and agriculture the requirements of the fan

Figure 7.32(a) Parallel.

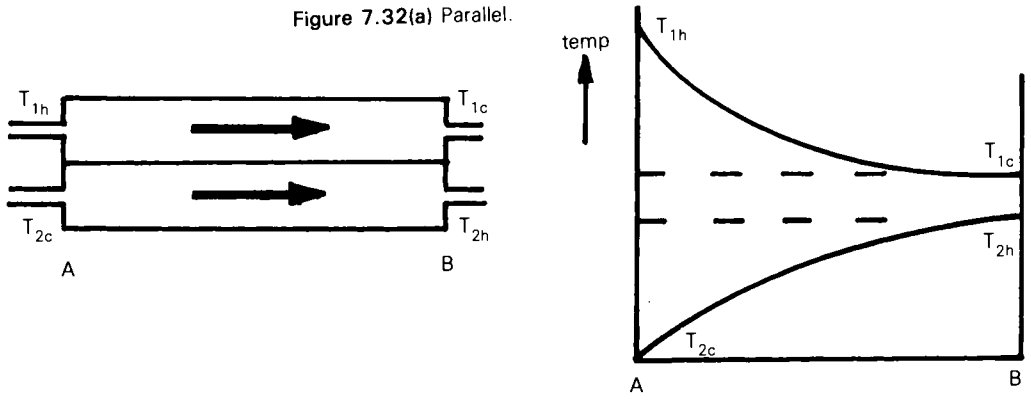


Figure 7.32(b) Counter flow.

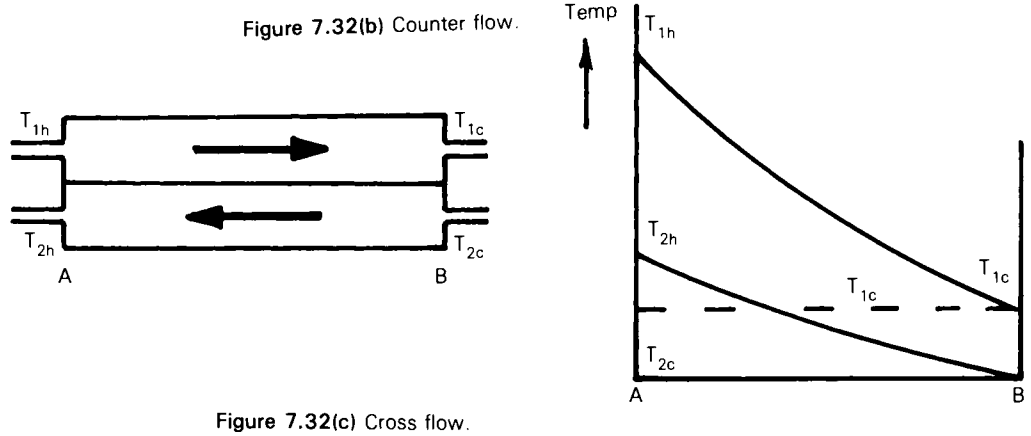


Figure 7.32(c) Cross flow.

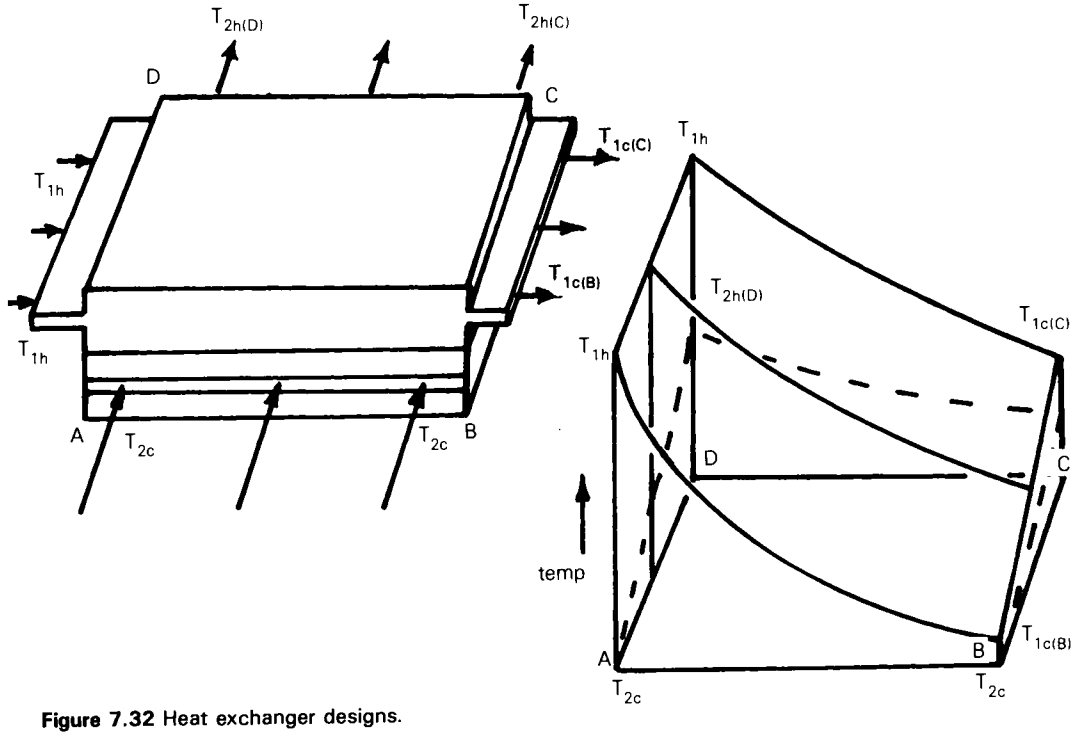


Figure 7.32 Heat exchanger designs.

are that it is low in cost, durable and reliable, and requires little maintenance. Fan blades are therefore usually made from sheet steel bent into a suitable curved shape. These are less efficient than aerodynamic sections, but the extra cost outweighs the small benefits. Problems may arise if the fan is very noisy. The noise level is related to the tip speed of the fan blades, and to their shape. Thus a larger fan operating at a lower speed will be quieter than a small fan at full speed delivering the same air flow, while narrow flat bladed fans are noisier than broad curved blades because they are more likely to generate air turbulence and to vibrate.

Speed control

A fan designed for the worst case will be too large for the ventilation requirements at other times. Speed control is therefore needed. This can be achieved by suitable electrical controllers, which will give a continuous variation in fan speed. These are expensive, and cheaper alternatives involve step controllers, where the fan can operate at two or three intermediate speeds. Simple fully on/fully off control is cheapest of all, and one option is to use several fans, which are designed to switch on progressively if the temperature continues to rise.

7.12 ALTERNATIVE POWER SOURCES

Depending upon circumstances, it may be necessary to explore alternative sources of power. The farm may be a long way from electrical power supplies, or it may be uneconomic to run power lines to a site where say a water pump is required. You may live in a country where power is just not available, or it is too expensive to use for the purpose in mind. Before starting on a project it is essential to ask a few basic questions about the alternative sources of power. Obviously one must know what sources are actually available. It is then necessary to find out or estimate how much power is available, and the grade of the energy. The flexibility of use, such as the prospects of storing the energy when demand is low, any seasonal variations in output, and any safety or legal requirements, need to be considered, in addition to the simple economics of the project. We will look very briefly at some alternatives, and attempt to highlight the features which need to be assessed.

7.12.1 Water power

Solar radiation causes water in the sea to evaporate. This water rises, condenses, and eventually falls as rain. As it flows back to the sea, the potential energy can be collected by hydro-stations, and converted to electricity. On the farm streams can be harnessed and the power can also be used to produce electrical energy, or it can be used to produce mechanical power directly. The hydraulic ram (Chapter 5) will even use water power to pump water uphill again!

The maximum power available from a source of water is given by *Equation 5.33*. However in practical terms this becomes:

$$P = e\ \gamma\ Q\ H \qquad \textbf{Equation 7.59}$$

where P is the power (W), Q is the flow through the turbine ($m^3\ s^{-1}$), H is the available head after any friction losses in the delivery of water have been subtracted (m), γ is the specific weight of water (9800 N m^{-3}), and e is the efficiency of the turbine, expressed as a fraction. It is immediately obvious that the flow and head of the potential source of power will determine the value of the resource. Measurements will need to be taken over several seasons if the resource is to be assessed accurately. Considerable earth works may be needed to convert a running stream into a source of power, even if the head is available over a distance.

Water turbines can be classed either as gravity systems, where the turning effect comes from the weight of the water, or impulse types, where the potential energy of the water is first converted to kinetic energy, and then fed to the turbine. In the first category the overshot and breast water wheels are to be found (*Figure 7.33*). They require a head of a few metres (in the case of the overshot the head must be more than the diameter of the wheel), and operate at very slow speeds with an efficiency in the 45 to 75% range. In the range of impulse systems, the undershot wheel, and the propeller turbine operate at low heads. The undershot wheel has a very poor efficiency of under 45%, while the propeller turbine can have a value of up to 80%. The Michell turbine requires a head of more than two metres, while the Pelton wheel needs at least a ten metre head (*Figure 7.34*). Francis turbines

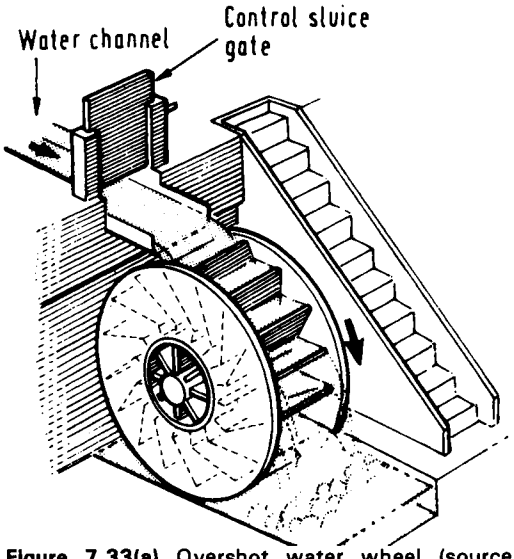


Figure 7.33(a) Overshot water wheel (source unknown).

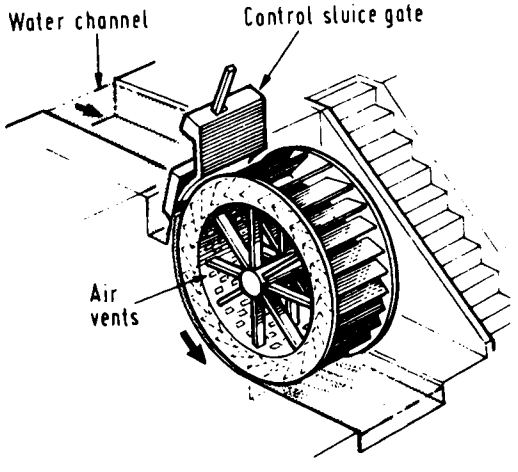


Figure 7.33(b) Breast water wheel (source unknown).

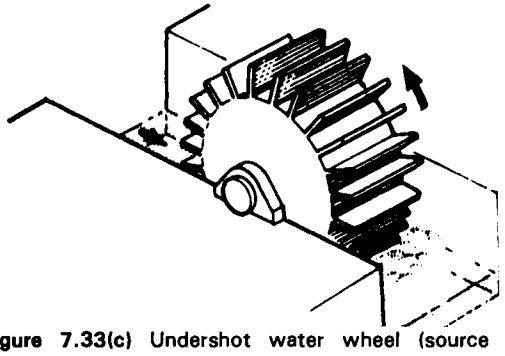


Figure 7.33(c) Undershot water wheel (source unknown).

are the type used in large scale hydro-electric stations, and are too complex for on-farm applications.

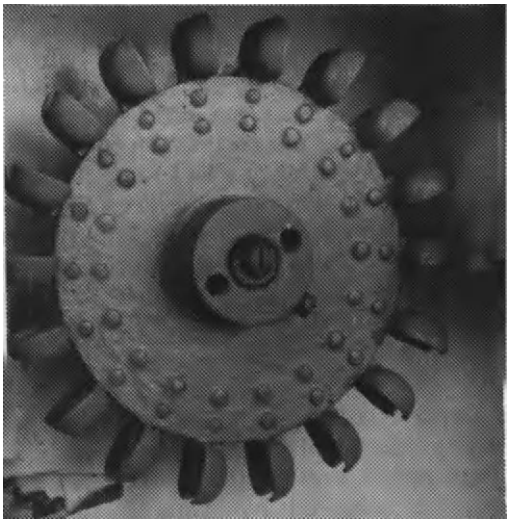


Figure 7.34(a) Pelton wheel.

The speed of the turbine is also important: gearing is an added cost, and will reduce the efficiency of the system. The area around a water wheel is not the ideal place for gears to be either. Water wheels all work at low speeds of the order of 20 rpm or less. Even for a piston pump this is rather slow. Michell turbines will operate at around 300 rpm, while the Pelton wheel can work at 1000 rpm, which makes these units more suited to driving pumps or generators.

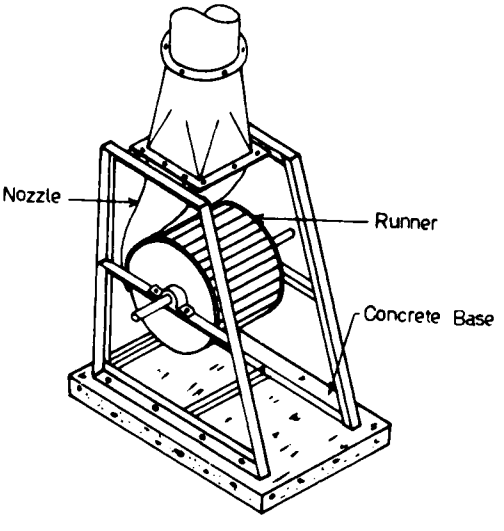


Figure 7.34(b) Michelle turbine (MAF Tech).

The installation of any water power system requires careful thought and effort. The site must be protected from possible flood damage, and yet the pump must work at minimum stream flows. The foundation must be solid, and the site must be accessible. If the water contains solids, then a screen or filter may be required to prevent excessive wear on the turbine or ram. In addition there may be legal requirements relating to the use of a water resource, and to the generation of electricity. Approval from the authorities will be required for the installation.

7.12.2 Methane generation

Methane is produced, mixed with other gases, by the anaerobic decomposition of organic materials. It is given off by an anaerobic effluent pond, and the mixture is often called Marsh Gas. Although the gas is formed naturally, the energy can only be harnessed by controlling the reaction and optimising the chemical processes. In the process there are a series of reactions which are brought about by the action of biological enzymes in the digesting system. The complex organic residues are first broken down to simpler organics. These are then fermented to produce volatile fatty acids. The methanogenesis process then converts these into methane gas. Other gases are also produced, including carbon dioxide, which is an unavoidable by-product making up a third of the total volume of gas output, hydrogen sulphide, which is very corrosive, and ammonia. The last process is the slowest and the most sensitive to the conditions in the digester. The temperature of the process must be kept in the range of 35 to 37°C for mesophilic operation or at 55 to 57°C for the faster thermophilic reaction. The former is slower but is easier to maintain in practice. The waste needs to be retained in the digester for between two and six days in order for the bacteria to develop and work. In practice retention times of 10 to 30 days are used for design, as this simplifies the control requirements.

The yield from a digester depends on the input material. The volatile solids (VS) which represents the proportion of the waste in the form of organic solid material, is the key ingredient. The production is about 0.5 m^3 of methane per kg of VS decomposed, which has an energy value of 37 MJ per m^3. However there are some major sources of loss. The main loss arises because many feed stocks are difficult to digest completely, and so only part of the total VS is broken down. For example dairy cow waste has already undergone some anaerobic digestion inside the cow. As a result, only 30% of the VS may be broken down in the digester. Some energy will also be needed to drive the pumps and to keep the digester warm. This can require between 20 and 50% of the total output! The total energy yield from cow waste is therefore unlikely to exceed 5 MJ per kg of volatile solids.

A typical digester system is shown in *Figure 7.35*. Here the waste is fed first into a balance tank which allows continuous regular loading of the digester with fresh waste. The gas is given off at low pressure around one kPa, and must be collected in a suitable expandable gas storage system. Depending upon the end use it may need to be compressed into cylinders, or the carbon dioxide and hydrogen sulphide may need to be removed. Untreated, 1500 litres of biogas at NTP has the same energy content as one litre of petrol. The gas can be used for domestic heating and cooking, in which case it can be used directly, providing adequate safety systems such as flame traps are installed. It can also be used in suitably modified engines. If it is required for powering transport, then it will need to be compressed.

7.12.3 Wind power

About 2% of the solar energy arriving on earth is eventually converted to wind. Unfortunately capturing this power on a large scale requires very large structures. A machine to produce one MW in a ten m/s wind would need to have rotating blades 70 metres in diameter. Nevertheless wind turbines with up to three MW capacity have been designed. Wind machines which produce a few kW can be useful in farm situations, particularly for pumping water in remote areas, or for power generation to small communities. The wind has indeed been used by mankind for centuries as a source of power for transport, for grinding corn and pumping water.

A variety of different machines have been developed over the years (*Figure 7.36*). Different designs have different uses and advantages. A useful parameter for assessing

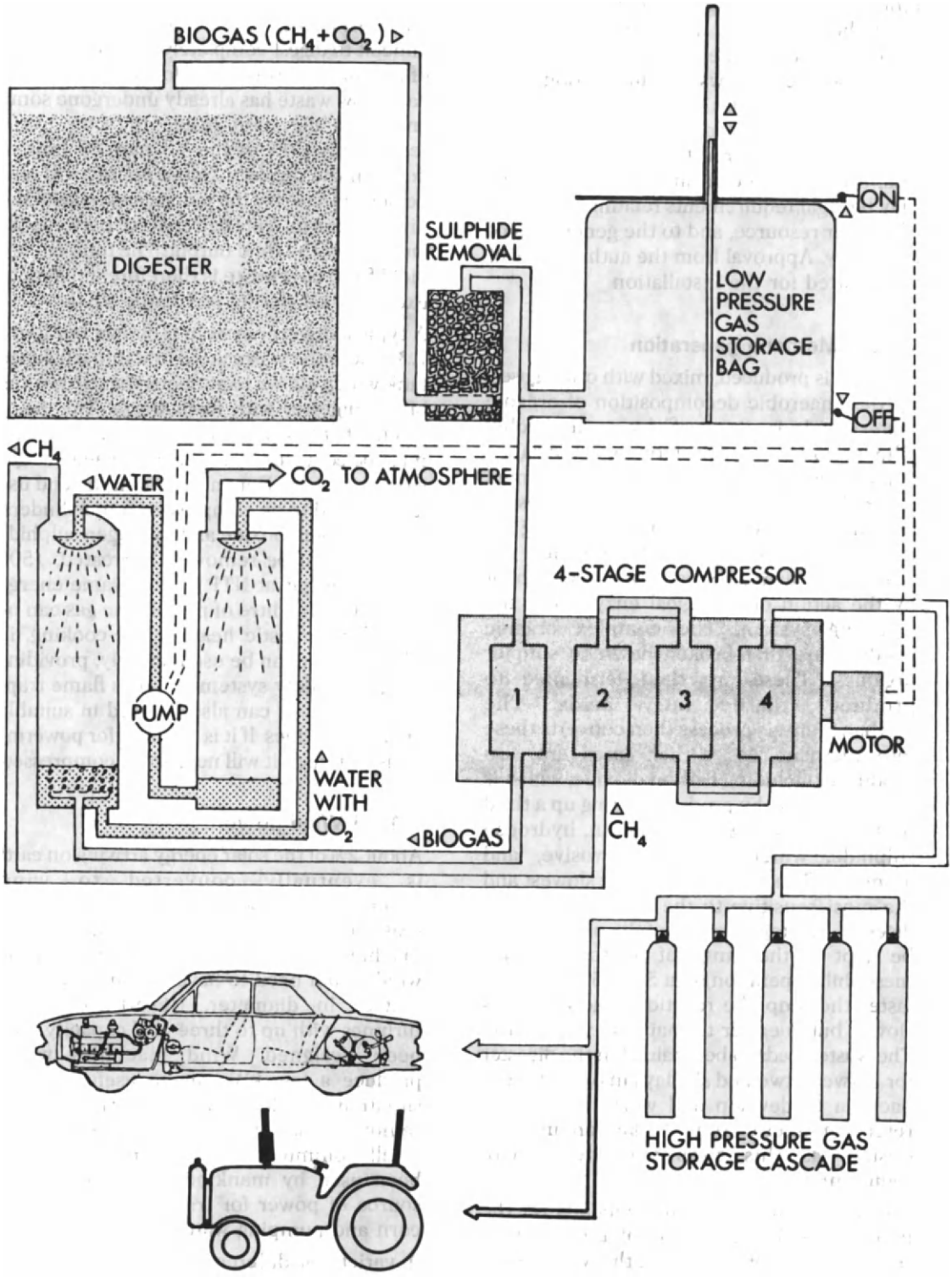


Figure 7.35 Production and use of biogas in vehicles (Martin and Stewart).

their performance is the *Tip Speed Ratio* (TSR). This is the ratio of the speed of the tip of the outermost point of the windmill to the wind speed, or:

$$TSR = \frac{\text{Speed of tip of blade}}{\text{Wind speed}}$$

Equation 7.60



Figure 7.36(a) "Dutch" traditional windmill.

The Dutch windmill, with its canvas sails which need to be furled in high winds, and its variants, have played a vital part in European history. They were beautiful, slowly moving complex masterpieces of traditional engineering. They are most efficient at a TSR of around three (*Figure 7.37*). Their modern equivalents use more automatic methods for preventing damage in high winds. The multiblade windmill also turns slowly, but has a high torque. It is well suited to pumping water and is usually designed to drive a positive displacement piston pump directly. This windmill generates its optimum output at a TSR of unity. Overspeeding is prevented by various mechanisms which turn the windmill out of the wind if it is too strong.

Two and three blade rotors are carefully designed so that the blade is a good aerofoil shape. This gives a greater efficiency, but only at TSR values around seven. These machines

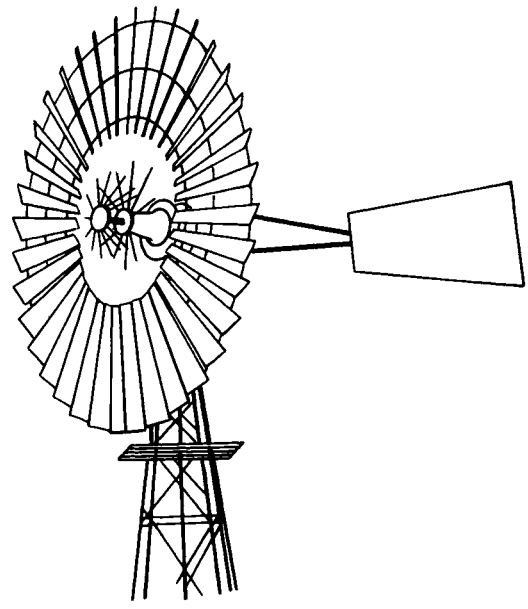


Figure 7.36(b) Multi-blade rotor

can be connected to generators to produce electrical power, and commercial systems producing between 2 and 200 kW can be purchased.

All the above windmills are horizontal axis machines, that is the blades rotate about a horizontal shaft. In order to drive equipment on the ground the torque must be turned through 90° by a gear system located on the spindle. They must also be able to rotate to face the wind, unless designed to capture only the most frequent winds. Alternative designs with vertical axes have been developed, which avoid these difficulties. The Savonius S-rotor is a simple device, which is easy to make but has a very low efficiency. The Darrieus rotor is more efficient, but requires a high TSR to operate and will not start by itself. Often small S-rotors are used for this purpose.

The power output from a wind machine will depend on the area of the wind intercepted, the wind speed, and the efficiency of the system. For theoretical reasons no windmill can ever collect more than 60% of the kinetic energy in the wind, and for practical reasons only about 65% of this can be actually harnessed, as *Figure 7.37* indicates. Thus the maximum power output will be given by:

$$P = 0.5\ E\ \rho\ A\ v^3$$ **Equation 7.61**

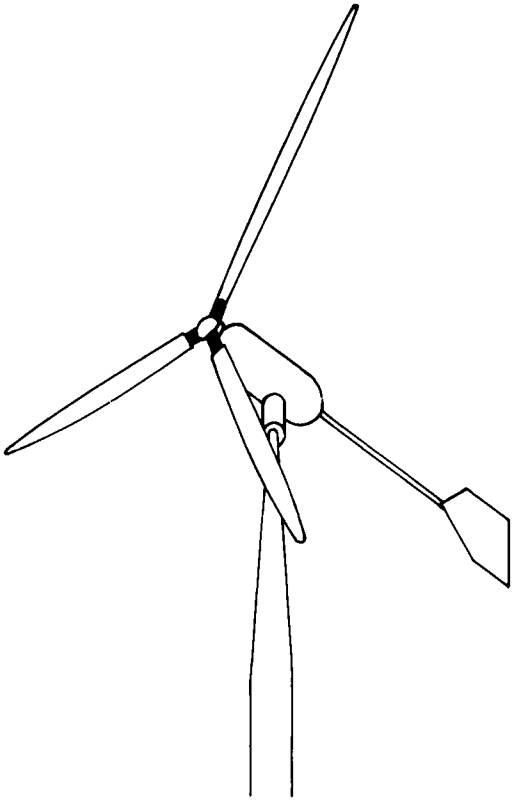


Figure 7.36(c) Three blade rotor.

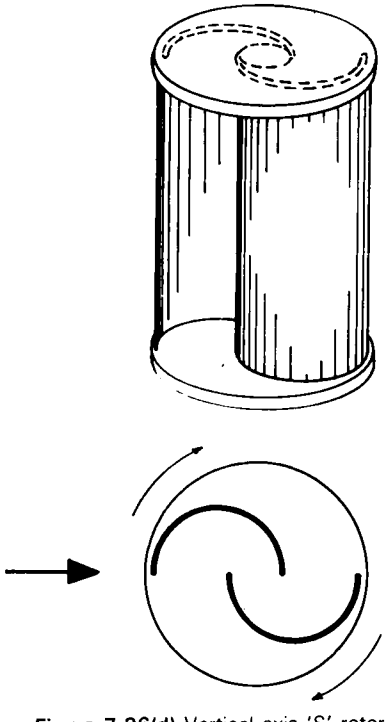


Figure 7.36(d) Vertical axis 'S' rotor.

where E is the efficiency from *Figure 7.37*, ϱ is the density of the air, A is the cross-sectional area which the windmill intercepts, and v is the wind speed some distance away from the windmill.

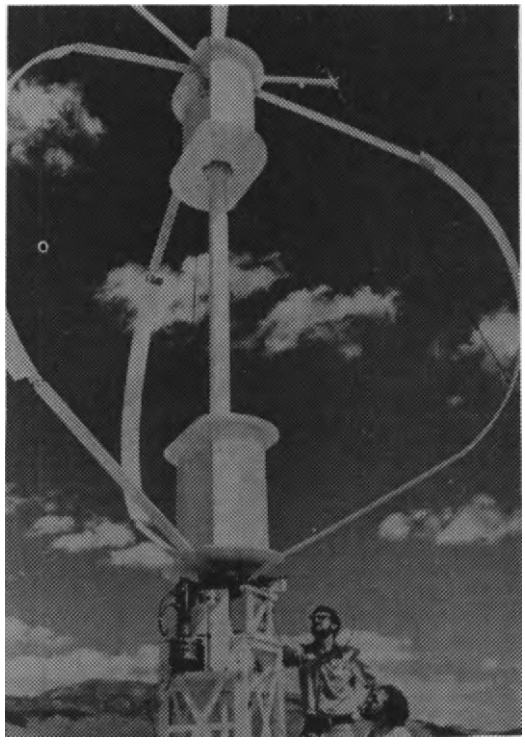


Figure 7.36(e) Darrieus rotor.

Installing a windmill first requires that a good site be selected. Ideally this requires that wind records be kept for long periods beforehand. The variability of the wind is often overlooked: a site which always seems windy when you are there may have periods of very little wind at all. The average wind velocity will always be much less than the peak gusts. If continuous power is needed then wind systems are not likely to be much use. A further complication arises because the wind speed increases with height. Thus wind machines need to be as high off the ground as possible.

7.12.4 Solar energy

Solar energy is, in the end, the source of all our power. Coal and oil come from solar energy converted to organic materials around 10^9 years ago. Although the energy bathing our planet every second is immense, by the time it reaches the surface of the earth the

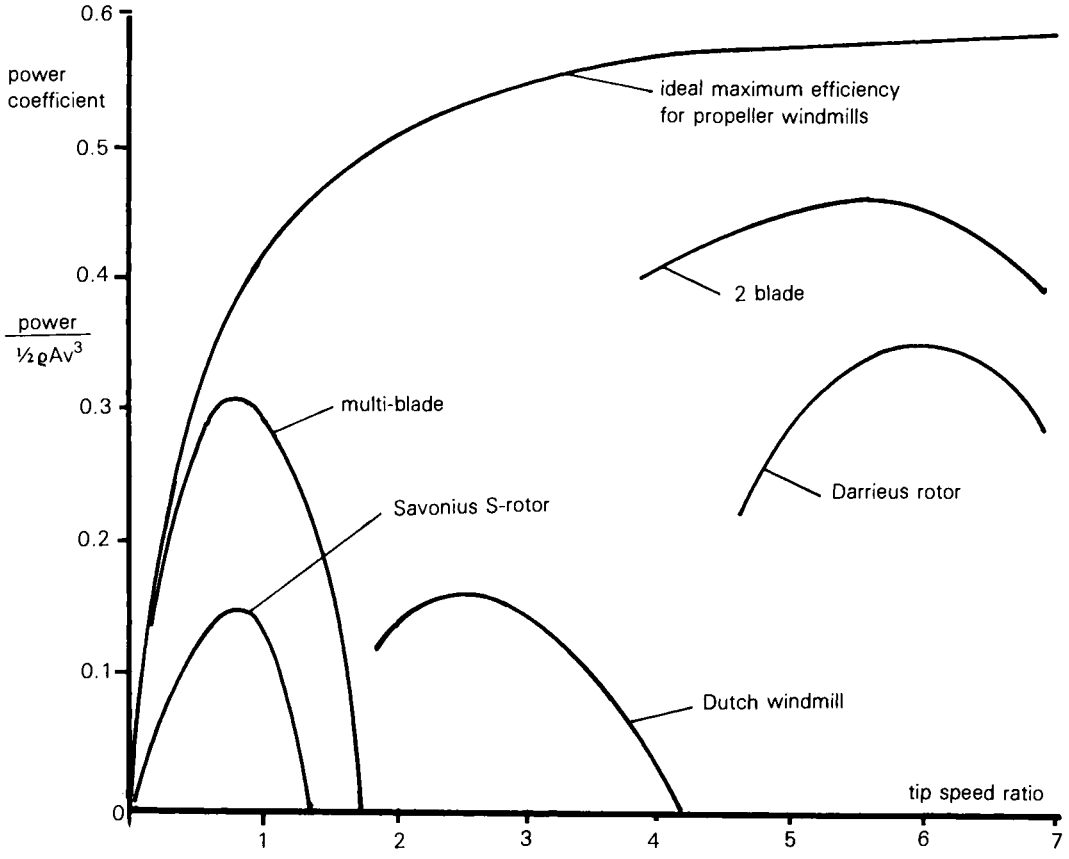


Figure 7.37 Efficiencies of wind machines.

maximum power intensity is no more than about one kW per square metre, and this only in clear unpolluted skies in warm countries. It still works out at 20 barrels of oil per hectare! Solar energy can be converted to electricity through solar cells and other devices, but the efficiency of conversion is not more than 20%. Thus large arrays of panels are required to generate useful quantities of power. Alternatively the energy can be converted to heat and used to generate power through turbines. This process is also inefficient. If heat is what is required then solar energy can be used to produce hot water. This process has an efficiency of as high as 60%, and can be a much more attractive proposition. Solar water heaters can be of a relatively simple design, involving a plate to absorb heat, and a series of pipes to pass the water across the plate (*Figure 7.38*). Such a collector will heat water up to 60°C, but becomes less effective at higher temperatures.

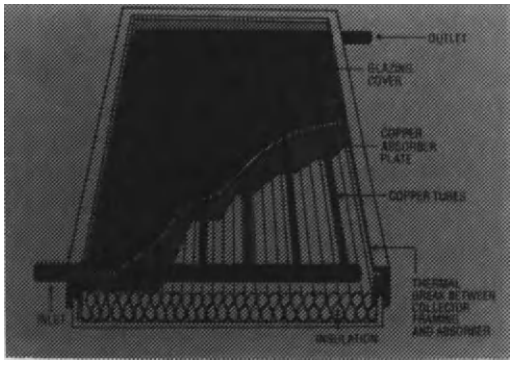


Figure 7.38(a) Schematic diagram of flat plate solar water heater (source unknown).

Solar energy can also be used for specific applications. Solar panels can be used to keep batteries charged in remote areas. This means that electric fences can be set up in remote areas, and they will operate for long periods without the need for regular maintenance visits to change batteries. Solar panels are used around the world to power remote

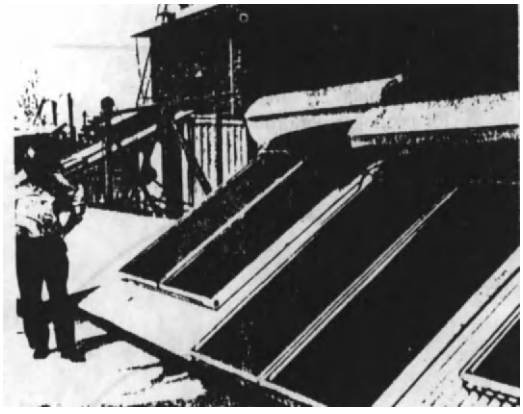


Figure 7.38(b) Flat plate solar water heaters. A commercial heater with the storage cylinder at the head.

weather stations and navigational aids, not to mention their use in space craft. A solar powered aircraft has also been flown successfully.

hopelessly inefficient, which does not improve the situation. In theory a piece of dry wood weighing 1 kg (about $450 \times 100 \times 50$ mm) will produce enough heat to boil 60 litres of water, the equivalent of a one kW heater running for five hours!

Wood burns in two steps. The first results from heating. The wood breaks down into a mixture of gases, volatile liquids, and a solid charcoal residue. Of these 80% is gaseous. This will only burn easily at temperatures of 600°C or higher. In an ordinary fire these gases are cooled almost as soon as they are given off by contact with cool air drawn in above the wood and the cool sides of the burner. They therefore do not burn, and end up as smoke, soot and creosote deposits in chimneys. These deposits account for 80 to 90% of the energy available in the wood! The main secret to efficient combustion is simply to keep the temperature of the gases emitted

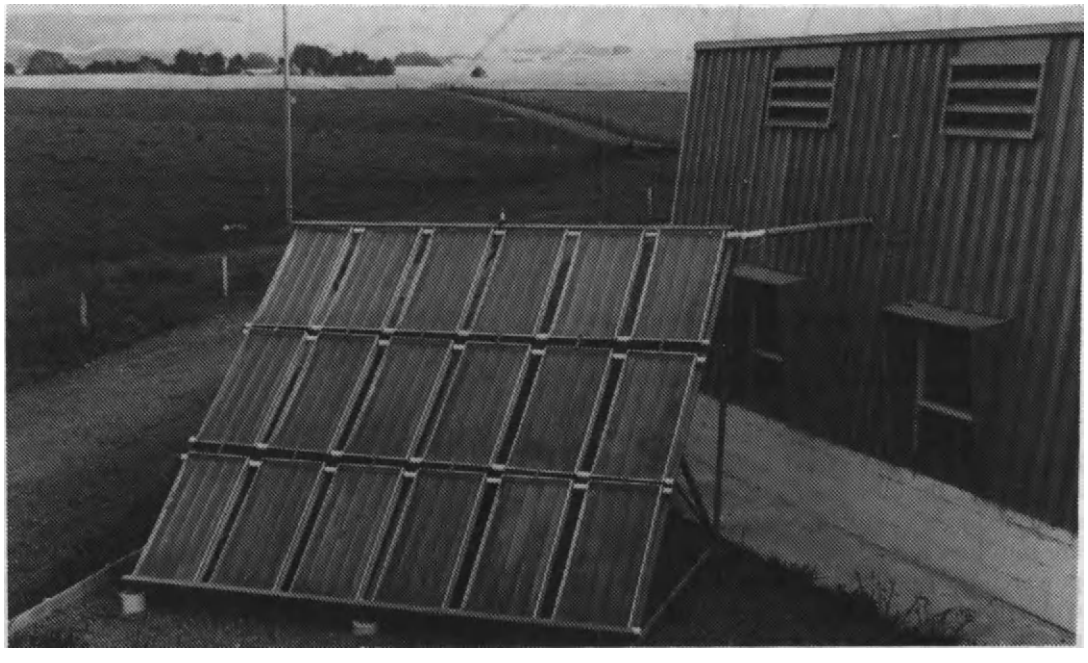


Figure 7.38(c) A solar water heater for a farm dairy. These panels pre-heat 720 litres of water per day for cleaning purposes.

7.12.5 Wood

Wood has always been used as a source of fuel. Unfortunately in many countries the rate of use of the resource is exceeding the rate at which it is being produced, with tragic consequences to local and global agriculture and climate. Most woodburning systems are

as high as possible, by controlling the air allowed into the combustion chamber, and by insulating the burning area. Thus burners must be fully enclosed, and the air inlets controlled. The exhaust gases can be deflected around steel baffles over the grate so that they stay as long as possible in the hot area. Relatively simple designs will increase

the power output ten fold (that is from 6% for an open fire to 60%). The exhaust gases are cleaner and heat exchangers can be used to extract heat without rapid sooting up.

The advantages of wood burners are that the fuel can be readily grown on the farm, and it is renewable on a short timescale. There need be no distribution problems, wood is cheap and safe to store, high temperatures are easily obtained, and costs are quite small. Disadvantages include the inconvenience, pollution and dirt levels of conventional burners, and the additional labour inputs which are needed.

The main uses for wood burners are obviously to heat water or for heating buildings. The CO_2 can be useful in enriching the environment in a greenhouse. Around the world there are a few motor vehicles which operate on wood. The wood is made to give off the volatile gases in a heated chamber, and then the gases are allowed to enter the engine where they are burnt in the normal way. The method works, but few people are prepared to wait the extra half an hour while the wood gets going. The performance is also less than perfect!

7.12.6 Other sources of energy

Other alternative sources of energy include using crop residues as a source of energy. Straw is used as a major heat source for buildings in Denmark, Sweden, and other European countries. Where stock are housed the possibility of recovering some of the heat from the exhaust air from a livestock building is a possibility.

To sum up alternative energy sources may well be available on the farm. However there are always drawbacks which need to be considered. A sound study of the resource always helps in decision making.

7.13 ENERGY CONSERVATION

It is very appropriate to discuss the ideas of energy conservation immediately after the section on alternative energy sources, because in many respects conservation is as effective as an alternative source of power. Saving energy is usually straightforward common sense.

In the area of cultivation considerable savings in fuel can be achieved by operating tractors sensibly. During heavy cultivation operations the implement size should be selected to match the tractor power, so that the engine is always operating at just below the rated engine speed. If light draught operations are in progress then the highest possible gear should be selected to keep the engine in the medium speed range. If the tractor hydraulics are in use then they should be set correctly. The tractor should not be allowed to idle for more than around 20 seconds. It uses less fuel to restart the tractor. A tractor is designed as a machine for cultivating and not as a runabout. It should therefore not be used for simple light transport jobs. Motor bikes, cars or even your feet save fuel. Regular maintenance, especially of air cleaners, injectors, and tyre pressures is required. Checks to ensure that the exhaust is not blocked, the brakes are not binding, and there are no fuel leaks, will help to prevent excessive fuel wastage. During cultivation operations the tractor should be set to produce the right amount of wheel-slip. As a guide, this is around 8 to 16% for a two wheel drive, and 6 to 12% for a four wheel drive, with the higher values needed in softer soils. Ballasting, in the form of weights or water filled rear tyres, increases the traction and can improve the efficiency of operation. However, unnecessary ballast just wastes fuel. The tyre pressures should be set correctly. On soft soils lower tyre pressures (eg, 80 kPa) result in greater fuel economy, whereas this is not advisable on hard surfaces. For roadwork 140 kPa is more economic. A compromise is often adopted.

During seed bed preparation, farmers often waste time and fuel by making unnecessary cultivation passes. If the soil is cultivated when it is in the correct moisture condition the number of cultivation passes will be reduced. The number of passes can also be reduced if soil compaction is minimised during the season, by attention to tyre pressures and soil condition during other operations.

Some farmers also plough too deeply. Many cereal crops are unaffected by the depth of cultivation, so providing there are no wheel ruts, drainage, or trash burial problems, it is unnecessary to cultivate below the sowing depth. Halving the ploughing depth can reduce the draught by a factor of three. This saves on the power requirements and hence

fuel consumption dramatically. Direct drilling is one method which uses chemical weed control instead of burial, and is therefore a minimum cultivation technique.

Energy savings can be made by the right choice of an irrigation system. Centre pivot, big gun, and travelling irrigator systems operate at high pressures, and consume more power than lower pressure systems such as trickle irrigators, microjets and simple low pressure spray line systems. Again, maintenance can save fuel and improve the performance of any irrigation system.

In the greenhouse, a major energy use is in heating. These costs can be reduced substantially by using thermal screens at night in winter (a cloth which can be dragged over the top of the crop on wire guides). In cold climates (such as the UK) the energy saving can be up to 60%. Smaller percentages will be achieved in warmer regions. Savings can also be made by using double skin claddings or even double glazing.

Other savings can often be made to heating costs in both greenhouses and animal housing by ensuring that thermostats are set correctly, and checking to ensure that doors shut properly (and are!). If the heaters and fans in a building are badly sized or incorrectly controlled, it is quite possible for heaters to be on at the same time as the fans switch on to cool the building down!

In the milking shed hot water for cleaning the dairy equipment is usually heated by electricity. In practice many farmers heat too much water to too high a temperature, without considering the cost. Over a year this can add up to a significant waste of energy. Hot water cylinders are sometimes badly insulated (especially if the insulation gets wet, since then its effectiveness is drastically reduced), or located in drafty positions. Hot water valves can leak. Even a small trickle adds up to a substantial loss over 24 hours. Fortunately it is relatively easy to check the power consumption of a water heater, since most are connected directly to electricity meters. A simple calculation of the energy required compared with that actually used will indicate wastage, as discussed earlier. The use of heat recovery systems on refrigeration condensers has also been explored and this is economical in some situations.

If cold water is plentiful, then plate heat exchangers are usually worth installing to cool milk from the cow by the first 18°, rather than requiring the refrigeration system to cool the milk all the way from 33°C down to 4°C.

Farm water supplies can also use unnecessary amounts of power. The smaller the pipe size the greater the head loss, and the more power that is required for a given flow rate. This needs to be considered when the system is being designed.

As stated at the beginning of this section, energy conservation is usually just common sense combined with a little background understanding of the system. Often regular maintenance is all that is needed.

7.14 EXERCISES

1. Calculate the current flowing in a ten ohm light bulb powered by a three volt battery. Calculate the power output.
2. A current of 20 amps flows through a resistance of 30 ohms. What is the voltage drop across the resistance?
3. A 500,000 volt supply line has a resistance of 0.05 ohms per kilometre. Calculate the power loss in transmitting a current of 200 amps a distance of 200 km.
4. An arc welder has an effective resistance of 10 ohms. (a) What current will it require if the power input is 16 kW, and the PF has been corrected to 1.0? (b) What will the voltage need to be? (c) Suppose the welder is supplied by a cable whose resistance is 2.4 ohm per km. The cable is 700 metres long (from the power source). What voltage is actually applied to the welder, and what is the new power input? (d) What is the power lost in the cable?
5. What current will be required in each phase of a three phase motor if the power factor is 0.75, the line voltage is 400 V, the motor has an efficiency of 75%, and the power ouput required is 48 kW?
6. Find out about a piece of electrical equipment installed in a building known to you. Briefly explain what it does and how it does it. Obtain or estimate its electrical characteristics (usually written on a plate on the device), and estimate

the cost of using it for 12 months at 25 cents per unit (you will need to make an intelligent estimate of how much time the equipment is used for during the year).

7. If the cost of electricity is 30 c/kW h, calculate the annual cost of running the following: a three kW fan operating for five minutes every quarter of an hour during the day over a summer period of three months; a five hp vacuum milking pump running two hours per milking session on a seasonal supply farm; a three hp Vat refrigeration unit running for ten hours per day on a town supply farm; a 25 hp irrigation pump running at maximum rated power for 600 hours per year; twelve 100 W fluorescent light tubes running for two hours per day on a town supply farm.
8. If the true power input to a star connected three phase motor is measured as being 35 kW, the phase voltage is 230 volts and the current is 65 amps per phase, what is the PF and the angle of lag Ø?
9. A six cylinder four stroke engine with a CR of nine has a bore of 100 mm and a stroke of 88 mm. Calculate (a) The clearance volume, (b) the brake power if $P_b = 8$ bar at 3000 rpm, (c) the fuel consumption per hour if the BTE = 22% and the fuel energy value is 46 MJ/kg, (d) the sfc.
10. Calculate the heat loss through a three mm sheet of glass with a surface area of 1.5 m^2 if the temperature difference is 25°C.
11. Estimate how hot a black surface would get if left in the sun on an insulated surface if the radiation was 950 W/m^2, and the air speed was five m/s. Assume the air temperature is 20 C. Hint: solve the equation by intelligent trial and error.
12. How much power could be extracted from a water source if the flow rate was 5 m^3/sec and the available head was 30 m (select a suitable system, and make reasonable estimates of the efficiencies of the systems).

7.15 AIMS OF THIS CHAPTER

When you have studied this chapter, you should be able to achieve the following tasks.

1. Determine the MA and VR of simple machines.
2. Calculate the brake power from Prony brake test data.
3. State and apply the power law, and use it to calculate the energy required and the cost of electricity for operating equipment.
4. Explain what an alternating voltage supply is like, and why the RMS voltage and current models are useful.
5. Describe briefly why a power factor can arise, and explain the practical implications of a low power factor. Solve simple problems involving inductive loads.
6. Outline some sources of electrical power, and describe briefly the generation and distribution system. Explain the terms three phase, single phase, and ripple controlled supplies.
7. Describe the structure and operation of three phase and single phase motors, including overload avoidance, starting methods, star and delta configuration, and motor selection.
8. Discuss safety factors and first aid procedures involving electrical systems.
9. Describe the operation and main components of spark ignition and compression ignition internal combustion engines, including ignition systems, and fuel properties.
10. Describe ideal and real indicator diagrams for engines and calculate the power output from an engine using brake mean indicated pressure. Discuss engine efficiency and calculate it from test data.
11. Explain the principle of operation of a refrigerator, and explain and discuss the terms COP, heat pump, and vacuum cooling.
12. Discuss the processes of heat transfer, and calculate heat flows for a variety of situations. Discuss the design of heat exchangers.
13. Outline the main features of fans.
14. Describe alternative sources of power which may be available in the rural sector, including energy conservation.

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Buildings: Materials, Designs and Construction

Chapter 8

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8.1 INTRODUCTION

In horticulture and agriculture, buildings are mainly built to serve a particular practical function. They represent a major part of the improved value of the property, and they are essential for the smooth functioning of the business. It is therefore important that they are soundly built, using the right materials, to the right design, and in the right place. Unfortunately a large number of rural structures are unsatisfactory for one reason or another. The most obvious failures are those involving structural collapse (*Figure 8.1*). Such failures may occur through poor design or workmanship, or because the structural loadings were underestimated. Mechanical failure invariably occurs at the weakest point, so it is essential to consider a structure in its entirety, and this means studying everything including the foundations and soil type, the materials for construction, and the fixing devices, as well as the design. There are other types of failure other than mechanical collapse. A structure which fails to do the job for which it is designed is a different kind of failure, and one which can have long term consequences. For example, if a greenhouse is so designed that the temperature inside is too hot for the plants on a sunny day, then the grower may lose the crop. Buildings in the wrong place may be

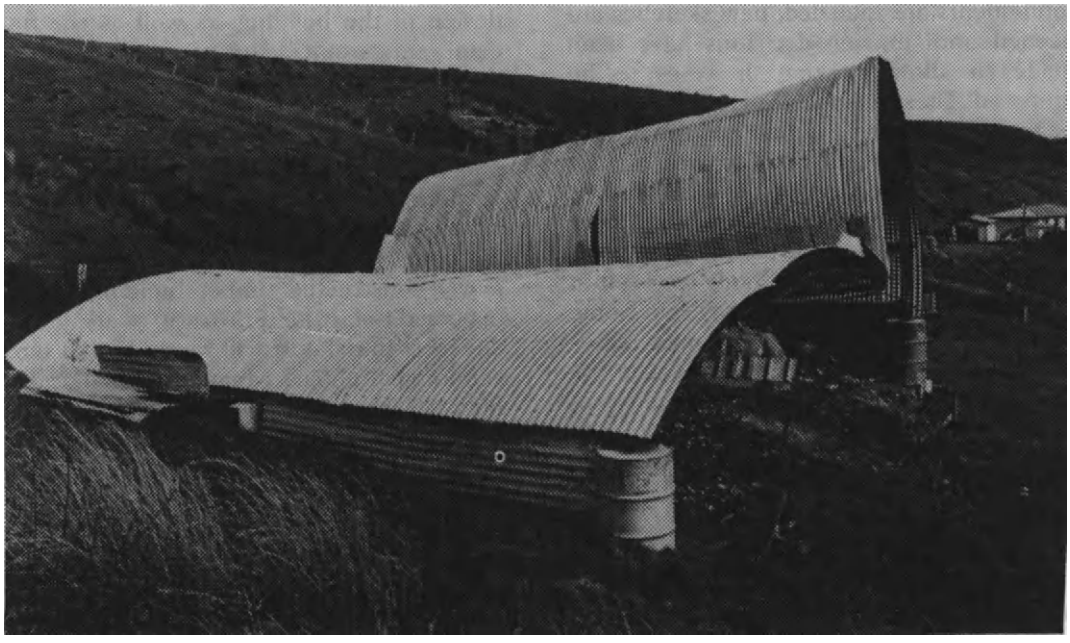


Figure 8.1 Collapsed circular barn.

uneconomic to use and will end up as expensive junk stores. Before we consider the mechanical design of a structure, we will therefore first discuss the more general aspects of putting up a structure or building. This is followed by a discussion on materials, and then the requirements of specialised buildings such as greenhouses and stock housing are discussed.

8.1.1 Siting

The siting of a building depends upon a number of factors. Important factors include the purpose of the building, and the requirements for services such as electrical power, water, gas, and drainage. It may be necessary to site the building close to others so that these services can be extended to it. It is also important to consider whether the building will need to be accessible in all weathers by vehicles other than farm tractors. For example, a milking shed must be reachable by the milk collection tanker.

The site conditions should also be considered. The site should allow for satisfactory drainage and the soil strength should be adequate. If the soil is not suitable, the cost of providing a good foundation could be very high. For example, peat soils are not good for building purposes. This will be considered in some detail below. There may be other natural problems with the site, such as the danger of flooding, or land movement. Security could also be a problem. Remote buildings could be subject to animal or human damage in some countries.

The building may need to service a particular part of the farm, or it may be affected by the weather. For example, greenhouses must be sited to receive the winter sun without shading, but they should also be out of the prevailing wind. A milking shed should be sited so that the prevailing winds and rain do not make life uncomfortable for the milker or the cows waiting to be milked.

Finally, it is worth considering whether the building could be used for other purposes without major expenditure, particularly if the type of farming may change.

A careful consideration of these points will help in the selection of the most appropriate site. As with most choices the site will often be the one which offers the best compromise. Having chosen the site we can begin the process of designing the building.

8.1.2 Design

The process of designing a building is usually one which requires a considerable amount of discussion and planning. Initially rough sketch layouts are a good idea as a basis for discussion. As the design evolves and new

refinements are included, new sketches are needed until enough decisions have been made to allow working drawings to be prepared. These are the drawings which will be used for obtaining quotations and for the construction phase. It is much better and far less costly to make changes and modifications before construction begins, so the more thought that goes into the planning stage the better. Careful planning is likely to result in a better building which will pay handsome dividends during its lifetime. In many cases farm buildings and greenhouses can be supplied in standard configurations and sizes at a much reduced cost. The initial details to be established are:

a. Orientation

If the building is intended for uses where one side is likely to remain open to the elements (eg, for servicing machinery or for milking), it is an advantage to ensure that the open side faces the sun. The closed sides should be sited to face the prevailing wind. If the building cannot be orientated to face the sun, then the working area should be designed to be draught free, and a high standard of artificial lighting should be allowed for. In hot countries it may be better to ensure that there is good ventilation, and that working areas are shaded.

If the site is exposed to wind or snow (or earthquake), then particular care is needed to ensure that the building can withstand the worst probable loads it is likely to endure in its lifetime. Design loads should include an extra factor, which will depend on meteorological and other data. Such details are given in local building codes (eg, BRANZ, 1976, 1978, or NZS 4203).

b. Size and layout

For any particular building the ultimate size and layout will be a compromise between a variety of different alternatives. It is advisable to consider as many alternatives as possible, providing that one does not become too confused with detail. In many cases there are standard sizes for particular features, and there is no point in deviating from these unless there is a good reason.

c. Choice of materials

The choice of materials may affect the overall design of the building, as well as the fine details. Important factors to consider are cost, durability, serviceability, and how well the building will blend in with its environment. Galvanised iron (strictly galvanised steel) may be a cheap cladding material, but it may be quite unacceptable if it spoils the view! When comparing the costs of different materials, it is also worth remembering that a well-constructed timber building can be expected to last for at least 50 years, and so cheapest initial cost will rarely be the most economical choice when maintenance and lifetimes are considered. On the other hand, on a limited budget, it may be more sensible to build a large building using less costly materials, rather than putting up an inadequately sized building with the best materials available.

8.1.3 Legal requirements

In most countries there are strict legal regulations which govern the construction of buildings. In New Zealand a building permit must be obtained where the structure is: any permanent structure enclosed or partly enclosed with or without a roof, any retaining wall more than 1.2 metres high or within 1.2 metres of a boundary, any wall more than 2 metres high, tanks with a capacity of 20,000 litres or more, or grandstands.

The permit must be obtained before construction starts, and the local authority has the power to demand the demolition of any unauthorised building. Details required on the permit include full plans, details of foundations, a legal description of the land, the location of the building relative to the boundaries, the estimated value of the building, and specific calculations where required (eg, buildings more than ten metres high, including masts and aerials). The local authority may wish to inspect the work at certain key stages of construction. In particular inspections immediately prior to pouring concrete, after closing the building in, and on completion are common. Copies of all these plans and calculations must be held by the local authority. These files are sometimes available to the public, and they can be a useful source of designs for similar buildings, and the authorities are often very helpful in providing information and advice. In some cases (eg, milking sheds), special provisions must be met. Waste disposal

systems must meet with Regional Water Board requirements, while milking sheds must be approved by the Ministry of Agriculture.

Having discussed the general details of planning a building, we will now consider the engineering aspects in more detail.

8.2 SOILS AND FOUNDATIONS

Soil properties are a vital component in agriculture and horticulture. The soil type affects which farming systems will be successful, and which will not. Similarly the soil's engineering properties determine what can and cannot be built and how. Ultimately, all structures rest on the soil and it is important to know the strength and properties of the soil before construction starts. In this case, important factors are the loads the soil will support, its stability when used to form embankments or to fill in low spots, and the extent to which water can move through it. Soil is also used in its own right as a building material for dams and embankments, and in some countries for building and for insulation (is ice the soil of the eskimo?). In some cases it will be relatively simple to establish the suitability of a particular soil by simple observation. In other cases a more detailed study involving some of the tests outlined below will be needed.

One important difference between the farmer's interest and the engineer's is that the latter is normally not interested in the topsoil. In practice topsoil is unable to support loads, flows when wet, and cannot be compacted properly. It is usually removed from the site before the serious work of creating a good foundation is started. In some cases the topsoil may be too deep to be removed, and this gives the engineer a problem. Peat soils are a good example of this. On the other hand underlying layers of clay and gravel are more likely to be desirable building materials.

8.2.1 Principles of soil mechanics

The study of soil mechanics has been developed since the eighteenth century, most notably by a scientist named Terzaghi. The development of multi-storey buildings gave a strong impetus to this study. Soil is a very complex material, with many forms and types. Models of soil behaviour are necessarily approximate, and do not always apply to all soil types. The choice of the best model for a particular soil often depends on local knowledge and experience with that soil type. Classification of a particular soil often helps in deciding which models are best to use.

We begin with some ideas about what makes up a soil. Soil is a mixture of three things, namely solid particles, water and air, mixed in varying proportions. Obviously the solid component determines the essential nature of the soil, since the way in which the particles arrange themselves will determine the space available for the air and water. The solid component includes organic matter, which consists of partly decomposed vegetable matter and fully decomposed matter (humus) which is vital for the farmer, and inorganic matter. Initially we will consider the inorganic matter, since, with the exception of peat soils, this is the part which forms the bulk of most soil types.

8.2.2 Soil particles

Soil particles come in all shapes and sizes, from immense boulders such as Ayers' Rock in central Australia, to the finest clay particle which can only be seen with a good microscope. The shape can vary from a round pebble to a flat flake of mica. In order to say something useful about this range of materials it is necessary to group soil particles in some sensible way, and one of the most obvious methods is to categorise particles in terms of their size. To avoid getting into difficulty with the meaning of the term size we simply resort to a test which differentiates between different sizes, and the most obvious and easiest is to put the soil through a sieve consisting of a square steel mesh. Those particles which pass through the sieve can be called one thing and those which do not can have another label. In this way we have arrived at the terms gravel, sand, silt, and clay, as listed in *Table 8.1*.

The particle sizes listed in the table are based on a British classification of the terms. The range of particles in any particular soil can be determined by sieving the soil and plotting the cumulative fraction of the soil held on each sieve, as shown in *Figure 8.2a*. This curve is called the *Grading Curve*. In practice the sieves used do not necessarily

Table 8.1 Particle size classification

Particle size range mm	Classification
less than 0.002	Clay
0.002 – 0.006	Fine silt
0.006 – 0.02	Medium silt
0.02 – 0.06	Coarse silt
0.06 – 0.20	Fine sand
0.20 – 0.60	Medium sand
0.60 – 2.0	Coarse sand
2.0 – 6.0	Fine gravel
6.0 – 20	Medium gravel
20 – 60	Coarse gravel
60 – 200	Cobbles (stone)
more than 200	Boulders (stone)

particle size alone is an inadequate description of soil properties, since the behaviour of the fine particles can have a much greater effect on the mechanical properties of the soil than larger particles do. It is therefore necessary to consider their properties separately, as is discussed below.

Soil particles are formed by a variety of processes. Some are formed by erosion of the bedrock, while others are deposited by water and wind. Others are formed as a result of volcanic activity. The mineral composition varies widely, yet in engineering terms there are some similarities between soils with similar particle size distributions. For example clay soils tend to be formed from complex minerals and are in the form of thin sheets or platelets. In general the platelets consist of alternate layers consisting of magnesium,

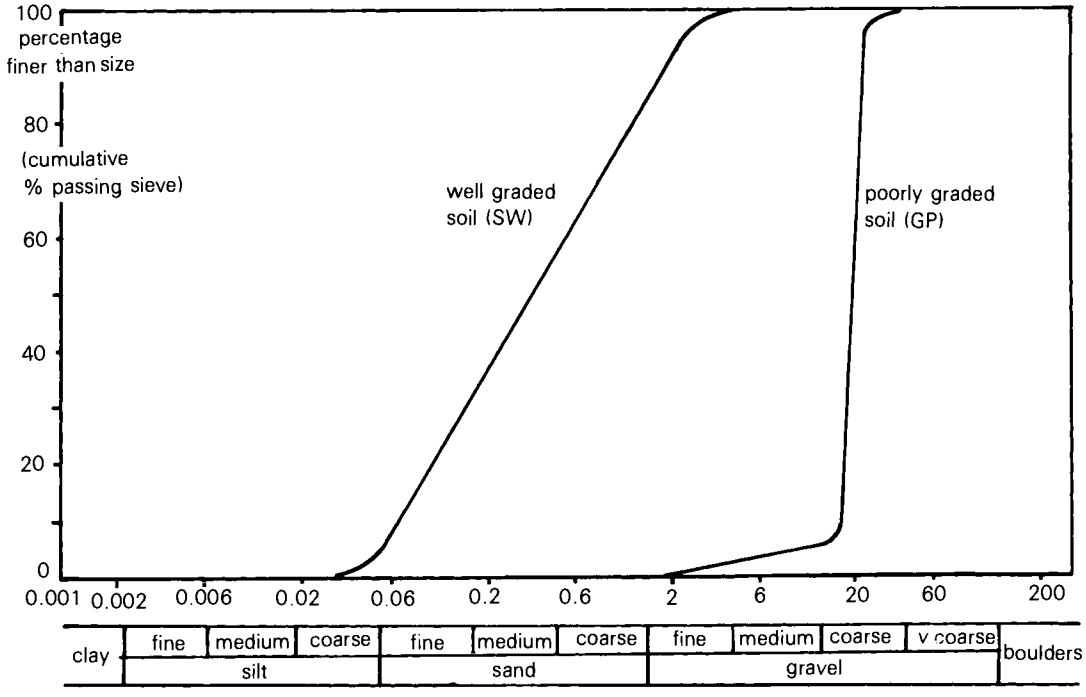


Figure 8.2(a) Grading curves for soils.

correspond to the sizes given. The standard set of sieves used in practice have meshes of 6, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075 mm hole size. Particle size analysis is important in the selection of suitable materials for filter designs for dams and drains. It is also used in the selection of aggregate for concrete mixing, and in selecting suitable material for chips for road surfaces. Unfortunately the distribution of soil

aluminium and silicon compounds. Coarser grained soils are composed of rock fragments of varying shapes and sizes, predominantly formed from quartz.

8.2.3 Relationships between soil components

The proportions of solid, air and water can be described on a volume or mass basis. They are described by a number of terms which all

have their use for one reason or another. On a volume basis (and with reference to *Figure 8.2b*), if V_v is the volume of air and water (the total void space), and V_s is the volume of the solids, then the *Void Ratio* e is defined as:

$$e = \frac{V_v}{V_s} \qquad \textbf{Equation 8.1}$$

For single grained soils e is around 0.5, while for organic soils it can be as high as four or five.

The *Porosity* n is defined as:

$$n = \frac{V_v}{V} \qquad \textbf{Equation 8.2}$$

where V is the total volume. The porosity is always less than one, of course.

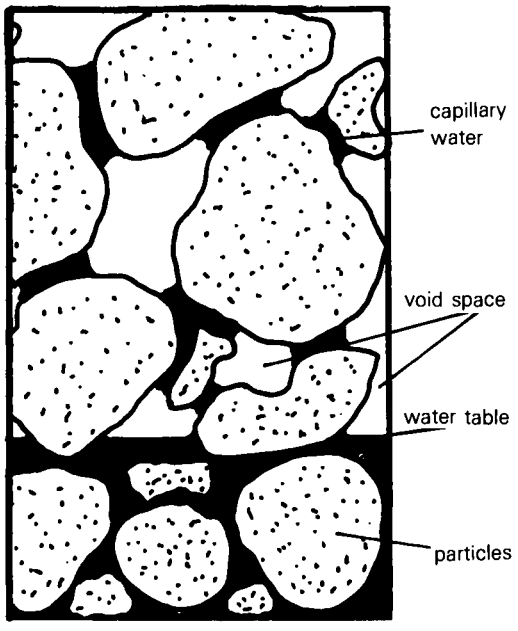


Figure 8.2(b) Soil components and structure.

The total void space is made up of the volumes occupied by the water and the air. If there is so much water in the soil that there is no air left, then the soil is said to be saturated. In practice this is the state of most soils below a certain level. This level is known as the Water Table (*Figure 8.2b*). Its depth at any time varies, depending on the amount of rain and the drainage system in the area. Rivers, lakes, floods and open drains occur where and when the water table is above ground level. Few plants will grow under saturated conditions, although there are some important exceptions such as rice.

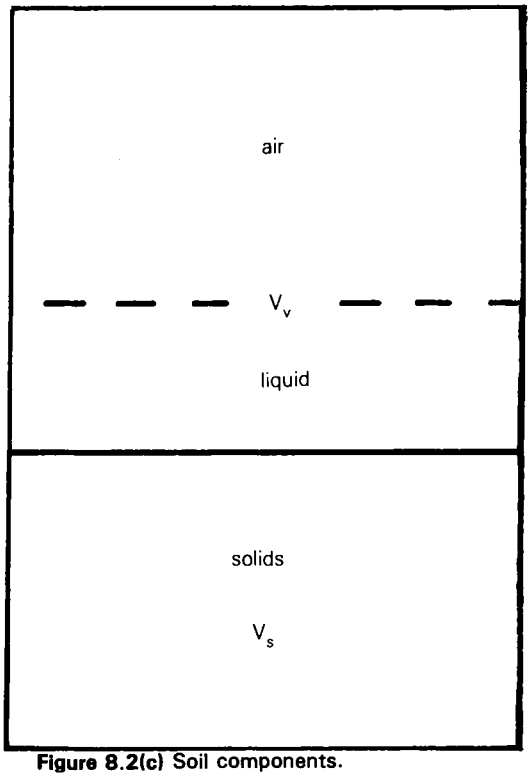


Figure 8.2(c) Soil components.

Water is always present in soil. However the extent to which it is held in the soil varies dramatically, so that three types can be identified. Gravitational water is water which is not retained by the soil at all. After rainfall, it percolates down through the soil voids, and is only retained below the water table where the soil is saturated.

If the soil is allowed to drain so that all the gravitational water is lost, water still remains. Capillary water is retained in the soil by capillary action (ie, it is held between the soil grains by surface tension, as in *Figure 8.2b*). This water is available to plants, and can be removed in the laboratory by air drying. Fine grained soils lift water up from the water table by capillary action, so that plants with roots above the water table may still receive a plentiful supply of water.

Finally a small quantity of water is held in the soil very strongly. This is called Hygroscopic water, and it is held as a thin film adsorbed onto the soil grain surfaces by molecular attraction. It is not available to plants, and can only be removed by oven-drying the soil.

When considering the ratio of solid and water, it is preferable to consider the mass ratios, since these are easier to measure. The

relationships between the relative proportions of solid and water are defined as follows:

The Water Content w is given by:

$$w = \frac{M_w}{M_s} \qquad \textbf{Equation 8.3}$$

where M_s is the dry mass of the solids (not the total soil mass), and M_w is the mass of the water. These can be measured by oven drying for 24 hours at 105 to 110°C.

Other parameters used are the *Bulk Density* (P) and *Dry Density* (Pd) given by

$$P = \frac{M}{V} \text{ and } Pd = \frac{M_s}{V}$$

Equation 8.4

where M is the total mass of the wet soil, and V is the total volume.

8.2.4 Support

Obviously, the soil must be able to support the weight of the new building. If it is not strong enough then the soil could fail, in which case there is considerable bulk soil movement and the building may collapse. The soil must also support the building without excessive settlement occuring. Settlement arises because the soil particles pack closer together as a result of the extra load placed upon them. This is especially likely in soils which have been disturbed, such as areas of fill. It is important to ensure that the soil is therefore compacted adequately. If the soil settles unevenly, then differential settlement will occur. This arises if the degree of compaction differs over the site, and will cause cracking in concrete slabs, while doors and windows will jam, and internal linings may open up. In bad cases the building may develop a noticeable lean (*Figure 8.3*).

8.2.5 Stability

The stability of soils refers to the ability of the soil to stay firm and not move when it is on a slope, or when a cutting or embankment is built. As you travel through hilly country the roadside will probably include several cuttings where the hill has been cut through to make the road flatter. Some of these



Figure 8.3 Soil settlement effects (Amsterdam).

cuttings may be very steep, while others may slope back continuously on a relatively gentle incline. Yet others may be benched, with narrow horizontal strips constructed between the near vertical drops. On very difficult spots the cutting may even be covered with wire netting. Each of these systems is designed so that the cutting is stable. The differences arise because the soil stability differs markedly from one soil type to another. The soil properties which affect stability include cohesion, the angle of shearing resistance (also known as the angle of internal friction, and related to the angle of repose), and the amount of water present in the soil. The last factor implies that drainage is important to ensure that some cuttings remain stable. We will see this by considering these soil properties.

8.2.6 Soil friction

When two surfaces slide over each other friction forces oppose the movement, and will prevent sliding from occurring up to a limiting sideways force. In the same way soil particles resist sliding. The maximum friction force is a function of the force or pressure at right angles to the direction of sliding, just as is the case in normal sliding. In soils it is measured using a shear box (*Figure 8.4a*). It consists of two rectangular metal boxes which form a frame around the soil sample. A slowly increasing force F is applied to the upper box as shown, until the soil shears. The force F is noted and the experiment repeated with a series of weights placed on top to increase the normal force R at right angles to the shear surface. In this way a graph can be plotted of F against R which looks like *Figure 8.4b* for granular soils. The slope of the curve is called the angle of shearing resistance Ø, so that:

$$F = R \tan \emptyset \qquad \textbf{Equation 8.5}$$

This can be compared with $F = \mu R$ in the normal friction case (*Equation 3.29*), where μ is the coefficient of friction which is equal to the tangent of the angle of a slope when a block begins to slide under its own weight.

For loose granular materials such as sand or gravel, Ø equals the angle of repose (ie, the angle a pile of the soil will make, which is around 25° to 35° for loose sands and gravels). As the material is compacted the value of Ø increases.

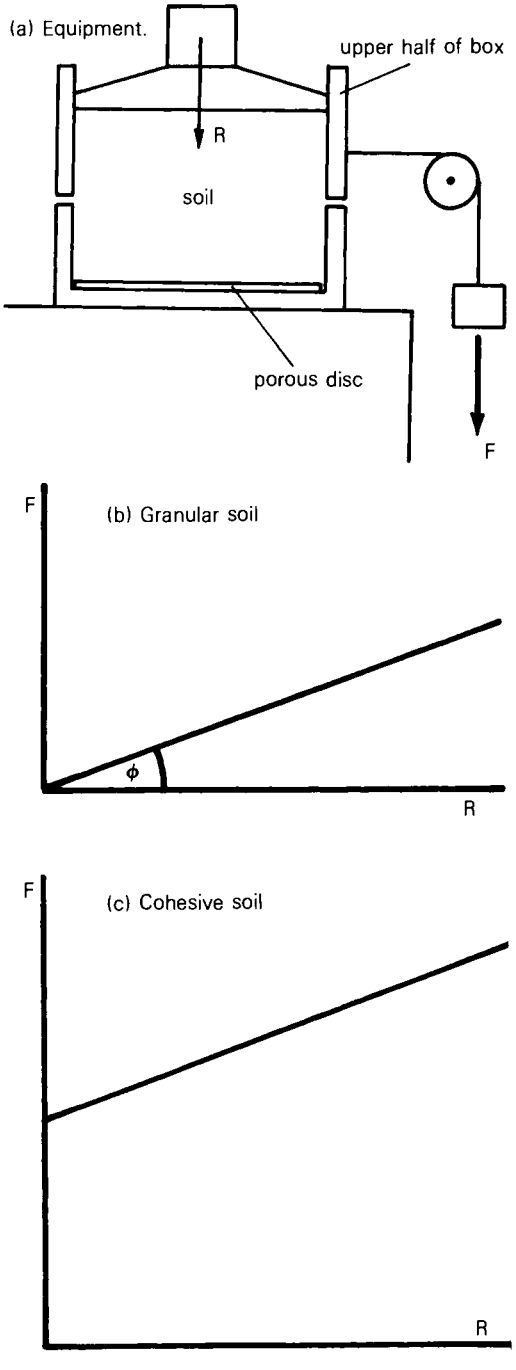


Figure 8.4 Soil shear box and results.

8.2.7 Pressure in soils

The pressure in a dry soil depends on the load the soil is under. This is produced by the weight of the soil on top, together with the

load arising from any buildings or other structures. In order to sustain the load, their must be a force between contacting grains of soil. The pressure on the soil will be the net force divided by the total area, even though the localised stress on individual grains may be higher. The resistance to deformation will depend upon this pressure.

If water is present between the grains, then some of the force can be taken by the water as well. Thus the water can be under pressure, and this pressure is called the *Pore Pressure*. As the water has very little shear strength, it does not stop any deformation of the soil. Thus, from the point of view of soil deformation and strength, the pore pressure has no effect. The effective stress on the soil which determines the resistance to movement will therefore be:

Effective stress
= total applied stress − pore pressure
Equation 8.6

This is really only an approximation to the real situation. However this model works quite well to soils which are more than 80% saturated. As the pore pressure does not contribute to the shear strength of the soil it is sometimes called the neutral pressure.

Below the water table of a soil the pore pressure is the same as it would be if it were under hydrostatic pressure due to water alone. Thus the pore pressure will increase with depth, starting from zero at the water table, just as if it was free standing water. Above the water table there will be considerable quantities of water, held in place by soil capillary action. The water may completely fill the voids (capillary saturation), or there may be partial saturation where the water in the voids is continuous, or it may exist in separate pockets. The capillary forces which attract and hold the water in place also generate attraction forces between the soil grains. This attraction is called the soil suction, and it is a pressure which is less than atmospheric pressure. When the capillary water is in equilibrium, the suction exerted by the water between particles is balanced by the pressure between the particles themselves. The size of the suction depends on the size of the void spaces, and is greatest if the voids are very small. Thus fine grained soils have the greatest *Soil Suction*. As the water dries out the soil suction increases, and in very fine grained soils the soil suction can be very high indeed (as much as 15 bars). The water holding capacity of soils has been discussed in Chapter 5.

8.2.8 Cohesion and the effect of water content

Many soils exhibit shear strength which is independent of the normal pressure. This is called cohesion, and is due to the bonding between adsorbed ions at points of grain contact. Thus the cohesion is the shear strength of the soil independent of normal pressure. A pure clay soil will exhibit cohesion with scarcely any internal shear resistance, ie, the opposite behaviour to loose granular soils. The results from a shear box test on a cohesive soil are shown in *Figure 8.4c*. On the other hand, sand, gravel, and some silts behave as in *Figure 8.4b*, and they are called cohesionless soils. Water content affects the shear strength of a cohesive soil significantly. This is because the soil suction in unsaturated soils increases the forces between grains significantly, while the pore pressure can absorb some of the soil pressure at higher water contents.

In cohesionless soils increasing the water content can increase the shear strength due to capillary action. Thus on the beach, a wet sand is often firmer to walk on than dry sand.

8.2.9 Plasticity

Cohesive soils can deform through very large amounts without rupture, and this property is known as plasticity. It is associated with clay minerals of colloidal size, and is greatly affected by the water content. In such soils, instability can result from indiscriminate work on the farm. For example, a cutting for a farmtrack may become unstable, because the angle of the side is too great, or because shrinkage cracks allow extra water to enter the bulk of the soil. This water cannot drain away easily, and so the soil beneath the cutting becomes increasingly saturated, and less stable. Eventually a very large part of the hillside will become unstable and slip, leaving a very unsightly muddy mess!

8.2.10 Drainage

Drainage may be required not only to ensure the long term stability of a building, but temporary drainage may also be needed so

that the water table can be lowered to enable construction work to take place. For example, saturated or over-wet soil cannot be compacted properly. Dewatering can be achieved by using well points. The number, depth and spacing will depend on the level of the water table, and the permeability of the soil (a measure of how easily water can move through the soil). This is defined as follows:

The *Coefficient of Permeability* K is the rate of flow per unit area of soil under a pressure head of 1 metre per metre length of flow. Thus:

$$K = \frac{Q\,L}{A\,H} \qquad \textbf{Equation 8.7}$$

where A is the area, L is the length of the flow path, H is the head (metres), and Q is the flow rate (m^3/s). Permeability is classified as in *Table 8.2*.

will cause a significant increase in the load on the wall. This can be achieved by using clean crushed "metal" or "river run" (ie, coarse sand or a fine gravel) as backfill against the wall, and installing a drain at the base itself.

On the other hand if we are building a dam, we will want the soil to be impermeable. The permeability can be reduced by compacting the soil to its maximum density, as will be discussed below.

8.2.11 Grading of soils

Grading refers to the range of soil particle sizes in a soil. A well graded soil is one which has a range of particle sizes, with equal amounts of each size. The grading curve for such soils is a straight line covering a wide range of particle sizes, while poorly graded soils have irregular curves with steep rises.

Table 8.2 Classification of permeability

Value of K (m/s)	Classification	Typical Soil Types
greater than 10^{-3}	High	Gravels, coarse sands
$10^{-3} - 10^{-5}$	Medium	Sands
$10^{-5} - 10^{-7}$	Low	Silts, fissured and weathered clays
$10^{-7} - 10^{-9}$	Very low	Fine silts, clays
less than 10^{-9}	Impermeable	Homogeneous clays

Example

Calculate the flow rate of water through an embankment 25 m^2 in area and 2 m wide if $K = 10^{-6}$ m/s, and the hydraulic head between the sides is 5 metres.

Solution:

$$Q = \frac{KAH}{L} = \frac{10^{-6} \times 25 \times 5}{2}$$

$$= 6.25 \times 10^{-5}\ m^3/s$$

$$= 3.75 \text{ litres per minute}$$

Once a structure is completed it may still be necessary sometimes to keep the water table low. For example, swimming pools and ponds may float up out of the soil if they are emptied when the surrounding soil is saturated!

In some cases we are keen to ensure that the soil is free draining. For example, it is important to drain the area at the foot of a retaining wall. This will prevent the build up of pore water pressure against the wall, which

Figure 8.2 shows examples of well and poorly graded soils. Well graded soil particles pack together so that the void space is relatively small. Well graded soils are usually stronger and more stable than poorly graded soils.

8.2.12 Soil classification

A classification system is a model of a type of soil which enables one person to describe a soil so that others know exactly which soil the person is talking about. This is particularly useful for engineers and contractors. There are various types of soil classifications. A common type is the "tri-linear" chart, of which the USA Department of Agriculture's silt, clay, and sand triangle is a good example (*Figure 8.5*). The soil scientist's classification unfortunately does not give sufficient information to be useful to an engineer, even though it is a very colourful description of the soil type, and very helpful to the farmer and planner. Many countries have now adopted the "Unified Soil Classification System",

developed in 1952 by the USA Bureau of Reclamation and the USA Corps of Engineers from the work of Professor Casagrande, of Harvard University. This classification is used around the world by engineers and others.

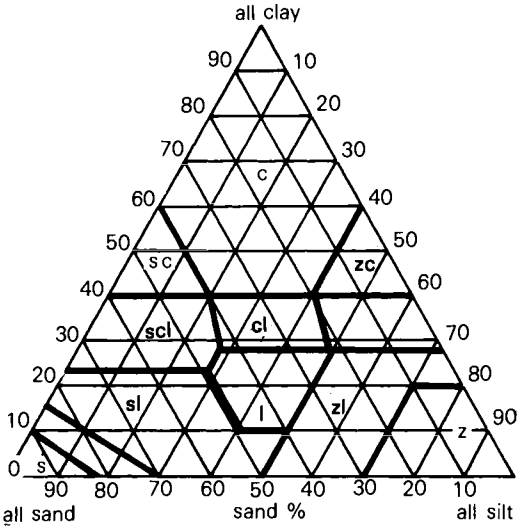


Figure 8.5 US Department of Agriculture's soil texture chart, s = sand, c = clay, z = silt, l = loam (Farr & Henderson, Longman, UK).

8.2.13 The unified soil classification system (*Tables 8.3* and *8.4*)

The system allocates a two letter symbol to the soil. The first letter describes the particle size and type, while the second details the properties of the soil, taking into account the nature of the fine particles (*Figure 8.6*). Thus a SW soil is a sandy soil which is well graded (ie, it has a wide range of grain sizes with similar amounts in all sizes, but with hardly any fine material).

The system is based on three main features of the soil. These are the size of particles, the amounts of various sizes, and the characteristics of the fine grains in the soil. Stones and rocks larger than 75 mm are automatically removed and excluded from the classification.

The classification of a soil can be made in the laboratory or in the field. The field tests are relatively simple and will often be sufficient. We will first outline the laboratory methods and then discuss field tests.

The first identification is whether or not the soil is highly organic, ie, a peat soil. This can be established quickly by inspection, since peat soils have a rich dark colour, a characteristic smell, and a stringy spongy feel. They often have a fibrous texture. Peat soils are given the classification symbol Pt.

If the soil is not a peat then it is sieved through a fine 75 μm sieve. If more than half the soil is retained on the sieve it is immediately classified as a coarse soil, and the first letter will be either G or S (gravel or sand) as indicated in *Figure 8.6*. The coarse fraction is put through a 4 mm sieve and if more than half is retained the soil is a gravel (G), while if more than half goes through it is a sand (S).

Next the fines are considered. This is the component going through the fine (75μm) sieve. If less than 5% of the soil went through this sieve the soil is defined as being "clean" (low fines). A soil described as "with fines" has more than 12% passing the fine sieve. Soils with fines content between these values are border line and given a dual symbol eg, a GC-GW soil would be a well graded gravel-sand mixture with a clay binder.

The next assessment is to establish the properties of the fine component as a function of its water content. First, the larger particles are removed, this time using a 0.40 mm mesh sieve. The so-called *Atterburg Limits* (named after a Swedish physicist who proposed the tests in 1911) are used to define the soil type in the laboratory. They are determined using simple but well defined and reproducable tests. These will be described briefly, but for precise details the New Zealand Standard NZS 4402 should be consulted.

To sum up, the soil's classification is defined by letters which divide soils into a series of broad divisions. Each letter has a particular meaning, as follows:

G = gravel
S = sand
M = silt
O = organic
C = clay
W = well graded
P = poorly graded
L = low liquid limit
H = high liquid limit

A combination of two of these is used to define the soil.

The engineering properties of each soil type can then be defined, since the beauty of the

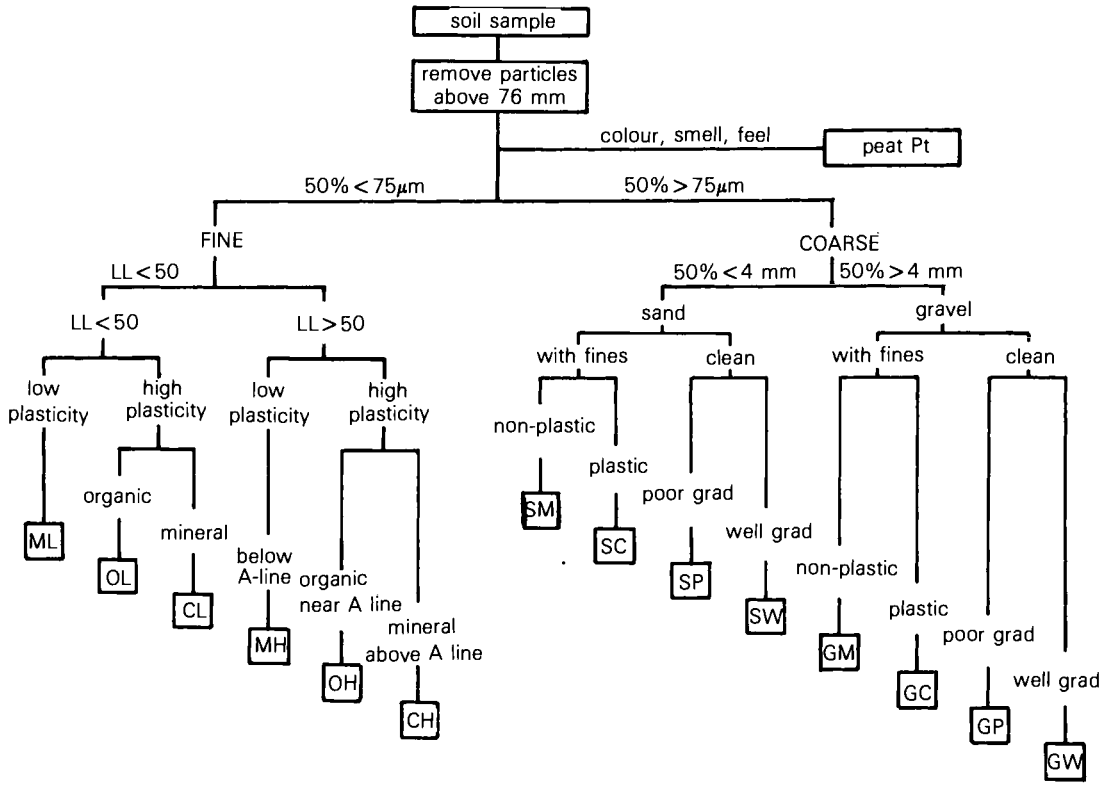


Figure 8.6 Soil classification.

classification is that all soils in a particular classification behave in similar ways, and for most purposes the suitability of the soil for a particular purpose can be decided. *Table 8.3* describes the engineering properties of soils according to their classification.

8.2.14 Plasticity measurements to establish Atterburg Limits

a. Liquid Limit

This defines the water content at which the soil begins to exhibit shear strength, ie, some plasticity. A moist sample of the soil is placed in a special cup which rests on a hard rubber block (*Figure 8.7*). A trapezoidal groove of specified shape is cut with a special tool. The Liquid Limit is defined as the water content at which the groove closes after the cup is tapped 25 times onto the rubber block. This is found by performing a series of tests at various water contents and counting the number of blows to close the gap. The results are then plotted on a graph, and the liquid limit read from the graph.

b. Plastic limit

This is the water content at which the soil crumbles when rolled by hand into threads 3 mm in diameter on a glass plate. This is a trial and error procedure. It is defined in NZS 4402.

c. Plasticity index

The Plasticity Index (PI) is the difference between the liquid limit and the plastic limit expressed as percentages. It represents the range of water contents over which the soil is in a plastic state.

d. Shrinkage limit

When a cohesive soil dries out, surface tension forces compress the mass and the void ratio decreases. When the surface tension forces are balanced by the direct stress between particles, the soil ceases to shrink, and the volume becomes constant. The moisture content at which this occurs is known as the Shrinkage Limit. Linear shrinkage and shrinkage limits can be

Table 8.3 Engineering characteristics of soils

Group Symbol	Typical Names	Shear Strength	Compress-ibility	Permea-bility	Compaction
GW	Well graded gravels, gravel-sand mixtures, little or no fines.	High	Very slight	High	Good
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines.	High	Very slight	High	Good
GM	Silty gravels, poorly graded gravel-sand-silt mixtures.	High	Very slight	Medium-Low	Good
GC	Clayey gravels, poorly graded gravel-sand-clay mixtures.	High	Slight	Low	Fair
SW	Well graded sands, gravelly sands, little or no fines.	High	Very slight	High	Good
SP	Poorly graded sands, gravelly sands, little or no finds.	Usually high*	Very slight	High	Good
SM	Silty sands, poorly graded sand-silt mixtures.	Usually high*	Very slight	Medium	Good to poor*
SC	Clayey sands, poorly graded sand-clay mixtures.	High	Slight	Low	Fair
ML	Inorganic silts and very fine sands silty or clayey, slight plasticity.	Medium	Medium	Medium	Good to poor
CL	Inorganic clays of low to medium plasticity, gravelly, sandy, silty, clays.	Medium	Medium	Medium-Low	Good to fair
OL	Organic silts and organic silt clays of low plasticity.	Low	High	Low	Very poor
MH	Inorganic silts, micaceous fine sandy or silty soils, elastic silts.	Low	Very High	Low	Poor to very poor
CH	Inorganic clays of high plasticity, fat clays.	Medium to Low	Usually high†	Low	Fair to poor
OH	Organic clays of medium to high plasticity.	Low	Very high	Low	Very poor
Pt	Peat and other highly organic soils.	Very low	Very high	Very high	Very poor

* Depends on density and drainage conditons. † Depends on consistency in place.

measured by observing the behaviour of a soil sample in a mould as it dries.

Once the plasticity index and the liquid limit have been determined, the classification can be made with the aid of the chart in *Figure 8.8*. The "A" line on the graph distinguishes the clay soils (above the line) from the organic or silt soils (below the line). This final classification defines the soil type. Even here there is considerable overlap of different soil types if the liquid limit is under 25%. For example, a soil with a LL of 20% and a PI of 8% could be CL (sandy clay), SP (clayey sand) or CL-SC (well graded sand and clay mixture).

8.2.15 Field tests

The tests given above are relatively slow but give results which are not dependant upon the technician's judgement. The following tests can be performed quickly in the field, and give a reasonable classification. However the results will differ between technicians, as the tests are less clear-cut. Three properties, dilatancy, dry strength, and toughness, are assessed.

a. Dilatancy

If a pat of moist soil is held in the palm of

Table 8.4 USDA Soil Classification System

Field Identification Procedures (Excluding particles larger than 3 inches and basing fractions on estimated weights)						Group Symbols	Laboratory Classification Criteria	
Coarse Grained Soils More than half of material is larger than No. 200 sieve size. (The No. 200 sieve size is about the smallest particle visible to the naked eye)	**Gravels** More than half of coarse fraction is smaller than No. 4 sieve size. (For visual classifications, the ¼ size may by used as equivalent to the No. 4 sieve size.)	**Clean Gravels** (Little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes.			GW	$C_u = \frac{D_{60}}{D_{10}}$ Greater than four. $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and three.	
			Predominantly one size or a range of sizes with some intermediate size missing.			GP	Not meeting all gradation requirements for GW	
		Gravels with fines (Appreciable amount of fines)	Plastic lines (for identification procedures see ML below).			GM	Atterberg limits below 'A' line, or PI less than four.	Above 'A' line with PI between four and seven are borderline cases requiring use of dual symbols.
			Plastic lines (for identification procedures see CL below).			GC	Atterberg limits above 'A' line with PI greater than 7.	
	Sands More than half of coarse fraction is smaller than No. 4 sieve size. (For visual classifications, the ¼ size may by used as equivalent to the No. 4 sieve size.)	**Clean Sands** (Little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.			SW	$C_u = \frac{D_{60}}{D_{10}}$ Greater than six. $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$	
			Predominantly one size or a range of sizes with some intermediate sizes missing.			SP	Not meeting all gradation requirements for SW.	
		Sands with fines (Appreciable amount of fines)	Non-plastic lines (for identification procedures see ML below).			SM	Atterberg limits below 'A' line, or PI less than four.	Above 'A' line with PI between four and seven are borderline cases requiring use of dual symbols.
			Plastic lines (for identification procedures see CL below).			SC	Atterberg limits above 'A' line with PI greater than 7.	
Fine Grained Soils More than half of material is smaller than No. 200 sieve size. (The No. 200 sieve size is about the smallest particle visible to the naked eye)	**Identification procedures on fraction smaller than No. 40 sieve size**							
			Dry strength (crushing characteristics)	**Dilatancy** (reaction to shaking)	Toughness (consistency near plastic plastic limit)			
	Silts and Clays Liquid limit less than 50		None to slight	Quick to slow	None	ML		
			Medium to high	None to very slow	Medium	CL		
			Slight to medium	Slow	Slight	OL		
	Silts and Clays Liquid limit greater than 50		Slight to medium	Slow to none	Slight to medium	MH		
			High to very high	None	High	CH		
			Medium to high	None to very slow	Slight to medium	OH		
Highly organic soils			Readily identified by colour, odour, spongy feel and frequently by fibrous texture.			Pt		

* Boundary classifications: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well graded gravel-sand mixture with clay binder.

* All sieve sizes on this chart are US standard.

Information required for describing soils

Give typical name, indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geological name and other pertinent, descriptive information, and symbol in parentheses.

For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics.

Examples

Silty sand, gravelly; about 20% hard angular gravel

particles 12 mm maximum size; rounded and subangular sand grains coarse to fine; about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand, (SM).

Clayey silt, brown; slight plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).

Determine percentages of gravel and sand from grain size curve. depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows:

Less than 5%	GW, GP, SW, SP,
More than 12%	GM, GC, SM, SC,
5% to 12%	Bordering cases requiring use of dual symbols.

Field Identification Procedures for fine grained soils or fractions

These procedures are to be performed on the minus No. 40 sieve size particles (0.4 mm). For field classification purposes, screening is not intended; simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pot of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surfact of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun or air drying and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the collodial fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH Group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimens. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit)

After removing particles larger than the No. 40 sieve size, a cube of soil about 12 x 12 x 12 mm is molded to the consistency of putty. If too dry, water must be added, and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about 3 mm in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherance of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the 'A' line.

Highly organic clays have a very weak and spongy feel at the plastic limits.

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the hand and shaken vigourously by striking one hand against the other the surface of the pat may become glossy with minute droplets of water. This is known as Dilatancy and is a property of silts. Clays do not react this way.

b. Dry Strength

If a pat of soil develops marked strength after drying this is an indication of a clay. Silts and sands have little dry strength.

c. Toughness

If a pat of fine soil can be rolled into a thread between the hands without crumbling this is an indication of clay content. The field tests based on these properties are described in detail on the classification chart (*Table 8.4*), and the resulting classification is also indicated.

8.2.16 Soil compaction tests

The strength and permeability of a soil is significantly affected by the density of the soil. The maximum strength occurs at maximum dry density. The density which can be achieved in practice depends on how

much load can be applied by the compacting equipment and also on the water content of the soil. For a particular compaction effort

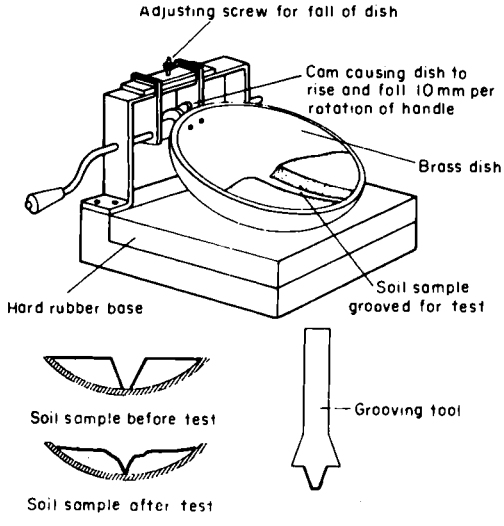


Figure 8.7 Liquid limit apparatus (G N Smith).

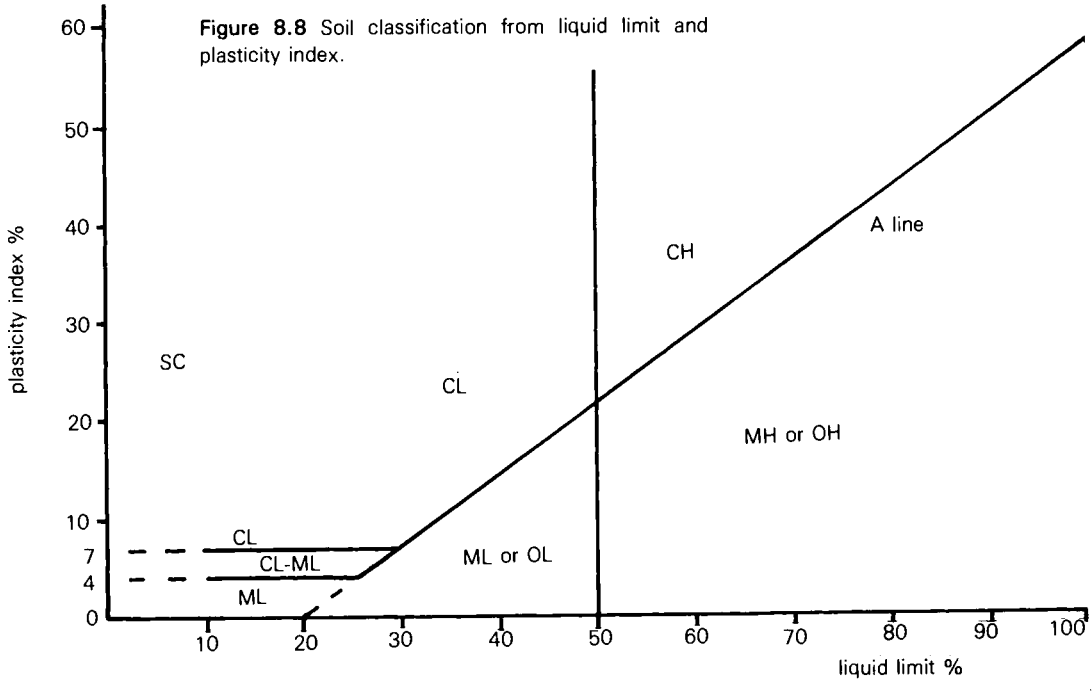
there is an optimum moisture content at which the soil will reach a maximum dry density. This fact is vital for successful compaction of soil. If the water content is either well above or well below the optimum when it is compacted then the soil will not reach its maximum compaction and will be less strong, more permeable, and likely to settle more. Thus it is important that the optimum moisture content for the soil is known and that the moisture level is checked during construction.

8.2.17 Proctor density

Also known as the New Zealand Standard Compaction Test, the Proctor Density Test is a standard test for determining the relationship between dry density and water content for a given compaction effort. It is described in detail in British Standard 1377 and NZ Standard 4402: (1987). A cylindrical mould measuring 105 mm in diameter and 1000 cc in volume is used (*Figure 8.9a*). The soil is tamped into it in three equal layers, and each layer is subjected to 25 blows from a 2.5 kg hammer falling through 300 mm. The last layer should just overfill the mould. The excess is then cut off and the bulk density found by weighing. After testing the dry density and soil water content are found by oven drying a small sample at 105 °C for 24 hours.

The test is repeated over a range of moisture contents and the results are then plotted as in *Figure 8.9b*, which will indicate the optimum moisture content and the maximum dry density. In some tropical soils misleading results will be obtained if the soil is excessively disturbed (eg, by drying and then

Figure 8.8 Soil classification from liquid limit and plasticity index.



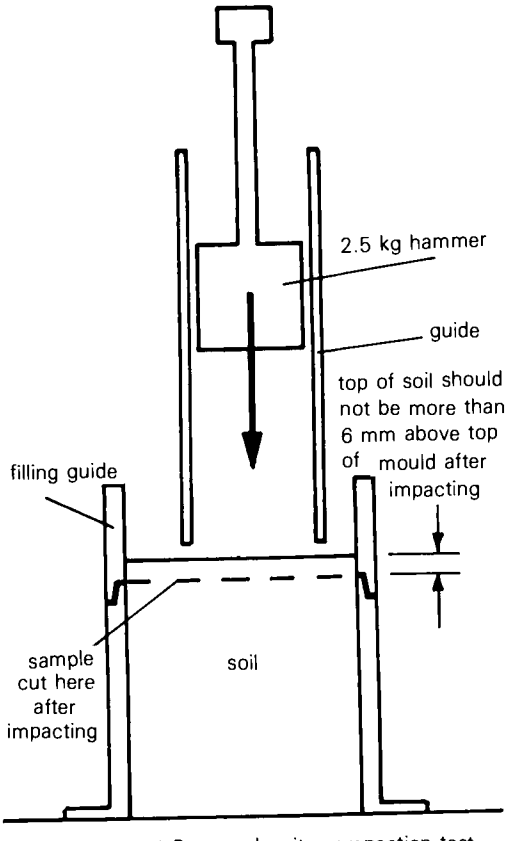


Figure 8.9(a) Proctor density compaction test.

rewetting). It is therefore important to avoid altering the soil moisture content more than necessary. Once tested the material should be discarded and new material should be used for the next moisture content.

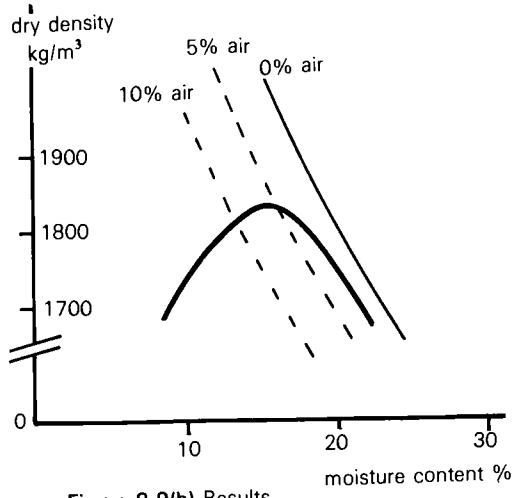


Figure 8.9(b) Results.

The Figure also shows the theoretical curves for 0, 5, and 10% air voids. The 0% curve is the density which would result if all the air was removed so that the void space was entirely filled with water before drying. This would correspond to total compaction. In practice the actual density is always less than the ideal, because a certain amount of air is always trapped in the compacted specimen along with the water. The dry density always peaks and then falls away again, as in the Figure. At low water content the density falls because the soil does not compact properly, due to frictional forces between the soil particles. These forces increase as the water content is reduced due to the decrease in lubrication provided by the water. If the soil is too dry, then the soil particles cannot rearrange themselves into a more closely packed arrangement easily, and so the soil will not reach its maximum level of compaction. On the other hand, at high water contents, the water itself prevents total compaction.

In the field, it is unrealistic to expect to place soil at its maximum density, and normally some tolerance is allowed (eg, 5%). Good soil compaction requires that the right equipment is used at the optimum soil moisture content (OMC). The OMC depends upon the soil type, and is attained when there is no excess pore water present to limit the amount of compaction, but there is still enough to provide lubrication. The void space can then be reduced to a minimum.

The right equipment also depends upon the soil type. Sands and gravels, and other cohesionless soils, can best be compacted with vibrating rollers. These devices literally shake the particles into place. Under dry conditions, cohesive soils (clays, loams, and fine clay-silts) can be compacted with "sheeps-foot" rollers, which punch the soil into place. An alternative is to use a heavy roller, weighing typically ten tonnes, with smooth steel rollers or rubber tyres. However the most suitable roller will depend on the soil type and condition.

8.2.18 Sampling of soils in-situ

Sometimes the water content and density of the undisturbed soil at a site is required. These can be obtained by the Washington or Balloon Densitometer Test, which involves digging a hole about 300 mm × 300 mm and weighing and drying the soil removed. The volume is then determined by placing a

rubber "balloon" in the hole and filling it with water from a calibrated plunger pump. This gives the moisture content and the in-situ density. Alternatively the density can be determined quickly using a Nuclear Densometer, which uses the absorbtion of particles emitted from a radio-active source as a means of determining the density.

A rapid measurement of the moisture content also can be obtained by comparing the amount of penetration of a penetrometer under a set load with the results obtained from a laboratory calibration using a similar soil.

It is also possible to assess the in-situ soil strength and consistency by very simple tests. In clay soils a vane shear tester can be used to measure the shear strength of the material (*Figure 8.10*). Alternatively very simple methods as indicated in *Table 8.5* can be used.

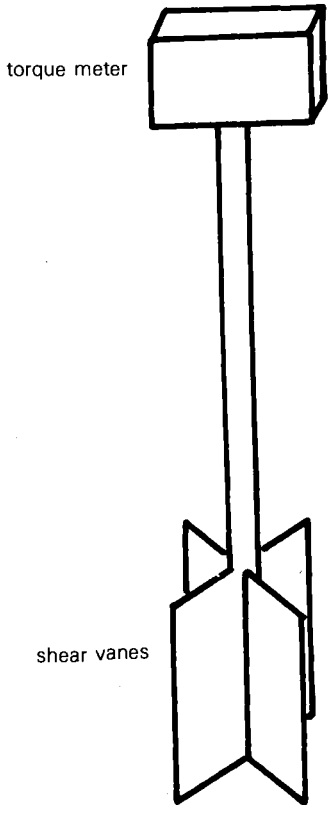


Figure 8.10 Vane shear tester.

Table 8.5 Simple methods for assessing soil properties in the field

a. Cohesive soils

Very soft	– Squeezes between fingers
Soft	– Easily moulded by fingers
Firm	– Moulded by strong finger pressure
Stiff	– Dented by strong finger pressure
Very stiff	– Dented only very slightly by finger pressure
Hard	– Dented only very slightly by pencil point

b. Cohesionless (coarse grained soils)

Loose	– 12 mm rod pushes in by hand
Moderately dense	– 12 mm rod easily driven in by hammer
Dense	– 12 mm rod penetrates 0.5 m when driven in by hammer
Very dense	– 12 mm rod penetrates less than 100 mm when driven in by hammer

8.2.19 Scala penetrometer test

Alternatively the Scala penetrometer may be used. This consists of a steel probe on the end of a long rod to which an anvil is attached part of the way up. A 9 kg hammer drops through a set distance of 504 mm onto the anvil, and the number of blows for each 75 mm of penetration is recorded. The tip is driven to a depth of at least twice the greatest width of the footing so that the properties of the soil are studied throughout the entire load bearing region. The soil may be assumed to have a safe bearing pressure of not less than 100 kPa providing it takes more than three blows per 75 mm depth of penetration down to a depth equal to twice the width of the footing below the underside of the footing, and more than two blows per 75 mm below this. In addition no organic topsoil, peat, soft clay or fill

materials should be found from a test bore augered to the same depth. This is an adequate foundation for a straightforward domestic timber building of one or two storeys. As an alternative, the allowable bearing pressure can be calculated from charts (eg, Stockwell, 1977), and values of up to 500 kPa can be obtained for very stiff and hard soils.

Stones and gravel can cause problems with this test, and in fine sands where there is a shallow ground water table, the test may suggest that the soil is unsuitable when in fact it would be capable of sustaining the 100 kPa load. Specially developed local soil tests may be a more appropriate means of assessing whether specific design is required in these cases.

8.2.20 Applications

Before a building is constructed a thorough costing should be undertaken. As site preparation can be a substantial part of the cost, it is important that an initial site survey to assess the soil characteristics should be completed, and the cost of siteworks estimated. Tasks that must be included are: the removal of the top soil and any vegetation, the removal of excess soil (cuts), addition of soil to build up low spots (fill), compaction of the soil to give an adequate bearing capacity and permeability to water, incorporation of any services (drainage, sewerage, water, power, telephones, etc), replacing topsoil after construction, and landscaping to return the area around the site to its original state or better. This includes the removal of waste.

Most problems arise in the areas where fill is added. These arise for a variety of reasons but the most common faults are due to using unsuitable fill material (eg, sand for a dam wall), the inclusion of vegetation and top-soil in the fill, the target permeability is not achieved, or the compaction is inadequate due to the use of the wrong equipment or the wrong procedures (and sometimes failure to use any procedures at all!).

The permeability of soil depends upon the soil type and the level of compaction. Mixtures of gravels with silt and up to about 30% clay content are often the best. In practice it is rarely possible to obtain the maximum compaction, but with good supervision it is possible to get to within 5% of the ideal Proctor density. However the soil must be compacted thoroughly and at the correct moisture level in order to attain this degree of compaction.

8.3 FOUNDATIONS

8.3.1 Preliminary field studies

The soil must support the building or structure. In practice some general guidelines have been developed for residentiial buildings, implement sheds and covered yards, which mean that soil strength measurements are not needed. For example, in New Zealand, the standards state that a soil can be assumed to have a safe bearing capacity of 100 kPa provided there are no indications of slope instability or records of landslips in the area, and adjacent buildings are supported on similar foundations successfully. There must be no evidence that fill has been put on the site, or that buried services have been put in at some earlier time. If the ground slopes, or buried top-soil, soft clay, or soft peat are found then specific design help should be sought. Maximum bearing pressures for various soil types are given in *Table 8.6.*

Table 8.6 Maximum bearing pressures for various soil types

	kPa
Alluvial soil, peat, or soft clay	53
Medium clays	160
Firm dry clays	215
Loose gravels, compact sands, compact pumice, hard clay (dry)	320–430
Shale or soft rock	1070
Hard rock	4300

If there is any doubt then an investigation should be conducted to determine the actual bearing capability of the soil, and the building must then be designed accordingly, usually by a consulting engineer. As more marginal land is used for building, this step will be needed more and more often.

It is current practice to ensure that the foundation is set on solid undisturbed ground. This means that the base will always be below ground level. In firm rock the base should be 150 mm below ground level, while in areas

of expansive clay (ie, where the clay dries out in summer giving large cracks) it should be 450 mm below ground level. In other soil types 300 mm is sufficient.

8.3.2 Principles of foundation support

Foundation theory is very complex, but some of the basic features will be described here. Soil fails as a foundation material either by shear failure or by excessive settlement. There are three main types of failure.

In *General Shear* the foundation suddenly settles, and will tilt if free to do so. There is usually some heaving (movement upwards) of the surrounding soil. The zone under the foundation where failure occurs is quite small, and is roughly as deep as the width of the footing. This type of failure usually occurs in dense or incompressible soils. In *Local Shear* there is a slow plastic movement of underlying soft soil which results in the gradual displacemant of the soil away from the foundations. This type of failure occurs in loose or highly compressible soils.

Settlement is caused by consolidation due to the slow expulsion of air and water from the soil under pressure, thus causing a reduction in the void space. It occurs in all fine grained soils. Sand and gravel are less susceptible, as they are free draining, but peat soils are very prone to settlement. When a building sits on a soil, the resulting pressure is dispersed through the soil. The resulting extra pressure on the soil falls with increasing depth, while the natural pressure the soil is under increases with depth. At a depth of twice the width of the footing the extra pressure is negligible, and so the depth of interest is no greater than this.

Settlement will be most serious if it is not uniform. Differential settlement can result in unsightly damage to the building, varying from cracks in the walls to uneven floors, and tilted walls. The leaning tower of Pisa and the canal-side buildings of Amsterdam are classic examples of differential settlement (*Figure 8.3*). In practice settlement cannot be prevented, but it should be limited to not more than 25 mm in total or 12 mm differential for light timber buildings. If brick or block structures are being built even this level of settlement may prove totally unacceptable.

8.3.3 Foundation types

Various foundation types can be used depending on the soil and the building type. Examples are shown in *Figure 8.11*. Piles are required when the top layers of soil are poor, and raft foundations are a way of spreading the soil loading over a larger area in soils with a low bearing capacity. Raft foundations can

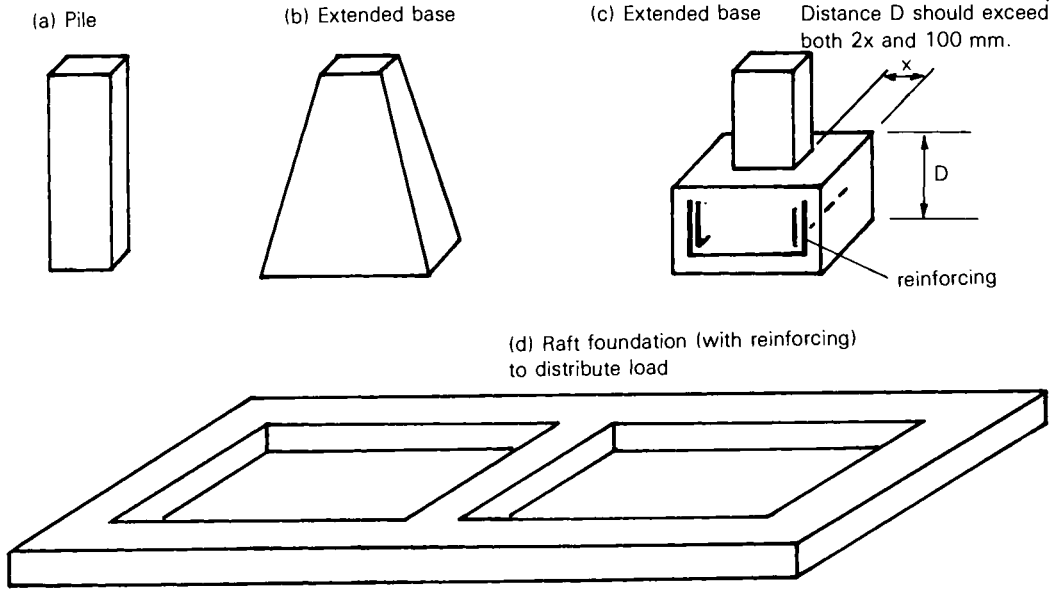


Figure 8.11 Concrete foundations.

be used in peat soils but such soils are generally best avoided if possible, unless a solid base can be reached under the peat.

In many situations the foundation must not only support the building, but it must also prevent the building from being blown away in strong winds. It is quite possible for upwards wind loads to exceed the weight of a farm building, and stories of record breaking flights by all-to-identifiable flying objects are fairly common! Guide lines are usually provided by manufacturers which indicate the minimum mass of the foundation for most structures. Obviously the building needs to be securely attached to the foundation in these cases.

8.3.4 Roads and farm tracks

The same considerations which apply to building foundations also apply to roads, tracks and races (a race is any fenced track used to move stock or machinery on the farm). An example of race construction is shown in *Figure 8.12*. The substrate must be well prepared and strong enough to support the working surface, and drainage must be considered. If necessary, in very soft soils, a commercial filter cloth (essentially a strong porous plastic woven sheet) can be laid to separate and retain the soil in the base and sub-base. The base layer consists of compacted soil or gravel (but not top-soil), built up above the level of the ground to form a crown as indicated. This ensures that water is shed from the surface quickly and easily. The top wearing layer needs to be a thoroughly compacted layer of well rounded gravel soil with particles less than 25 mm in diameter, and with a 15-30% clay content. Other local materials may also be suitable, providing water cannot percolate into the core of the road. The road surface must be well bonded to the substrate, and proper materials are required. If the substrate is a clay, or a quarry waste, it is possible in some cases to improve the properties of the top 100 to 500 mm by *Lime Stabilisation*. This involves adding 2 to 4% of lime in the form of calcium oxide (burnt lime) or calcium hydroxide (slaked lime). Calcium carbonate (agricultural lime) and limestone ($CaCO_3$) are not suitable. Lime stabilisation can improve the strength, shrinkage and swell characteristics, and can reduce the plasticity index. However, it is necessary to do simple laboratory checks to ensure that lime stabilisation does indeed improve the properties of any particular soil.

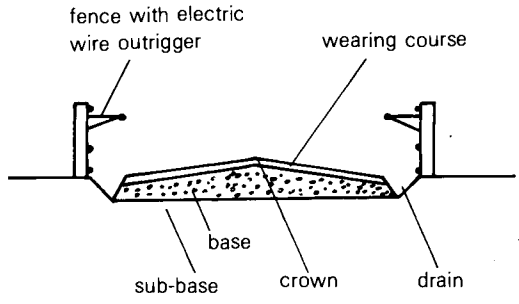


Figure 8.12 Farm race construction. The electric wire on the outrigger is to prevent stock from trampling in the drain.

8.4 CONCRETE (*Figure 8.13*)

Concrete is one of the most common construction materials. It is relatively easy to use for large and small jobs, and is readily available. It is strong, hard wearing, cheap, and is resistant to biological attack. It is easily formed into any shape. Once set it is hard to remove, and will not distort. The apparent ease of use is deceptive: it is possible to do a bad job in laying concrete, and we will now highlight some of the important facts and techniques which lead to better results.

Concrete strictly consists of four components. These are cement, coarse aggregate, fine aggregate (or sand), and water. The relative proportions of these four determine the properties of the concrete, both during mixing and pouring, and when the concrete has set. In New Zealand the coarse and fine aggregate are often just called aggregate, and can be obtained as a single product called builder's mix or pre-mix. The fine aggregate is usually called sand in New Zealand (particles which pass through a 4.75 mm mesh sieve).

8.4 Cement

Cement is a chemical which acts as a glue in concrete. Portland cement is the most common type and is produced by heating a limestone rock to very high temperatures under controlled conditions. It is hydroscopic (ie, it absorbs water from the air), and will harden in the bag if it is not stored properly. In use, cement undergoes a chemical reaction when mixed with ample water. This reaction is relatively slow; the cement takes about two

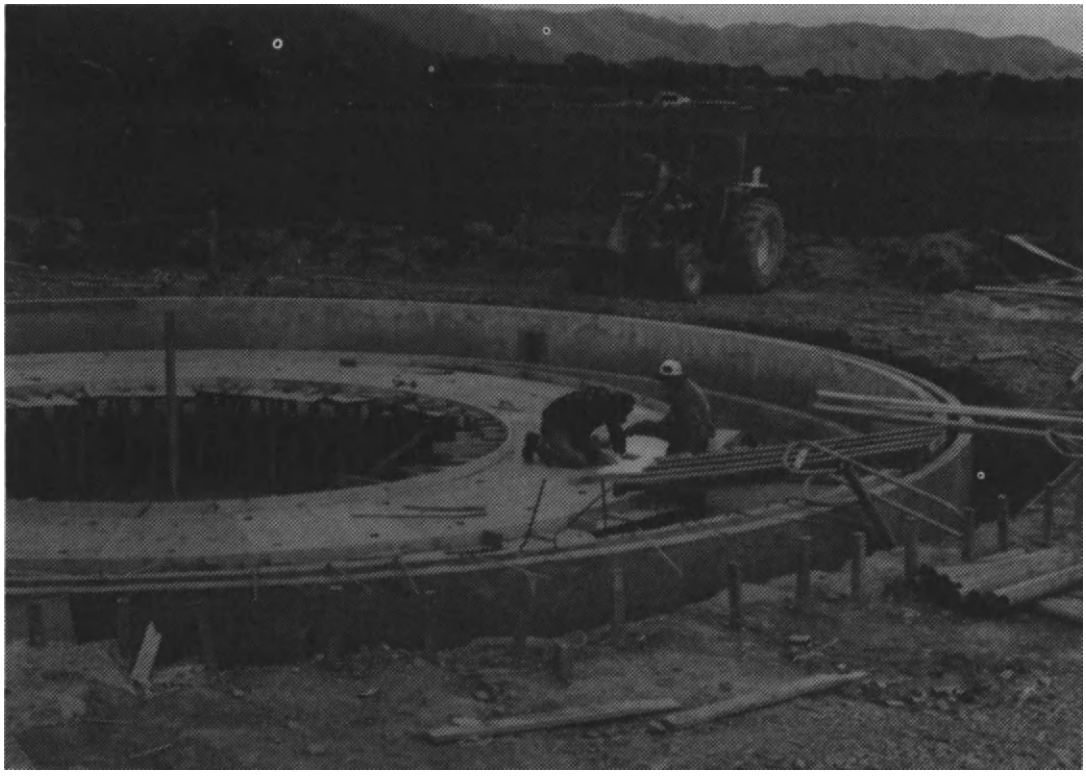


Figure 8.13(a) Formwork for a floating rotary milking shed.

hours to achieve "initial set", (where it becomes stiff but still very weak), and about ten hours to achieve final set, where it is quite firm. Additives (admixtures) are available which will reduce these times substantially. After the final set, the reaction is still not completed, and the cement continues to harden with time, especially in the first month. The reactions which produce this strength still require water, and so new concrete should be kept wet after the final set is completed. As cement hardens it contracts, resulting in shrinkage cracking of the concrete. It is tempting to add more cement to a mix in the hope that this will increase the strength, and certainly too little will cause insufficient bonding of the aggregate. Too much is very expensive, and results in more shrinkage of the concrete, so that surface crazing and shrinkage cracking are worse. Cement is also susceptible to corrosion by acids, as discussed below.

8.4.2 Water

Water is required to start the chemical reaction which causes the concrete to harden.

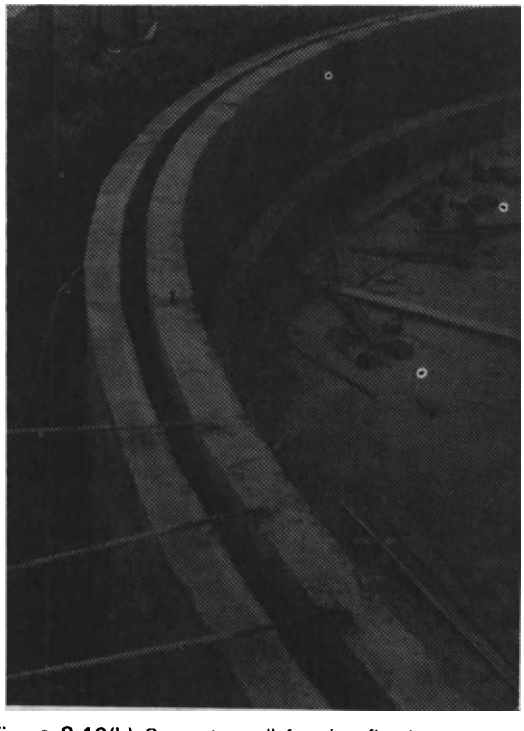


Figure 8.13(b) Concrete wall forming floating rotary outer shell, mid shell and inner shell.

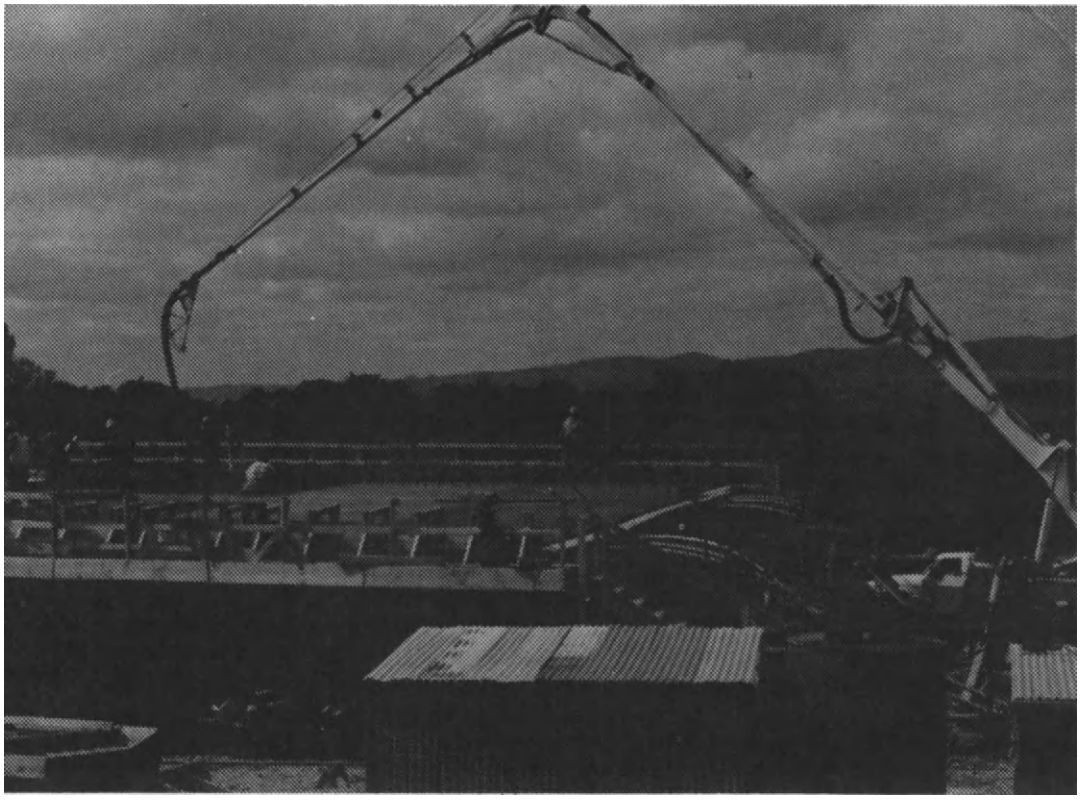


Figure 8.13(c) Concrete placement pumped via an overhead pipe.

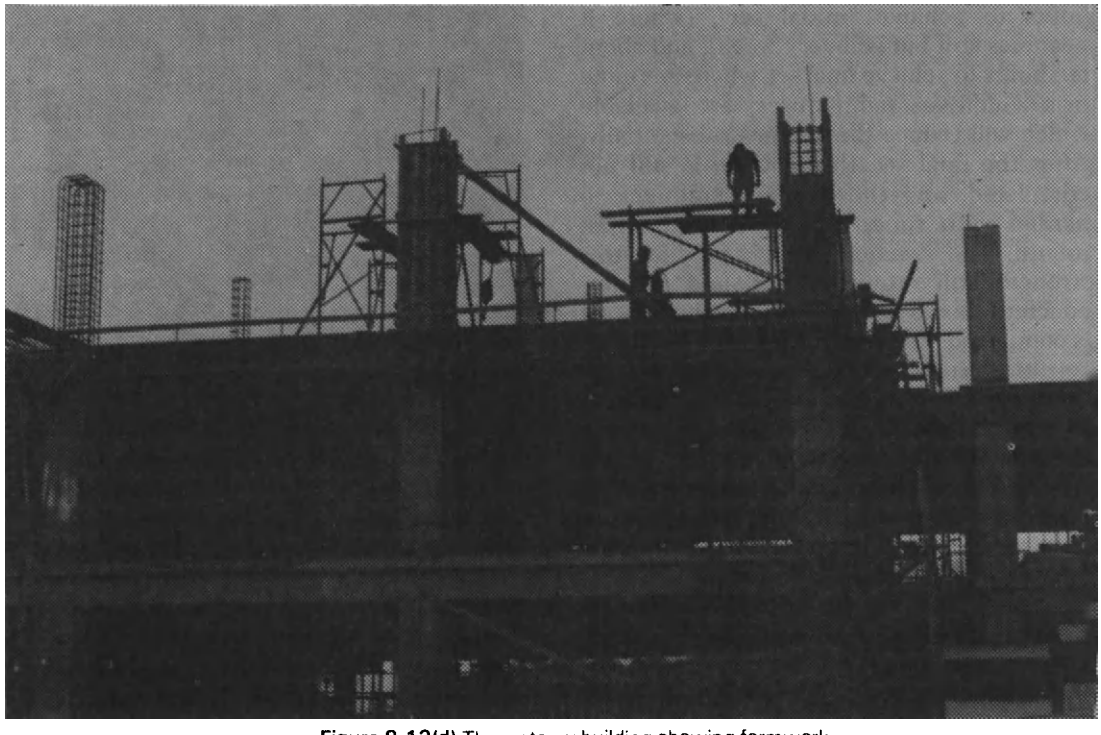


Figure 8.13(d) Three storey building showing formwork and reinforcing of pillars.



Figure 8.13(e) Levelling concrete immediately after pouring.

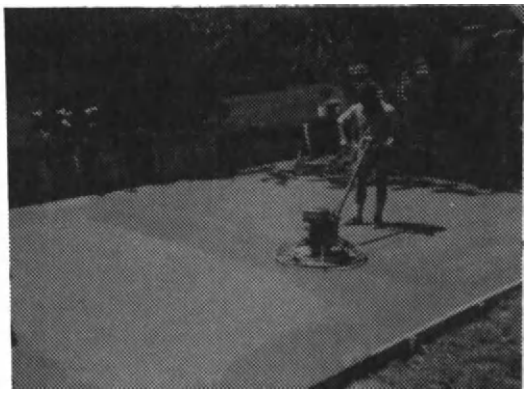


Figure 8.13(f) Smoothing concrete with a power float.

However in practice more water is used in the initial mix so that the concrete is easier to work and form. The ease of working is called the workability of the concrete, and is indicated by the *Slump Test*. This is a test where a sample is placed (in a specified manner) into a cone shaped mould 200 mm high. The mould is then removed and the amount the sample slumps is measured.

Table 8.7 Slump test data

Slump mm	Strength of concrete MPa	Application
10	40-50	Prestressed, or precast concrete, made in factory, with simple reinforcing. Intense mechanical vibration will be essential as the concrete will be hard to work.
50-75	30-40	Prestressed units with complex reinforcing.
50-100	30	Dairy shed floors with minimal cracks, and joints at 4-5 metre intervals.
75-125	30	Precast wall panels with awkward shapes, paths, standard floor slabs.
75-125	17-20	Footpaths and other low strength applications with reduced cement content.

Table 8.7 indicates typical acceptable slump test values for a variety of applications.

With fixed proportions of solid components, the slump test indicates the ratio of water to cement in the mix and is a useful quality control check. Although workability is an advantage during concreting, the extra water reduces the final strength of the concrete and also makes it more permeable to water. For the strongest concrete, the water used in the mix should be kept to a minimum. Acid attack can be serious in factories, milking sheds and other areas where effluent or other acids can be spilt. It is made worse if the concrete is weak, porous or has many surface cracks (eg if too much cement is used). Thus the proportions of water and concrete in the mix have a major influence on the resistance of the concrete to acid attack. If too much cement is used in the mix the effect can show up quite quickly. Most aggregates are not affected by acid attack, so the surface becomes uneven and pitted as the cement dissolves away, exposing the aggregate (eg *Figure 8.13g*).

8.4.3 Aggregate and sand

Cement is far too expensive to be used on its own. Hence aggregates and sand are used as inert void fillers around which the cement and water paste spreads and locks together as it sets. The best concrete mixtures are carefully graded to give the ideal proportions of different sized particles, so that the smaller particles fill up the spaces between the larger particles. This results in a mixture which has a low void space, and results in a concrete of maximum strength. If the aggregate is not properly graded, then the resulting concrete will be hard to work to produce a smooth



Figure 8.13(g) Erosion of concrete in the floor of stock yards.

surface. Extra water and cement are likely to be needed in the mix, and the result will be poor quality concrete of low strength and acid resistance.

Proportioning can be done either by volume or by weight. The most accurate way is by weight having taken into account the moisture content of the aggregate. Most ready-mix concrete plants batch by weight and are able to achieve significant savings through strict control of the constituents. They are also able to produce concrete suited to the specific requirements of the customer, thereby saving costs because the concrete provided is not stronger than necessary. In many regions it is cheaper to obtain ready mixed concrete rather than mixing your own. The latter option can be more costly because: there is less control over quantities (ie more cement is often needed or added), site losses and wastage can occur more easily, high labour costs will result since the work will take longer, and accurate ordering of constituents is difficult in practice (ie one may well need 1.3 m^3 of aggregate to make 1 m^3 of concrete, because sand bulks in volume when wet). Quite often there will also be some leftovers which are wasted. It is also more difficult to produce good concrete by hand mixing, because the mixing will rarely be sufficiently thorough. If proportioning by volume is to be carried out, then some means (other than visual) should be used to determine the relative volumes (eg, a measuring box).

8.4.4 Concrete placement

a. Site preparation

If the concrete is to carry out the functions for which it is intended, the preparation of the base upon which it is to be laid must be sound. This means that:

a. The soil must be of sufficient strength to support the loads that are transmitted through to it by the concrete (ie, there must be no soft spots).
b. The depth of concrete being poured must be kept as uniform as possible to prevent cracking in the thinner regions.
c. Under floor slabs, if possible a thin layer of either fine gravel or sand should be

placed between the sub-soil base and the concrete. Not only does this permit any irregularities in the preparation of the base to be levelled out, but it also permits the concrete the freedom to move if the temperature fluctuates, without bending and cracking. A damp-proof course should also be laid between these layers.

b. Boxing (Formwork)

The boxing is the structure which must be built to contain the concrete until it has hardened (*Figures 8.13a* and *d*). Most boxing is made from timber. It must be strong. Concrete has a density of approximately 2.35 tonnes/m^3. If the boxing is not adequately supported and fixed, it will move or, even worse, collapse. The boxing should be left in place for at least three days on unprotected beams, to allow concrete to gain initial strength. On floor slabs it is possible to strip the boxing after 24 hours. However a longer period should be allowed under cold conditions or when the concrete has a high slump test value.

c. Compaction

The single most important factor to consider when placing concrete is to achieve adequate compaction. Leaving air voids in the finished concrete can result in a significant decrease in strength. For every 1% under compaction, there is a 5 to 6% decrease in strength. It is therefore important to compact the concrete, and a variety of methods are available.

Tamping is done with a long straight rod of metal or timber. The rod is used to pat the surface repeatedly. If the surface is over-tamped this can have the effect of bringing fine particles to the surface, which results in a weak surface. This soon powders and breaks up in use. On major sites a mechanical vibrator is normally used. This helps to remove air voids throughout the concrete. When placing the concrete, the concrete mix should not be dropped from any great height, as this will cause segregation, ie, the separation of the fine and coarse particles. Instead a flexible pipe (a "tremmie") should be used (eg *Figure 8.13c*).

d. Screeding (*Figures 8.13e* and *f*)

Screeding is the process of working a flat board backward and forward over the concrete to produce a level surface and the initial finish. Once the flat surface has been obtained the concrete should be left until the surface water has disappeared. Then the final surface finish is obtained by smoothing the surface with a metal or wooden trowel, or a power float. These will produce a smooth surface which could be slippery. If a non-slip surface is required then the concrete should be finished with a broom, within two to six hours after the concrete has been placed.

e. Curing

After the final set has occurred (about ten hours) the concrete should be kept moist for the next seven days. This allows the chemical reactions which require water to be completed, and prevents surface stresses being created in the surface through differential curing rates and temperatures. Curing can be achieved by using (for example) wet sacks, wet sand, creating a pond on the surface, or by continual sprinkling with water. Warm humid conditions are ideal.

f. Shrinkage and controlled cracking

Cement contracts slightly as it cures. In addition concrete expands and contracts with temperature. These changes in size will inevitably cause cracking, unless allowances are made. This is done by either pouring the concrete in sections about two cubic metres in volume (eg, a 100 mm thick slab 20 square metres in size). Alternatively the concrete is poured and then cut with a concrete cutter so that the concrete cracks in a regular way along the cuts. Normally a cut about 30% of the depth of the concrete will be sufficient to induce cracking at that point. The amount of cracking can be reduced by using steel mesh in the concrete, and by keeping the water/cement ratio low. Proper curing and the provision of a suitable base will also minimise cracking.

8.4.5 Reinforced concrete

Concrete is roughly ten times stronger in compression than in tension. It is therefore advantageous to avoid conditions where the concrete is under tension. This is not always possible, but it is possible to improve matters considerably by using steel reinforcing rod in regions of tension. For example, the upper layers of the beam in *Figure 8.14* are under compression, but the lower layers are under

tension (Chapter 3). The beam is therefore likely to crack from the bottom upwards. Once started the crack will develop rapidly and the beam will collapse. However if steel rods are placed as in *Figure 8.14* these rods will sustain the tension rather than the concrete.

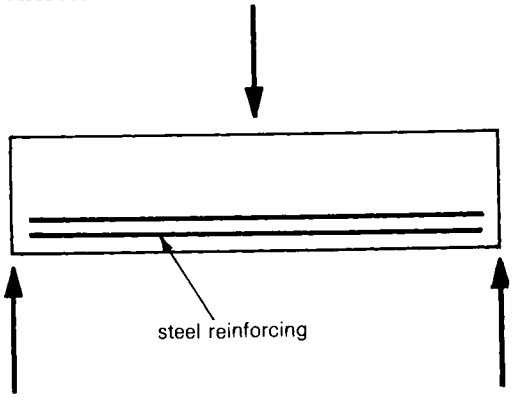


Figure 8.14(a) Concrete reinforcing.

available, possesses moderate strength and which has good fastening characteristics. The only material which comes near to meeting these requirements is timber, and as a result, timber is widely used in the building industry. It is also a renewable resource which is a further strong point in its favour. However, timber does suffer from creep under continuous loading, and is a relatively weak material when compared to metal. As a natural product, there is a wide variation in its mechanical properties, which depend upon the particular species, the growing conditions, and the husbandry of the grower. It is also susceptible to fungal and insect attack. Timber's natural durability and its ability to absorb preservatives, which increases its resistance to attack, are not sufficient to allow timber to be ranked on an equal basis with other materials, such as steel. To prevent accelerated decay, timber must

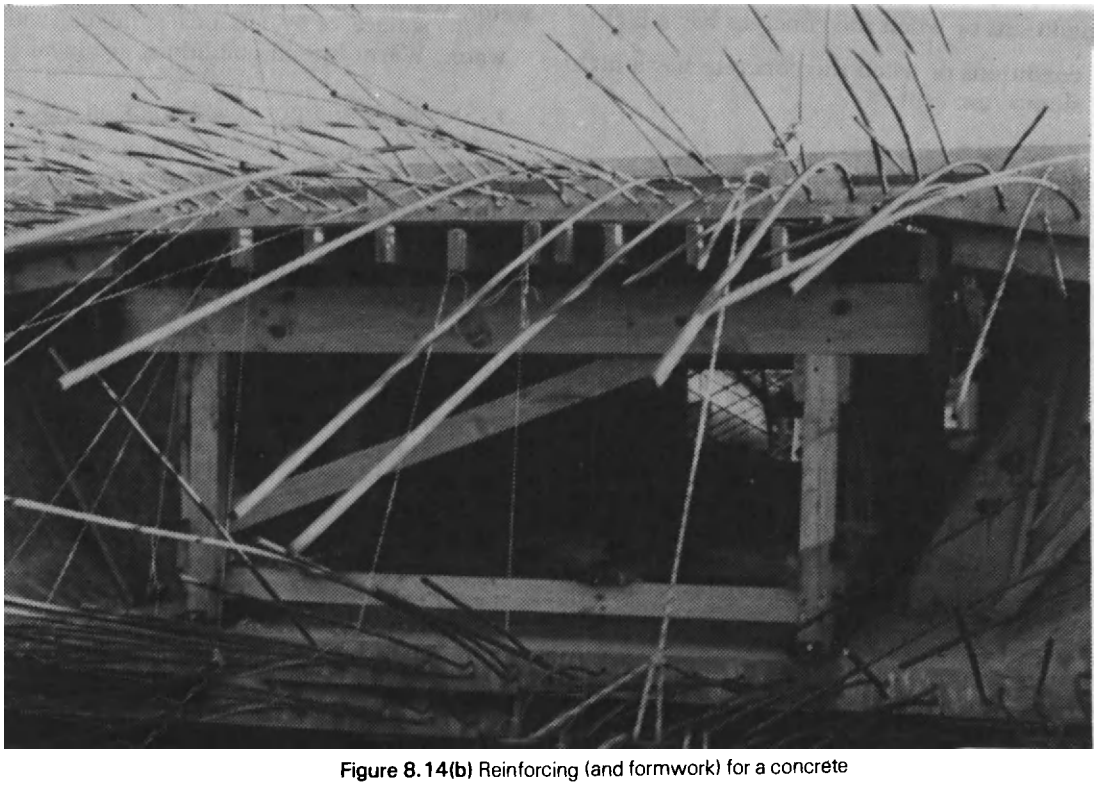


Figure 8.14(b) Reinforcing (and formwork) for a concrete structure.

8.5 TIMBER

8.5.1 Introduction

The building industry, in general, requires a material which is easy to handle, durable, shock resistant, light, relatively cheap, readily

not only be treated, but it must be protected from moisture by painting, and therefore requires continual maintenance in exposed situations. In New Zealand the natural durability of untreated timber varies from less than five years for timbers such as tawa and

pinus radiata, to more than fifteen years for macrocarpa, black and red beeches, matai, totara, puriri, hinau, and silver pine.

The most important properties of timber from the engineering viewpoint are its type, density, strength, hardness, dimensional stability, durability (with and without preservative treatment), fire resistance (also with and without treatment), and its nailing characteristics. These will be discussed in the following sections.

8.5.2 Types of timber

Biologically, timber can be grouped into two basic groups known as "hardwoods" and "softwoods", but these terms bear little relationship to the physical properties of the timber. However, within each species it is usually possible to distinguish between the heartwood near the centre of the tree, and the sapwood which makes up the outer part of the tree trunk. Trees grow by producing new layers of wood on their external surfaces each year. The new layers are used to store food and conduct sap to and from the upper parts of the tree, while the older wood gradually loses its ability to do this, and in some species deposits (called extractives) give it a darker colour and can make it harder and more durable. Thus this heart timber near the centre of the tree will be the oldest, and may be more durable than the newer sapwood near the outer surface. It is not necessarily any stronger unless it is also denser than the sapwood. It is also less easily impregnated with preservatives, as the deposits block the channels which conduct fluids. When a tree is cut both heartwood and sapwood are produced, and so it is possible to obtain both types. In some varieties the heartwood cannot be distinguished easily from the sapwood.

Grading

Timber is sold in grades, which are based on the number and type of defects in the timber. Use of the right grade for the job ensures that the timber is put to its most appropriate use, and consistency of the finished product is maintained. The classification given in the New Zealand standard (NZS 3603) is different for indigenous and exotic species. The grades include an engineering grade which must be used where the component has been specifically designed, a finishing grade, which is suitable for a natural finish, building A grade for indigenous species, and Number 1 framing grade for exotics such as pinus radiata, and commons or box grade which is suitable only for rough or temporary work. Timber can be graded visually or by machine; the latter involves a machine which applies a bending load to the timber and checks the deflection; the timber is then automatically sprayed with a dye to indicate its strength and modulus. Slightly higher design loads can then be used. Other factors which affect the grading of the timber are the presence of pith, wane, bark and in particular any bark surrounding knots. The occurrence of pith and bark is particularly important in export material, since these areas are more likely to be infested with undesirable insects.

8.5.3 Mechanical properties

a. Density

The strength of timber is in part determined by its density. Where strength is critical, timbers of a certain minimum density may be specified. Timber density is defined as the average weight of a given volume of timber with all the moisture removed.

b. Strength

Wood is anisotropic. This means that it has different mechanical properties in different directions (ie, its properties along the grain are different from those perpendicular to the grain). In order to describe its properties in full it would be necessary to specify values of mechanical constants for each direction. This is not very practicable, but the more useful parameters are often monitored. *Table 8.8* gives basic design working stress data for a number of timbers. These figures vary a little according to the type of load, and its direction relative to the grain, and NZS 3603 should be consulted for full details. Design values are affected significantly if the timber is used in the form of a narrow column under compression, with length to breadth ratios in excess of 40:1. The design code uses correction factors to reduce the allowable design loads in these situations. In addition the design load is also affected by a factor which relates to the duration of the load. The figures in the Table apply to fixed or dead loads (eg, more than eight weeks duration). For wind and earthquake loads, the allowable load can be 1.5 times this value.

Table 8.8 Basic working stresses for visually graded timber (NZS 3603)

Species	Grade	Bending Stress Parallel to grain MPa Dry	Green	Modulus of Elasticity GPa Dry	Green
Radiata	engineering				
	$< = 150 \times 50$ mm	9.4	7.7	10.5	8.8
Pine	engineering				
	$< = 150 \times 50$ mm	8.3	6.8	10.0	8.0
	No 1 framing	6.0	5.0	8.0	6.5
Douglas	engineering				
	$\leqslant 150 \times 50$ mm	8.5	7.7	10.4	8.7
Fir	engineering				
	$> 150 \times 50$ mm	7.6	6.8	9.9	8.0
	Standard building	6.0	5.0	8.0	6.5
Rimu	engineering	10.4	7.7	10.9	9.5
	Standard building	6.7	5.1	9.5	8.3
Hard Beech	engineering	15.0	14.5	15.5	14.1
	Standard building	10.0	9.6	13.6	12.1

Figures for dead static loads. For medium term loads (eg, frequent snow, of 1–8 weeks duration) multiply by 1.25. For short term loads (crowds, vehicles, of 6 hrs–1 week) multiply by 1.35. For brief loads (wind, earthquake, erection, of 0.5–6 hrs) multiply by 1.5. For instantaneous loads (impact and pile driving) double the allowable load. For columns, and for loads other than bending, refer to NZS 3603.

From these figures it can also be seen that timber gains strength as it dries out from the "as cut" green state. With the larger sections imperfections such as knots can become critical. Hence timber grading is important. The strength of timber is generally considered to be approximately proportional to the timber's density. There is relatively little difference in strength properties between heartwood and softwood of the same density and moisture content. The timbers normally used in New Zealand fall in the light to medium strength categories.

c. Hardness

Hardness is a measure of the wood's resistance to indentation. The determination of hardness is achieved by measuring the load required to push a 11.3 mm steel ball into the wood to half its diameter. Hardness, like most properties, is proportional to density. Hardness and the ability to wear evenly without splitting are vital assets for woods to be used for industrial floors and in uncovered floors of houses.

8.5.4 Moisture content and shrinkage

The moisture content of timber is measured as a percentage by weight. It is measured by drying samples in an oven and is defined as:

$$MC = \frac{(\text{Initial weight} - \text{Dry weight}) \times 100}{\text{Dry weight}}$$

Equation 8.8

Timber is never totally free of moisture. In use it reaches an equilibrium moisture content with the environment of about 15%. When wet the moisture content can be as high as 120%. In this case most of the moisture is present in the cavities of the timber, and is relatively free to be removed. At about 30% MC all of this free water has gone and the rest is contained inside the cells of the wood. This level is called the Fibre Saturation Point. Once this level is reached shrinkage starts to occur as the timber dries further. This is a process involving a change in dimensions of the timber. Shrinkage is negligible along the grain of the timber, but is significant across the grain. Tangential

shrinkage is normally double the amount of radial shrinkage, and this results in distortion or warping of the timber. The extent of warping depends upon the type of timber, its place in the log, and the method of sawing. The different types of warping are shown in *Figure 8.15.*

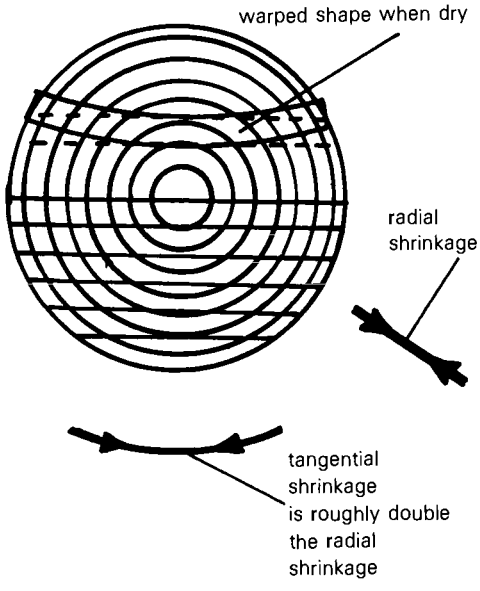


Figure 8.15(a) Flat sawn.

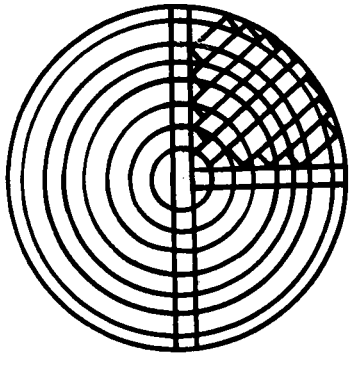


Figure 8.15(b) Quarter sawn.

8.5.5 Stability

The Stability of timber refers to its ability to hold its shape as the air humidity changes. Heart timbers are more stable then sapwood, but painting improves the stability of all timbers. The stability depends upon the method of cutting of the timber, the moisture content, and the seasoning given to the timber.

a. Types of sawing

The manner in which the planks are cut from the log affects the properties of the resulting timber, since the growth rings meet the face in different directions. This is indicated in *Figure 8.15* which shows the two main traditional methods, ie, quarter and flat sawn.

When timber is quarter sawn, the growth rings meet the cut face of the plank at an angle of greater than 45°. The advantages of quarter sawn timber are that it shrinks less in width, and it twists and cups less. In wood used for furniture, such as oak, sycamore or mahogany, it gives a better finish, and surface wear is more even. During seasoning there is less splitting compared to flat sawn timber.

In the flat sawn method the growth rings in most of the planks meet the face at an angle of less than 45°. The advantages of flat sawn timber are that it is cheaper to cut at the mill and there is less wastage. The timber dries more rapidly than quarter sawn timber under the same conditions. Any knots present are round, rather than spiked as in quarter sawn timber, and in some woods (eg yellow pine, cypress, douglas fir and redwood), it gives a more attractive finish.

The above methods are often replaced in modern mills by computer based cutting methods, where the log is measured and the cuts are calculated to minimise wastage.

b. Seasoning and stacking

Seasoning of timber is a process which reduces the moisture content of timber down to the equilibrium moisture content. Seasoning stabilises the timber, reduces the chance of fungal attack, enables the timber to receive paint better, and strengthens it. If the timber is seasoned properly the amount of warping is minimised. Air seasoning involves storing the timber in the open air and takes anywhere between six months and two years. The timber should be stacked in layers (with suitable equal thickness fillets between the layers) 450 mm off the ground on suitable bearers, and must be protected from sun and rain. The top layer should also be held down with some heavy weights. Variations in board thickness in any one layer should be avoided. When timber is stored on farm the same methods should be used.

Kiln seasoning is the artificial drying of timber and is achieved by controlling air circulation,

temperature, and humidity inside a kiln. Kiln drying is faster than air drying, and all the timber can be dried to a specified moisture content. The timber is also sterilised and the resins and gums in the wood are hardened in the process, and do not bleed after drying. In some types of kiln the wet timber enters the kiln at one end and moves slowly through. The heated air enters from the opposite end so that the driest timber is exposed to the hottest driest air. In others the timber stays in one place, and the air conditions are adjusted as it dries. This type offers a better degree of control over the drying process.

8.5.6 Durability and preservatives

Durability is a measure of the timber's ability to withstand attacks by fungal decay, marine infestations, or insect borers, in an untreated or unmodified state. The natural resistance of various timbers to attack is due mainly to deposits of heartwood substances which give heartwood a distinctive colour. The normal method for the determination of durability is to bury specimens of standard size in the ground for lengthy periods (eg, one to ten years). These tests are known as graveyard tests. If timbers are used in accordance with sound building practice, have adequate ventilation, are kept isolated from dampness, and have no direct connection with masonry, then they will have a much greater useful life. If the design detail of a building is good, properly treated sapwood can perform as well as heartwood in most situations.

a. Insect attack

Insect tunnels in timber spoil its appearance, and in very large numbers can reduce the strength of the timber. There are a number of different types of insect known in various countries as woodworm or borer, and the damage done varies. The common New Zealand house borer prefers the sapwood of both hardwoods and softwoods, but will also attack heartwood. Heart totara, heart kauri, oregon and redwood are resistant to attack. The insect will only attack timber with a low moisture content. On the other hand, pin-hole borer attacks only unseasoned timber in felled logs, sawn timber, and sometimes unhealthy standing trees. The term pin-hole arises from the characteristic holes or tunnels, which run across the grain and are stained with ambrosia fungus. The two-toothed longhorn is another New Zealand native insect which attacks a large variety of timbers including the heartwood and sapwood of rimu, totara, matai, kauri, miro and macrocarpa. In other countries termites are a major problem, capable of weakening wooden structures to the point of collapse, while in cooler climates the death-watch beetle has the same effect in old oak beams used in ancient monuments and churches.

b. Fungal attack

Fungi have special root-like hyphae which can dissolve out the starches and sugars manufactured by other plants. A minimum moisture content of 20% and a small amount of air is needed for their growth. Rot fungi live on the plant cell contents and also attack the cell wall, causing the timber to become dry and brittle, so that it crumbles when touched. Dry rot fungi require water, but they are able to generate special hyphae which spread out over concrete, brick and steel to locate wet areas. These hyphae then transport moisture back to the main body of the mycelium, so that seemingly dry timber will rot.

8.5.7 Treatment of timber

As discussed above, timber has a natural durability. However for most purposes, this is insufficient against the attacks it receives from the environment, and it is therefore necessary to give a chemical treatment to the timber to increase its durability. Timber can now be treated with chemicals which remain effective for long periods of time. Treatment equipment consists of a pressure vessel and the process involves the application of standardised procedures to impregnate the timber with a water borne weather resistant chemical, generally of the copper-chrome-arsenate type. The chemicals should not affect the adhesion of paint to the timber, or alter the strength of the timber. This is normally the case, as long as the treatment process does not involve undue pressure or temperature. Treated timber should still be properly stacked, as discussed elsewhere.

The aim of treatment is to reduce the timber's susceptibility to both insect attack and decay. To be effective, the preservative needs to be applied to the timber both at an adequate level of chemical concentration and also to an adequate depth. Protection over a long period of time is also needed.

Timber treatments depend upon the end use. *Table 8.9* indicates the uses and hazard situations for which the different treatments are appropriate. In all cases, except for smaller sizes, the timber must be branded according to the treatment given.

Table 8.9 Timber treatment

Brand	Use
Marine hazard–H6	Marine ply and timber in contact with sea water, oyster farming timbers.
Severe decay hazard–H5	House piles and poles, power and telephone transmission line poles, horticultural posts and poles (severe sites), plywood for foundations in ground contact, sawn timber.
High decay hazard–H4	Fence posts, agricultural posts for barns, cribwalls, plywood in ground contact, mushroom boxes, concrete boxing, sawn timber, timber in ground contact, fresh water piles.
Moderate decay hazard–H3	Fence rails, battens, palings, decking, exterior joinery, plywood, stained weatherboards.
Termite hazard–H2	Where termite hazards exist (not applicable to New Zealand, but may be relevant for export products).
Low decay hazard–H1	Framing, flooring, plywood, interior finishing, painted weatherboards.

The preservative should be retained in the timber for a lengthy period of time. For example timbers treated for ground contact should last for at least 50 years. Some of the lighter treatments use water soluble chemicals and these can be leached out if the timber is exposed to water. Building materials should therefore be covered on a building site. Marine timbers are subject to considerable chemical and insect attack, and the preservatives are under severe test to the extent that the service life cannot be entirely guaranteed.

When a treated timber must be cut, the exposed surfaces should be retreated with an effective preservative, such as copper or zinc naphthenate. This may not be easy if the cut is in a high hazard area, and professional advice may be needed.

Sometimes the preservative treatment fails to prevent decay. In these cases the most common reasons are either a failure to use timber with the correct treatment, eg, using water soluble preservative in an exposed area, or deep cutting of timber in high hazard areas. Failures can also occur due to inadequate treatment at the processing plant. This type of problem can occur due to the variable nature of timber. Decay or insufficient drying of the timber prior to treatment can also affect the success of the process. For these reasons treatment plants are carefully monitored and licenced to ensure that standards are maintained.

8.5.8 Fire resistance

Timber burns in the presence of extreme heat and air. This characteristic is an undesirable feature of timber as a structural material. However, when timber burns the charred material is moderately stable and acts as a protective cover for the underlying wood, reducing the rate of combustion.

Timbers chars at a rate of between 0.5 and 0.8 mm/min. The Fire Resistance Rating (FRR) specifies how long a structural member must support its designed load in a fire. Figures normally used for FRR are 0.5, 0.75, 1.0 and 4.0 hours depending upon the usage of the structure. Thus commercial buildings would require longer FRR values. For the purposes of determining the minimum dimensions of a structural member, allowances must be made for the loss of timber resulting from a fire of a duration as specified by the FRR. Regulations for fire resistance are given in the New Zealand Standard NZS 1900, while structural fire resistance ratings are given in SANZ report No MP 9 (1987)).

The fire retardant treatment of timber reduces flame spread, the rate of fuel consumption, and the density of the smoke produced. Treatment for fire retardation

involves pressure impregnation with suitable chemicals. For example, one commercial system uses ammonium phosphate. In a fire this reacts to produce ammonia gas which dilutes the oxygen levels at the burning surface, and a phosphate which produces a hard charcoal layer which insulates the underlying wood. In addition moisture is produced which lowers the temperature by evaporative cooling.

8.5.9 Timber connections

In many cases of failure in timber structures the failure occurs at the joints rather than in the timber itself. Fastening and securing timber is a major problem which must be dealt with properly. Density, strength and hardness of the timber all affect the final strength of a joint. A number of terms are used to describe the strength of a joint. The most general is the *Joint Efficiency*. This is defined as:

$$\text{Joint efficiency} = \frac{\text{Strength of joint}}{\text{Strength of material}} \times 100$$

Equation 8.9



Figure 8.16(a) Timber joiners. Included in this photograph are a nail, a serrated nail, a wood screw, a Z nail, a galvanised steel joining plate, a coach bolt, a gang nail plate, and four "bulldog" or claw ring connectors (which are placed between the pieces of timber).

Joints in timber can be made with a very large range of fasteners. The most common are nails, screws and bolts, followed by glue, gang nails, grooved nails, rings and other patented devices. Some of these are shown in *Figure 8.16*.

Nailing is quick and simple, requiring only a hammer or a nail gun. The latter is faster and easier to use but potentially very dangerous. It should only be used by trained persons. Joint effectiveness is dependent on whether

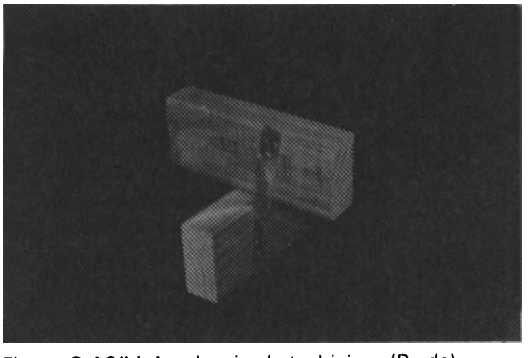


Figure 8.16(b) A galvanised steel joiner (Pryda).

the timber is green or dry: dry timber holds nails better, but is more difficult to nail into. Harder timbers tend to split at the ends, and nail (and screw) holes must often be drilled beforehand, which is time consuming and tedious. Nails driven into the end grain have very little holding power. Plain nails are important because they are one of the easiest and commonest connectors in use. However they are also one of the weakest. The withdrawal force for a 4 mm diameter nail in radiata pine is only about 4 N/mm length of the nail in the timber, while the shear load is 340 N. To avoid splitting nails should not be placed closer than 20 times the nail diameter apart unless the holes are pre-bored.

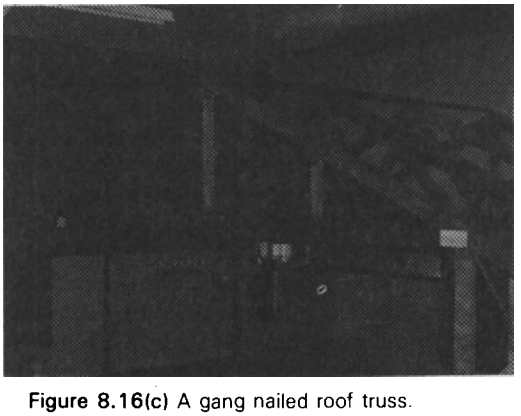


Figure 8.16(c) A gang nailed roof truss.

Joint strength can be improved by using grooved or spiral nails. Screws are stronger against withdrawal (15 N/mm for a 4 mm diameter screw), but slightly weaker in shear. Gang nails are much stronger since they consist of a large number of small nails over a large area. They are applied by hammering, or with a hydraulic ram, and are common in prefabricated trusses, butt joints and for attaching purlins to rafters. Glue joints are also considerably stronger than nailed joints, but must be prepared properly. Full details of the design and relative strength of joints are given in the New Zealand Standard NZS 3603. Although the art of joinery is still practised in quality woodwork, specially cut tenon joints are rarely used in building construction, although some precut building systems involve preparing the timber joints at a factory on semi-automatic machines. On site the best joint will be the one which is strongest and the least expensive in time and materials.

8.6 STEEL AND OTHER METALS

For strength and rigidity in tension, metals and alloys are virtually unbeatable in the construction industry. Metals are elements which conduct electricity. The metal used most in construction is iron (Fe), but it is rarely used in its pure state. If carbon is added to iron in small quantities (from 0.15 to 3.5%), the result is a material which is stronger and more durable, which we now call steel. Legend has it that this was discovered by accident when iron age dwellers heated their iron weapons and implements over charcoal fires to hammer them into shape. The addition of other elements can improve the strength properties even further, and can also alter other properties, such as machinability and corrosion resistance. Stainless steel is thus an alloy of iron, carbon, chromium and nickel, and possesses very good resistance to chemical attack. The cost of steel is extremely low, and its properties can be altered virtually at will by heat treatment, which makes it a very useful material for general farm use. It is produced from iron ore (pig-iron) which is melted in a furnace. Other elements are added according to the type of steel required, and the mixture is then poured into moulds and cooled (*Figure 8.17*). Often continuous round bar moulds are used, and the steel can



Figure 8.17 White hot molten steel is poured into a mould.

then be drawn through dies to produce wire and other products.

8.6.1 Types of steel

There are many types of steel in use today which have been developed for special purposes. These may be loosely classified as either straight carbon or alloy steels. Straight carbon steels are used very extensively in agricultural and horticultural machines and equipment, and these will be dealt with more fully. We will describe heat treatment processes here, even though this will mean a slight digression away from the subject of buildings and structures, in order to consider some important practical uses of steels on the farm.

Alloy steels are steels which have small amounts of one or more other metals such as tungsten, nickel, chromium, silicon and vanadium, mixed with the steel. These metals are used in steel to give it certain desirable properties, such as great strength, hardness, resistance to corrosion, toughness and resistance to shock. High tensile steel is made so that it can have up to four times the strength of ordinary steel. Stainless steel (which contains chromium and nickel) is very resistant to corrosion. High speed steel is used for drills and machine tools. It can still keep its cutting edge when nearly red hot.

Carbon steels may be classified into three main groups, according to the amount of carbon present.

(a) Low carbon steel (often referred to as mild steel) contains carbon from 0.1 to a maximum of 0.5%. This steel is used everywhere in large quantities and is produced by steel rolling mills in all standard shapes. Rolled steel joists, channel iron, single iron rounds, flats, sheet steel, wires and many other shapes are all readily available. This steel, because of its excellent properties of strength, toughness and ease of working, is used in bridges, buildings, motor vehicles, tractors, farm implements, domestic appliances and in practically every other field.

    Most of the rounds and flats used around a farm are black mild steel. They can be readily worked by hammering, heating, welding and machining. Cold rolled steel is a high grade of low carbon steel and is bright, rather stiff and is quite exact in dimensions. Its strength is higher than black mild steel and is widely used for axles and shafting. Mild steel cannot be hardened and tempered, although limited case hardening is possible.

(b) High carbon steel, also known as tool steel or cast steel, contains carbon from 0.5 to 1.5%. Because it can be readily hardened and tempered (as discussed below), it is widely used for tools, such as hammers, chisels, pickaxes, saws, punches, screwdrivers, knives, drills and many others.

(c) Cast iron contains between 3.0 and 3.5% carbon, usually with silicon, manganese, phosphorus, and sulphur in varying quantities. Its composition is less critical and it is often produced from scrap metal, so that it is less expensive than steels with a lower carbon content. It can be melted and poured into intricately shaped moulds, and it is used widely for components which need to be heavy and solid, but which do not have to sustain high stresses. Its properties depend upon the rate at which the casting is cooled, and also upon the levels of manganese and silicon. White cast iron is produced when the casting is cooled quickly. It is very hard, and has good abrasion resistance, but it is a very brittle material, and is more likely to break under impact than steel. Grey cast iron (so called because the fracture surface has a grey colour) is produced by slow cooling, and this is quite soft and can be machined easily.

8.6.2 Heat treatment of steels

Hardening

Hardening is the process of heating steel to a critical point called recalescence, and then cooling quickly in water, oil or air. At the recalescent point, which is when the steel appears cherry red in colour, the atomic structure of the steel changes. The steel is no longer attracted by a magnet. Cooling quickly prevents the structure from changing back to the free state, as it would if allowed to cool slowly. This makes the steel very hard. The degree of hardness is determined by the amount of carbon in the steel and the rate of cooling. Air is the slowest cooling agent

followed by oil and then water. The higher the carbon content and the more rapid the cooling, the harder it will be. Harder steels are more resistant to wear and abrasion, and have greater strength.

Tempering

A steel which has been hardened will be hard, but it may also be too brittle, and must be softened or tempered to allow the steel to withstand the hammering, bending or twisting it will receive in normal use. This may be done by reheating it to a certain temperature and then cooling again. The amount of softening (tempering) that is given to the tool will depend on the temperature to which it is reheated.

All bright steel, when heated, changes colour. The colour, which appears on the surface of the metal, is due to an oxide coating. The change occurs during the tempering process, so that the colour of the metal can be regarded as an indication of the final hardness after quenching.

The colours, in order of appearance from cold, are as follows:

Light straw	204°C
Dark straw	245°C
Purple	285°C
Blue	310°C

As will be seen, the lighter the colour the lower the temperature, and so the lighter colours will leave the steel in the harder condition. The harder the steel the more brittle it will be, and a balance must be struck between these two properties.

The following is a guide to tempering colours:

Light straw – knives and wood chisels.
Dark straw – punches.
Purple – cold chisels, picks, axes, screwdrivers and most sharp edged tools.
Blue – springs.

Hardening and tempering such tools as chisels, pickaxes and crowbars is usually carried out in one heating. In preparation the tool must have a ground or bright surface so that the tempering colours will show clearly. For example, the following procedure can be used to harden the cutting edge of a tool. The whole end of the tool (70 mm to 80 mm) is heated to an even cherry red. Then the first 25 mm is dipped into a bucket of water and moved around rapidly until it is cold. The scale is removed quickly with a piece of emery cloth wrapped around a file. This allows the tempering colours to be distinguished easily. Heat flows from the hot parts of the tool towards the cooled end, bringing the band of tempering colours with it. When the correct colour reaches the cutting edge, the edge is dipped in the water again, and left until the red heat disappears. Then the entire end is submerged. If the whole end is cooled while some red heat remains, the red portion would become hardened and would probably break in service.

Some steels, particularly spring steels, are made for oil hardening only. Oil, cooling at a slower rate than water, leaves the steel in a tougher condition than water cooling. Oil hardened steels are able to withstand continuous flexing and shock.

Annealing

Bar tool steel is supplied in the annealed or soft condition, making it possible to saw, drill or machine. In many cases where tools have been made from old springs, files or sawblades, the steel must be softened before it can be worked. The steel is heated slowly to a uniform cherry red heat and allowed to cool slowly away from draughts in say, a box of dry lime or ashes. The slower the rate of cooling the softer will be the steel.

On no account should tool steel be overheated beyond a bright cherry red. Temperatures in excess of this damage the steel leaving it coarse grained and weak. If forging say, a pick head, the steel should be hammered only when it is between a cherry red and a medium heat, as forging at too low a temperature also damages the steel.

Case hardening

This is a process used to harden the outside skin of a low carbon steel. It is used on occasions where it is desirable to have steel with a strong tough core, and also to have a hard wearing surface on the outside. Mild steel pins, pawls and other parts subject to wear can be case hardened, using a commercial case hardening powder.

The item to be hardened is heated to a red heat and then dipped into the powder which adheres to the hot metal. It is then reheated

to a cherry red and then plunged into cold water. The surface should now be hardened to the point where a file can scarcely make an impression. This is brought about because the steel absorbs carbon from the powder. The depth of the case will only be between 0.4 mm to 0.8 mm.

A greater depth of case may be obtained by repeating the powder process two or three times. By using special furnaces and compounds, manufacturers can produce a hard layer up to 1.5 mm deep.

8.6.3 Corrosion of metals and its prevention.

Corrosion of a material is the removal of the material by chemical activity. The rate of removal depends on the environment surrounding the material. Water and oxygen are needed, and other chemicals such as sulphates and nitrates accelerate the corrosion process. Some materials, such as stainless steel, are extremely stable and corrode only very slowly even in very hostile environments. Others, such as aluminium, corrode rapidly, but the corrosion product (eg, aluminium oxide) forms an inert protective coating which prevents further corrosion. However, if this coating is removed by mechanical or other means then further corrosion will occur. Corrosion can also be prevented by chemical inhibition. Steel is easily corroded, but if a layer of zinc is placed on the wire, this will corrode before the steel, and the steel will therefore remain intact until the zinc has gone. This is known as galvanising, so that galvanised iron (steel) sheeting is really a steel sheet which has been coated with a layer of zinc. Small defects in the zinc coating will not be too serious, since the surrounding zinc will still provide sacrificial protection.

Another form of protection is to paint the steel, with the aim of preventing the air and water from reaching the metal. Some products are coated with aluminium which serves the same purpose. With these forms of protection small defects could become sites for localised corrosion, so that good preparation and workmanship are very important.

8.6.4 Use of steel in buildings

Compared with other materials, steel is an excellent low cost high strength material which is readily available world-wide. For construction purposes beams and girders made from mild steel (around 0.25% carbon) are generally used. The "I" shaped beam is one of the most common forms (*Figure 8.18*). It is in this shape to take advantage of the stress distribution pattern in a beam under bending. As we know (Chapter 3), the greatest stresses are at the edges of the beam furthest from the neutral axis. The I-beam has its flanges just at this point, resulting in a component which produces the maximum rigidity and strength at the least cost and weight. I-beams are produced in a wide range of sizes, and the strength properties are available from the manufacturers.

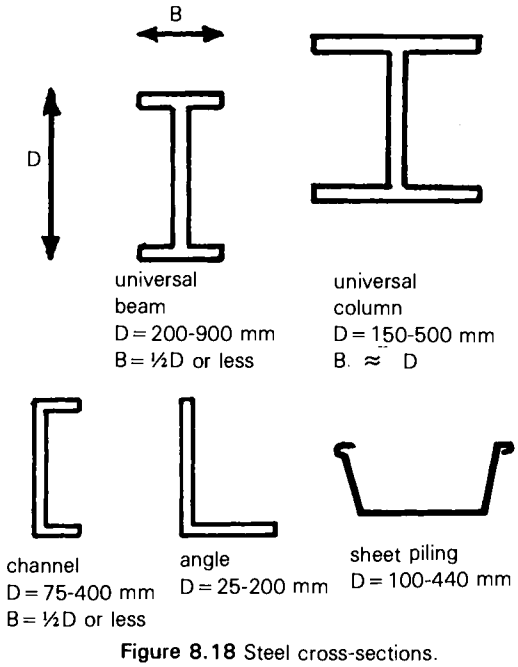


Figure 8.18 Steel cross-sections.

8.7 CONSTRUCTION SYSTEMS

8.7.1 Flooring

For heavy duty areas such as workshops, milking sheds or other other places where a long life, hard wearing surface is required, a concrete floor is the most appropriate choice. Concrete is also used for housing in areas where it is less expensive than timber. It has a higher heat capacity than timber, and so it helps to retain a constant temperature in the room. The basic requirements for a concrete floor are that the area must be well drained,

the ground properly compacted, and a suitable fill used, so that the floor will not crack in service. Sand or fine gravel (pea metal) should be used to attain the final levels, and a suitable damp-proof course must be used between the sand and the concrete. This can be a polythene sheet, bitumous impregnated felt, or a synthetic malthoid barrier. It should be placed at least 150 mm above the surrounding ground level.

Reinforcing steel is often used in the concrete to distribute loads from walls and to minimise shrinkage and cracking. If heavy machinery and vehicles are going to run over the concrete then heavy duty reinforcing is required. Examples of typical construction designs are shown in *Figure 8.19*.

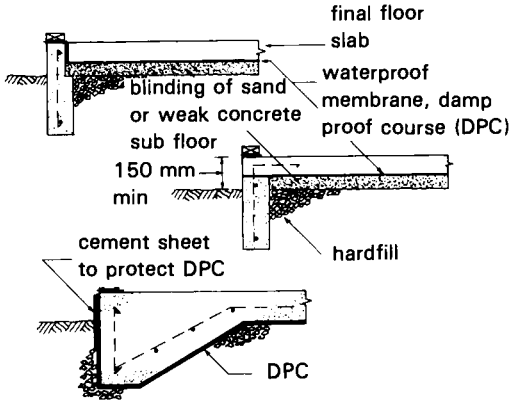


Figure 8.19 Examples of concrete floor foundations.

Timber flooring consists of conventional pile, sleeper and floor joist construction overlaid with timber, plywood or particle board flooring (*Figure 8.20*). The timber sizes depend on the span and expected load carrying capacity, while pile spacings depend on the soil bearing capacity. Types of piles can vary from precast concrete to driven short timber piles, providing the latter are properly treated with preservative.

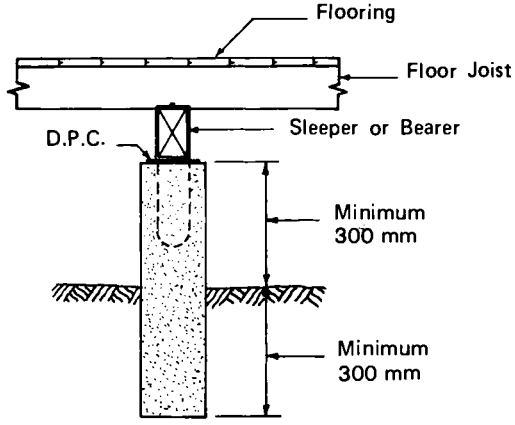


Figure 8.20 Timber floor construction.

If concrete piles are used, the use of a suitable damp proof course (DPC) (usually malthoid) is essential between the timber and the concrete. The importance of the DPC cannot be over emphasised, especially with respect to minimising the potential decay hazard. It should be at least 300 mm above the surrounding ground level.

The type of flooring used depends on the use, the loading and the wearing characteristics. As a guide only, some approximate design loads are given in *Table 8.10*. Nowadays a vapour barrier between the floor and ground is required. This is formed using draped perforated aluminium foil, which prevents groundwater evaporation from beneath the floor of timber houses diffusing into the house.

Table 8.10 Design loads for flooring

Description	Live load (kPa)
Floors for livestock	400
Floors for light storage (eg, baled hay up to 3 m stack height)	600
Floors for implements and light vehicles	700
Floors for woolsheds (3 bales stack height)	700
Floors for bagged grain or fertiliser (stack height – 2 bags on end)	1400

c. Slat and grating floors

For animal and bird housing slatted floors provide a convenient way of enabling self cleaning into an underfloor effluent pit or channel. The slat spacing should not exceed 40% of the hoof width, and the slats should ideally be tapered with the thicker edge uppermost. Wood, concrete and metal gratings can be used.

8.7.2 Walls

The walls of a building must support and secure the roof and ceilings, and any other structures such as water tanks, or equipment

in the loft. They must also provide bracing for the structure to prevent lateral movement. This arises because wind loads and other horizontal forces induce sideways movement of the structure. If the walls are not braced properly, then the structure may be able to shear as illustrated in *Figure 8.21*. This problem is particularly important in timber frame buildings.

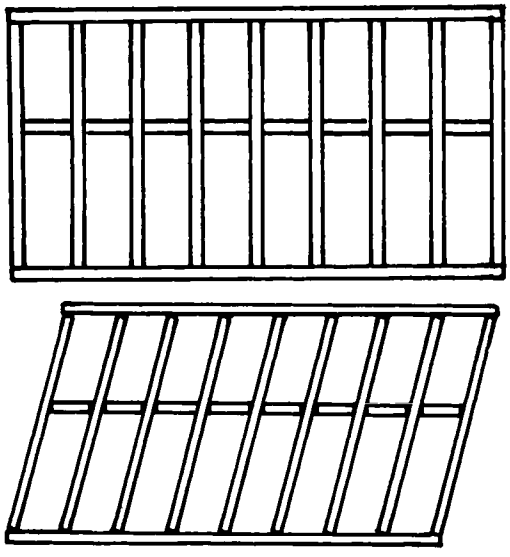


Figure 8.21 Failure of an unbraced wall.

There are four main forms of wall construction. These are solid concrete, cavity block, brick, and timber framing.

a. Solid concrete

This type of wall construction is limited to large commercial buildings, since it requires complex boxing, together with considerable expertise in the placement of reinforcing, and the equipment and knowledge to place and vibrate the concrete correctly. Some buildings are constructed from precast concrete slabs which are poured on a level surface and tilted into position.

b. Cavity block

This system is now used extensively. It involves using concrete blocks bound with mortar and reinforced with steel rods at appropriate points. An example showing typical details of this form of construction is shown in *Figure 8.22*. Although not particularly difficult, cavity walls require some care for a good result, and should be designed properly.

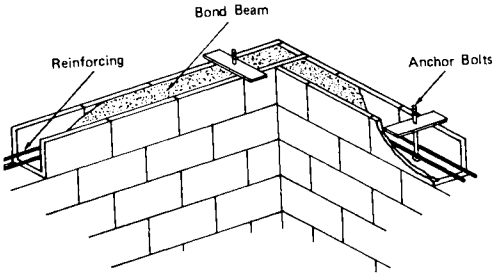


Figure 8.22 Block wall construction.

c. Brick construction

Although common in many cooler countries, brick is relatively rare in New Zealand, other than as an external cladding or veneer. This is largely a result of the relatively high cost of brick structures compared with other materials, but also because a heavy, two layer brick wall is a serious hazard in an earthquake. Elsewhere, bricks made from mixtures of cement, concrete, sand or soil and mud have been made successfully.

d. Timber frame

This is the most common form of construction in New Zealand thanks to the ready availability of materials. The New Zealand Standard NZS 3604 covers the requirements for size and spacing of the timber. *Figure 8.23* illustrates the normal construction pattern.

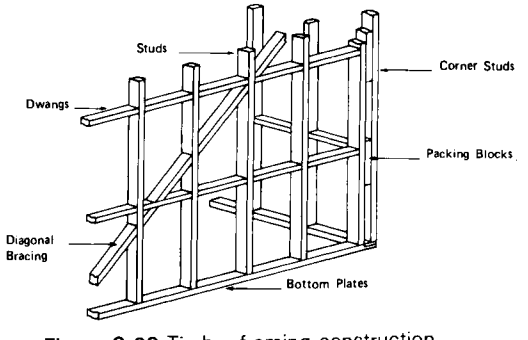


Figure 8.23 Timber framing construction.

One of the key components in a frame structure is the bracing. This gives the structure rigidity. Bracing can be provided by diagonal timber members or with galvanised steel strip. The strip is easy to use because it will run from one edge of the frame to the other, and the studs it crosses over are just notched or checked on their sides so that the strip fits into the notches. It is then nailed into

place. Another alternative is to use the wall cladding as bracing. The cladding must be in the form of a strong panel which must be nailed or stapled to the frame, and must meet the appropriate regulations. This type of bracing is called sheet bracing, and is often used in addition to diagonal steel or timber bracing.

The amount of bracing required depends upon the wind loads, the location, and the earthquake loads. The wind loads depend upon the area exposed to the wind and upon the size of the roof. Suitable bracing is placed at right angles to the side under load (eg, parallel to the wind direction). The bracing required to withstand earthquake loads is defined by the earthquake zone and the size, shape, and height of the building. In general bracing is distributed at the corners of external walls and throughout the building at not more than five metre intervals. In New Zealand different bracing structures are given a bracing unit value, and the sum of these bracing unit values must exceed defined minimum values in all directions.

8.7.3 Wall claddings

The choice of a wall cladding will depend upon the cost, availability, appearance and durability of the material.

a. Weatherboard

This is a cladding which consists of planks of timber nailed horizontally or vertically and which overlap to produce a waterproof surface. Although modern timber is treated against rot and insect attack, timber weatherboard must be painted every five to ten years. Galvanised iron weatherboard is an alternative which is less expensive and looks similar from a distance.

b. Stucco or roughcast

These are terms for cement plastered surfaces applied onto concrete or other backing materials. A rigid backing, usually in the form of precast cement and fibre wallboards is normally used. However, a non-rigid backing consisting of a waterproofed building paper or bitumised felt, and covered with a galvanised metal mesh to provide a key for the concrete, has also been used. These walls are strong and reasonably durable, although cracks may develop over a long period of time or if there is any settlement.

c. Galvanised steel (iron)

Corrugated steel sheeting is one of the least expensive forms of cladding. It is not particularly pleasing aesthetically, but it is durable. It will require painting, particularly in polluted atmospheres such as animal shelters or fertilizer stores, and in highly salty atmospheric situations within a few kilometres of the coast. Any overlaps between sheets are particularly susceptible to rusting as moisture is trapped in between the sheets. Fortunately nowadays long-run sheets can be purchased which are cut to the length required for the building, and these eliminate the need for overlaps in the middle of a run. However edge laps between sheets and covered areas at the ridges cannot be avoided. These are potential rust spots in the long term, and should be given an extra coat of protective paint before assembly.

Other types of metal sheeting are also available. Different shaped sections are more appealing and more durable. Precoated coloured steel sheets offer a cladding which does not require painting for at least 15 years.

d. Other materials

Aluminium, stainless steel and other metal sheeting can be used for special situations. In addition, fibreboard, constructed from reconstituted wood, can be used as a cladding. These have replaced asbestos based sheets which are a major health hazard.

Plastic corrugated sheeting can also be used as a cladding. Transparent sheets will allow natural light into a building. However plastics are generally not as strong as other materials, and unless treated against ultraviolet radiation will go brittle after a few years. Glass fibre reinforced plastic is another alternative for special situations where stringent hygiene requirements must be met (eg milking sheds).

8.7.4 Roofing

Galvanised steel is the cheapest and most common form of roofing material used in New Zealand. Colour steel and metal tiles are more attractive but slightly more expensive. However the durability is probably better. Both are light weight, which is a significant advantage in areas which are prone to earthquakes. In colder and very much hotter countries materials with better insulation properties are more common. Slate and

concrete tiles are used in countries where resources are available or where the environment is too polluted to allow galvanised iron roofs to last for more than a few years. Earth, thatched and ice roofs are also known in different parts of the world. Examples of roof construction methods and types are shown in *Figure 8.24*.

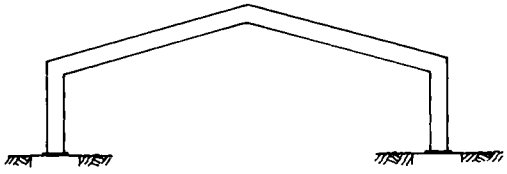


Figure 8.24(a) Portal frame.

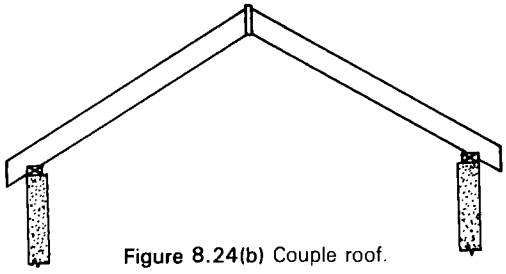


Figure 8.24(b) Couple roof.

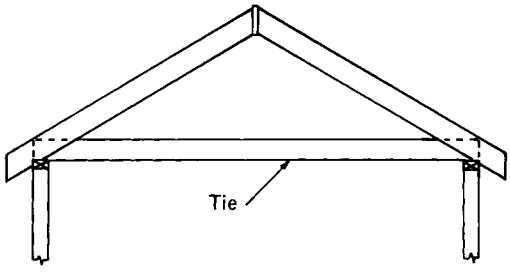


Figure 8.24(c) Couple close roof. The tie prevents spreading of the roof.

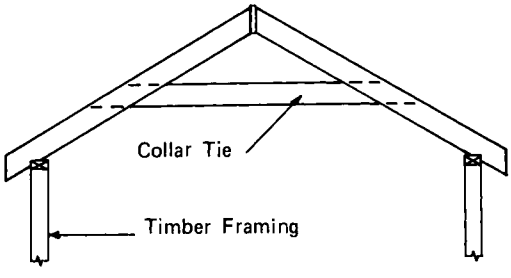


Figure 8.24(d) Collar tie roof.

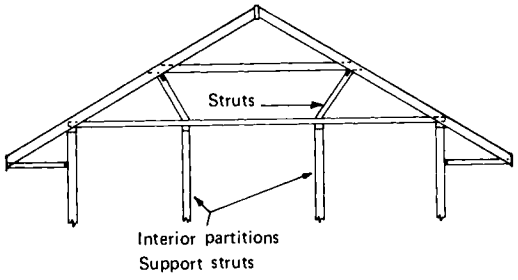


Figure 8.24(e) Couple close/couple tie.

8.7.5 Pole frame construction

Pole frame construction is an economic and viable way of constructing buildings on sloping or difficult sites (*Figure 8.25*). It is also an economic design for many farm buildings. It is particularly applicable for steep hill sections where the site should not be disturbed more than necessary. The major design factor to consider is achieving a suitable embedment of the poles to gain structural stability, particularly against wind loading and earthquake. This will depend upon the height and length of the building, the diameter of the poles, the wind velocity in the area, the slope of the ground, whether the building is clad or open, and the properties of the soil. Poles are normally embedded in concrete. In general the pole embedment depths are in the range of 1.2 to 2.4 m.

When using poles there are a few practical considerations. Where bolt holes are drilled to obtain permanent fixing, all the exposed timber surfaces must be liberally coated with the original preservative. Bolts and structural plates must be galvanised and liberally coated with grease or bituminous solutions to prevent corrosion due to the preservative salts. Nylon sheathed or powder coated components can also be used. Attention to fixing details is critical if the structure is to be a success.

8.8 GREENHOUSES

The siting of a greenhouse involves many factors. Nearness to market, climate, soil type, and ground topography are obviously important factors. In addition, a sheltered site is essential since the wind can break panes of glass or rip plastic films, and will present

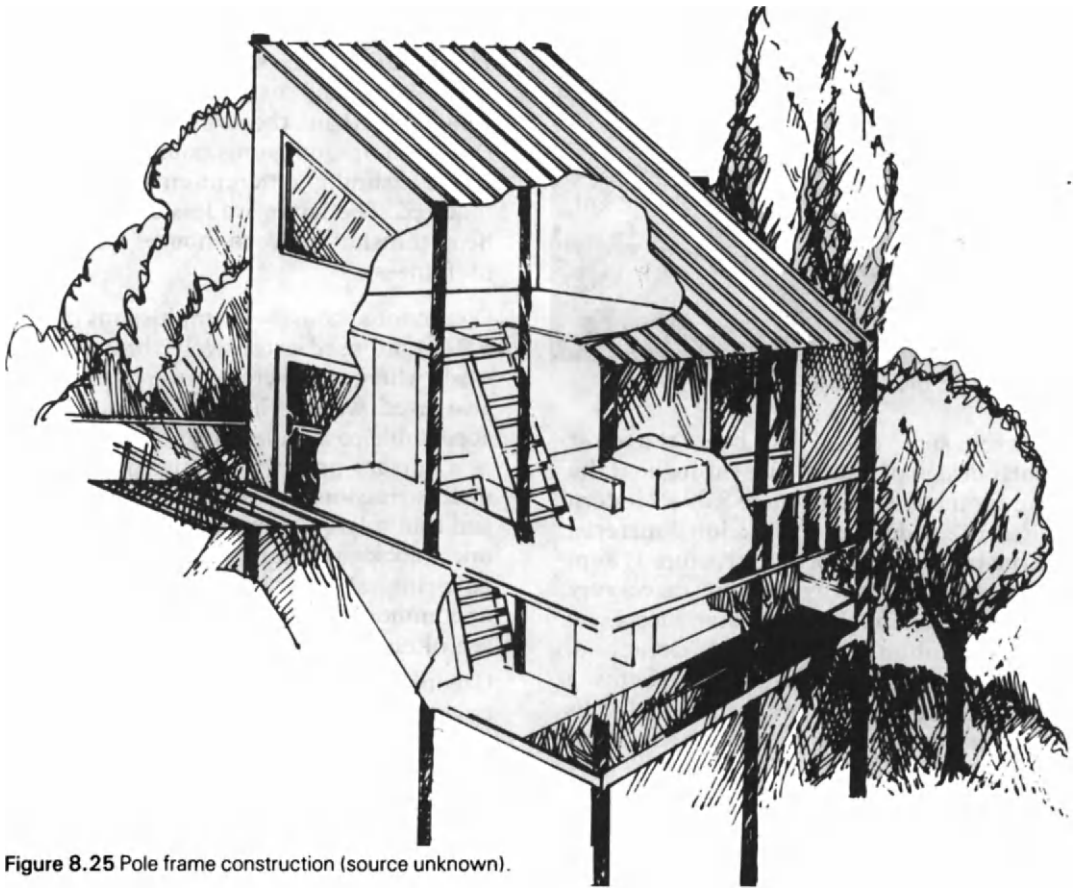


Figure 8.25 Pole frame construction (source unknown).

ventilation problems as growers adjust ventilators according to the wind direction. A strong wind will also greatly increase the heat loss from a greenhouse by increasing the U-value of the film coefficient (Chapter 7). For example a wind velocity of 7 m/s will double the heat loss from a glasshouse compared to still conditions. Shelter is therefore needed. It may be living or non-living and should not shade the greenhouse. Perforated shelters are better than solid obstacles because of wind eddy effects with the latter. A reliable water supply is essential (eg, a 270 m^2 tomato house could use 130,000 litres over a six month period).

8.8.1 Greenhouse design

The range of designs used throughout the world is not extensive, although it has been increased with the advent of plastic films. Once a greenhouse has been erected it is not easily modified so that it is essential the correct decisions are made at the start. A poorly designed greenhouse can affect the environment to the extent that good crops cannot be grown. The environment inside the house is often determined by the design, and by the materials used, as we shall see. First we will outline the main types of design.

The simplest design of all is the lean-to greenhouse. This has a very limited commercial application. The house is built onto one side of an existing building facing the winter sun, and is quite pleasant for domestic situations. The house can be designed to be a solar heat collector to heat the rest of the building. However, as a greenhouse, it is small, ventilation is often poor, and the transmission of sunlight is limited to one side of the house.

Uneven span houses, as shown in *Figure 8.26*, have the advantage that in mid-winter they will transmit more light. The house must be erected so that the large expanse of roof faces the sun, and will therefore have an East/West orientation. This house is more expensive than the traditional even span and has not been widely used.

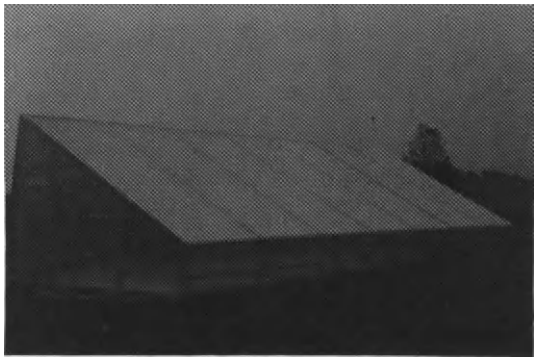


Figure 8.26 Uneven span greenhouse (Sweden).

The even span house has been the most popular design of greenhouse throughout the world for many years (*Figure 8.27*). Modern designs use wide sheets of cladding material and the internal supporting structure is kept to a minimum. As a result they have very good light transmission characteristics. Even span greenhouses may be detached, contiguous (where each section shares a wall), or continuous, where the internal walls are replaced by a simple support structure.

Detached houses are the most expensive. They are however separate units, transmit more light, and can be more effectively ventilated than the other arrangements. Detached or contiguous houses can be used where distinctly different environments are required. The latter are less common, since heat transfer between houses limits their usefulness.

Continuous houses or multispans (*Figure 8.27c*) are used extensively throughout the world where single crops are grown. They are also used where the one environment is acceptable to a wide range of species (such as a nursary producing house plants). Their main attractions are the reduced capital cost and that a large crop is easier to manage in one block. In Europe blocks of houses covering six to ten hectares are not uncommon. Because of the roof pattern they are often called ridge and furrow blocks.

Greenhouse size has an effect on the environment within. Small houses have good ventilation and light transmission, but the

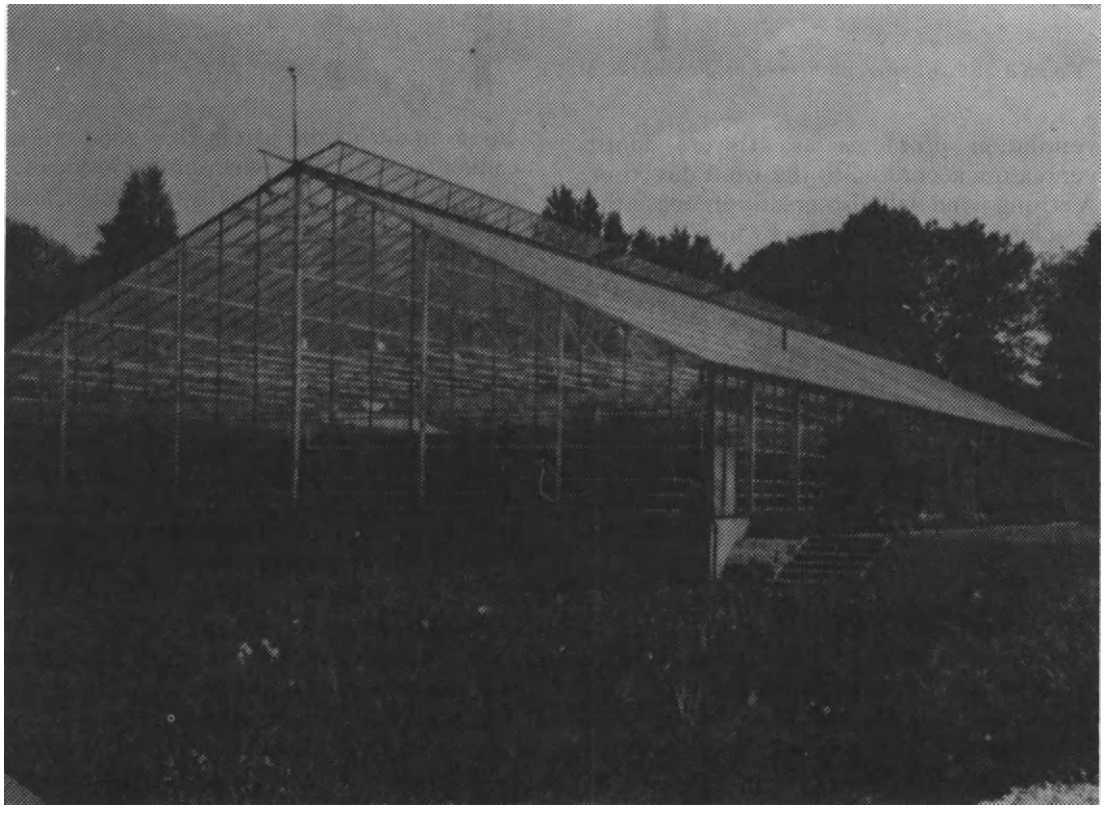


Figure 8.27(a) Even span greenhouse (Denmark).

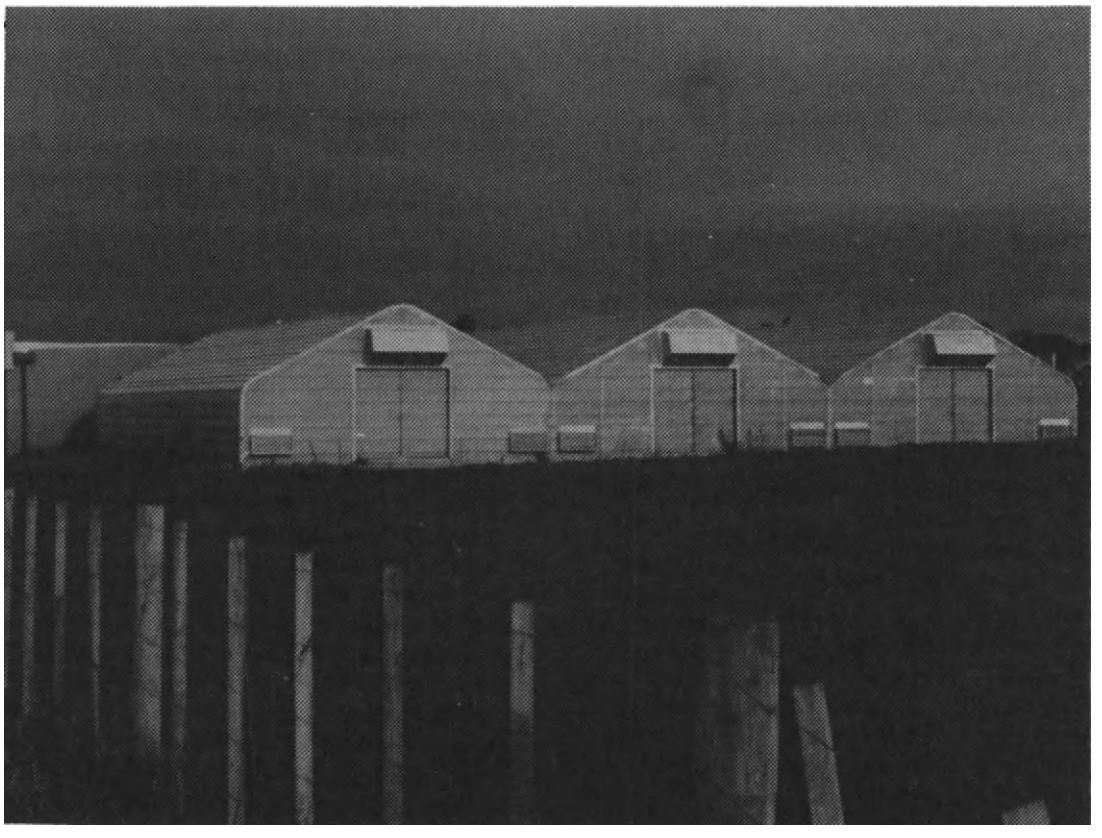


Figure 8.27(b) Contiguous even-span greenhouses. These are clad with a rigid non-translucent fibreglass material.

heat loss is high, and the temperature can vary rapidly. If the ventilation is good the humidity tends to be lower. This is particularly true for small glasshouses. In a large greenhouse the larger bulk of air and the smaller surface area to volume ratio means that temperature fluctuations occur more slowly.

The pitch of the greenhouse roof (the angle to the horizontal) depends on several factors:

First, the greater the pitch of the roof the greater the cost. Second, it could be chosen to give maximum winter sunlight transmission. Although at a latitude of 40° the mid-day sun is at an angle of 27° to the horizon in mid-winter, a pitch of 63° would not be the best! Apart from being very steep and very costly to build, research has shown that it does not collect the maximum amount of sunlight anyway (Critten, 1987). It is not clear yet what the optimum angle would be, but it appears not to be too critical. In order to achieve the same end, solar water heaters

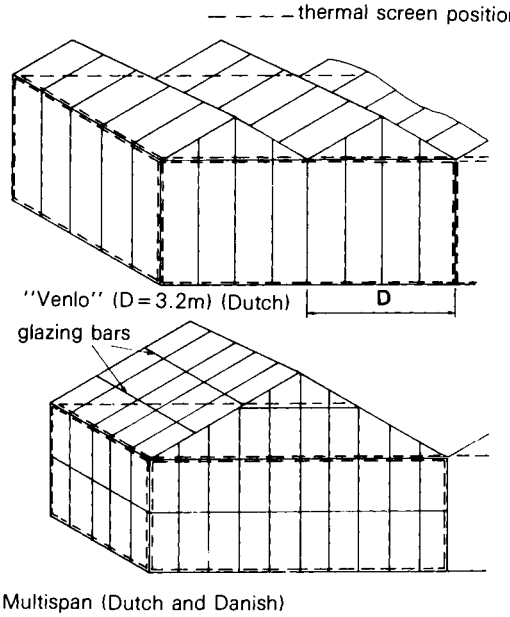


Figure 8.27(c) Continuous multispan greenhouse.

are set at about 40° to 50° at this latitude. Third, in some countries snow loading is an important consideration. Fourth, if the greenhouse is built from glass panes which are overlapped, and if the roof is too flat, then water will enter the house through the glazing gaps under surface tension. If the roof pitch is more than 26°, or there are no glazing gaps, then this will not occur.

The orientation of a greenhouse is the direction in which the ridge runs. At higher latitudes, an East/West orientation can collect more direct winter sunlight than a North/South orientation (eg, as much as 50% more in the UK). In lower latitudes the difference is much less.

8.8.2 Control of the greenhouse environment

The grower with a greenhouse crop has the big advantage of being able to exert some control over the environment of her crop. This enables her to influence the timing of the maturity of the crop, and to produce improved yields with greater consistancy and fewer disease problems.

The greenhouse environment can be divided into above ground and below ground parameters. Above ground the key factors are solar radiation (including visible, infrared and ultraviolet radiation), temperature, air changes (ventilation rate), moisture (humidity), and the composition of the atmosphere (particularly the carbon dioxide, CO_2, and oxygen, O_2, levels). Below ground factors include soil temperature, moisture, physical condition of the soil, nutrient status, pH value, and the composition of air in the soil. The change in the level of one factor will often affect the others. Thus an increase in solar radiation will raise air temperature and so influence the moisture content of the air (humidity). This will also raise the soil temperature. Changes in soil moisture will bring about changes in soil temperature, nutrient availability and possibly the composition of the soil air, by impeding the exchange of CO_2 in the soil with O_2 in the air.

Ideally it would be nice to control the greenhouse so that the growing plant's temperature and environment were set at the right levels. To do this we would need to detect the way the plant was behaving by measuring its temperature and activity, such as the flow of sap in the stem. Unfortunately this type of measurement is very difficult and expensive, and so instead we control by fixing the temperature (and sometimes the humidity and carbon dioxide levels in the air) in the greenhouse to values which experience suggests suit the plants. Thus sensors are used to measure the environment inside the greenhouse, and the outputs from these are used to control the environment to within what we believe is an acceptable range for the plants.

Control is achieved in a limited number of ways. The house can be ventilated, by opening vents, or by switching fans on which blow air in or suck it out. Ventilation is measured by the number of complete air changes achieved in the house per hour. It is a way of reducing the temperature, reducing the humidity, or increasing the CO_2 levels if they are depleted. Unfortunately ventilating does all three at the same time, and this may not always be what we desire! For example on a cold day, opening the vents to reduce humidity will cause the temperature to drop below the desired level. It is therefore necessary to specify a heirarchy of control preferences. Thus if the temperature is too low, the controller can be set so that ventilation is stopped, regardless of the humidity and CO_2 requirements. In many greenhouses this is done by default since only the temperature is controlled in any way.

Carbon dioxide levels are measured in microlitres per litre (μl). This is the same as parts per million (ppm) on a volume basis, but the meaning is clearer. CO_2 depletion is often ignored, even though in a closed house during the day, the level may fall as low as 100 μl from the normal air levels of 330 μl. Many growers now use CO_2 enrichment to increase yields. This involves burning propane gas so that the waste gas (which is rich in CO_2) raises the level to 1000 μl or more. This has a marked effect on the yield of many crops. Unfortunately CO_2 enrichment is only effective during the daytime when plants are photosynthesising, and if the temperature rises so that venting is required for cooling enrichment becomes impractical. Carbon dioxide analysers are relatively costly, as are regulators which control the levels. Frequently the enrichment involves burning propane at a known rate based on the size of the house and the air

change rate, and assuming that target levels are met as a result.

Temperature control requires an accurate sensing system. The sensors must be placed in an aspirated screen. This is a box with insulated sides which shield the sensors from direct sunlight as well as radiant and conducted heating (*Figure 8.28*). The box



Figure 8.28 Aspirated screen.

contains a fan which draws air into the box and over the sensors at a minimum air speed of three metres per second. The screen must be mounted in a position which is at about the same temperature as the air around the plant (ie, it must be not too high, or in a corner where temperatures are not likely to be representative of the whole house). In an automatic greenhouse the sensor will be linked to a controller which is programmed to open the vents or switch the fans on if the temperature is too high, or to operate the heaters if it is too low (*Figure 8.29*).

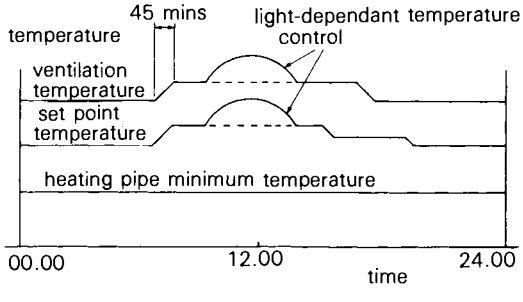


Figure 8.29 Automatic control sequence. During the day the set point and ventilation temperatures vary according to insulation levels.

Humidity is hard to measure and control accurately. It is not clear how crucial humidity is to the vigour of the crop. At high humidities the chance of disease appears to increase, while at low humidities crop water losses are higher. Often a compromise is aimed at of around 70% RH. Relative humidity is measured by a special sensor, or by wet and dry temperature sensors in the aspirated screen (*Figure 8.28*). Environmental measurements are discussed further in Chapter 12. These sensors rely on the cooling effect produced as moisture evaporates from the wet wick around the wet bulb. The temperature of the wet bulb is reduced by an amount which depends upon the relative humidity. The value can be obtained by reference to a chart known as the psychrometric chart (*Figure 11.8*). In an automatic system the temperature difference is automatically converted to an input voltage to the controller.

Ventilation systems

Ventilation is achieved through appropriately placed vents. These can be opened by a motor

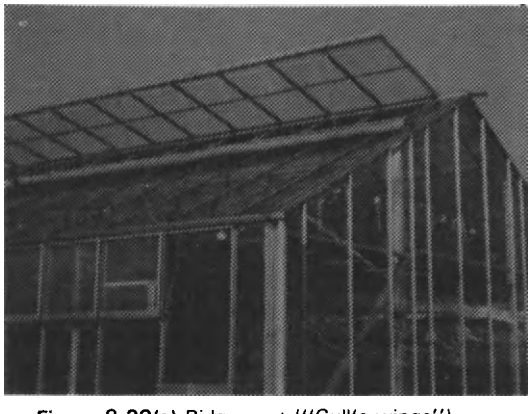


Figure 8.30(a) Ridge vent ("Gull's wings").



Figure 8.30(b) Side vent.

which drives a shaft running along the length of the greenhouse. Vents can be in the ridge or the side. In New Zealand, in many single span greenhouse designs, they are required in both places for adequate ventilation in summer (*Figure 8.30*). Side vents are of little use in multispan houses, and large ridge opening vents are needed (eg, 50% of the ridge area). Automatic systems need to have sensors to measure the amount of opening, and the outside wind speed and direction. This is so that the vents are only opened on the lee side of the house if the wind is strong enough to damage the windward side ridge vents. The controller usually opens the vents slowly by small increments, and then pauses to see if the action is sufficient to correct the problem. This is because ventilation rate depends considerably on wind speed and temperature difference, and a sudden in-rush of cold air could cause serious thermal shock to the crop. As a guideline a well designed house should have at least 60 air exchanges per hour. The size of the ventilation area must be adequate. It is governed by the size of the ventilators and how far they can open. Minimum ventilation areas are often specified as a fraction of the total greenhouse area. In New Zealand one would expect that the total ventilation area would be at least 25% of the floor area.

Venting can also be achieved with fans placed in the ends of the house. If required, the air can then be distributed around the house through perforated ducts (*Figure 8.31*).

Other cooling systems

Other methods used for cooling greenhouses include painting the cladding with a removable whitewash (this reduces radiation levels and hence the potential photosynthetic rate), or by shading with a removable screen. An interesting alternative is to pass a dilute solution of copper sulphate through the channels in dual skin rigid acrylic claddings. This absorbs the incoming infrared radiation, but not the photosynthetically active visible radiation. This therefore reduces the heat load



Figure 8.31 Perforated duct. This duct is made from sheet metal. Collapsible polythene tube ducts are more common (eg, see *Figure 8.34b*). They can be placed above or beneath the plants.

without reducing photosynthesis.

Another method for cooling involves evaporative cooling. Water is forcibly made to evaporate using either a "fan and pad" or by misting (*Figure 8.32*). The fan and pad consists of a pad of fibrous material about 100 mm thick which is placed across the air inlet

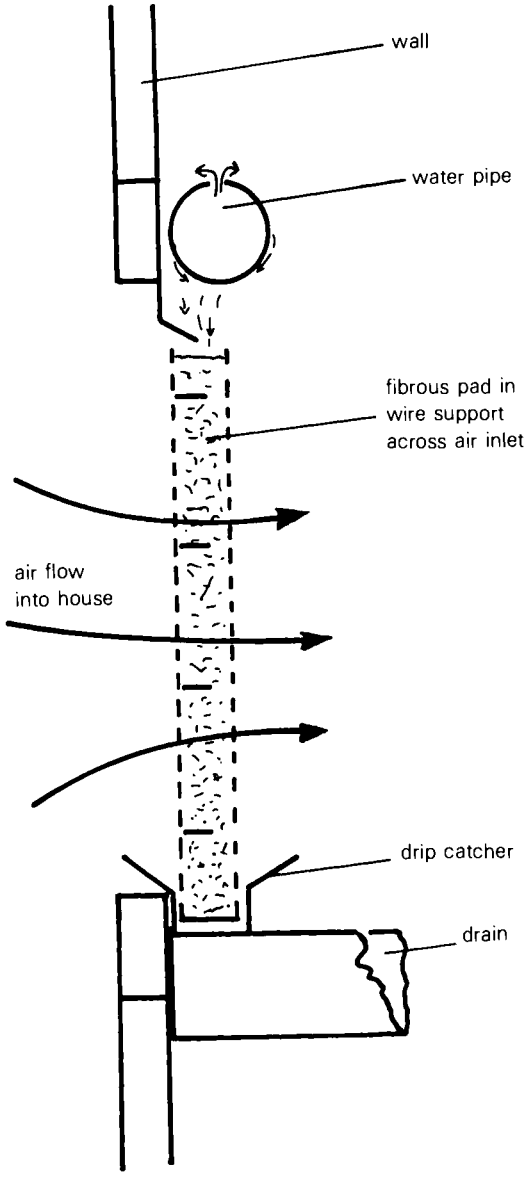


Figure 8.32 Wet pad for raising water content of incoming air.

ventilators. Water is continually fed onto this pad to keep it moist. The moisture evaporates, cooling the air, but also raising the relative humidity. The temperature drop is limited to a little less than the wet bulb depression, but this can still be very worthwhile. The pad increases the resistance to air flow and the fans must be made larger as a consequence. Misting is achieved with nozzles which spray a fine mist into the house when operated. Unless care is taken, plants close to the nozzles may be permanently wet.

In some hot countries refrigeration systems are needed. The incoming air is cooled by a refrigeration air conditioning system. This is an expensive alternative if other options work.

8.8.3 Heating

Greenhouse heating is required in most houses during the winter in most parts of the world. Heat is lost through conduction through the cladding and the soil, and by reradiation. It is also lost by ventilation or through glazing leaks. Heat is also required to evaporate water into a dry atmosphere, and this also represents an effective heat loss. Of these the losses through the cladding are the greatest. In New Zealand a design guide of 8 $W\ m^{-2}{}^{\circ}C^{-1}$ is often used as an estimate of the expected heat transfer coefficient for typical greenhouses. Thus a 30×10 m greenhouse with an exposed surface area of 465 m^2, and with a temperature of 12°C above ambient would require a heater with a capacity of $8 \times 12 \times 465 = 44.6$ kW.

Heating can be supplied by burning any fuel to produce hot air, or from water heated through a heat exchanger. Air can be distributed through perforated polythene ducting, while hot water is circulated through pipes. Since hot air rises, the pipes should be as low as possible, and distributed throughout the crop (*Figure 8.33*). However if they are

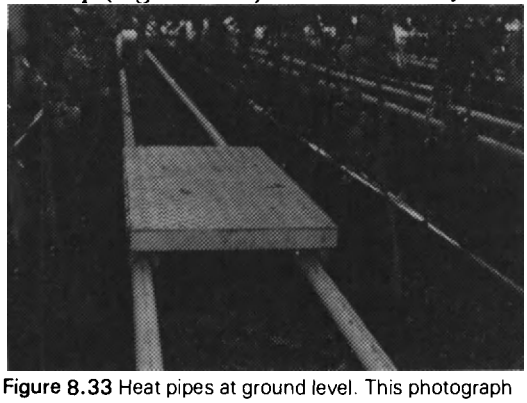


Figure 8.33 Heat pipes at ground level. This photograph also shows a convenient use of the pipes to assist fruit pickers.

very hot, they can be hazardous to workers.

The choice of fuel is largely governed by cost and availability. Waste heat from power stations and industrial complexes can be utilised in many localities, and this can offer considerable cost savings as well as being environmentally desirable. Waste heat from animal stock houses has also been considered by some growers. Storage systems which collect solar power during the day and release it at night have been used in many parts of the world. These can be costly to build, and often difficult to control satisfactorily.

Heat pump systems have also been used. Here the heat is extracted from the outside air or from the local ground water and dumped in the greenhouse. Another technique is to condense water from the air, thus extracting the latent heat which would otherwise have escaped. Fuller details of these and other methods are given in the references.

8.8.4 Energy flows in a greenhouse

Solar radiation is made up of a range of wavelengths (Chapter 3). Some materials transmit some of these wavelengths, but are opaque to others. When solar radiation strikes a greenhouse there will be some reflection of the incoming radiation, but the remainder will be transmitted into the house. The energy will be absorbed and used in various ways. Some will be absorbed by the soil. Some energy will be conducted downwards to the cooler soil below, while some will be reradiated as long wavelength infra-red radiation. The layer of air in contact with the ground will also be warmed by conduction and then this warm air will rise by convection, so that the air in the greenhouse warms up. Thus solar radiation, which is transmitted by air, raises the air temperature indirectly. The plants, workers, and buildings also give off long wave radiation. Wet surfaces will also lose water by evaporation. This requires heat, and is an important cooling process.

About 30% of the radiation energy striking a plant is reflected or transmitted. The rest is used by the plant. Between 0.5 and 2% is used for photosynthesis, 49% for transpiration, and the rest (about 20%) maintains the temperature of the leaf. It is interesting to note the small amount of energy used in photosynthesis and the large amount used in transpiration. The latter is very important in greenhouse energy considerations as an unheated greenhouse with full crop cover will run at a lower temperature than an identical greenhouse containing few plants. This is because with full ground cover about half of the energy entering the greenhouse is used in transpiration, rather than heating.

In practice, allowing for some loss by rafters, up to about 70% of the solar radiation striking a greenhouse is transmitted, depending on the design, orientation, latitude and time of the year.

The energy balance for a greenhouse is found by adding the energy inputs and subtracting the net losses. The inputs are: (a) the solar radiation entering, and (b) the supplementary heating from the heaters. The losses are: (c) the heat loss through the cladding by conduction and long wave radiation, (d) the heat loss by infiltration of air (hot air leaves and cold air enters), and (e) the fraction of the incoming solar radiation which is used up in causing evapotranspiration (since this energy is also lost through the humid ventilation air flow). The energy balance per second can therefore be written as:

$$(a) + (b) - (c) - (d) - (e) = 0$$

or:

$$t\ I\ A_f + H = U\ A\ (T_i - T_o) + M\ C\ (T_i - T_o) + E\ F\ t\ I\ A_f$$

Equation 8.10

where t is the transmissivity of the cladding, I is the solar radiation (W/m^2), A_f is the area of the greenhouse floor, H is the heating system input (W), U is the heat transmission coefficient of the cladding (including both radiant and conducted heat losses), A is the surface area of the cladding, T_i is the inside temperature, T_o is the outside air temperature, M is the mass of air (kg/s), C is the specific heat of dry air at constant pressure ($J\ kg^{-1}\ °C^{-1}$), E is the ratio of the energy used in evapotranspiration to the total solar radiation energy and F is a crop factor, which represents the fraction of the greenhouse space actually covered by the crop. F has a value of one for fully grown crops occupying the entire greenhouse, and takes smaller values if the crop is small, or there are wide clear areas of ground between plants. E is usually taken as 0.5 for greenhouses. The value of C for dry air at STP is approximately 1010 $J\ kg^{-1}\ °C^{-1}$.

8.8.5 Glass as a cladding material

All the emitted radiation from a greenhouse is in the far infrared part of the spectrum, at wavelengths of 6 to 16 μm. Glass transmits wavelengths between 0.3 and 3.5 μm, so that it allows most of the solar radiation to pass through. However it is opaque to longer wavelengths. Infrared radiation is therefore either reflected back or absorbed by the glass, reducing the heat loss substantially. The transmissivity for solar radiation and the opaqueness to long wave radiation make glass an ideal cladding for greenhouses. These properties are not always shared by other cladding materials.

Glass does have disadvantages. It is a heavy material, it is brittle and it must be used in small sheets. This increases the amount of roof support required (*Figure 8.34*). Rafters must be spaced correctly for the size of glass used, whereas simpler procedures are needed for lighter cladding materials. Glasshouses will also have glazing gaps between panes, which affects the ventilation rates, and this can reduce the level of absolute control the grower has over the environment.

Glass panels 3 mm thick are commonly used for horticultural purposes. They are available in a range of sizes, and the spacing of wall and roof bars is determined by the size selected. Larger sheets of glass have the advantage of increased light transmission, since there are fewer glazing bars. Old houses may have sheets of glass $460 \times 460 \times 3$ mm or similar, whereas panes in modern glasshouses are more often 760 (or 610) $\times 610 \times 3$ mm or larger.

The panes may be over-lapped or butted, with over-lapped glazing being most common. Butted glazing means that the end of each sheet of glass is butted up against the next. With this system it is hard to prevent leaks and to replace broken panes. Overlaps (or laps) are usually about 10 mm. In time they will collect dirt. The glazing gap allows the exchange of air between outside and inside the glasshouse even when all the ventilators and doors are closed. This has an effect on the environment within. Such gaps allows heat to be lost from a closed glasshouse by convection, a problem that does not occur with plastic film greenhouses.



Figure 8.34(a) In a conventional glass clad house the glazing supports can intercept a large fraction of the incoming light.

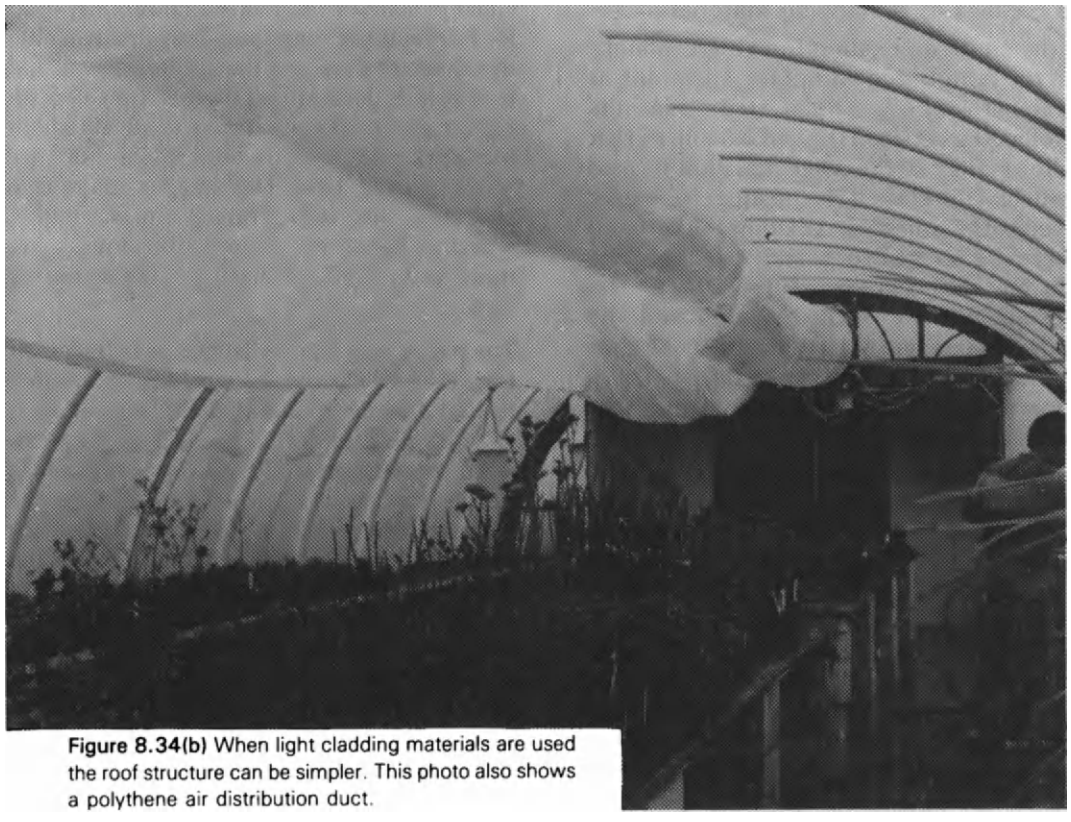


Figure 8.34(b) When light cladding materials are used the roof structure can be simpler. This photo also shows a polythene air distribution duct.

One common type of greenhouse is called the *Venlo* (*Figure 8.27c*). Here each side of the ridge roof is made up of a single row of large panes of glass. The size of these panes limits the house to a narrow span but houses of this type are erected as a multi-span or ridge and furrow block. Construction is simple and is based on a row of posts which support the gutters with roof bars or rafters attached directly to the gutters. The gutter also acts as a walk way for replacing panes of glass in the roof. In a wooden house the large panes of glass are often slid into a groove in the rafter without the use of putty. The end and side walls are usually glazed traditionally with smaller panes of glass. The common method of roof ventilation is to allow for the raising of every third or fifth pane of glass.

8.8.6 Non-glass claddings.

In the last 20 years a range of materials have come on the market which can be used to cover greenhouses. These include film materials such as polythene and PVC, and rigid materials such as fibreglass. An extremely important characteristic of any cladding is its transmission characteristics. For example, polythene and glass both transmit satisfactory amounts of solar radiation, but glass is opaque to long wave radiation while polythene is not. This is a disadvantage of polythene. At night under clear sky conditions the temperature under an unheated polythene structure may be lower than outside. This is because energy is being lost by radiation. It is not being reflected back by clouds and there is no opportunity for warm air to move in to replace the cold air inside. In practise this problem does not arise, thanks to the condensation of water on the inside of the film. Since water is opaque to long wave radiation the water acts as an effective barrier.

All film materials deteriorate under the action of ultravoilet light and other weathering processes. This is a major problem and the life, ease and cost of replacement must be considered. With some materials the percentage light transmission falls as the material ages.

Plastic claddings are available as either film or rigid materials. Products are used around the world, although the formulation may differ between countries. A wide variety of

designs are available for plastic covered greenhouses (*Figures 8.26, 8.34b,* and *8.35*). These vary from systems with a rigid plastic cover of fibreglass supported by a steel frame, which has a life time of the order of a glasshouse, to bubble houses with no internal structure, and made from a single sheet of polythene. These are kept inflated by an air pump, and will last little more than a year. In between there are circular houses constructed on curved plastic pipe or steel frames, with replaceable skins which are changed every two or three years, and double skin film houses where the two skins are kept apart by a small fan which continuously blows air into the gap between the two films.

Figure 8.35 Plastic skinned greenhouses.

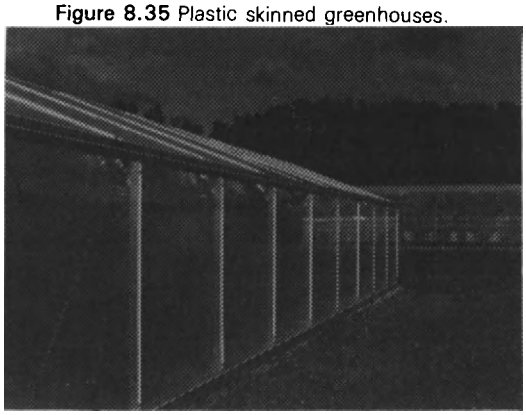


Figure 8.35(a) Wooden frame.

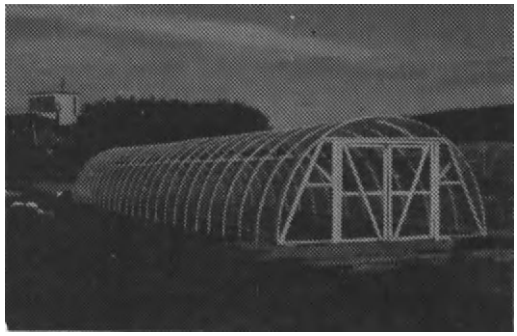


Figure 8.35(b) Tube framed tunnel house.

a. Plastic films

Major film materials include polythene or polyethylene (a polymer of ethylene), EVA (a copolymer of ethylene and vinyl acetate) and PVC (a polymer of vinyl chloride). Various chemical additives can be included in these films (lubricants, stabilizers, antioxidants, etc) and films may be clear or diffuse with matt or shiny surfaces. Pigmented films are also used. As the thickness of a film increases so does its life and cost. To obtain wider sheets films must be welded and this increases the cost. Life expectancies are influenced by the site and the care taken in erection and operation.

Plastic films degrade by photo-oxidation with the partial breaking of the long molecules into shorter components. This is mainly under the action of ultraviolet light. Materials become brittle and lose their strength and there may also be colour changes. Factors affecting the deterioration of plastic films include the type of film and its formulation, the thickness of film (thicker films last longer), the level of ultravoilet radiation, mechanical stress including rubbing, the temperature (the rate of degradation increases with temperature), the presence of oxygen and the level of humidity, and the age of the film (as the film ages the rate of break down increases).

The aging of films is a natural process and will occur most rapidly at hoop supports on tunnel houses due to mechanical stress. Some hoops will absorb solar radiation and heat up, increasing the temperature of the film in contact with them. The temperature of the support structure (and hence the skin) can be reduced by painting hoops white to reflect rather than absorb radiation, or by painting a strip on the outside of the film to "shade" the hoop. A strip of insulation material between the hoop and the film can also be used to prevent heat transfer. To maximise the life of plastic films any sharp points on the supporting structure should be covered or removed. An even tension on the film is also advisable. Plastic skins should be prevented from rubbing against galvanised iron surfaces, since this will cause rapid wear.

Ordinary polythene film breaks down after one year whereas UVI polythene (UVI = ultravoilet light inhibited) will last two years (but cost more). A typical EVA film is 85% ethylene and 15% vinyl acetate. The latter has been added to make the film more opaque to long wave radiation. PVC film is thicker and has a longer life. These three films have been used extensively and growers have to balance the cost of the film against their expected life and replacement cost. New materials are being introduced with improved properties and these should also be considered.

b. Rigid plastic materials

Rigid plastic materials include rigid PVC, glass reinforced polyester (GRP) or fibreglass, acrylic sheet, and polycarbonate sheet. These are available as single of double walled products.

GRP sheets are now treated with a film of PVF (polyvinyl fluoride) which greatly reduces the weathering at the exposed surface. In earlier formulations this weathering resulted in a drop in transmission characteristics as the glass fibres became exposed. All these materials are expensive, but are light and available in large sheets which simplifies construction. They are claimed to have a long life without any fall off in light transmission. Double walled sheets will reduce the heat loss from the greenhouse.

The transmission characteristics of plastic covering materials are shown in *Table 8.11*.

remove the film during the summer. The same concept is behind the marketing of the double walled acrylic and polycarbonate sheets. Thermal screens, which are pulled over the crop at night, and removed during the day, have also proved to be good energy savers in colder climates (*Figure 8.36*).



Figure 8.36(a) Thermal screen partly unfurled.

Table 8.11 Transmittance data for plastic materials and glass*

Material	Transmittance %		Thickness
	Photo-synthetically active radiation	Long wave (Thermal)	(mm)
Glass	90	0	3.0 mm
Polythene	89	69	0.125 mm
EVA (Agphane 101)	90	40	0.125–0.2 mm
PVC film	90	12	0.30 mm
Rigid PVC (round corrugations)	72	4	1.5 mm
Rigid PVC (square corrugations)	63	4	1.5 mm
GRP (Duralite)	82	1	2.0 mm
Acrylic sheet	80	2	various
Graphlon	80	42	0.25 mm

* The properties of these materials depends on the composition and so this table should be taken as a rough guide only.

8.8.7 Double glazing and thermal screens in greenhouses

Double glazing involves the use of a plastic film to line the inside of a greenhouse producing a dead air space between the glass and film, so reducing heat loss. Fuel savings of 30-40% have been reported from the use of this technique. Lining films of thickness 40-50 microns are used and with a wooded greenhouse the film can be easily stapled to the wall bars and rafters. There is some loss in light transmission and growers may



Figure 8.36(b) Thermal screen furled in sections.



Figure 8.36(c) Thermal screen furled to one side of house.

8.8.8 Comparison of plastic greenhouses and glasshouses

The light transmission characteristics of a double-skin greenhouse is very similar to that of a glasshouse. This is because the second layer causes additional light reflection which compensates for the absence of extra glazing bars, etc.

Plastic greenhouses (film and rigid) are much more airtight than glasshouses as they lack glazing gaps. Thus, when the ventilators are closed there will be little air exchange between inside and outside the greenhouse resulting in higher humidities and lower carbon dioxide concentrations. A grower will have to adjust ventilation techniques accordingly. Where CO^2 enrichment is practiced then a more air tight house will be an advantage.

Plastic houses are usually ventilated by fans. One reason for this is the lack of supporting structure in the greenhouse on which to attach ridge and side ventilators.

Over a period of time the heat loss from a plastic film greenhouse and a glasshouse is similar. This is because in both cases the houses are covered with thin materials, so that the main determining factor for heat loss is the difference in temperature between inside and outside the house rather than the nature of the covering materials. Glasshouses have glazing gaps whereas plastics are not as effective in stopping long wave thermal radiation. The heat transmittance coefficient suggested for the range of greenhouses used in NZ is 8 W/m^2 for every °C temperature difference for a single skin cladding. For a double skin a figure of 4 W/m^2 is often chosen.

8.8.9 Fan selection for use in greenhouses

Fans can be used to force air into a greenhouse (producing a small positive pressure), or to suck the air out. The air flow pattern in the latter case is probably a little more even, particularly around the fan. Provision must be made to allow the air in or out of course, so that the air flows through the house. Ventilators are therefore required which will open automatically whenever the fans are switched on, and close when the fans are shut down.

In order to select a fan, in the same way that a water pump is chosen, it is necessary to know the flow and pressure requirements. Estimating the operating pressure across the fan is not particularly easy. For example, what pressure (or vacuum, if the fan is used to suck the air out) would be developed in a greenhouse? This will depend on how easily the air can flow through the ventilators. If the house is well sealed the air pressure level will rise (or fall) and the fan air flow will fall. Fortunately this can be avoided by recognising the need for air to go in and out in the design! A design value of 25 Pa is often used as a guide in selecting fans for greenhouses. The air flow can be calculated by determining the number of complete air changes required per hour, although this is not a very satisfactory criterion. The reason for this is that the air flow is intended to produce cooling, and it must therefore be designed to match the heat load produced by solar radiation. The radiation levels are related to the floor area of the house rather than the volume, and so fans should also be sized on the same basis. The design data will therefore depend on the maximum solar insolation and the way in which that radiation is absorbed. It will also depend on the maximum allowable temperature in the house, and the maximum outside air temperature. Design figures for an area are thus based on the air flow in cubic metres per second per square metre of floor area ($m^3 s^{-1} m^{-2}$). Accurate design therefore requires that studies be done of local meteorological data, and the worst case used as the basis for sizing the fans. Unfortunately such a calculation will usually give a very large fan, which will be costly to buy and operate. The grower may then have to consider alternative methods of cooling the house, such as misting, painting or shading the greenhouse.

Fans must be guarded so that workers cannot be injured. Louvres fitted on the outside will achieve this and also prevent air flow when it is not needed. A wire mesh on the inside will also be needed.

Inlet configurations

The movement of air inside a greenhouse is affected by the design of the house and by the position of the fans and the ventilators. There is always a problem of ensuring that the fresh cool air is distributed around the house and that there is no danger that the air will flow in and out without altering the temperature of the plants! Air flow patterns are affected by the fact that hot air rises. Thus exhaust points should be high up in the structure, while inlets can be lower.

When plastic covered houses are used, in many designs ventilation is only possible through the end structures. This seems to be acceptable, because there is generally less space over the top of a crop and hence most of the incoming air must mix with the old air and circulate through the crop, as it passes along the house. There is some evidence that polythene and other plastic clad houses require less air cooling than glass clad houses, because the heat loss through the polythene is greater.

An example will illustrate the method of estimating the size of the ventilation system.

Example

Calculate the minimum air exchange rate to maintain the temperature within a greenhouse completely covered with a crop at 27°C when the outside temperature is 22°C if the maximum solar radiation level is 1000 W m^{-2}. The greenhouse measures 100 m by 50 m, and the wall height is 3 m. The roof is a multispan structure with 10 spans each 5 m wide with a roof angle of 26°. The U value of the cladding is 8 W m^{-2} $°C^{-1}$, and its transmission coefficient is 0.7.

Solution: The total area of the cladding is given by:

$$A = \frac{100 \times 50}{\text{Cos } 26} + 3(100 + 100 + 50 + 50)$$

$$+ 10 \times 2 \times (0.5 \times 5 \times 2.5 \text{ tan } 26)$$

$$= 6524 \text{ m}^2$$

The radiation entering the greenhouse is given by:

$$t \; I \; A_f = 0.7 \times 1000 \times 50 \times 100 = 3.5 \times 10^6 \text{ W}$$

The heat loss through the cladding is:

$$U \; A \; (T_i - T_o) = 8 \times 6524 \times (27 - 22)$$

$$= 261{,}000 \text{ W}$$

Note that this is only 7% of the total heat entering the house.

Using the values F = 1 for complete cover, and E = 0.5 for the fraction of solar energy used for evapotranspiration, and $C_{air} = 1010$ J kg^{-1} $°C^{-1}$, then from *Equation 8.10*, the required ventilation rate can be calculated:

$$M = \frac{0.5 \times 3{,}500{,}000 - 261{,}000}{5 \times 1010} = 294.9 \text{kg/s}$$

The volume of this mass of air can be found by dividing by the specific weight of the air. This is 1.14 kg m^{-3} at 27°C, so the volume will be 259 m^3 s^{-1}. The actual volume of the greenhouse is $3 \times 5000 + 10 \times 304.8 = 18{,}050$ m^3, so the number of air changes required will be:

$$\text{Air changes/minute} = \frac{259 \times 60}{18050} = 0.86$$

Thus the required ventilation rate results in a complete air change in just over a minute. This will maintain no more than a five degree increase in temperature above ambient. Unfortunately, if the ambient temperature were to exceed 22°C, the inside temperature would be correspondingly higher. The chances of the site producing a combination of high air temperature and high solar radiation therefore can affect the design. The design of fan ventilation rates is thus dependent upon a full knowledge of the climatic conditions at the site.

In order to generate the desired air flow suitable fans must be selected. In this example some large fans would be needed to produce the 260 m^3 s^{-1} air flow.

8.9 HOUSING FOR STOCK

Like human beings, stock are homeothermic. This means that they maintain a constant body temperature by the production or dissipation of heat. The environment determines whether or not the animal must generate heat or dissipate it. As we are concerned with production it follows that we must try to provide an environment which

causes stock to be highly productive. Thus if meat is the end product the environment will need to be designed for maximum weight gain. There is good evidence to suggest that this can be achieved if the animal is not stressed by the environment. This requires good control of the air temperature and humidity. Researchers have found that for most animals there is a comfort zone, or a range of temperatures and humidity levels within which the stock are healthy and contented, and in which production is maximised. If the temperature is too low the stock must use up more of their food intake in generating heat to maintain body temperature, and so production is lowered in terms of feed input. If the temperature is too high the animals may be uncomfortable and lethargic. They must eliminate heat by sweating or panting, and the humidity of the air affects these methods of heat removal. They may reduce their intake of feed and reduce their rate of growth. Heat stress can also lead to illness and death.

Animals in confinement tend to alter the air composition by reducing the oxygen content and increasing the CO_2 and water vapour levels, and also by adding ruminant gases, ammonia, and dust particles. Fortunately if we remove the moisture levels by ventilation, we will also deal with the other problems at the same time. The object of the design of an animal building is therefore to provide a functional structure which keeps the stock in their comfort zone. To achieve this requires that the building will allow adequate ventilation around the animals themselves. In addition the building should be pleasant for humans to work in, and should also be easy to clean and maintain. Stock inevitably produce effluent, and this must also be dealt with efficiently and effectively.

Animal houses also need to be durable and able to confine the stock. They need to be designed so that animals can easily be isolated and attended to without risk to the worker. If regular operations must be performed on the stock, the buildings should be designed with this in mind. The building must also be designed around any special requirements of the stock. Thus, for example, piggeries require special mating areas and pens for individual sows. Supplementary heating must also be provided for the newly born piglets until they are old enough to cope with normal ambient temperatures. Examples of the designs for some animal houses are described in the references.

8.10 FRUIT SUPPORT STRUCTURES

In order to produce top quality fruit, it is necessary to control the growth of the tree (or vine, etc) so that the leaf canopy and the fruit are grown to the right extent and in the right places. In some fruits shading is important to avoid sun bleaching, while in others the fruit requires direct sunlight on it to produce the desired stage of maturity. Too much or too little foliage can affect the quality significantly. It is therefore advantageous to construct support structures which can be used to tie the branches so that they grow only in the desired directions. In addition vines and some fruit trees are not able to support themselves or their fruit load, and so a support structure is needed. Various designs have been developed for particular crops and some of these are shown in *Figure 8.37*. The main features of a support structure are that it should be designed to carry the maximum load (ie, the load at full maturity and full crop load with a high wind blowing); it should provide for the vine to grow in the way required for top production and quality; it should allow pruning and spraying operations to take place without hindrance; it should be durable and economic; and it should enable the fruit to be harvested without difficulty either mechanically or manually, depending on the crop. Materials used have included the full range of timber, steel wire, steel posts, and plastic wire. With any structure the end assemblies must be strong enough to carry the load, and the wire must not break.



Figure 8.37(a) Continuous pagoda system (kiwifruit).



Figure 8.37(b) A-frame or Tatura trellis (eg pears).



Figure 8.37(c) T-bar with wings (eg kiwifruit, grapes).

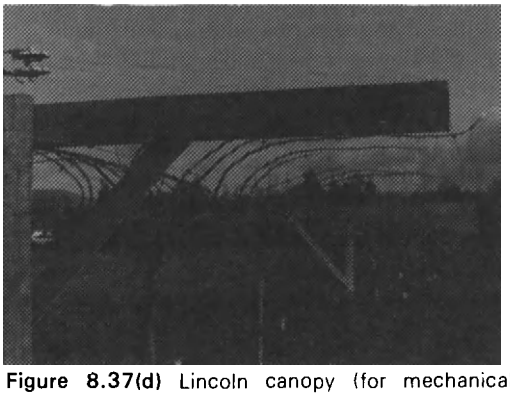


Figure 8.37(d) Lincoln canopy (for mechanical harvesting of apples).



Figure 8.37(e) Steel Y-frame (eg pears).

roblems can arise if the wire is threaded rough metal supports or staples so that it being bent at these points. Failure is more kely at these points than anywhere else.

.11 EXERCISES

List the main factors to be considered in choosing a site (in order of priority) for each of the following: (a) a dairy shed, (b) a greenhouse growing orchids, (c) a store for explosives, (d) a piggery.

What is the coefficient of permeability of a soil if the head between the sides of an embankment 10 m thick is 4 m and the flow rate through a section measuring 20 m by 1 m is 2.5 litres per hour?

A soil is graded as SP-CH. What does this mean and what properties could it have?

A water tank is to be placed on a set of concrete piles on a medium-strength clay soil. If the total volume of the tank is 50 tonnes, what is the minimum number of piles needed if each has a base area of 200×200 mm?

Discuss the implications of the Proctor density test to the ramming of fence posts.

6. List the key factors which will result in a strong concrete slab being laid.
7. What is the maximum load that a 5 m long piece of 100×50 mm green radiata pine can sustain if it is loaded in the centre at right angles to its length?
8. Investigate the cost of available greenhouse cladding materials, and obtain technical data for them. Consider the design requirements and cladding costs for a greenhouse measuring 30 m by 10 m. Making any necessary estimates, calculate the heating input required at night to maintain a temperature of 18°C when the temperature is 2°C outside.

8.12 AIMS OF THIS CHAPTER

1. Discuss the siting and design of rural buildings.
2. Describe soil types, classifications and the properties of soils from an engineering viewpoint. Explain the meaning of the terms soil friction, stability, cohesion,

pore pressure, permeability, and other terms related to the behaviour of soils in practice.

3. Discuss the effects of water content on soils, defining the terms liquid limit, plastic limit, and plasticity index, and describe methods of determining them.
4. Identify a soil in terms of the Unified Soil Classification System, by completing simple laboratory or field tests, and use this classification to predict the behaviour of the soil in general terms.
5. Explain the relevance of the Procter density to the preparation of earthworks.
6. Outline the main principles for establishing good foundations for buildings.
7. Discuss the properties of concrete, and discuss techniques for working with it, including site preparation, composition, mixing, curing, and reinforcing.
8. Discuss the properties of timber as a building material, including ways in which its strength, durability and fire resistance can be altered.
9. Discuss methods of joining timber.
10. Outline methods of constructing floors, walls and roofs in simple buildings, using timber, concrete and other materials.
11. Describe the principles of greenhouse design, and the effects on the greenhouse environment.
12. Compare different cladding materials for greenhouses in terms of their physical properties and their influence on the environment inside.
13. Describe the energy flows in a greenhouse, and calculate the heating and cooling requirements from simple models.
14. Discuss the principles of greenhouse environmental control and measurement.
15. Discuss the design of housing for livestock.
16. Describe the requirements for a fruit support structure, giving examples.

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Fencing

Chapter 9

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9.1 INTRODUCTION

The subdivision of land for farming has been a fact of life for centuries, ever since the time of the enclosures in Europe. Nowadays it is increasingly important for efficient farm management. The need for controlled pasture management to increase pasture utilisation requires considerable subdivision. However, fencing can be expensive, and cheaper effective fencing systems are most desirable. Fences are required for yarding, subdivision, farm boundaries, and for temporary fencing. They must keep stock in, but particularly in horticultural situations it is often more important to keep animals and vermin out! Different types of animals require different systems, but all fences should give long service for low cost and minimum maintenance.

Today many different fencing designs and materials are available, with a correspondingly large variation in cost and extent to which the fence is stock-proof. The choice of structure depends on the function of the fence, the type of stock, the cost, soil type and topography, and the individual preferences of the farmer and fencing contractor. For example in New Zealand the Ministry of Agriculture has produced details and costs for at least 35 fence designs (MAF, 1982).

Even modern fencing materials may last up to fifty years, and so considerable care should be taken in positioning fences and selecting materials, in order to obtain the fullest possible benefit from the work. Aerial photographs and thorough surveys are extremely useful in this respect.

There are at least five major types of rural fencing around the world (*Figure 9.1*). Where the skill survives and materials are available



Figure 9.1(a) Dry stone wall.



Figure 9.1(b) Hedgerow.

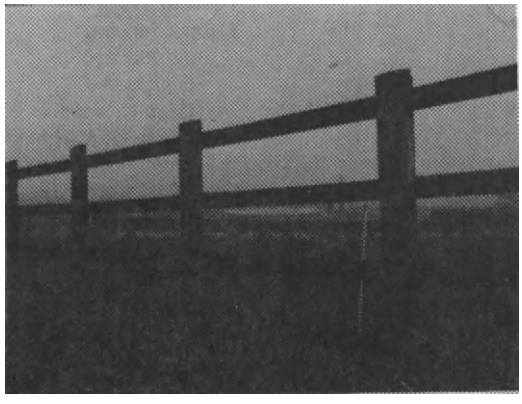


Figure 9.1(c) Post and rail fence.

the dry stone wall is perhaps the most aesthetically satisfying. Each stone is placed in such a way that it locks against its neighbours to produce a strong long lasting barrier. However in modern times it is rarely used. In many countries hedgerows provide a natural fence. Maintenance is high, and valuable land is used up unless the fence is trimmed regularly. Trimmings are woven into the bushes to form a continuous barrier. The hedgerow can be a home for wild flora and fauna, and is therefore highly valued by conservationists.

All timber post and rail fences are used where durability and appearance are important. They are also used for horse paddocks and in stockyards. However, they are expensive, since the timber rails are not cheap, and the distance between posts is limited to the length of the rails. For practical use, cost, and low maintenance, post and wire fences are the most appropriate type of mechanical fencing system. Lastly, electrical fencing is the least cost option for a system which can provide an effective barrier to stock. We will consider these last two types of fencing systems in this chapter. We will start by considering the materials which make up the fence.

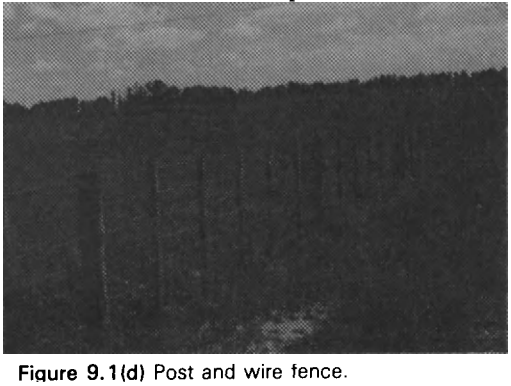


Figure 9.1(d) Post and wire fence.

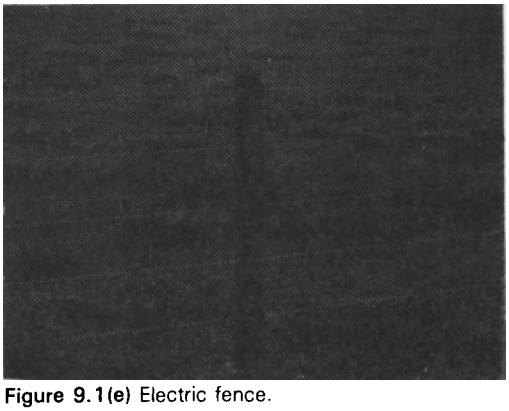


Figure 9.1(e) Electric fence.

9.2 FENCING WIRE

In New Zealand a number of wire types are available. Traditionally 4 mm diameter mild steel has been used (known as No 8 or "farmer's friend"), but it has been largely superceded by smaller diameter "high tensile" steel wire, which is less than half the price for the same strength. Both have a galvanised zinc coating which protects the steel from corrosion. The coating is around 0.20 to 0.26 kg of zinc per square metre of wire surface area, and should conform to the national manufacturing standard (NZ 3471 in New Zealand). Buyers should check this if in doubt.

In some countries aluminium coated wire and plastic wires with relatively high strength are available. Stranded wire can also be purchased for specific fencing applications. *Table 9.1* gives a summary of the mechanical properties of these materials. The table includes data on the length of wire in a 25 kg reel, and values of the breaking load and yield point load. Permanent damage is done if the wire is strained beyond the yield point (Chapter 3), and maximum tensions should not exceed 60% of the yield load at any time. Recommended wire tensions on fence lines are lower than this to allow for temperature effects and other changes. Thus 2.5 mm high tensile wire is normally set at 1500 N, while 1.6 mm wire is set at 800 N (Schuler, 1987).

(a) High tensile wire

High tensile wire is produced from a medium carbon steel rod which is forced (cold drawn) through a series of dies to reduce the diameter of the wire progressively until the required size is reached. The galvanised zinc coating is then applied. The cold drawing process increases its tensile strength. At the same time the material becomes more resilient (ie, it tends to be harder to deform permanently) but also more brittle. It is required to pass various quality control checks, which include a minimum tensile strength, and a wrappability test where the wire must be wrapped around its own diameter without failure. In areas where corrosion is a major problem extra heavy galvanised wire should be used (eg, with a minimum zinc coating of 0.35 kg/m^2).

Table 9.1 Properties of fencing wire (Manufacturers' Data)

Wire diam. (mm)	Nominal Coil weight (kg)	Length per coil (metres)	Approx. yield point (N)	Breaking load (N)	Manufacturers recommended maximum tension (N)
High tensile (E = 207 GPa)					
1.6	25	1584	1500	2200	900
2.5	25	648	4300	6000	2100
3.15	25	408	5800	8200	2900
3.55	25	321	8500	12000	3000
4.00	25	253	9700	14000	3200
Mild steel (E = 207 GPa)					
1.6	25	1583	600	900	400
2.0	25	1013	900	1400	500
2.5	25	648	1600	2100	980
3.15	25	408	2500	3600	1500
3.55	25	321	3200	4600	1900
4.00	25	253	4000	5800	2400
5.00	–	–	6300	9000	3800
High tensile strand (7 strands)					
1.6 (4.8*)	54	250	–	14200	9600
2.0 (6.0*)	86	500	–	25400	17200
2.5 (7.5*)	67	250	–	40000	26900
3.15 (9.5*)	213	500	–	53700	36400
Stainless steel (304) (soft) (E = 207 GPa)***					
2.64	–	–	1200	3400	–
3.25	–	–	1800	5100	880
Stainless steel (304) (spring hard) (E = 207 GPa)***					
2.64	–	–	7300	8800	4760
3.25	–	–	10600	12400	6710
Plastic wire (E = 1.5 GPa)					
2.0	4	1000	1200	1400	–
3.0	5	500	2600	3000	–
Plastic polyamide wire (nylon 6)					
2.5	11	1870	–	2300	–
3.0	11	1320	–	3000	–
4.0	11	770	–	5200	–
5.0	11	500	–	7600	–
6.0	11	390	–	11000	–
Aluminium coated steel (E = 207 GPa)**					
2.5	–	750	4800	6000	1500
Barbed wire (high tensile wire, 75 mm between barbs)					
2.5	25	203	–	–	–
Aluminium 6061–T8 (improved strength)***					
3.15	25	1185	2100	2300	1120
3.25	25	1115	2200	2400	1200
Aluminium AP160–H9					
3.25	25	1115	1200	1400	540

*Finished product diameter (mm)
**Values vary considerably according to source.
***Based on data from NZAEI (1987).

The brittleness and springy nature of the wire have resulted in some farmers viewing it with considerable suspicion. However with practice, it becomes easy to use and to work with.

(b) Mild steel

Mild steel is a low carbon steel, and although produced in a similar manner to high tensile, it does not harden, due to its low carbon content. As a result it is less brittle, and less resilient, and can be bent into odd configurations easily. It has a lower tensile strength than high tensile wire and so it must be thicker in diameter if it is to be under the same tension.

(c) Aluminium coated wire

Intended for use in corrosive environments, these consist of a high tensile steel wire to which an aluminium coating is metallurgically bonded. Typically, the coating accounts for 25% of the cross-sectional area, making it about 0.2 mm thick on 2.5 mm wire. As pure aluminium is low in strength and soft compared to steel, some care is needed to avoid damaging the coating. The wire must be handled with care, and special staples and plastic wire protectors are required for stapling. Special joiners should also be used instead of knots, and alloy type permanent wire strainers rather than conventional chain strainers should be used for tensioning. The wire is relatively expensive: it is about two or three times dearer than ordinary high tensile steel wire of the same diameter.

(d) Plastic wire

Plastic wire manufactured from polythylene terephthalate (PET) (sometimes known as mylar) has the advantages of lightness and very high corrosion resistance. Its tensile strength approaches that of mild steel of the same diameter, but it has a low Young's Modulus, which means that it will stretch much further under the same tension (*Table 9.1*). Figures suggest that it would be three times more expensive than mild steel (or high tensile) wire of the same diameter. It has been suggested that plastic wire 4 mm in diameter would be suitable for fruit support wires, since it may be less abrasive than galvanised steel wire, and would therefore reduce the incidence of lesions on young wood or vines. However the wire itself is very sensitive to abrasive wear against supports.

(e) Galvanised wire strand

This product has been developed mainly for horticultural applications where multiple single wires would otherwise be needed because of the tensions involved. It is suitable for use as a diagonal bracing for horizontal end assemblies, or for tie-downs to "dead-men" for support canopies or wind breaks. The strand consists of seven high tensile wires twisted together.

(f) Electric fencing ribbon and strand

This type of "wire" consists of a plastic ribbon 12 mm wide, or a 2 to 3 mm diameter strand consisting of plastic filaments and fine metal wires woven or twisted together. Both are convenient to handle, clearly visible and light, and suitable for temporary electrified fences. However, their electrical conductivity is poor, and they can be used only over short distances. Twine is available as a netting.

(g) Barbed wire

Typically, barbed wire consists of two galvanised wire strands wrapped together with sharp pieces of wire protruding every few cm. It is three times as expensive as 2.5 mm high tensile wire. It can rust early at the plaits, resulting in a limited life. It is still used by some farmers to prevent stock pushing their heads through a fence. However, the fence should be built strongly enough to withstand loads produced under these circumstances. Others use barbed wire to prevent stock from pushing wooden battens sideways. This can also be avoided by stapling the battens correctly. A third use is to prevent damage to netting, caused by stock leaning over the fence. Again adequate design could help to eliminate this problem. Possibly the only suitable use of barbed wire is to deter humans, and even this use is doubtful. Barbed wire will damage hides and pelts, and electric fencing will usually do a better job wherever barbed wire is used.

Barbed wire should NEVER be electrified. Stock or humans can be killed if they are unable to release themselves from an otherwise safe electric fence, and the possibility of becoming entangled in

electrified barbed wire is high. In some countries the electrification of barbed wire is illegal.

(h) Woven wire netting

Woven wire comes in rolls of various widths, wire spacings and gauges. Netting with small spacings is extremely stock proof. It is very useful for temporary enclosures for docking etc. While slightly faster to erect on flat country than other non-electric fences, the netting rolls are awkward to handle and it does not easily follow the ground contour. Tensioning, particularly on hill country, is not a simple matter. The initial tension must be judged correctly to allow the netting to be pulled down into hollows.

9.2.1 Wire corrosion

In farming the environment is generally not too bad for galvanised fencing wire. If the air is clear and unpolluted (as in most parts of New Zealand!), and the relative humidity is low, then the loss of zinc will be very slow. In these areas commercial wire products will last at least 20 years. Once the zinc has gone the steel will begin to corrode, but even this process will be fairly slow. However, in industrial areas in the world, where acid rain is a common occurrence, or in areas close to the sea, the rate of corrosion can be high.

Salt spray, or prolonged contact with fertilizers and other chemicals, will accelerate corrosion. New wire should not be stored near fertilizer bins, or in buildings where chemicals have been stored recently. On the other hand wire coils should not be stored outside, as water trapped between the strands will cause some corrosion to occur, producing a white "rust" of zinc hydroxide. It is therefore advisable to store wire on dry timber in an area which is clean, dry, and well ventilated, and to stack coils in such a way that air can circulate easily through and around the coils (eg, in pyramids). New deliveries of wire should be checked for signs of localised corrosion.

Excessive corrosion can occur at localised points on a fence-line. Examples of this are where the wire is in contact with either timber posts treated with copper compounds or with unprotected metal wire. Durability trials carried out near Rotorua (a thermal area with a sulphurous atmosphere) by the NZ Agricultural Engineering Institute indicated that copper-chrome-arsenic preservatives have an adverse effect on galvanised wire coatings, leading to the loss of the coating within four years (ie, five times the normal rate of corrosion) where the wire was in contact with the post (Garden, 1980). Electric fence insulators can help to reduce this problem, since they prevent contact between the wire and the post. However the problem of staple corrosion remains.

Corrosion rates can also be high if water is trapped in contact with the wire. This situation can arise at joints if the wire is wrapped around itself several times. For this reason the number of finishing turns on a knot should be kept to a minimum (eg, not more than two or three).

After the galvanising has been destroyed by damage or weathering, the wire will continue to be serviceable but its strength will decrease rapidly. As the rate of loss of metal is the same for thick and thin wire under the same conditions, 2.5 mm wire should fail 1.5 times as fast as 4 mm wire after rusting begins. When selecting wire for harsh environments, it is difficult to state which wire will last longer. Some calculations indicate that a 4 mm diameter mild steel wire will last about 40% longer than a 2.5 mm wire, largely because there is more metal to corrode after the zinc has gone. In some areas this can alter the economics involved in choosing between high tensile and mild steel wires.

Plastic wire will not rust. However, over a long period of time ultra-violet light will cause an embrittling effect, even though UV inhibitors added to the plastic will reduce the rate at which this occurs. Aluminium coated wire has been used in areas where corrosion is a problem. However it has not proved successful commercially in New Zealand, and manufacturers now recommed the use of 3.75 mm wire with an extra heavy galvanised coating. The corrosion of electric fencing joints is discussed in section 9.7.8.

9.2.2 Tensions and tension loss in fence wires

During the lifetime of a fence the wire tension is likely to vary. For example, 2.5 mm high tensile wire is normally loaded to 1.5 kN in mechanical fences, and 0.9 kN in electrical fences. In practice it is unfortunately not

unusual for fences to be overstrained to 4.5 kN during straining, and to 3 kN during tying off (even though a competent fencer should be able to avoid such undesirable overloads). Nearly all new strainer assemblies will "give" slightly, and the wire tension will drop within a few months of installation. Settling movements of 50 to 100 mm are not abnormal, and the resulting drop in tension depends on the length of the strain and the wire diameter.

9.2.3 Theory

Models of the behaviour of metals under tension have been discussed in Chapter 3. The stress strain curve is shown in *Figures 3.10* and *3.11*. High tensile wire fails with much less plastic deformation than mild steel wire. However in fencing, as in nearly all other situations, we design things so that we are working at stresses much below the yield point. The rest of the analysis will therefore consider only stresses and strains which are in the elastic region.

From Equation 3.16, if we substitute for ϵ and σ and rearrange, we get:

$$x = \frac{L\,T}{A\,E} \qquad \textbf{Equation 9.1}$$

where x is the extension (metres), L is the initial length of the wire with no applied load (metres), T is the tension (Newtons), A is the cross-sectional area (square metres), and E is the Young's Modulus. For steels E = 207 GPa (*Table 9.1*).

Suppose the strainer posts move by combined distance d metres during settling, then the tension will drop. From *Equation 9.1*, the loss in tension will be given by:

$$\delta T = \frac{d\,A\,E}{L} \qquad \textbf{Equation 9.2}$$

Thus the tension loss for the same amount of movement will be less if A is smaller or if L is greater. This explains why it is harder to strain short lengths of fencing, since the loss in tension (δT) gets larger as L gets smaller. In addition, 2.5 mm wire ($A = 4.9 \times 10^{-6}\ m^2$) stretches more during tensioning than 4 mm wire ($A = 12.6 \times 10^{-6}\ m^2$) because its cross-sectional area is smaller, and it so will absorb the movement of the strainer posts without losing so much of the tension.

Example

Calculate the final tension in a 200 m length of 2.5 mm wire initially at 1500 N if the strainers move by 100 mm.

Solution: In Chapter 3 (section 3.6) we showed that the extension at a load of 1500 N was 0.291 m. Now the tension loss will be:

$$\delta T = \frac{0.1 \times 4.9 \times 10^{-6} \times 2.07 \times 10^{11}}{200} = 507\ N$$

Thus the final tension will be $1500 - 507 = 993$ N

If a 4.0 mm wire is used the same calculation leaves a tension of only 196 N!

On short strains it is very difficult to maintain tension even with small diameter wire, because the extension lost due to end strainer movement and due to releasing the chain wire tensioners during straining is comparable to the extension produced by the tension. For example, a movement of 60 mm on a 40 m long 2.5 mm wire at 1500 N will reduce the tension to zero. In this case the options are to overtighten the wire initially or to install a permanent wire strainer in the fence line. The first option could result in damage to or failure of the wire, and may also cause greater end strainer movement due to the higher initial tensions. For example, in this case, 4.0 mm wire would need to be strained to 5.4 kN if the strainer were to move only 60 mm. In mild steel this exceeds the yield point. The alternative is therefore preferable, although slightly more expensive. A third option would be use a smaller diameter wire.

During its normal working life fencing wire is subjected to occasional high loads (from stock, machinery, or humans). These loads may cause further strainer movements, or even cause the wire tension to exceed the yield stress, thereby causing the wire to stretch permanently. Air temperature also affects wire fences. Like all metals, steel contracts in the cold and expands in the heat. Thus in cold weather fencing wire contracts, increasing the wire tension. The coefficient of thermal expansion is about $15 \times 10^{-6} °C^{-1}$, so a 200 m length would contract by about 120 mm if the temperature fell from 30°C to −10°C. All steel wires would contract by the same amount, regardless of diameter. In extreme cases the

elastic limit of the wire could be exceeded, or the strainer may move, either of which will result in slacker wires when the weather warms up. In all cases 2.5 mm wire is much less likely to lose tension than 4.0 mm because of its greater extensibility (ie, a smaller increase in tension will result from the stretch required to make up for the contraction).

9.2.4 Permanent tensioners

In modern fence designs it is important to maintain the wire tension. This can be achieved by using permanently installed, ratchet controlled (or otherwise) built-in strainers. The tensioners can be adjusted not only during construction but periodically throughout the life of the fence. In selecting a tensioner care should be taken to avoid designs which cause any stressed part of the wire to be bent around a sharp edge, as this may cause early failure. Some typical tensioners are shown in *Figure 9.2*.

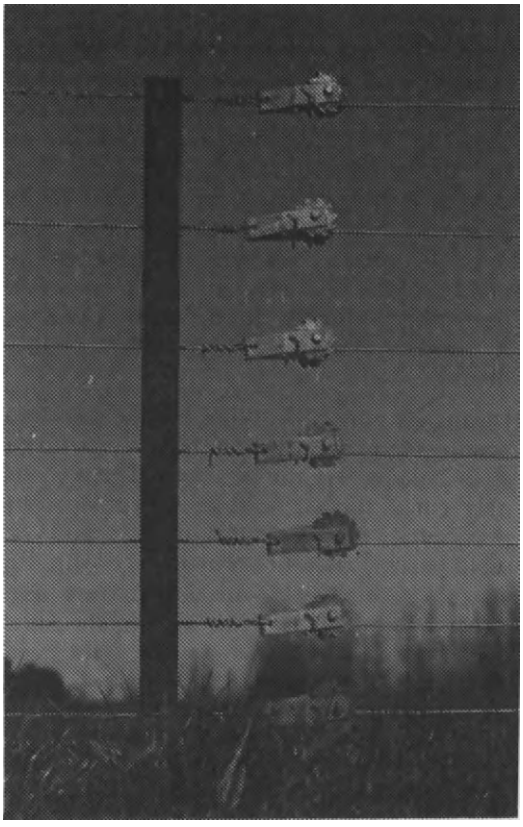
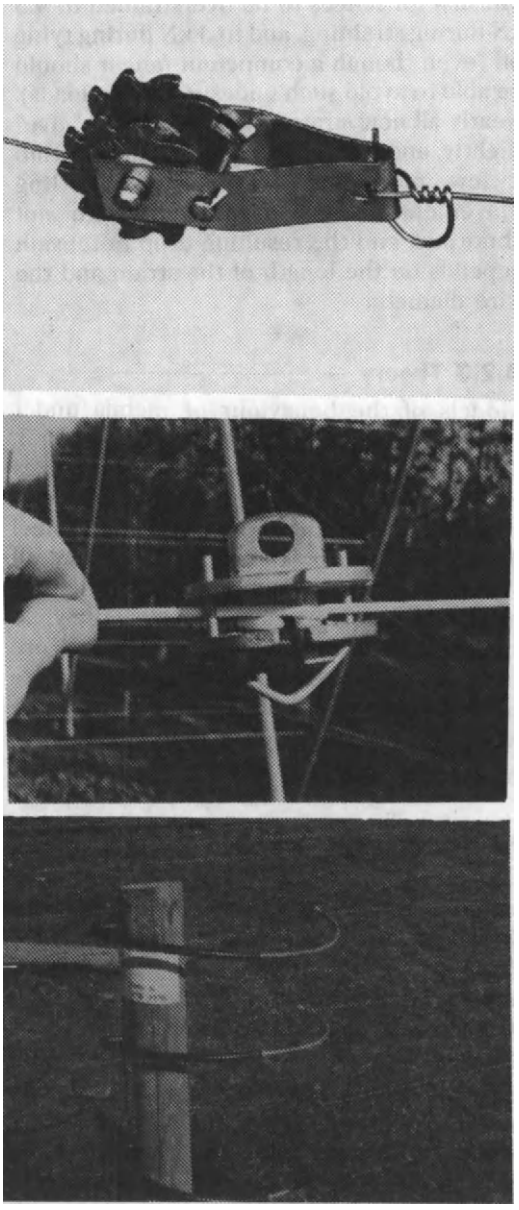


Figure 9.2 Permanent tensioners (ratchet type, photo courtesy of Ernest Hayes Ltd).



9.2.5 Joining wire

Each knot in a wire is a weak spot. NZ Wire Industries recommend using a "figure of eight" or a reef knot (*Figures 9.3a* and *b*) for joining wires. These have strengths of around 70-75% of the wire itself for 2.5 mm high tensile wire. In comparison the common double loop knot (*Figure 9.3c*) has a strength of only 47% of the wire. These knots are not recommended for aluminium coated wire, since the soft aluminium coating is damaged by the knot. Instead commercial wire joiners are recommended. One version of these

involves two spring loaded jaws which grip the two wires. The long term durability of these devices is not known.

Figure 9.3 Wire knots.

Figure 9.3(a) Figure 8 knot.

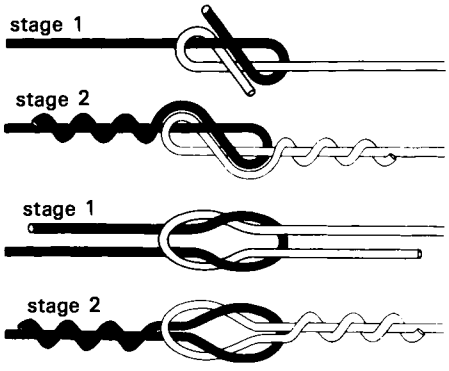


Figure 9.3(b) Reef knot (strictly a "thief's knot").



Figure 9.3(c) Double loop knot (not recommended).

When tying wires off at strainer posts, NZ Wire Industries recommend the knot shown in *Figure 9.4*. Correctly tied this has a strength of over 90% of the wire itself. Not more than two or three finishing loops should be applied to these knots. Again, if aluminium coated wire is used the manufacturer's pamphlets should be consulted.

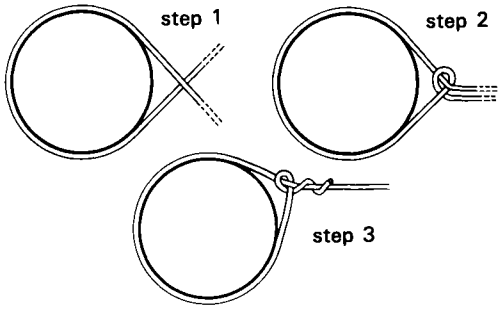


Figure 9.4 Method for tying wire to strainer (NZ Wire Industries).

9.2.6 Breaking wire

When a wire is tied, the loose ends must be dealt with. Normally if the excess is cut with pliers, this leaves a jagged end which can be dangerous. It is possible to snap high tensile wire fairly easily by applying a "reversed torsional twist", which gives a neat tidy break which is not jagged. No great strength is required for this, although demonstrations are impressive! The method is depicted in *Figure 9.5*. First a "handle" is formed parallel to the line wire to manipulate the wire easily. Second the wire is wound around the line wire two or three times. Third the handle is twisted so that it is perpendicular to the line wire. Finally the handle is turned as shown, causing the wire to break cleanly close to the line wire. This method will work easily with high tensile wire, but requires a little more e

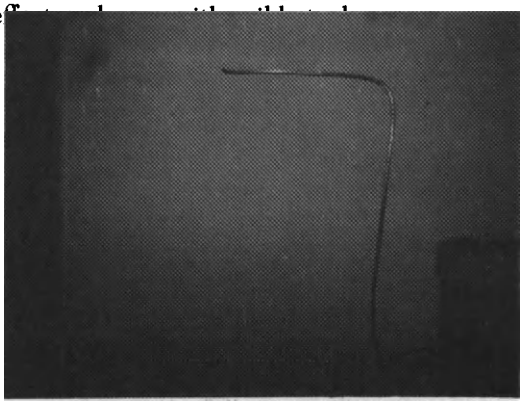


Figure 9.5(a) "Handle"

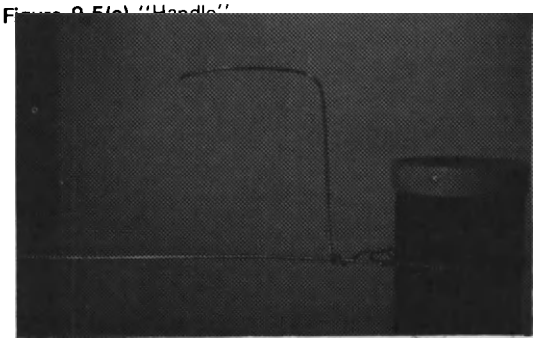


Figure 9.5(b) Wire wrapped tightly around itself.

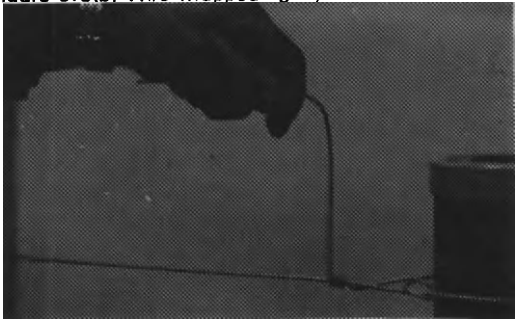


Figure 9.5(c) Twisting handle (starting position).

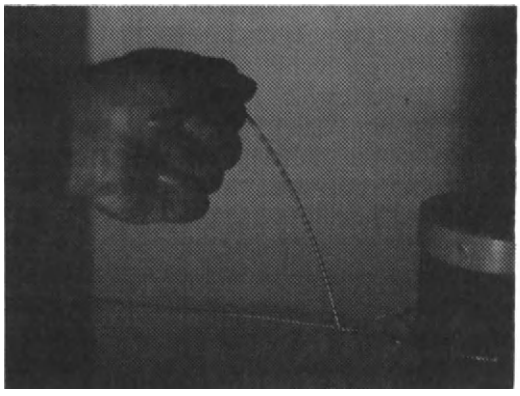


Figure 9.5(d) Twisting handle (end position).

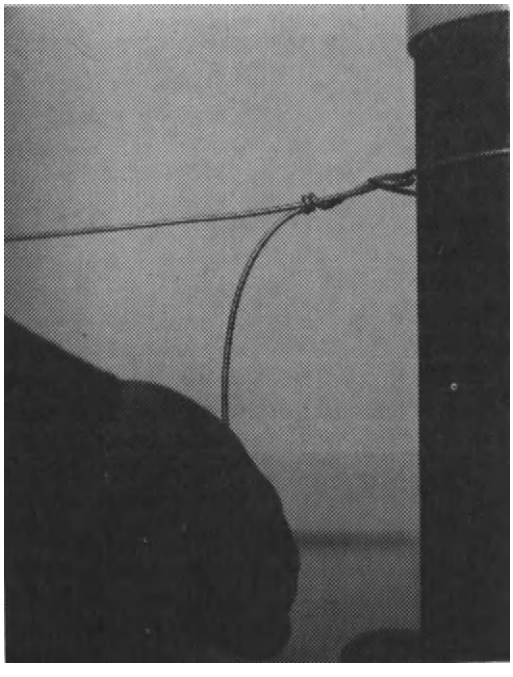


Figure 9.5(e) Rotating end (note direction).

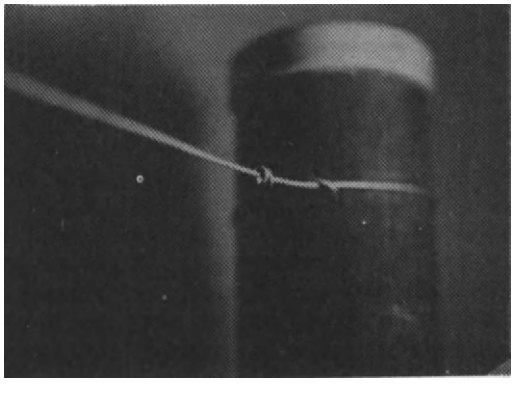


Figure 9.5(f) Wire about to break.

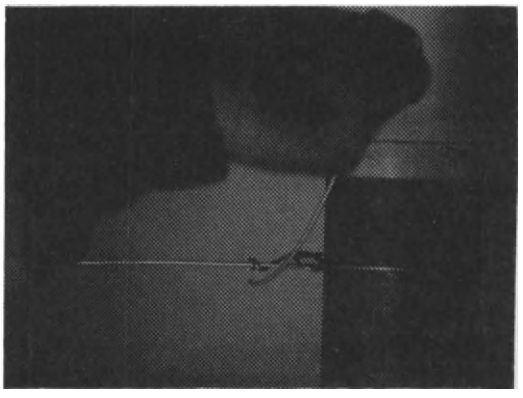


Figure 9.5(g) Wire snaps.

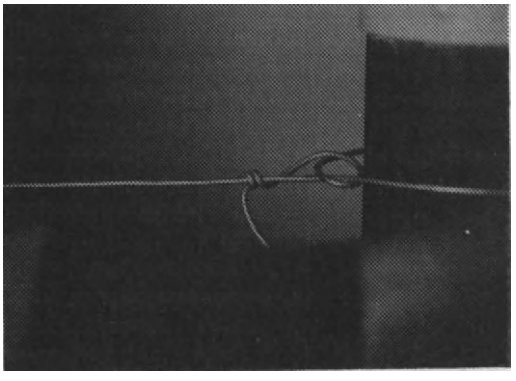


Figure 9.5(h) Finished end (the wire end is smooth and will not cut hands, fruit or hides which rub against it).

9.2.7 Tension meters

A commercial type and a home made meter are shown in *Figure 9.6*. The latter requires a metre of free wire without battens. The wire is pulled sideways by the spring balance, and the tension is 20.4 times the spring balance force (in Newtons) when the deflection is 12 mm (proving this is left as a simple exercise in resolving forces). If the balance is calibrated in kilogrammes, then the force in Newtons is found by multiplying by 200. Alternatively, if a ratchet wire tensioner is used, a torque wrench could be adapted to indicate wire tension. However, the wrench would need to be calibrated.

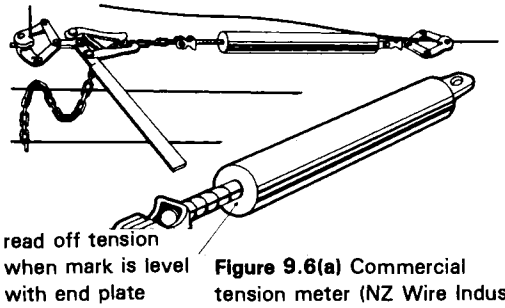


Figure 9.6(a) Commercial tension meter (NZ Wire Industri

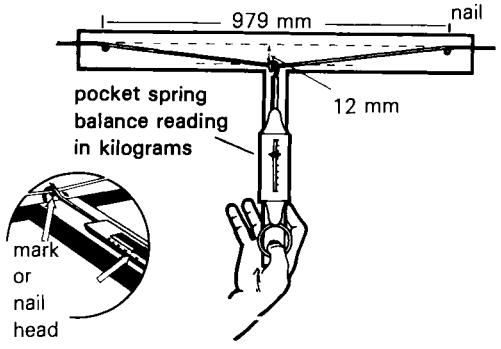


Figure 9.6(b) Home made meter. When the deflection is 12 mm, the tension in Newtons is 200 times the balance reading in kg (NZ Wire Industries).



Figure 9.6(c) Tensioning a wire using a chain link tensioner.

9.3 POSTS, BATTENS AND STAYS

9.3.1 Timber posts

Traditionally large diameter posts have been used, since they took longer to rot. Nowadays, chemically treated posts are available, and post durability depends mainly on the chemical treatment. The standard of treatment is most important and can be inadequate in some posts produced by mills

Table 9.2 Post sizes (NZS 3607) and relative strengths

Posts	length (m)	Minimum diameter or face width (mm)	Relative strength of a minimum sized post in the class**
No 1A Round	1.8	140	1.8
No 1 Round	1.8	115	1.00
No 2 Round	1.8	90	0.48
No 3 Round	1.8	65	0.18
No 1A Half Round	1.8	185	1.00
No 1 Half Round	1.8	150	0.54
No 2 Half Round	1.8	115	0.24
No 1 Quarter Round	1.8	90*	0.47***
No 2 Quarter Round	1.8	70*	0.22
Others			
No 1 Strainer	2.1; 2.4	200	5.3
No 2 Strainer	2.1; 2.4	175	3.5
No 3 Strainer	2.1; 2.4	150	2.2
Stay	2.1; 2.25; 2.4	90	0.48

* Diameter would be twice this value.

** Compared to a No 1 post of 115 mm diameter, and assuming the timber has the same intrinsic strength and quality. The loading is at right angles to the cut face for half and quarter round. On average a No 1 radiata pine post would fail at a bending moment of 12.0 kN m (or under a force of 9.88 kN applied 1.22 m from the point where the post is held), as shown in the example below.

*** Quarter round posts are more likely to be affected by knots, if the saw cut passes through a nodal swelling. These values are for loading perpendicular to a cut face: if the post is placed with the faces at 45° to the load the strength is reduced by one third.

with poor quality control, or from homemade sources.

Timber posts are graded on their minimum diameter. However the strength of timber depends upon a number of factors. Apart from post diameter, the most important are the density of the outer wood, and the presence of defects. There are significant differences in the intrinsic strength of timber from different forests, since different growth rates, or differences in the age of trees when cut, will affect the density of the products (Walford, 1987; Hellawell, 1982).

Knots and other defects will reduce the strength of a post, but the effect is less severe than in sawn timbers. This is because the natural growth process generates nodal swellings around knots, which increase the local strength. When these are cut or planed off the result is a major loss of strength (*Figure 9.7*). However, providing posts are not machine shaved, but are merely trimmed and debarked, the nodal swellings retain much of their strength, and compensate for the presence of a knot (Hellawell, 1982). In New Zealand, the current standard (NZS 3607) describes the minimum sizes of posts for various grades, and indicates the maximum allowable size of knots (as a guide, this is not more than one fifth of the circumference). *Table 9.2* gives the classification of fence posts and strainers.

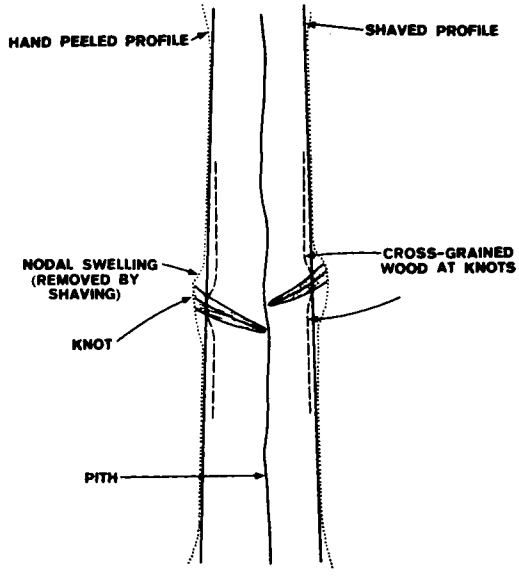


Figure 9.7 Effect of shaving a wooden post (reproduced by courtesy of the NZ Forest Research Institute).

9.3.2 Relative strength of posts

In theory the strength of a post against bending is proportional to the cube of the radius. Thus a post 200 mm in diameter will be eight times stronger than a post 100 mm in diameter, providing that the timber in both is of the same intrinsic strength. In practice it will also be more mature. The relative strength of half and quarter round posts is listed in *Table 9.2*.

These figures are calculated from the section modulus, Z, using the minimum post diameters for each class. The section modulus is given by *Equation 3.45*, and the maximum bending moment a post can sustain is given by *Equation 3.46* (Chapter 3). Values of Z are given in *Table 9.3*.

Table 9.3 Section moduli for various cross sections of radius R

Shape	Z (m^3)
Round post	0.785 R^3
Half round	0.191 R^3
Quarter round (loaded perpendicular to cut face)	0.096 R^3

The value of σ for posts is hard to assess. For both timber and concrete posts the strength varies widely from one post to another. Research has suggested that a design figure of 12.4 MPa can be used for radiata pine posts (Walford and Hellawell, 1972, NZS 3603, Table 34), which allows a factor of safety of about 6.5. This means that, in effect, less than one in twenty posts would fail at double this load. If the posts are shaved this design load should be reduced by at least 25%, or, about 9.3 MPa.

Example

Calculate the design load and the average failure load for a 115 mm (No 1) round post embedded in the ground if the force is applied 1.22 m from ground level, with a factor of safety of 6.5.

Solution: The radius of the post will be $0.115/2 = 0.0575$ m. Thus, from *Equations 3.45* and *3.46*, and *Table 9.3*, the design load F is given by:

$$F = \frac{12.4 \times 10^6 \times 0.785 \times (0.0575)^3}{1.22}$$

$$= 1.52 \times 10^3 = 1.52 \text{ kN}$$

Thus the average failure load will be $1.52 \times 6.5 = 9.88$ kN.

Similar calculations give 4.7 and 1.8 kN for No 2 and No 3 grade round posts respectively. Concrete posts 100 mm by 75 mm have a theoretical failure load of 1.4 kN (Based on NZS 3153 (1974)), while steel waratahs fail at only 0.7 kN (Clarke, 1976).

As a general guide, Clarke suggested that timber posts set ten times their diameter into most soils have a 50/50 chance of breaking when pushed over. In general posts are set 600 mm into the ground as this gives satisfactory resistance against overturning. It has been found that the thickness of the post has little to do with its resistance to overturning.

9.3.3 Timber treatment

Fence posts and battens should be properly preserved, or their life expectancy may be greatly reduced. In New Zealand, posts should be branded correctly in accordance with the Timber Preservation Council's Standards indicating that they have been treated in an approved plant. It is possible to obtain fence posts which have been preserved by other than approved methods but these may not be satisfactory. The H4 category covers timber in ground contact (*Table 8.9*).

During the treatment of timber the preservative must be forced under pressure into the timber from the outside. Accordingly the resulting concentration is greatest at the surface and decreases towards the centre. In practice the gradient is very small in sapwood, but heartwood and some hardwoods can cause problems. Ideally, all cuts and holes made in treated timber should therefore be painted with a recommended preservative. If posts are to be pointed for driving this must be done before treating.

9.3.4 Concrete posts

Concrete is inherently brittle, and posts are likely to break or crack if struck by a high sideways force. A 75 mm radiata post is as strong as a 75 mm/100 mm concrete post. Chemical corrosion of the fencing wire ceases to be a problem with concrete posts, but abrasion could be a factor. In New Zealand, the manufacturing criteria and strength of concrete posts are covered by Specification NZS 3153 (1974). Concrete posts could be used where extreme durability is required, but a high standard of manufacture is required, since if moisture attacks the reinforcing, it will rust and apparently swell, "bursting" the post.

9.3.5 Battens (droppers)

Timber battens are expensive to buy and staple, particularly if used in traditional New Zealand quantities of 125 per 100 metres (ie, about five between posts on the conventional seven wire fence with posts at four metre intervals). Recent fence designs either eliminate battens completely or reduce their number to one per post interval. The absence of battens is compensated for by increasing the number of wires. Alternatively wire battens or even polypropylene string ties can be used. Wire battening machines have been developed, although they are not in widespread use. When battening it is recommended that safety spectacles should be worn.

Battens require an H3 category decay treatment (a retention of 5.4 kg/m^3). and need not be individually branded.

9.3.6 Staples

For normal softwood fence posts and battens, staple holding power is relatively low. Longer staples with barbed points can be used. In posts, 50 mm long 4 mm diameter staples can be used, while 30 mm x 3.15 mm staples are suitable for pine battens. Ungalvanised staples should not be used as exposed steel in contact with fencing wire will destroy the galvanising and speed corrosion. If anything the staples should be more heavily galvanised than the wire. Threading wire through holes in steel standards, hardwood stakes and battens is practised in the South Island of New Zealand and in Australia, as it can be quicker than stapling on flat to rolling country. In addition staples tend to work out of posts in climates with extremes of hot and cold, or alternating wet and dry periods.

9.4 END STRAINER ASSEMBLIES

9.4.1 Angled stay assembly

The angled stay assembly is the traditional type of end assembly (*Figure 9.8*). When properly constructed it is strong and reliable and it can be used to support a gate. A detailed method of construction is given in the references (Schuler, 1987; Studman, 1989). Constructed in this manner, and in firm soils which can be easily dug and compacted, this assembly is as strong as the single horizontal stay assembly. However it may be weaker in soft peat.



Figure 9.8(a) Assembly.

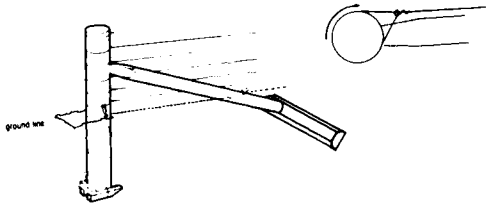


Figure 9.8(b) Schematic (NZ Wire Industries).

The stay must be placed in the direction of the thrust. The stay should preferably be at least 2.4 m long and free of large knots. A stay block is required, which could be a No 1 half round H4 category treated post. The stay block should be at least 0.9 m long in strong soils, and double this in weak soils. Foots, made from H4 category treated timber, are attached to the post to prevent it being lifted out of the ground. The need for this can be seen by taking moments about the centre of the stay block for all the forces which act on the assembly: the fence wires produce a net couple acting to lift the post out of the ground. This can only be prevented by friction forces against the side of the post, or by the addition of a foot, which gives additional resistance to lifting. The foot can be joined to the post by notching the post and nailing with corrosion resistant nails, or by using a hardened spring-grade stainless steel (eg, type 304 S/S), as described by Schuler (1987). Reinforced concrete posts with a stay recess and concrete stays are also available.



Figure 9.8(c) Ramming the soil around the post.

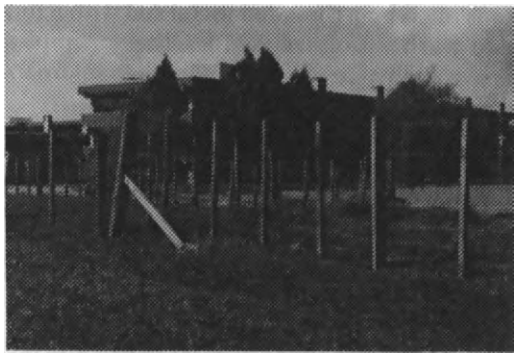


Figure 9.8(d) Failure of an angle stay assembly due to poor ramming and absence of a foot.

9.4.2 Horizontal stay assembly

In the horizontal stay assembly (*Figure 9.9*) the posts are driven into the soil, and foots are not used. This is advantageous in stony clay soils which are difficult to dig. Experiments indicate that the double horizontal stay assembly is stronger than the single, which in turn is as strong or stronger than the angle stay assembly. However the double horizontal stay is more expensive and is liable to collapse if the centre post comes out of line, and some advisors therefore do not recommend it. The single horizontal stay assembly is sensitive to misalignment, and needs to be built with care. A suggested construction method is described in the references. In the single span assembly, the horizontal stay (or rail) should be as long as possible and at least 125 mm in diameter. If screw-in gate hinges are to be fitted to the end, a 175 mm diameter post should be used.

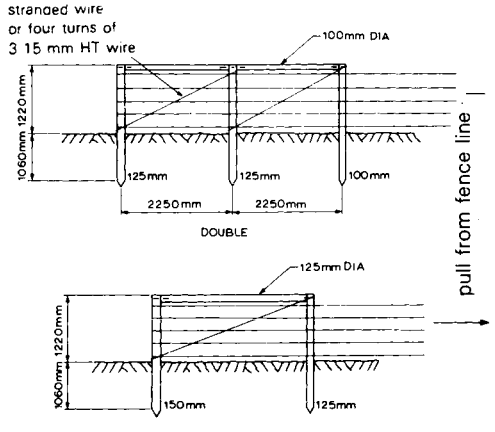


Figure 9.9 Horizontal stay end strainer assembly.



Figure 9.9(c) Horizontal strainer showing twitched wire and excessive notching to fit the rail. These are not recommended.

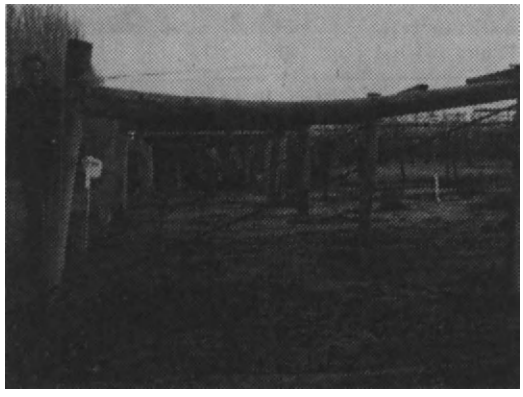


Figure 9.9(d) Horizontal stay (supporting an apple trellis). The stay was warped and has bent under the load.

The horizontal assembly must be braced with a diagonal wire under tension. Sometimes the wire is twitched up (wrapped around itself) with a part batten to obtain adequate tension. Twitching can damage the wire, and frequently, too much tension is applied. This can lead to failure of both the wire and the assembly. Instead, the wire should be tensioned with normal strainers (Schuler, 1987). High tensile stranded wire is well suited as bracing wire.

9.4.3 Tie down assembly

In this design the wires are tied back to a "dead-man" or stake which is driven into the ground at an angle (*Figure 9.10a*). This method is common for support wires for horticultural crops. The main disadvantage of the method is that it takes up extra space at the headlands or at the ends of the fence line. The dead-man can be replaced with a metal screw anchor (*Figure 9.10b*) which can be screwed into the soil without digging the hole

first. The assembly itself can be made quite strong, providing the dead-man is big enough. Tie downs are generally not used for fencing animals as they can be a hazard.



Figure 9.10(a) Tie down.



Figure 9.10(b) Screw anchor (Ernest Hayes).

9.4.4 Other designs

A number of other strainer designs have been suggested. For example, in the flexifence end assembly, the base of the stay is free to slide on a timber stay plate, and the assembly is tensioned by a threaded metal rod with a nut and washer (*Figure 9.11*). Other examples are described in the references (eg, Studman, 1989).

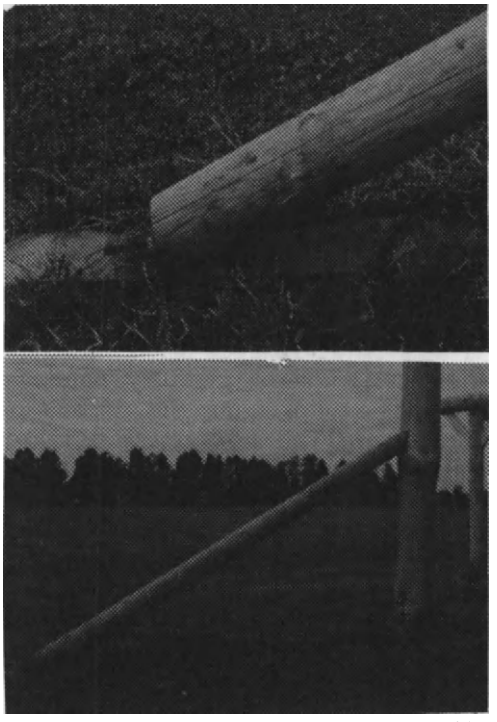


Figure 9.11(b) Examples of flexifence assembly.

9.4.5 Gates

Gates are an important and integral part of a fence system. Gates must be as stock-proof as the rest of the fence, and must also allow for ease of use and provide adequate access.

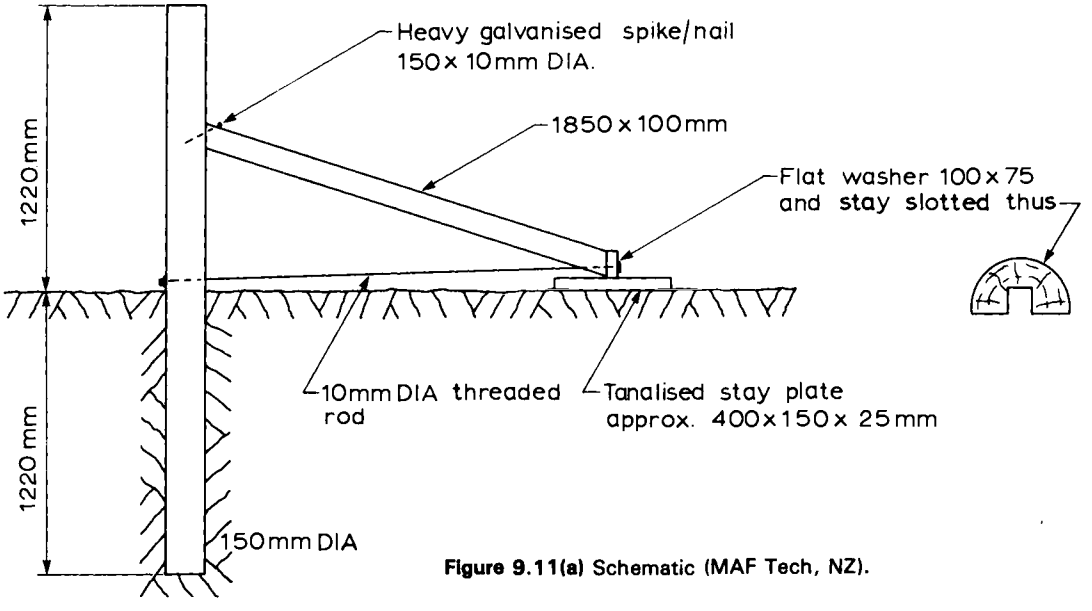


Figure 9.11(a) Schematic (MAF Tech, NZ).

Gates can be made from timber or galvanised steel, and a variety of one or two way catches are available. The gate should be mounted on a strong post, which should be well secured into the soil. When the gate is hung some allowance should be made for a little sag initially, as the gate and post settle. A good catch is worthwhile as string or fencing wire loops can be slow to deal with. Some gates have been produced which can be opened without dismounting from a motor cycle.

A popular "gate" in New Zealand consists of wire netting stapled at one end of an opening and the other end secured with wire. An improvement to this Taranaki gate can be made by using the securing device shown in *Figure 9.12.*

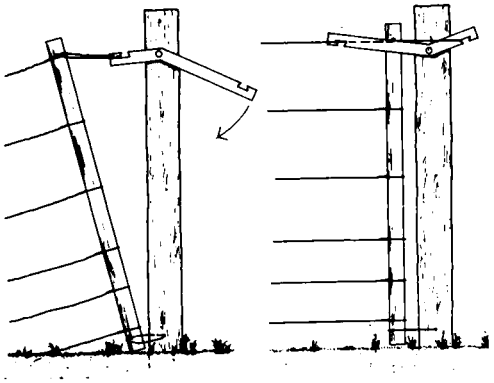


Figure 9.12 Taranaki gate tensioning mechanism (MAFF, UK).

9.5 SECURING POSTS IN SOIL

There are three main methods of placing posts in the soil. The posts may be placed in a dug out hole and the soil replaced and rammed, they may be machine driven directly into the ground (if necessary the bottom end of the post can be pointed first), or they can be placed in an augered pilot hole and driven in. Driven posts are firmer and harder to pull out than rammed posts. However dug posts can have foots attached to them, which increases the resistance to lifting appreciably. This may make them preferable in the long term in soft soil conditions. There are a variety of different methods of attaching the foots, including nailing, wiring, or notching the post (eg, Schuler, 1987).

9.6 FENCING DESIGNS

The purpose of a fence is to restrict the movement of stock. It must therefore be a barrier which either prevents or deters stock from crossing it. Mechanical fences must stop animals physically by ensuring that there are no spaces through which the animal can squeeze and no weaknesses which can be stretched or developed by stock to make a gap. For complete stockproofing the fence must also be able to withstand the maximum force which can be produced by the stock (eg, a charging bull). This can be too expensive, and some designs (such as the flexifence) will allow the stock through under extreme pressure by bending: after the stock has passed over, the fence springs back, leaving the farmer with an intact fence but a minor drafting problem!

With particular types of animals further design requirements arise. For example, fences to contain goats must be designed to prevent the goats climbing up over angled stays, while deer tend to "walk the fence-line" and can injure themselves seriously if there are any stays which protrude into the paddock at right angles to the fence. If pigs, goats, or rabbits are to be enclosed (or excluded), the fence designer must take into account their digging capabilities.

The height of fences must be sufficient to prevent stock from attempting to jump. Some sheep have been observed to clear 1.1 metres, while deer fencing must be higher still. In New Zealand the law requires a minimum height of two metres for boundary fences. Fences heights, in current practice for sheep, range from a minimum of 0.9 m for docile sheep on flat country, to 1.2 m on sloping ground.

As far as gaps between wires are concerned, it is probably uneconomic to attempt to make fences 100% lamb-proof, and it is generally thought to be unnecessary as long as the ewe is unable to break out. Wire spacings will depend on the size of the animal and how hard it can push against the wires. Forces of over 450 N have been recorded for Romney sheep, and this is certainly a lower estimate (Studman 1989).

In view of the variety of stock, differences in land topography, and (historically) the availability of fencing materials, it is not

surprising that a very wide range of fence designs have evolved. While a truly rational basis for design is still awaited, structures generally are a balance between effectiveness and economics, combined with the influence of tradition. Some typical examples of fence designs are shown in *Figure 9.13.*

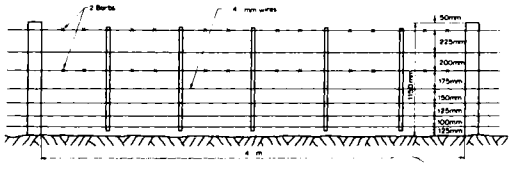


Figure 9.13(a) Traditional post and batten fence using 4 mm mild steel wire and two barbed wires (see also *Figure 9.1(d)*).

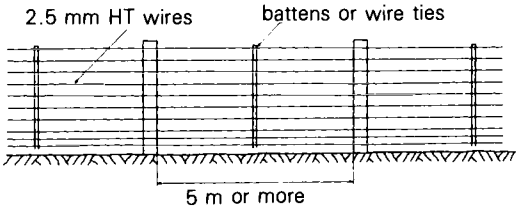


Figure 9.13(b) Ten wire fence using 2.5 mm high tensile wire.

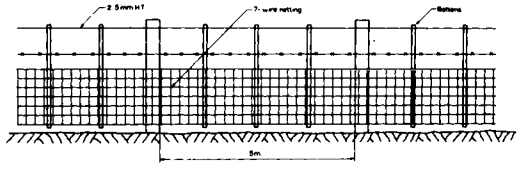


Figure 9.13(c) Post and batten netting fence. The function of the battens is unclear!

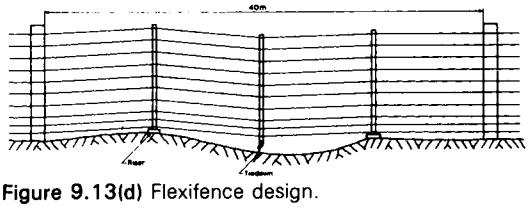


Figure 9.13(d) Flexifence design.

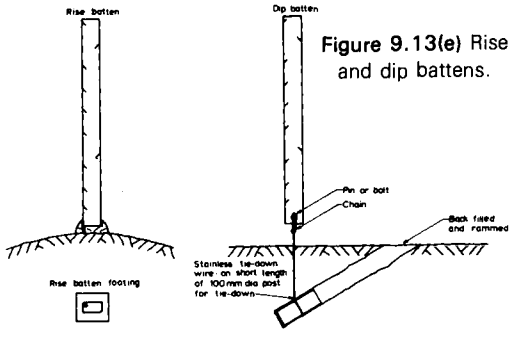


Figure 9.13(e) Rise and dip battens.



Figure 9.13(f) Rail plus barbed wire fence with wires pulled through drilled holes.



Figure 9.13(g) The test.

It is quite possible to select a design to match the requirements of individual farmers providing these are known and clear. In general the greater the strength and the level of stock proofing required, the greater is the cost. It is important therefore to decide how reliable the fence must be before choosing a design. Obviously the use of conventional high cost post and batten fences will be limited to situations where a high level of stock-proofing is essential (eg, some boundary fences and on stud farms). For sub-division,

or where the consequences of stock penetration are not likely to be disastrous, less expensive designs will have their place.

One fact which should be apparent is that very little scientific research has been done to determine optimum design values for mechanical fences. Most of the designs in this section are based on historical ideas, or "trial and error" methods of development. Some preliminary studies involving sheep have been completed at Massey University. To date these studies have identified some useful parameters, and generated just a little data for design purposes (Studman 1989).

However, for low cost stock barriers, the mechanical fence has a hard time competing with the electrical fence, which will be discussed in the next section.

9.7 ELECTRIC FENCING

9.7.1 Introduction

Electric fencing is a relatively modern method of restricting stock movement. The first widespread use of electric fencing occurred in the Wisconsin area of the USA in the early 1930s, assisted by the support of the local University. A variety of home-made devices were quickly developed, but many of these were highly lethal! Deaths of animals and humans resulted in the introduction of tight safety standards, which appear to have been more honoured in the breach than in the observance. Although there were many attempts to provide a safe system which was also reliable as well as stockproof, no satisfactory systems emerged until 1962 when D S M Phillips, a Physicist at the Ruakura Agricultural Research Centre in New Zealand, developed the first so-called low impedance energiser. This design concept, combined with advances in electronic components, has lead to the development of reliable effective energisers which comply with current safety standards and are therefore considered to be safe (providing they are installed correctly). The book by McCutchan (1980) represents a comprehensive review of electric fencing systems.

The main difference between electric and non-electric fencing is that the former is a psychological barrier rather than a mechanical obstruction. Stock should be introduced to electric fences under lush grazing conditions. The animal learns to associate the unpleasant experience of an electric shock with the fence and therefore develops an aversion to fence lines. As a result stock learn to avoid contact with the fence, preferably by keeping away from it even when feed is in short supply. The fence does not therefore need to be built strongly, and can be erected at a much reduced cost. It is also possible to use very simple temporary fences which can be moved easily and which allow stock to graze only part of a paddock. While electric fencing can be designed to be a physical as well as a psychological barrier, the extra cost usually militates against this.

The design of an electric fence should maintain a balance between performance and cost. In some applications, such as temporary subdivision, a single wire may be satisfactory for cattle, while two or three wire fences may be adequate for sheep, goats and deer. Other applications will require additional wires and more elaborate standards of construction. Electric fences now provide a competitive type of fence for use as a permanent means of subdivision on all types of farm. Modern low impedence units are extremely powerful, and they are capable of electrifying long lengths of fence. Modern units are completely electronic, with no moving parts. The chance of failure is low, and most units are built from modules which can be replaced quickly in the event of failure.

9.7.2 Energisers

Energisers are designed to apply a very large voltage (typically between 3,000 and 10,000 volts) to the fence for a very short period of time (typically less than 0.3 milliseconds), and to repeat this about once every second. An electric fence energiser must generate enough power to give an electrical shock to any animal which touches the fence at any point. However it must do this job without doing harm to the animal being confined, or to any other animal or human who could come into contact with the fence. This has been achieved as far as we can tell by energisers meeting the standard specifications, which set limits on the size, duration and frequency of occurrence of the electrical shock.

Each country has its own set of standards, and

some are more stringent or soundly based than others.

In New Zealand, the standard for mains energisers (at the time of writing, NZS 6203, 1987) requires that:

1. The peak output voltage will not exceed 10,000 volts.
2. The time between pulses shall be at least 1.0 second.
3. The current shall not last for more than 50 milliseconds.
4. The maximum energy output per pulse shall not exceed 8 joules, when a 500 ohm resistor is connected across the output terminals (some energisers will output even more energy if the resistance is lower, so the resistance must be specified).
5. Other rigorous conditions regarding electrical isolation, radio interference, the effect of faulty components, strength of the container, temperature effects, and other factors must also be met. An energiser which meets these criteria should be as safe as it is possible to make one, given the job it must perform.

9.7.3 Electrical Aspects

A simplified electrical circuit of a typical energiser is shown in *Figure 9.14*. The key components in the circuit are the condensers C_1 and C_2, the trigger diode TD, the thyristor TH, and the output transformer T. In essence the thyristor controls the discharge of the main storage capacitor C_1, while C_2 governs how often the discharge occurs. The main storage capacitor C_1 slowly charges from the 230 V ac mains input through resistor R_1 and rectifier diode D_1. The rising voltage across C_1 causes capacitor C_2 to charge through R_2, and when the voltage across C_2 reaches a certain value the trigger diode TD switches on and the pulse of energy stored in C_2 passes through TD to the "gate" of the thyristor TH. This fires the thyristor, and almost all of the energy stored in C_1 is discharged through the primary winding of transformer T, producing a pulse in the secondary output circuit. The transformer increases the voltage by a factor of typically around ten. This sequence is then repeated at intervals of about one second.

In practice various additions are made to this basic circuit, such as those shown in the Figure. Here C_3 and D_3 combine with C_1 and D_1 to form a "voltage doubler" rectifier circuit, so that the normal 230 V mains will charge the storage capacitor C_1 to nearly 700 volts. The diode D_2 is connected across C_1 so that when it discharges through T its polarity will not reverse, so reducing the severity of the duty on C_1. On the secondary output winding of the transformer a voltage-dependent resistor R_3 is often connected. This has the property of decreasing its resistance value as the voltage across it increases. By selecting the type and numbers of resistors which make up R_3, the peak voltage under conditions of low fence leakage can be kept below the 10 kV limit. However, when the fence leakage is high and the output voltage decreases, the current flowing through R_3 decreases considerably.

As a visual indication that the energiser is

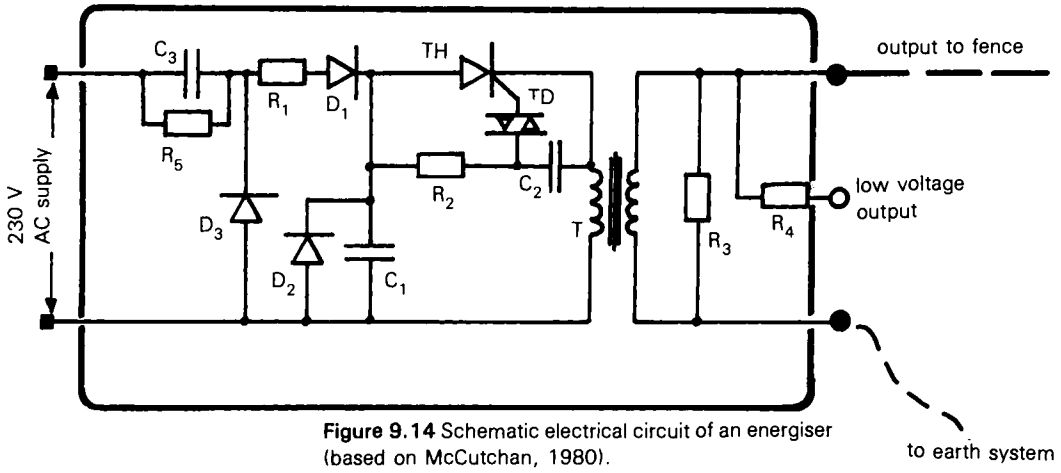


Figure 9.14 Schematic electrical circuit of an energiser (based on McCutchan, 1980).

operating, most models include a neon lamp. This may be connected across the output, in which case it flashes briefly at the same time as each pulse occurs. Alternatively it may be connected across the storage capacitor C_1, in which case it goes out when the pulse occurs and relights soon afterwards as the voltage builds up again. Most modern high power energisers have two alternative fence output terminals, and one method of internal connection is through a series resistor R_4. The lower voltage terminal is intended for use on fences and for special purposes around buildings. The resistor R_5 is added in some models to discharge capacitor C_3 after the energiser is switched off. Without this it is possible to get an unpleasant shock from the pins of the plug shortly after it is pulled out of the supply outlet. A typical output pulse from an energiser is shown in *Figure 9.15.*

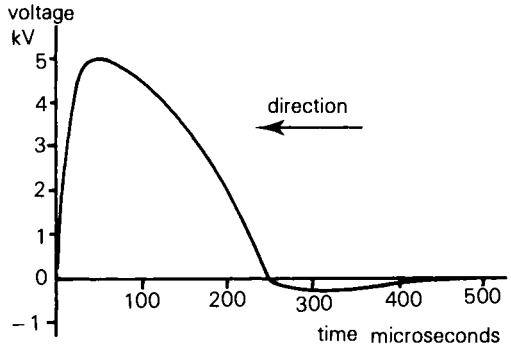


Figure 9.15 Output pulse from energiser. The arrow indicates the direction the pulse would be travelling in.

Analysis of energiser and fence system.

Using the black box model of an energiser, the equivalent electrical circuit for an energiser and fence is shown in *Figure 9.16.*

The output impedance of modern energisers R_O is typically around 20 ohms, which is fairly low. There would be little point in producing devices with even lower output impedances, since even in well-built fencing systems the impedance of the lead-out wires R_L and the earth return R_E are both usually around 10 ohms each. Since the effective output impedance of the fence's power source will be the sum of these three impedances, the energiser's output impedance is rarely the limiting factor. This can be seen from the analysis of the circuit diagram, where R_A represents the impedance of the animal. It depends largely upon the conditions at the points of contact between the animal and the fenceline, and the animal and the ground. The effective output impedance of the system supplying power to the animal, is $R_O + R_E + R_L$.

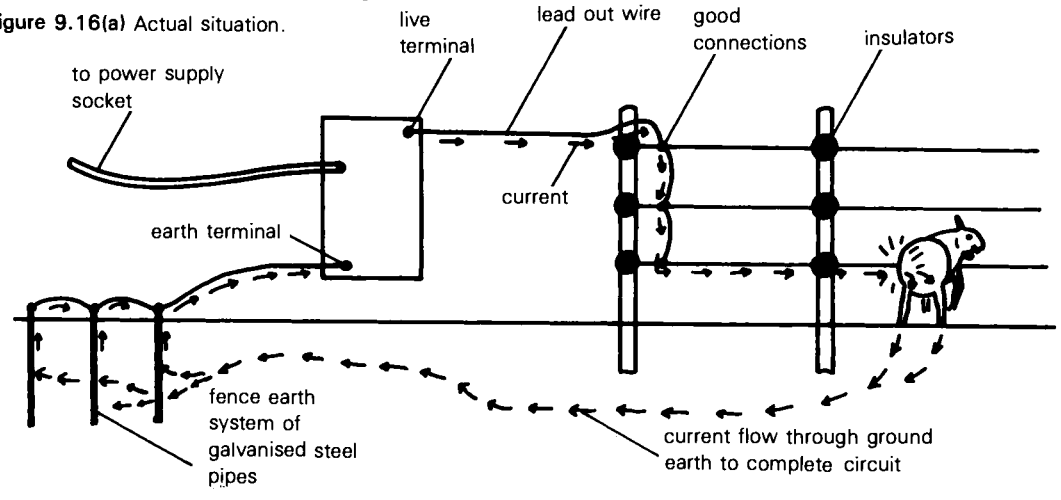
Example

The output impedance of a 5000 volt energiser is 20 ohms. If the earth return impedance is 30 ohms and the lead-out wire is 50 ohms, calculate:

(a) The effective output impedance of the supply system.

(b) The voltage produced on a sheep in contact with the fence if the sheep produces a load of 400 ohms and the fence has no shorts, or poor connections (ie, with reference to the discussion in the next section, this means that R_{L2} is zero and R_S is infinite, so they can both be ignored).

Figure 9.16(a) Actual situation.



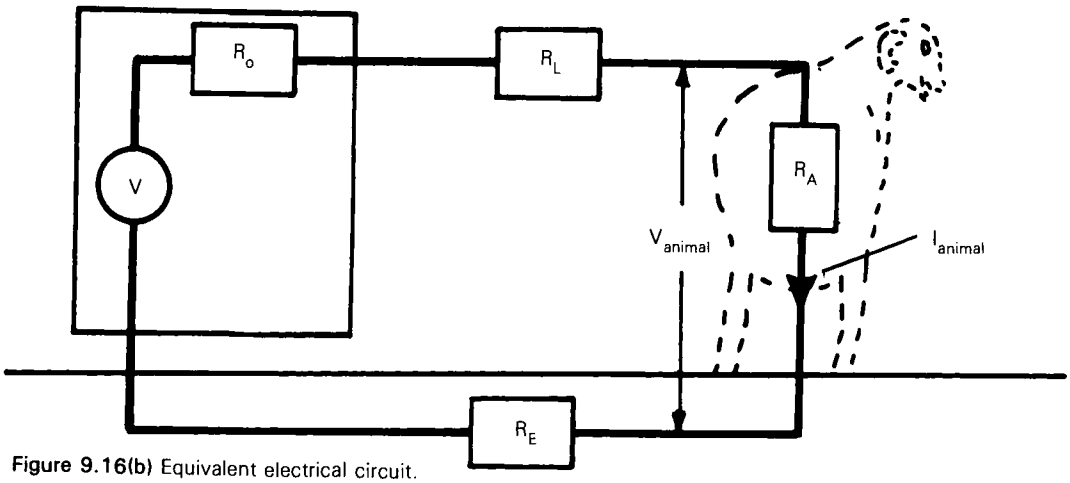


Figure 9.16(b) Equivalent electrical circuit.

(c) Draw the graph of output voltage on the sheep as a function of load (ie, the sheep's resistance).

Solution

(a) Effective output impedance = $R_O + R_L + R_E = 20 + 30 + 50 = 100$ ohms.

(b) Total circuit resistance (R_{tot}) = $R_A + 100 = 500$ (since these resistances are in series). Therefore using Ohm's law for the whole circuit,

$$I = V/R_{tot} = 5000/500 = 10 \text{ amps} \qquad \textbf{Equation 9.3}$$

There will be a drop in voltage through each resistance individually, and by applying Ohm's law to each, the voltage drop can be found. Thus for the sheep,

$$V_A = I\ R_A = 10 \times 400 = 4000 \text{ volts} \qquad \textbf{Equation 9.4}$$

Thus the shock received by the sheep is 20% less than might have been expected.

(c) The graph can be found by repeating the calculation of the voltage for various values of R_A. Alternatively we can derive the formula for V_A as a function of R_A:

$$V_A = I \times R_A$$

$$\text{But } I = \frac{5000}{R_{tot}} \qquad \textbf{Equation 9.5}$$

$$\text{and } R_{tot} = R_O + R_L + R_E + R_A = 100 + R_A \qquad \textbf{Equation 9.6}$$

$$\text{Therefore } V_A = \frac{(5000 \times R_A)}{(100 + R_A)}$$

$$= \frac{5000}{(1 + 100/R_A)} \qquad \textbf{Equation 9.7}$$

The graph of this is shown in *Figure 9.17* (upper curve—the other curves will be discussed below). This shows that the voltage is small if the resistance is very low, and rises to approach the optimum as the resistance increases. If the value of $R_O + R_L + R_E$ is greater (eg, say 500 ohms), the effect is as shown by the dotted curve. The voltage on the animal is lower, but still reaches the same value at very high animal resistances. Unfortunately, this is only a small part of the story, as we will now see.

9.7.4 Effects of poor fence construction

If a sheep presses harder against the fence, so that its resistance to electricity drops, *Figure 9.17* tells us that the voltage across the animal V_A will drop. However the current in the circuit will increase. This all passes through the animal and, as it is the current and not the voltage which animals sense (as discussed in Chapter 5), it will therefore experience a more painful shock. However, if the circuit resistance drops but only part of the current passes through the animal, then the result may be different. This happens if there are any poor insulators, or shorts due

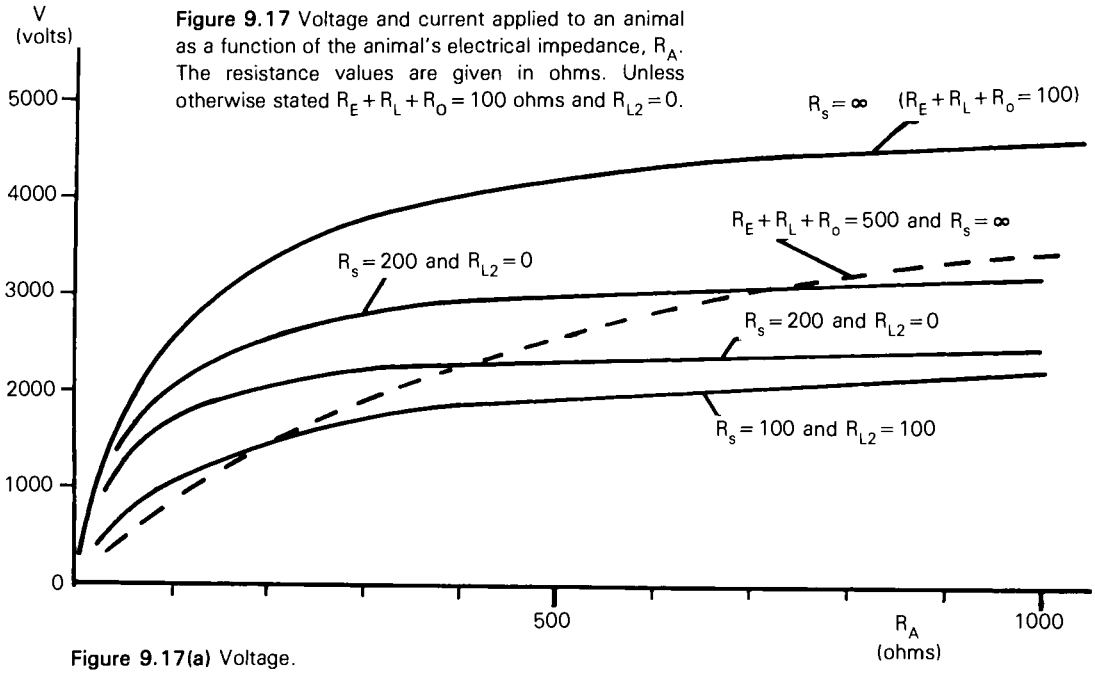


Figure 9.17 Voltage and current applied to an animal as a function of the animal's electrical impedance, R_A. The resistance values are given in ohms. Unless otherwise stated $R_E + R_L + R_O = 100$ ohms and $R_{L2} = 0$.

Figure 9.17(a) Voltage.

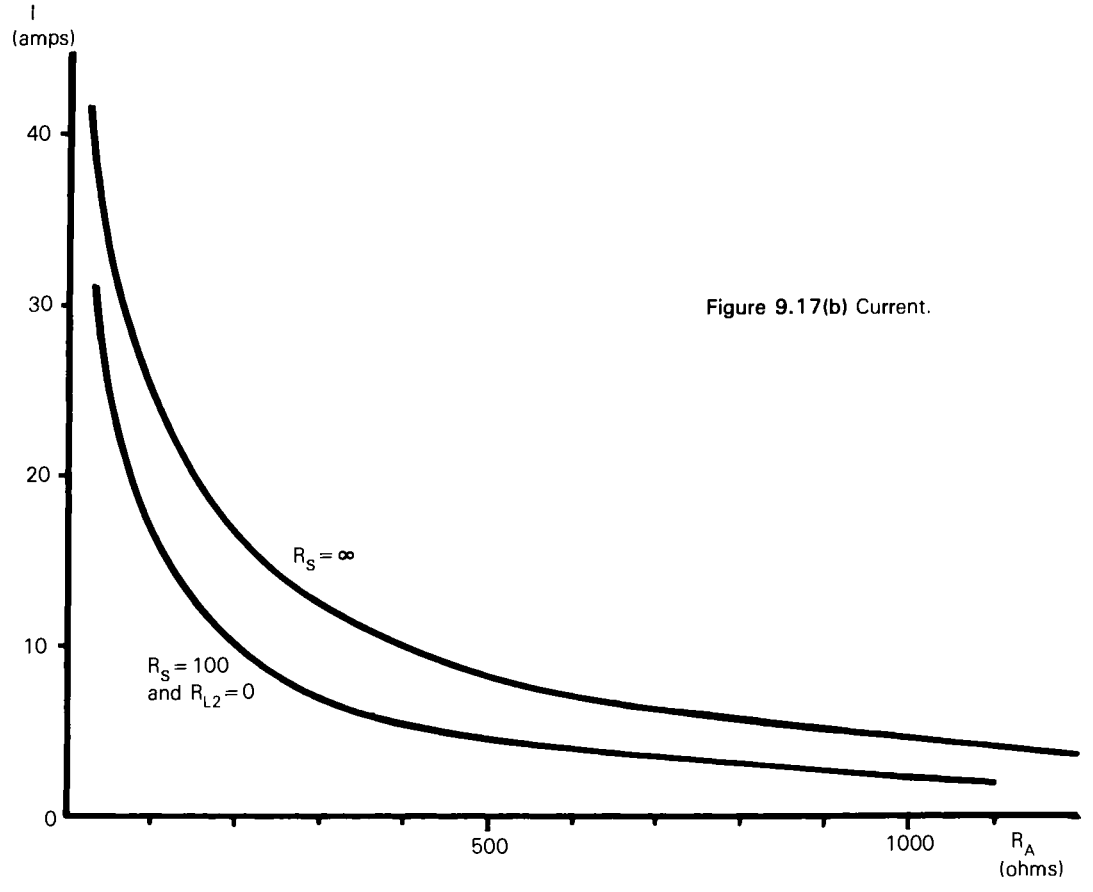


Figure 9.17(b) Current.

to wet grass touching the fence. The equivalent circuit diagram illustrating this effect is shown in *Figure 9.18*. In this Figure a "short" in the fence is represented by the

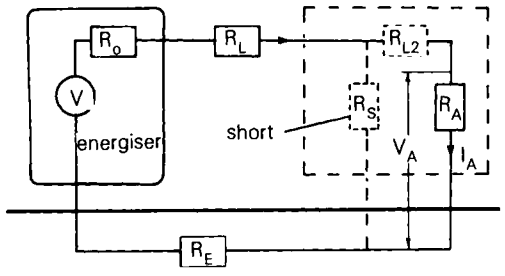


Figure 9.18 Equivalent circuit for energiser and fence with poor connections and leaking insulators.

resistance R_S which allows current to leak through it to the earth. Normally this resistance should be quite high, but poor insulators or wet conditions can result in low values. How much effect the short has depends upon how small the resistance is. It should be noted that the short will affect the entire fenceline. In addition we must add an additional line resistance R_{L2} which represents the effective extra series resistance of all the wires and poor connections in the fence itself. I_A and V_A represent the current through and voltage across the animal itself, while V is the voltage generated by the energiser, on open circuit (ie, when there is nothing connected to it).

For the full circuit of *Figure 9.18*, it can be shown that the voltage and current across the animal are given by the equations:

$$V_A = I_A R_A \qquad \textbf{Equation 9.8}$$

and

$$I_A = \frac{V R_s}{(R_L + R_E + R_O)(R_A + R_{L2} + R_S) + R_S(R_A + R_{L2})}$$

Equation 9.9

This looks awesome, but by considering practical cases, the equation tells us a lot about electric fencing.

First recall that R_O is the output impedance of the energiser. It is small and cannot be altered by the user in any way. R_A is the impedance (resistance) of the animal. It varies depending on how wet the soil is, how hard the animal touches the fence, and how much hair or wool covers the point of contact. Typically we could expect R_A to be 5000 ohms or more. All the other impedances are determined by how well the fence is constructed. The earth resistance R_E, and the line resistances R_L and R_{L2} should be as low as possible, by ensuring that the earth is properly constructed, and by using good lead-out wires and making proper connections. On the other hand R_S should be made as large as possible by using good insulators.

We can take typical values of these resistances and use them to see the effects of R_S and R_{L2}. For example if we assume $R_L + R_E + R_O = 100$ ohms, then *Figure 9.17* shows values of the voltage on and current through the animal for different values of R_S and R_L for various values of R_A. These show that R_{L2} has an effect at low values of the animal resistance, while R_S influences the effectiveness of the fence at any value of R_A. In practice R_A is usually large, and this is the most important practical case, since the size of the shock under difficult electrical conditions will be the important factor in establishing how effective the fence is. When R_A is large (say 5000 ohms), then *Table 9.4* shows values of the current through and voltage on the animal for various values of R_S. Quite clearly these values show that a bad leak can reduce the size of the shock by a factor of two or more.

One final point about *Equation 9.9*. Note that it is only the sum of $R_L + R_E + R_O$ which matters: if the earth and the line feed are poor, then you might as well buy a cheap inefficient energiser, since even the best energisers cannot overcome inadequacies here. Also note that it is the ratio of R_S to the sum of $R_L + R_E + R_O$ which determines the effect of R_S. A good energiser (low R_O) with a good leadout and good earth will help to overcome some of the effects of shorts in bad weather.

9.7.5 Selection of Energiser

The key criterion for an electric fence energiser is not the peak voltage output but the energy which it can discharge into a circuit with a specified resistance. The reason for this can be understood by considering what the energy represents. From our considerations of mechanics and electricity,

Table 9.4 Values of I_A, V_A, and instantaneous power W_A ($= V_A I_A$)

Except where stated it is assumed that V = 5000 volts, R_A = 5000 ohms, and R_{L2} = 0 ohms.

	R_S ohms	I_A amps	V_A volts	W_A watts
$R_L + R_E + R_O$ = 100 ohms	100	0.5	2470	1225
	1000	0.89	4460	3986
	∞	0.98	4900	4803
$R_L + R_E + R_O$ = 500 ohms	100	0.16	820	134
	1000	0.63	3125	1953
	∞	0.91	4550	4132
$R_L + R_E + R_O$ = 100 ohms	100	0.45	2250	1014
R_{L2} = 500 ohms	1000	0.81	4065	3305
	∞	0.89	4460	3985
$R_L + R_E + R_O$ = 100 ohms	100	0.05	2500	125
R_A = 50000 ohms	1000	0.09	4540	412
	∞	0.10	5000	498
$R_L + R_E + R_O$ = 100 ohms	100	4.55	2270	10330
R_A = 500 ohms	1000	7.69	3850	29590
	∞	8.33	4170	34722

we know that

energy = power × time

but in electrical terms power = volts × amps

Equation 9.10

Thus energy (E) = volts (V) × amps (I) × Time (t)

Equation 9.11

In the case of an electric fence energiser, all these variables change rapidly as the pulse is generated and absorbed. The energy must be found by integrating over the pulse. Thus:

$$E = \int V I \, dt = \frac{1}{R} \int V^2 \, dt = R \int I^2 \, dt$$

Equation 9.12

since I = V/R.

Energy can thus be obtained by measuring the area under the curve of the voltage (or current) squared against time, feeding into a known resistance. Energy output is thus a measure of how well the voltage and current are maintained over the period of the pulse. It is now believed that the total current flow is the factor determining the effectiveness of the shock. However this depends upon the animal's resistance, and as a means of assessing energiser performance is not particularly useful. Energy output into a known resistance is therefore probably the most appropriate measure of energiser effectiveness. The ideal energiser should maintain a high voltage for as long as possible consistent with the safety regulations so that the energy in the pulse is maximised.

Other terms and claims for energiser strength are not valid indications of the effectiveness of the energiser. In particular, claims relating to the voltage output at the end of a fence line are particularly useless since this depends upon how good the fence is! Some manufacturers now specify the energy output of their energiser at various loads, and this is to be encouraged, particularly when safety regulations limit the energy output for a particular load, as in New Zealand.

Types of energiser

In general electric fencing energisers fall into two broad categories, ie, mains or battery powered. Mains units are preferable for permanent fencing because of their greater power and because there is no battery maintenance.

The only situations where a mains unit will not be feasible will be in remote areas where there is no power. Where battery operated units are unavoidable it is necessary to hold spare batteries, which can be taken out into the field fully charged and exchanged for run down batteries. Alternatively periodic visits

to the units may be made with a small petrol engine driven generating set. In practice these systems do not seem to work too well, due to the problems associated with changing batteries before they become discharged. The rate of discharge can vary with conditions, and some rechargeable batteries can be damaged permanently if they remain uncharged for even short periods while in use. Wind charging generators have been used in some countries but have not been successful in New Zealand. They are prone to damage in storms. Site wind conditions would need to be carefully matched to the wind charger, its output and battery requirements. Solar powered units can be purchased. Although their initial cost is high, their performance appears to be satisfactory. They must be protected from stock but not shaded. In some countries water wheel powered chargers have been used, but these usually require too much maintenance to be viable.

In general battery powered units are designed to have a relatively low energy output, since this reduces the drain on the battery so that they will last longer between recharges.

9.7.6 Wire selection

The mechanical properties of fencing wire have already been discussed. For electric fences, the electrical properties must also be considered. These are given in *Table 9.5*, in which three electrical terms are listed. These terms need a little explanation! First remember that the lower the resistance the better. The first is the DC resistance of the wire. This is the normal measure of the resistance of the wire as we have described it in the chapter on electronics. As expected it depends upon the type and the cross-sectional area of the wire, and shows just how good aluminium is. Unfortunately the DC resistance is of little use in considering the ability of the wire to transmit a pulse from an electric fence energiser! The reason for this is that the current pulse is forced to travel in the outer layers of the wire and not throughout the wire as one would expect. This is known as the skin effect and arises because the electrons in a rapidly changing current pulse are forced to the outside of the wire by the electric and magnetic fields generated as a result of the changing current. The effective resistance depends upon the frequency of the pulse and the values in the table are those for a pulse at 3 kHz, which is the predominant frequency in a fence pulse. This means that the effective resistance to the pulse is higher than the DC resistance. The effective resistance does not drop as fast as the DC value with increasing wire diameter.

Table 9.5 Effective electrical resistances of wires for electric fencing (NZAEI)

Fence Description	DC Resistance ohms/km	Effective Resistance ohms/km	Characteristic Impedance ohms
Single wire			
1.6 mm HT (high tensile)	87.0	94.0	900
2.0 mm HT	52.0	69.0	740
2.5 mm HT	35.0	44.0	720
4.0 mm MS (mild steel)	13.0	37.0	660
5.0 mm MS	8.0	28.0	620
3.15 mm aluminium (6061-T8)	4.5	6.5	440
6 Strand "hot-strand"	7500	>7500	7020
1.6 mm double insulated Cable (buried 100-150 mm deep)	76.0	100	200
Multiple wire			
2×2.5 mm HT	17.5	23.0	360
3×2.5 mm HT	11.6	17.0	310
4×2.5 mm HT	8.8	14.0	260
6×2.5 mm HT	5.8	12.0	220
2×6 Strand "hot-strand"	3750	>3750	3730

Unfortunately real life is rarely simple, and the third column in *Table 9.5* demonstrates this! It arises because if we wish to analyse the electrical behaviour of the fence line as a whole, we must consider the electrical characteristics of the complete fence line assembly. The pulse is transmitted through the wire and back to the energiser through the earth. There are therefore two conductors (the fence wire and the earth return) and these two interact in a complex way. There will be some inductance and some capacitance between the two, and there will also be a finite resistance between the two, which will depend upon the effectiveness of the insulators, and will be distributed along the fence. The Characteristic Impedance, Z, is a measure of this impedance, and values are given in the table. For the record Z is calculated from the formula:

$$Z = \left(\frac{R+j\omega L}{G+j\omega C}\right)^{1/2} \approx \left(\frac{L}{C}\right)^{1/2}$$

Equation 9.13

where R is the effective resistance, L is the inductance (typically two to six milliHenries per km for 2.5 mm wire), G is the "shunt conductance" (ie, the reciprocal of the resistance between the two conductors, with typical values in the range 10^{-7} to 10^{-3} ohm^{-1} per km, depending upon the weed growth, etc), C is the shunt capacitance (typically 8 nanofarads per km), and ω is the frequency multiplied by 2π (Brockelsby et al, 1977). The term j means the square root of -1 which really only means that the current and voltage are not in phase.

The characteristic impedance is a measure of how much energy can be stored or transferred on the fence line for a given voltage. In general the lower the value the better. This is especially true in the case of lead-out wires, where the low effective resistance of aluminium, coupled with its low characteristic impedance, make it an excellent choice. The characteristic impedance can have significant effects on the pulse shape and its behaviour as it propogates along the fence line (eg, see NZAEI, 1987).

Table 9.5 also shows resistances for combinations of wires as well as for single wires. As can be seen there are many cases where a lower resistance is achieved by using two or more 2.5 mm diameter wires rather than a thicker wire. Using two wires can be not only cheaper but can improve the electrical performance. On the other hand, six wire hot-strand is a very poor conductor and can only be used over very short distances. Strands and hot tape with more wires have also been produced and these should be better electrically.

9.7.7 Wire tension

The tension in an electric fence wire need not be as high as in a non-electric fence. It needs to be tight enough to ensure that the wire never becomes slack, since loose wire can be a serious safety hazard, as well as causing short circuits. Recommended tensions are generally in the range of 600 to 900 Newtons. This means that strainer assemblies can be less strong since they will take lower loads.

9.7.8 Corrosion of electric fencing wire joints

Galvanised steel fencing wire is protected from corrosion by a sacrificial coating of zinc. The principles of corrosion have already been considered earlier. However, corrosion can also be accelerated by electrochemical reactions. Where two dissimilar metals are joined together in the presence of moisture the anodic or most strongly electropositive metal is sacrificed in the generation of electricity at the joint. This problem can occur in electric fences if lead-out wires of copper or aluminium are used.

When choosing materials for electric fence construction it is important to realise that where different metals are joined together, corrosion will occur due to electrochemical reactions, whenever the joint gets wet. An electrical cell (like a battery) is formed. The rate of corrosion and which metal corrodes depends on the electromotive potentials. These are listed in *Table 9.6*. Thus, joining copper to galvanised steel wire produces a cell capable of producing approximately 1 volt, with the resultant corrosion of first the zinc layer and then the steel core. When copper and galvanised wire are connected and the joint is allowed to get wet, rapid corrosion will occur. In addition the corrosion products reduce electrical contact between the wires so the joint will impede the energiser pulse. When aluminium and copper are joined, the

aluminium will corrode. When an aluminium wire is joined to a galvanised wire, the zinc coating will corrode before the aluminium, thus giving sacrificial protection. Copper is the material to be avoided, even though it may not corrode itself.

Table 9.6 Galvanic series for elements and materials
(Diamant, 1970; Kutz, 1986)

Metal	Electromotive potential (volts)
magnesium	+2.34
aluminium	+1.67
zinc	+0.76
chromium	+0.71
iron and steels	+0.44
tin	+0.14
lead	+0.13
hydrogen	0.00
stainless steel (316)	−0.09
copper	−0.34
stainless steel (passivated)	−0.58
silver	−0.80
platinum	−0.86
gold	−1.68

Note: Some materials can be made "passive" by dipping them in suitable acids to produce a dull-looking surface coating.

If it is necessary to join dissimilar metals, corrosion can be prevented if the joint is cleaned of ionic material and encapsulated to prevent the ingress of moisture. It is not clear how long such a seal would last in service.

As discussed earlier, insulators act as a barrier to protect the wire from the galvanic action arising from the use of preservatives in wooden posts.

9.7.9 Electric fencing strand and ribbon

The properties of electric fencing strand have already been discussed in section 9.2. Its use is limited to short distances as its electrical conductivity is poor. One advantage of the ribbon is that it can be seen easily by both stock and humans. It has been produced in a variety of eye catching colours, and there appears to be relatively little evidence as to the most effective colour for stock. White may be marginally better since it reflects all wavelengths, and would therefore be seen in poor light conditions, but orange and yellow may be picked out more easily by humans at least. Hot strand plastic netting can also be purchased.

9.7.10 Insulators

The purpose of an insulator is to prevent the flow of electricity through the support post to the earth. There is a very wide range of commercial insulators on the market and these can be classified into two types, ie, the moulded, individually attached insulators, and self-insulating posts. After earthing and poor connections, unsatisfactory insulators are the third most common cause of faulty electric fences. Various types are shown in *Figure 9.19.*

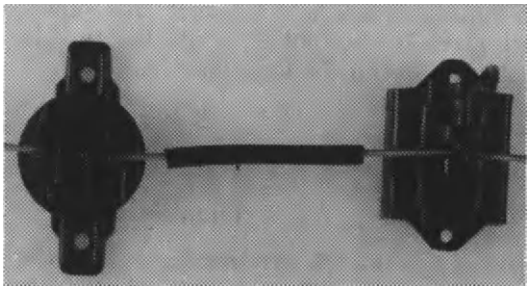


Figure 9.19 Examples of insulators.

Moulded insulators

These insulators are made from either plastics or ceramics. Plastic insulators are cheap and available in a bewildering range of designs, varying from the simplest, consisting of a short length of small bore plastic pipe slipped over the wire and stapled against the post, to weird mouldings with numerous projections which (while well designed) could double as a spaceship in a movie! Polyethylene and polypropylene are the most common plastics used. The main feature to check in an insulator is the shortest distance from the wire to the post, nail, or staple, over the surface of the insulator. This is because the electric current tracks over the surface rather than through the material, especially if the surface is damp. As a guide this surface path should be at least 25 mm long, and preferably over 40 mm in damp dirty areas. It should be remembered that any splits or through cracks in the plastic can act as direct shorts when wet or dirty, as will any metal staples used to attach the insulator. It is also preferable to use insulators which are attached at two points rather than by a single nail or staple.

This is because the load can be moderately high at times. If small bore tube is used it should not be slit, and should be attached with two skew staples at opposite angles. This bends the tube and should prevent it from slipping along the wire. Ordinary polythene pipe tubing is not recommended by energiser manufacturers, because they claim that it has a short life, and faults can be hard to detect. Corrosion of the wire inside the tube is also likely, and the staples used to hold the tube in place can easily damage the tube.

Ordinary plastics deteriorate quickly (a matter of four to five years) when exposed to ultraviolet radiation from the sun; this results in a brittle material with a weakened or cracked surface which is easily contaminated and which will therefore conduct electricity. Special ultraviolet inhibitors or stabilisers must be incorporated into the plastic during manufacture, to reduce the rate of deterioration. Unfortunately, it is not possible to tell by inspection whether or not such additives have been incorporated, and the onus is on the purchaser to select the insulator carefully. The NZAEI are conducting long term durability trials on fencing components in New Zealand. A design which allows the insulators to be replaced without first removing the wires is an advantage in the long term. It seems logical to place insulators on the shady side of a fence line to reduce their exposure to the sun.

Ceramic insulators

Ceramic insulators (usually porcelain) have very good electrical properties and do not deteriorate with time unless they are chipped. The glazing produced when the ceramic is fired gives a smooth self-cleaning surface, and a well made insulator will not absorb water. Unfortunately, unless the insulator is well made, water will enter the material and the resistance to current flow will drop. Breaks in the glaze can occur at the points where the insulator is supported during firing. As a guide, it is recommended that an insulator should not absorb more than 0.5% of its own weight of water when placed in water for 24 hours. Ceramics are brittle and will break under impact. They are also stronger under compression rather than under tensile loads. Ceramic insulators are more expensive than plastic ones but are still preferable where the insulator is mechanically loaded in compression. Other modern materials may also prove to be suitable for fencing use.

Self-insulating fence supports

If the fence post itself is an insulator then there will be no need for additional insulators. This is possible if materials which do not conduct electricity, and which do not absorb moisture, can be found. A third criterion is that they should be self-cleaning, so that dirt or contaminants do not build up on the surface. The principle contenders are fibreglass rods, plastic rods, untreated hardwoods such as the Australian iron-bark, and ordinary timbers treated with an artificial water-proofing agent such as penta-chlorophenol soaked in oil. All four have been used with some success. However in coastal areas a build up of salt deposits can affect the insulating properties of fibreglass insulators, while iron-bark supports may lose some of their insulation resistance in salty or wet conditions. This is offset by the reduction in resistance of any animal contacting the fence in these conditions. The build up of salt or dirt may also affect the electrical properties of timber posts in coastal or polluted areas, although there is no clear evidence for this yet. Similar effects could also occur on other types of insulator.

The mechanical properties of the posts are also a factor: hardwood posts are strong but brittle, while plastic rods vary dramatically in their strength and flexibility, and are subject to ultraviolet degredation if no inhibitors are incorporated during manufacture. Fibreglass rods may also exhibit surface deterioration with time, although plastic coatings may help to prevent this.

In spite of these considerations, self-insulating fence posts are in widespread use, particularly for temporary subdivision, and provide one of the least expensive forms of sub-division available at present.

One advantage of light flexible systems is that the fence can absorb charges by stock without damage. Some systems have been developed which exploit this to the full. In one system springs are included in the fence (these may help to protect fences where snow loads are likely to be a problem). In another system, the wires are tensioned with a length of spring steel curved in the form of a bow (*Figure 9.2*). The wire slides freely through the fibreglass

supports and it is claimed that the fence can absorb a great deal of deflection (as much as five metres) before anything breaks (Weir and Bird, 1980).

9.7.11 Temporary subdivision

The management of pasture and the feeding of standing crops to animals are techniques which depend on the ability of the farmer to control the stock within well defined areas. While farms can be divided into paddocks with permanent fences, there are many cases where it is advantageous to erect fencing of a temporary nature. In these cases electric fencing is a system which is hard to beat. Low cost light-weight equipment can be set up very quickly by one person, and can be moved in a matter of minutes. Stock can therefore be allowed to graze across a paddock progressively over a number of days, so that the grass or crop receives the minimum of trampling damage, and more of the crop is eaten by the stock. Examples of equipment for this type of management are shown in *Figure 9.20.*



Figure 9.20(a) Fibreglass post and wire feed-out reels.



Figure 9.20(b) Fibreglass posts.



Figure 9.20(c) Tumblewheel system (a row of these wheels are set out across the paddock and fed by a single live wire in the centre. A device in the centre keeps the four upper legs live, while the lower ones are disconnected automatically. The wheel can be rolled along to move a break-feed wire).

9.7.12 Alarms for permanent subdivision

The use of electric fencing for permanent subdivision is a slightly different matter. While it is technically and economically attractive, there is an understandable reluctance to entrust all the fences on a farm to an electrical system which can be put out of action by the failure of a component in the energiser, or by a wire coming loose. Some energiser manufacturers have realized that this concern is real, and have introduced a range of alarm systems, designed to detect a voltage drop in a fence line. They rely on receiving a pulse from the end of the fence line in between the main pulses, and activate an alarm if the test signal is not received. In addition the reliability of energisers has improved over the years. The farmer can therefore feel reasonably secure, although if the fence is vital (eg, a boundary fence on a stud breeding farm), an electric fence which is also a reasonably good mechanical barrier is a possible solution. On cost considerations, the electric fence is hard to beat, and some farms have relied solely on electric fences since 1960.

9.7.13 Physiological effects of an electric shock

Humans and animals have a nervous system which operates through electrical pulses transmitted to and from the brain. They will therefore experience discomfort if they touch an electric fence when the energiser discharges. The particular extent of the

sensation depends markedly upon the current and the duration of the shock, and varies from no sensation at all to severe discomfort (Chapter 7 discusses the effects of continuous currents). Serious effects such as heart arrest or ventricular fibrillation are most unlikely because the pulse lasts for only 50 ms, and because of the time delay between pulses. The one second gap enables the victim to remove themselves between pulses. One danger is that if an individual is unable to get free from the source of the shock, the skin resistance drops as the current continues to flow and the current therefore increases. Deaths have occurred when this has not been possible (eg, if the victim gets tangled up in loose or barbed electrified wire, or if the victim is in some other way unable to get free). Research data on the threshold between the various effects is not easy to collect, but the evidence indicates that the critical parameter is the energy in the discharge. This is related to the integral of the current squared against time, as discussed earlier.

The following safety precautions should therefore always be adhered to:

a. Barbed wire must never be electrified.
b. Wires should be kept taut and tidy.
c. Unused or old lengths of loose wire should never be left in the paddock.
d. Single wires across lanes and gateways must be flagged with a large marker. In preference an easily seen spring gate should be used.
e. Electric fence warning signs must be placed on fences where the public has access (this is a legal requirement in New Zealand).
f. Energisers must comply with all safety standards (this is the manufacturer's legal responsibility in principle).
g. The low powered terminal on an energiser (if available) is better for fences around homes, horse paddocks and self-fed silage.
h. Attention should be given to overhead wires, particularly in areas where trucks and aircraft are used (top-dressing pilots face a high risk from unmarked wires). Local aviation companies, and top dressing pilots, should be notified of any such wires.
i. The energiser earthing must be at least 2 m from any mains earth, or buildings.
j. Teach your children to be wary of electric fences.
k. Not more than one energiser should be connected to an electric fence or interconnected network.

9.8 PERMANENT ELECTRIC FENCE DESIGNS

Examples of fence designs are shown in *Figure 9.21(a-d)*. These designs are representative of the wide range of permanent electric fence designs which have been suggested. *Figure 9.21a* shows wire spacings for a sheep fence which is suited to undulating hill country, while *Figure 9.21b* shows one which is satisfactory on relatively flat country. In very hilly country six or seven wire electric fences have been constructed. For convenience *Figure 9.21b* shows the earthed wire system and *Figure 9.21a* the ground return or "all live" method of earthing (see below). Both can be used in either configuration. It is probably a good idea to insulate all wires during construction, even if it is intended to use the earthed wire system. This provides for flexibility in use. In spring time if the grass grows high, the bottom wire can become shorted out, lowering the voltage. It is therefore an advantage to be able to disconnect the bottom wire from the energiser when required. *Figure 9.21c* shows a two wire fence suitable for cattle.

The post spacing for these fences can be much greater than for non-electric fences, since the fence is not a mechanical barrier. On flat land 40 metre spaces between posts, with battens every ten metres, is adequate. On rolling country shorter gaps may be required. Fence tensions can also be lower, and 900 Newtons is sufficient. Spring loaded permanent tensioners can be obtained which help to maintain the tension.

In practice designs are available which range from the use of one to eight wires. Single wire fences can be used for breakfeeding, while two or three wire fences have been used successfully on dairy farms for permanent fences. The design of a fence depends on the stock to be contained, and special designs are needed for goats and deer in particular.

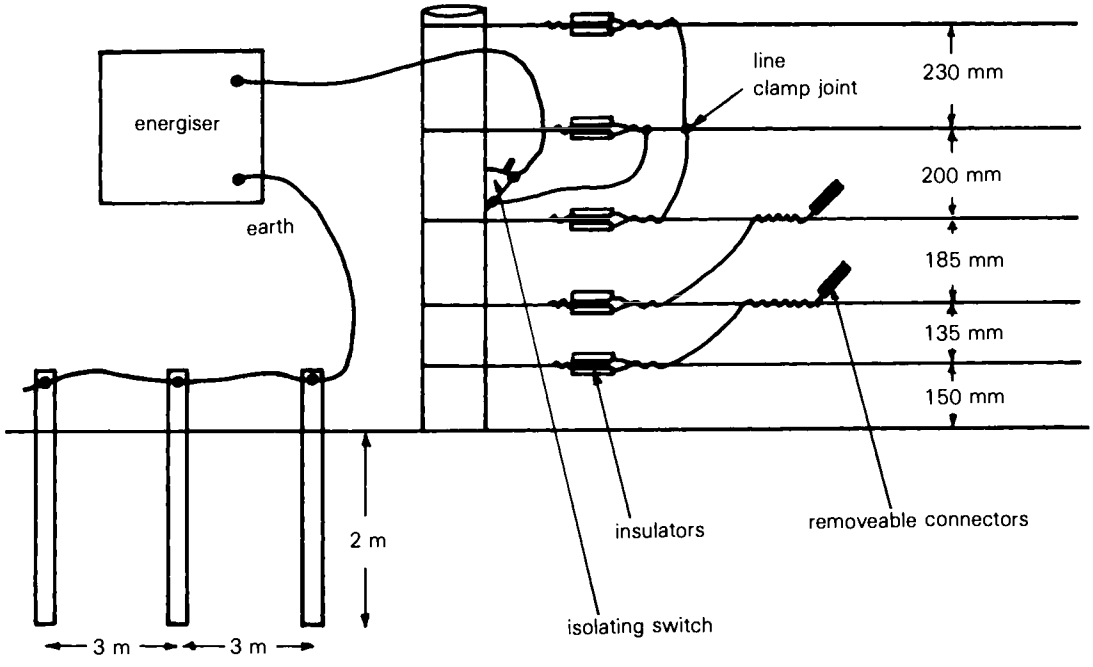


Figure 9.21(a) Design for sheep on hill country—all live wire system (based on original by Gallagher Electronics).

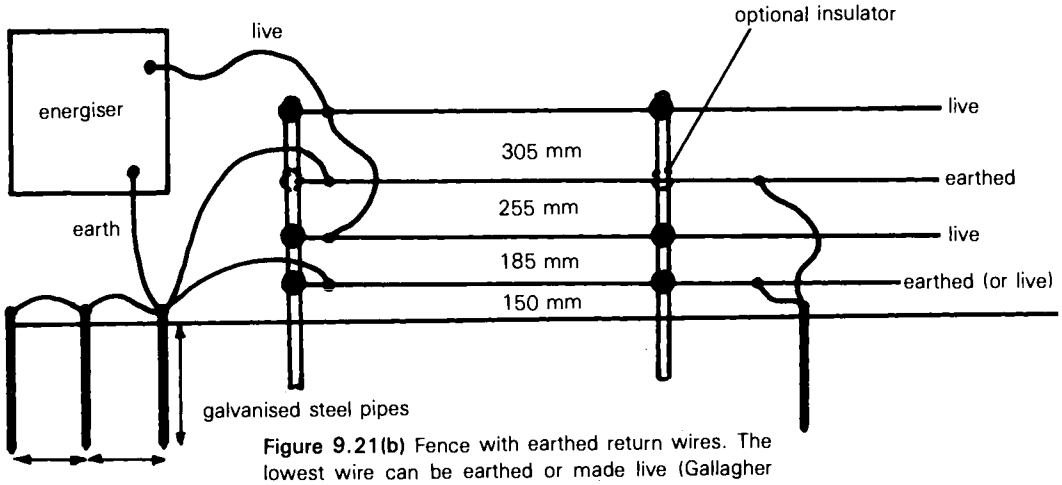


Figure 9.21(b) Fence with earthed return wires. The lowest wire can be earthed or made live (Gallagher Electronics).

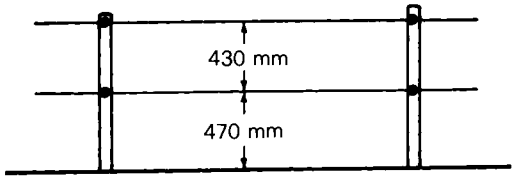


Figure 9.21(c) Simple fence for dairy farm.

Typical designs for these animals are shown in *Figures 9.22a* and *b*. For goats a five wire fence can be used, preferably with an outrigger for training the animals to respect electric fences. In addition a non-electrified wire 50 to 100 mm off the ground and under a tension of at least 1500 Newtons will help to prevent goats attempting to crawl under the fence. In this case the wire spacings should be 50 mm, 100 mm, 140 mm, 185

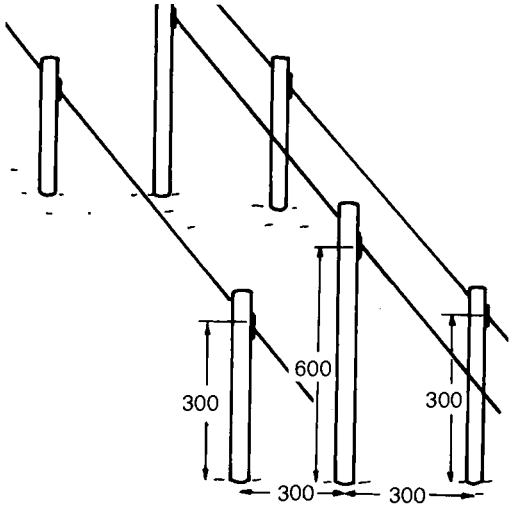


Figure 9.21(d) "grass fence". The centre wire is optional.

mm, 200 mm, and 230 mm (Gallagher Electronics, 1980; Lord, 1984). Goats are extremely good climbers, and angled stays have to be avoided in the fence design! Bucks are particularly difficult to control, and a higher fence with three extra wires at 230 mm intervals, together with an outrigger 450 mm off the fence line, will help to stop them jumping over.

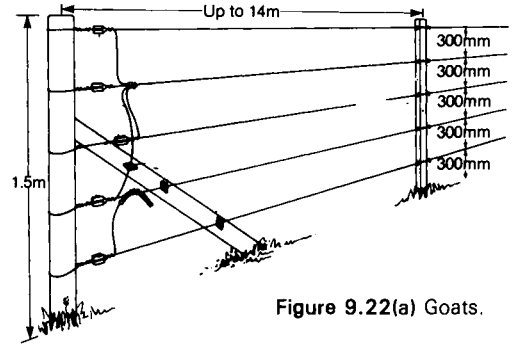


Figure 9.22(a) Goats.

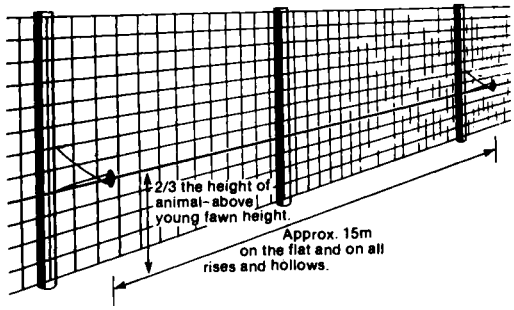


Figure 9.22(b) Deer. The outrigger wire should be placed at 0.67 times the height of a fully grown deer, so that it is above the heads of young fawn (Gallagher Electronics).

When deer are being contained, Government regulations may determine the type of boundary fence required. In New Zealand a 2 m high mesh fence is demanded. Internal fences are a different matter, and electrification can reduce the costs by a factor of as much as five! Two other problems arise with deer. First, the barrier must be high enough to prevent stock jumping over. Second, it must take into account the tendency of deer to "walk" the fence-line (ie, they choose to spend a lot of time walking parallel and close to the fence). This means that any protrusion into the paddock can be a hazard to the animals, and corner stays must be erected so that they do not protrude into the paddock. An offset wire helps to reduce this tendency. The outrigger on a mesh fence will stop deer from rubbing against the mesh and distorting it. A further problem arises during fawning. Young fawns should not be subjected to electrical shock for at least their first week of life, and the wires below 600 mm are often disconnected from the power supply during this period. If the fawns must be prevented from wandering through the fence, then unelectrified wire mesh could be used to seal the bottom 500 mm. For pigs a three wire fence with wire spacings of 150 mm (from the ground), 185 mm and 255 mm is recommended (Gallagher Electronics, 1986).

One of the more interesting attempts at original fence design was the "grass-fence" (*Figure 9.21d*). The idea here was that the grass remained uneaten between the two wires which were placed 600 mm apart. This became a visual as well as a psychological barrier to the sheep, since the sheep learnt to associate the line of grass with the electric shock, and stayed away from the area. Occasionally a third centre wire was added, as in the Figure. In order for the system to work, the energiser had to be powerful enough to sear any grass which grew too close to the wire. However in practice the fence has not been very successful, partly because lush grass growing between the wires shorted the fence out too effectively, (especially when the grass got wet and drooped onto the wire). The strip between the wires can also become a haven for weeds and the seeds are able to mature and spread into the paddock. However, the grass fence remains as an interesting example of an effort to use animal

psychology as a barrier, even though the concept has been abandoned in New Zealand.

Obviously the more materials used in the fence the more costly the fence will be to erect, but the more effective it will be (at least potentially) as a stock barrier. The design chosen thus depends upon the degree of stock-proofing required and the type of animal to be contained. It also depends upon the stress the stock are likely to experience. Stock have been known to charge an electric fence when they are under stress regardless of their fear of the fence, and in this case only a mechanically sound fence will survive. However under easy conditions, or where the animals are very docile, even one or two wire unelectrified fences can be quite adequate. Most manufacturers recommend strongly that stock should be trained to respect and fear electric fencing under easy conditions and before they are subjected to any stress. Unfortunately there is very little scientific data available to quantify the degree of stock-proofing, so at present the choice of the mechanical strength of an electric fence remains a matter of individual preference.

9.8.1 Maintenance and fault detection

A fence voltage tester is an essential piece of equipment for checking that a fence is operating correctly. The voltmeter is connected from any point on the fence line to the earth, to give the voltage at that point. They are not expensive and can speed the location of shorts. When a fault occurs on the fence line, there is usually a loss of voltage due to a low resistance path to earth (R_S as in *Figure 9.18*). This is known as leakage. It is indicated by a reduced voltage in the tester. As a guide a drop of 50% or more indicates a problem, such as a wire on the ground, or faulty insulators needing replacement. In wet weather the general leakage through the insulators will increase, and voltage drops of 30% are not unacceptable (NZAEI, 1987). Other equipment which can be obtained from some manufacturers includes a system for stopping the pulses while working on the fence. The power can be switched off and back on again with a portable hand unit from wherever the work is being done. The hand unit sends a signal back to a box next to the energiser which stops the energiser. This is very useful if the fence is a long way from the energiser. Faults can often be detected using an ordinary radio. A click will be heard near to shorts if the volume is turned up, with the radio off-station.

Other maintenance includes a periodic check to remove weeds. In times of feed shortages, it may be advisable to keep a backup energiser in case of emergency.

It is important to be able to isolate sections of the fence in order to locate faults, and this has an important bearing on the design of the fence layout.

9.8.2 Earthing

In order to complete the circuit when an animal touches an electric fence, an earth system is needed. The correct earthing of an electric fence is crucial to the effectiveness of the fence. All the current in the fence must return via the earth system and any poor connections (including insufficient ground stakes) will reduce the effectiveness of the shock substantially. A proper earth system is therefore essential if the fence is to work properly. If a fence is not working well the earthing should be one of the first things to check. There are two methods of providing an earth return.

a. Ground return system (all wires live)

For most soils and locations the ground itself is a very good conductor and can be used to return the current (*Figure 9.21a*). This system has the advantage that the circuit is completed whenever an animal touches any wire.

In order to use the ground as an earth, the energiser must be connected to the ground in an effective manner, and this task must be undertaken carefully and thoroughly. A full analysis of earthing design is given by McCutchan (1980). An example of an earthing system is shown in *Figures 9.16a* and *9.21a*. This system can be used for both ground and wire earth return systems. The connection should be built in an area which is always damp, even if this means using suitable connecting wires up to one km in length. All the joints should be well made and secure. Thus the wire should be clamped to the stakes and not just wrapped around them.

The earth stakes can be made from ordinary 15-20 mm diameter galvanised steel pipe cut into lengths of two to three metres. These should be driven into the ground at least three

metres apart in good damp conducting soils, and as much as 10 metres apart in dry, non-conducting soils. For safety reasons these pipes must be at least two metres from any other earthing system (eg, for a house or another energiser). The number of pipes required will depend upon the soil properties, and the NZAEI now recommend the following method for testing and installing the earthing system (NZAEI, 1987). After installing the first rod, the energiser is switched on and the voltage between the energiser earth terminal and the ground is measured with a digital voltmeter (DVM). The ground connection to the DVM is made simply by pushing the DVM lead into the ground, or if the distance is too great from the energiser, by using a short length of wire pushed a little way into the ground and connected back to the DVM. If the reading is less than 500 volts then the earth is adequate. If it is more the fence should be checked for shorts, by ensuring that the voltage across the output of the energiser is more than 3000 volts, and that nowhere does the voltage fall below 2000 volts on the fence line. If there are no shorts then more earthing pipes should be added until the voltage between the earth terminal and the ground falls below 500 volts. If five stakes have been added without success, then it is worth checking the earthing wire connections by measuring the voltage between the top of one of the stakes and the ground at least 1.5 m from the stake. This should be almost the same as the ground terminal reading. If it differs by more than 200 volts then there is a problem with the wire between the energiser and the stakes and this should be rectified. If it is satisfactory, then more stakes can be added up to ten, when you should probably consider choosing another site for the earth! If a second site is chosen the original earth system can and should be left connected. The second earth wire should be connected directly to the energiser earth terminal.

If a DVM is not available, then the following method can be used, although it is not as good, since it relies on current flow detection by a somewhat inaccurate device, rather than voltage measurement with a DVM, as you may realise. The fence line is shorted out with several steel standards as in *Figure 9.23*. In this method you must use yourself as a sensor and the back of your hand as a probe to give an indication of how good the earth is. If there is any sensation of a voltage, then the earth is inadequate and more stakes are needed. This method is less reliable and more painful than using a DVM.

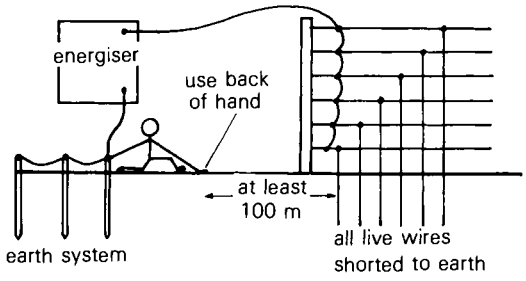


Figure 9.23 Earth testing method when DVM is not available (Gallagher Electronics).

In very dry soils, or those with a poor conductivity, a Bentonite and salt earthing system can be used. This involves digging or drilling several 70 mm diameter holes at least 10 metres apart and to a depth of at least 1.2 metres, and filling with a wet slurry of four kg of bentonite and two kg of salt. A stainless steel tube must then be used to form the electrode. Watering the earthing system can also help in very dry conditions.

Once installed it is recommended that the earth be checked regularly throughout its life since experience indicates that earthing connections deteriorate with time. The same is also true of the state of the fence lines themselves (since vegetative build up, etc, will cause problems).

b. Earthed wire return system

The earth return can consist of one or more wires in the fence line (*Figure 9.21b*). This approach is only required in very dry areas where the ground is a poor conductor of electricity. In these cases the contact resistance between the animal's hoof and the ground becomes very high so that R_A approaches infinity. Only desert areas are likely to qualify.

The animal must touch both the live and the earth wires before the circuit is completed. The earth wires should still be connected to the ground, and an additional earth peg every kilometre (preferably in a damp spot) is often used, although it is doubtful if this improves the situation. This system has the disadvantage that a short circuit between a

live wire and an earth wire can short the fence out completely. This design can however be very useful to deter animals and pests which tend to climb fences, such as possums, monkeys, humans, and snails.

9.8.3 Pulse shape and transmission effects

A typical pulse looks like the wave shown in *Figure 9.15*. This pulse travels along the fence line at around 150 metres per microsecond, and as it is about 0.3 milliseconds long, this means that by the time the energiser has finished sending the end of the pulse, the start will be about 45 km away! During transmission, the pulse is distorted and attenuated. Attenuation is caused because energy is lost in heating the wire, in generating electromagnetic fields around the wires, and through leaks. This results in a drop in the overall magnitude of the pulse. Distortion arises because high frequency components of the pulse travel slightly faster than low frequency components, and are more strongly attenuated. These effects mean that a pulse will tend to develop a steeper leading edge and a longer tail, but in the end the result is a fall of peak voltage.

A further complication occurs at the ends of a fence line. If there are no leaks or shorts at the end, the pulse can be completely reflected back along the wire. This means that near the end the voltage increases (it can almost double), since the reflected and transmitted wave combine together! However, if there is a short circuit at the end, then the reflected pulse cancels out the incoming pulse, resulting in a much reduced voltage. Effects between these two extremes occur where the fence divides or where there are changes in the electrical characteristics (eg, the characteristic impedance), such as where lead-out wires connect to the fence. The result is that the pulse can only be identified easily in a very long fence line, while in a short line the voltage is made up of a large number of reflections from each end. This description may help to explain why odd readings can be obtained at different places on a long fence line.

The normal variations in voltage on a fence line mean that checking the line is not quite as straight-forward as it would at first appear. It is a good idea to measure voltages at various points and in different weather and pasture cover conditions when the fence is new, so that when problems arise they can be sorted out much more quickly, by referring to this data.

9.8.4 Other equipment

In addition to the basic design of a fence, it is necessary to deal with other practical details such as how to electrify a gate, or a fence line which crosses a stream. *Figure 9.24* indicates some techniques for dealing with these problems. Most are self explanatory, but a few will be described briefly.

a. Lightning diverter (*Figure 9.24a*)

The probability of a lightning strike on an electric fence line is moderately high in many places. Such a strike is likely to damage the energiser. A lightning diverter and choke will help to prevent this damage. The choke is no more than a few turns of wire about 300 mm in diameter, through which the normal pulse flows without hindrance. The lightning strike is hindered by this device, and instead passes through the diverter to earth. The diverter is destroyed in the process, but costs only a few dollars to replace.

b. Crossing streams (*Figure 9.24b*)

The stream crossing system must include a device which will reduce or switch off the power entering the lower parts of the fence over the stream if they are submerged by rising water. From the theoretical considerations discussed earlier, a 1000 ohm high wattage resistor above the flood level could be used for this purpose if a commercial flood gate controller is not available. With reference to the diagram, A is a cut out switch, which can be used if a lengthy flood is likely. B is an insulated wire cable enclosed in plastic piping, C is a permanent wire strainer, which allows the chains to be raised or lowered easily, and D is a flood gate controller or voltage switch. E represents the maximum expected water level. Gallagher Electronics recommend that 3 mm chain be used, and that the distance X between the chains should be not more than 150 mm for sheep and 300 mm for cattle. The distance Y should be 150 mm above the average summertime water level F.

c. Gates (*Figure 9.24c*)

The double insulated cable under the gate should be buried at least 0.5 metres down, and should be well insulated. It is located inside a polythene pipe for protection.

d. Other details

Other details, including joints, switches, corner details, and a lifting gate are shown in *Figure 9.24d-i.*

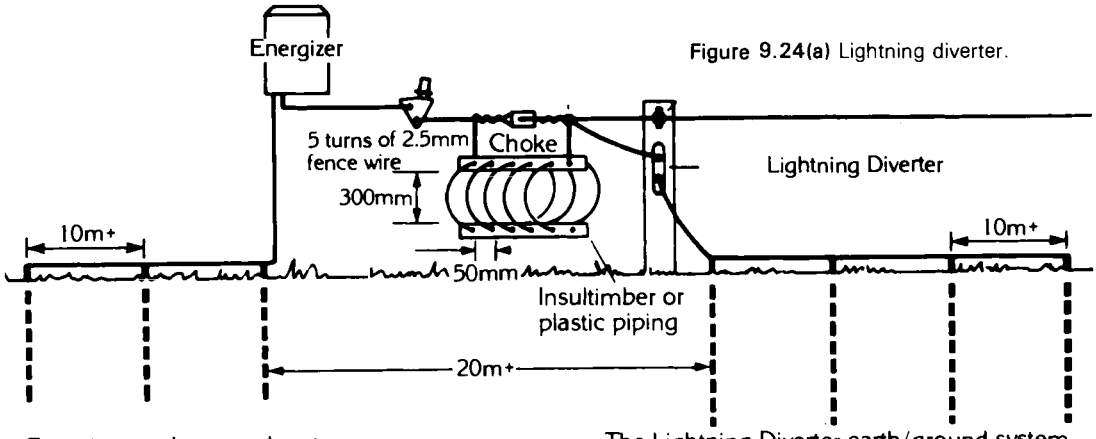
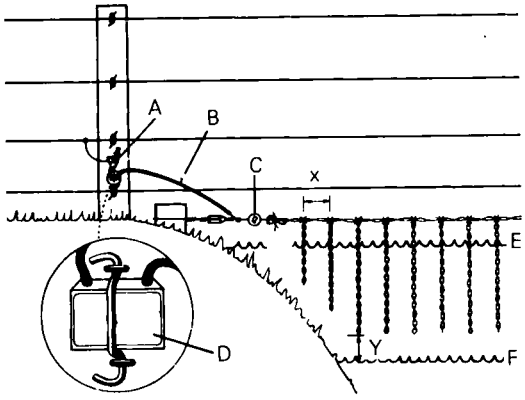


Figure 9.24(a) Lightning diverter.

Figure 9.24(b) Stream crossing and flood protection (see text).



9.8.5 Fence layout

An ideal arrangement for electrification of a farm is shown in *Figure 9.25.* The basic principle is to make the path from the energiser to any section of the fence system as short as possible. Ideally the energiser should therefore be located in the centre of the area to be electrified. However, this is rarely possible in practice since the energiser site will be governed by the source of power. If lead out wires are used, the voltage loss can be very high if a large fence system is being fed. In some cases a lead out of 5 km of 2.5 mm steel wire can halve the voltage. This is because the loss depends upon the current

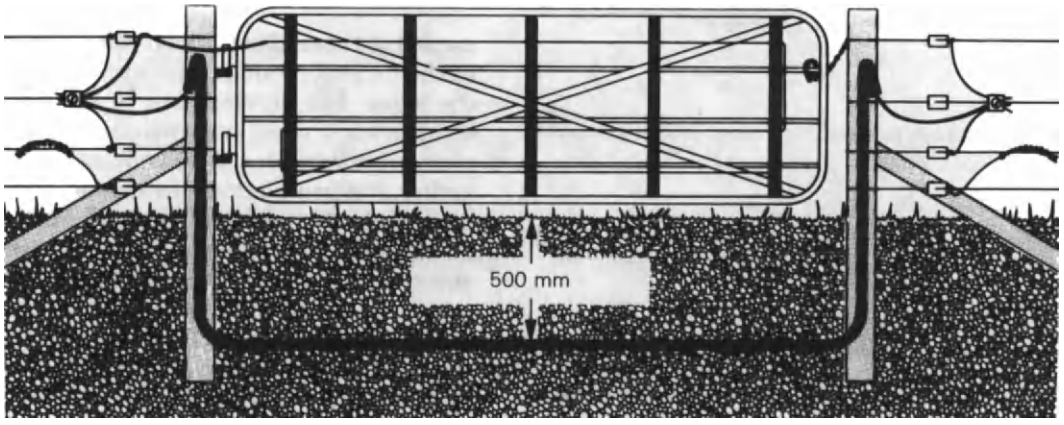


Figure 9.24(c) Gates.

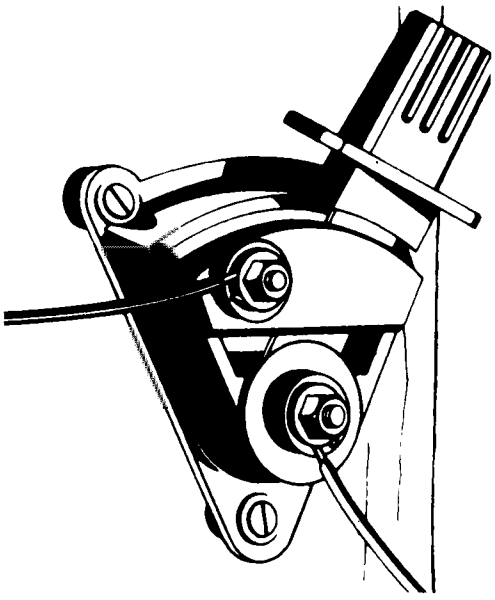


Figure 9.24(d) Cut out switch.

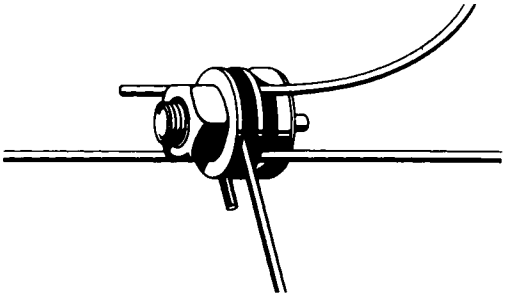


Figure 9.24(e) Wire clamp.



Figure 9.24(f) Bad joint (not recommended as it gives very poor contact).

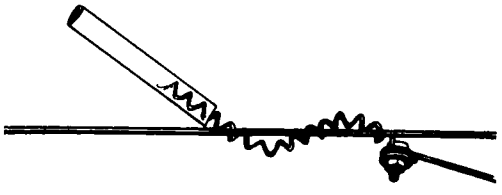


Figure 9.24(g) Removable connector.

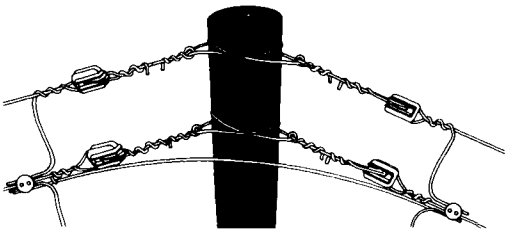


Figure 9.24(h) Corner detail.

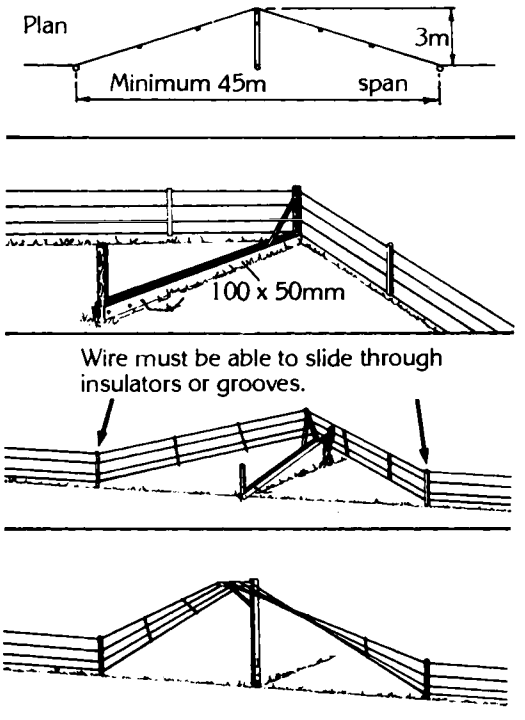


Figure 9.24(i) Offset lift gate (Gallagher Electronics).

carried in the lead out, which will be the sum of the currents required for each section of the fence. The problem can be reduced by using several wires in parallel, or by using aluminium wire for the lead out, as discussed earlier. Just using a thicker steel wire will not improve matters much at all, and the cost will be almost as great as if aluminium were used anyway. If such measures are not successful, another alternative may be to electrify other fence lines which then act as lead outs to the rest of the system. Failing this, battery, wind, or solar powered systems may be the only options.

The cut out switches shown in the Figure are

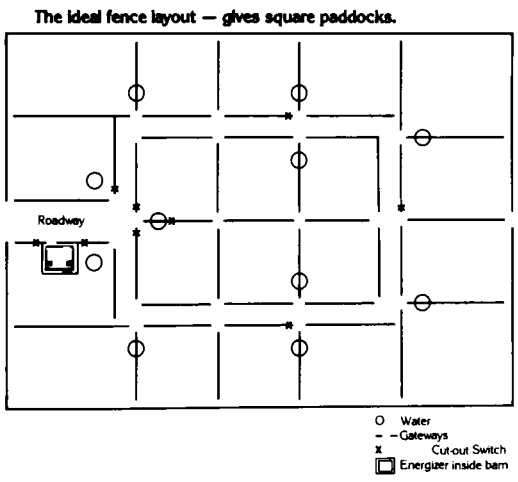


Figure 9.25 Electric fencing layout (Gallagher Electronics).

particularly useful in assisting with the location of any faults quickly, since any section can be removed from the circuit easily.

Fence line length

The total length of fence which one energiser can power in practice depends on a large number of factors, including effectiveness of the insulators, grass cover, and layout. As a very rough guide a medium to large energiser will probably handle no more than 20 to 40 km of fence line, and less if lead outs are involved. If more than one energiser is used they must be connected completely independently to separate fence systems.

9.8.6 Summary

The key points to a good electric fencing system are:

1. Good earthing;
2. correct choice of components (especially insulators);
3. good workmanship, especially with regard to connections;
4. regular maintenance checks;
5. never electrify barbed wire;
6. no loose or untidy wire;
7. follow the safety rules for installation;
8. train stock new to electric fences under easy conditions;
9. leave the power on (it is very low in consumption).

9.9 PROTECTION OF YOUNG TREES AND SHELTER BELTS FROM STOCK

The establishment of a shelter belt can only be achieved if stock cannot eat the young seedling trees. Protection can be achieved by fencing both sides of the belt, but this takes out valuable land area from grazing. In addition problems arise if any animals get inside the strip unnoticed! An alternative is to put an electric fence in a square around each tree (Malcolm, 1981). The square should be 2.5 to 3 metres each side. This prevents cattle from reaching over to eat the leaders (cattle have a reach of around a metre). Power can be supplied from an electric fence line running along one side of the square, so that only two extra posts out from the fence line would be required to form the square. A two wire circular halo system is another alternative, providing the diameter of the upper loop (at a height of around 900 mm) is at least 1.2 metres (Bird, 1981). The lower loop, around 200 mm off the ground, can be quite small to allow the stock to graze the grass.

9.10 PEST CONTROL

Fences are used not only to contain valuable stock, but also to keep undesirable creatures out, including humans. Both conventional and electric designs can be used of course, but the resourcefulness of some undesirables is truly amazing. Rabbits have proved to be capable of penetrating conventional fences with remarkable ease, unless the wire is continued some 200 mm into the ground. Some success against them has been achieved with electric fencing. Two or three wires at 100 mm intervals on stakes at an angle of 45° seems to be a good design since this discourages the rabbits from burrowing straight under. Electrified rabbit netting is also available commercially. For possum control an earthed wire netting fence one metre high can be used, with posts and stays on the inside, and with an outrigger set 100 mm off the netting and slightly above the top of it (Gallagher, 1980; Lord, 1984). Alternatively, a five or six wire fence can be used, with the bottom wires no more than 100 mm apart, and with an earth wire system (ie, alternate wires live and earthed). Vegetation must be kept clear of the low wires at all times to prevent shorting.

Human pests have remarkable powers of penetration of conventional fences, and wire designs present no obstacle. Wire mesh fences at least two metres high with one or two barbed wires on outriggers will deter all but the most determined miscreants, and electric systems with voltages well in excess of those discussed earlier have a reasonable chance of proving to be good psychological barriers (if they are legal of course). Even so the ability of humans to use tools to damage the fence or to insulate themselves makes total human-proofing very difficult.

However ingenious the devices used by humans, the most brilliant fence penetrator of all is undoubtedly the species of pachyderms, commonly known as the elephant. Their taste for succulent young palm oil trees and other tropical crops has proved to be one of the greatest forces in nature to threaten man's technological superiority. Conventional fences failed thanks to the elephant's strength. Log barricades were tried but the elephants soon combined resources to lift the logs away. Next ditches were dug. At a width of 2.1 metres these were successful for a time (less and the elephants stepped over: more and they slid down into them and climbed out the other side), but eventually the elephants managed to fill the ditches with logs. Water filled ditches merely served to demonstrate how well elephants could swim.

Electric fences were then tried. Sadly the energisers were not made in New Zealand, and were only powerful enough to irritate the elephants and encourage them to demonstrate their remarkable strength by demolishing everything in sight. When New Zealand made energisers were used the elephants were initially confused, but demolition of the shed containing the energiser was soon found to be the way to eliminate the painful sensations. When the sheds were rebuilt inside the fence tree trunks were used to flatten the fence, thereby shorting the wire to earth. Fences 2.4 metres high stopped this but now the elephant could get his trunk around the posts between the wires and pull the posts out. The posts were therefore electrified with wires running down each post. The elephant then turned his attention to the gates, which could be demolished in much the same way with a suitable tree trunk as the low fence. To counter this a hanging fence arrangement over each gate was devised. This looked like the solution until the bull elephant played his trump card: if junior was herded against the fence, thereby causing the young infant to squeal and fill the air with cries of pain, mother would proceed at full speed to determine the cause of her offspring's alarm. By the time this maternal gallop was over little remained of the unfortunate fence line, and the bull could proceed to claim his reward!

9.11 EXERCISES

1. Calculate the tension in a 100 m length of 2.5 mm fencing wire if the initial tension is 1500 N and the strainer posts move by 65 mm during settlement. Repeat this for 4.0 mm wire, and comment on the result.
2. With reference to the wire tension meter in *Figure 9.6b*, calculate the relationship between the force on the spring balance and the tension in a wire if the length of wire between the end pins is only 400 mm long, and the wire is still deflected by 12 mm. What force would be needed if the tension were 1500 N?
3. A fence line has ten wires, at 100 mm intervals from the ground, each at 1500 N. Calculate the size and position of the equivalent single force. What size of timber post would be required to sustain this load (without a stay) using a factor of safety of four and assuming that the tensile strength of timber is 12.4 MPa?
4. Based on the discussion of the strength of soil as discussed in Chapter 8, consider how a hole should be dug and rammed to give maximum holding power in the soil. Should the post be placed on one side of the hole against soil which has not been disturbed, or should it be put in the middle and rammed home all round? Consider this for the cases of an angle strainer assembly and a normal post.
5. Using the data from question 3, what would be the maximum force in a stay placed at 30° to the horizontal and 600 mm up the post? What would be the resultant downward force which would need to be supplied to prevent the post from rotating out of the ground?
6. Calculate the voltage and current which

passes through a sheep whose effective resistance is 4000 ohms if an electric fence energiser supplies 5000 v through a 1.6 mm single wire a distance of three km (use the effective impedance data).

7. Using the data from question 6, what would the voltage and current be if there were a 200 ohm leak half way along the fence line?

9.12 AIMS OF THIS CHAPTER

1. Describe fencing methods and discuss the properties of fencing materials and their effects on fencing design, construction, durability and effectiveness.
2. Discuss and calculate tensions in wires under given practical conditions.
3. Discuss a range of different fencing designs for various types of stock.
4. Explain the principles of electric fencing, including a description of a low output impedance energiser.
5. Analyse the behaviour of electric fencing systems, using a simple model based on Ohm's Law, but including the effects of leakage at a point, wire resistance, and earth resistance.
6. Discuss a range of different electric fencing designs for various types of stock, including sheep, deer, cattle, rabbits and goats.
7. Outline the practical aspects of electrical fencing systems, including construction details, earthing systems, farm layout, safety aspects, and fault finding.

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Milking machines

Chapter 10

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10.1 HISTORY

Although the first known mechanical aid for milking cows was recorded in 380 BC, when the Egyptians used wheat straws inserted into the cow's teat, the history of machine milking really dates back to only 1851, when a vacuum milker of sorts was developed in Britain. The first promising practical machine was developed by Murchland in Scotland in 1889 using a continuous vacuum produced by a hand operated vacuum pump. The next step was taken by Shiels in Glasgow who introduced a vacuum break to overcome the swollen teats induced by Murchland's device. In 1902 Hulbert and Park followed by Gillies in 1903 lodged patents for a double chambered cup, a crude version of the modern cup. Since then, advances in detail design, modern materials, and improved knowledge of milking physiology have brought about a considerable increase in the efficiency of the milking machine.

10.2 PHYSIOLOGY OF MILKING AND ITS EFFECT ON MANAGEMENT

Milk is synthesised and stored in the mammary gland or udder. The bulk of the udder is made from tissue with the characteristics of an extremely fine sponge (*Figure 10.1*). This "sponge" is made up of very small secreting units known as alveoli connected by a network of ducts. A network of fine contractile cells surrounds the alveoli and it is these cells which squeeze the milk out of the sponge when the cow gives milk. At the base of the udder the main ducts join together in an opening known as the milk cistern. From here the milk passes to the teat cistern by way of an opening in the base of the milk cistern.

The bottom of the teat connects with the outside via a small duct called the streak canal. This is closed by a springy circular muscle or sphincter. In most cows, a small pressure differential across the sphincter will be enough to force milk through the teat.

10.2.1 Stimulation

When the udder is stimulated a signal is passed to the hypothalmus in the brain. This causes the posterior pituitary gland to release the hormone oxytocin into the bloodstream. This causes a contraction of the alveoli contractile cells, causing milk to be ejected,

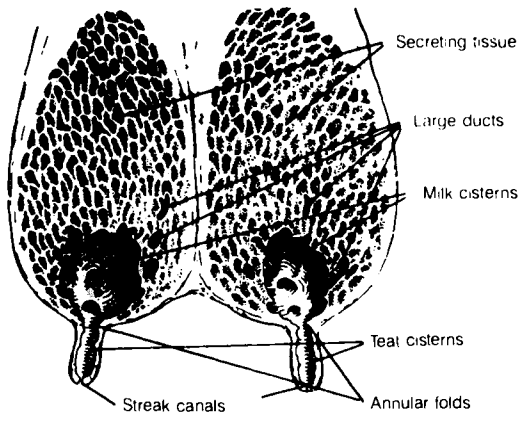


Figure 10.1 Cross-section of a cow's udder.

thus initiating what is known as the milk "let down". This reflex process can take around 30 seconds. In a well run shed the cow will associate a let down with the milking routine. This requires a constant routine in which the cow is quietly and considerately treated. Poor stimulation or an emotional disturbance during milking may sometimes cause milk flow from the cow to cease for a short period.

Milk secretion in the alveoli continues for 15 to 16 hours from the last milking; after that it declines due to accumulation and pressure. An 8/16 hour milking routine will not therefore affect production, although there is a progressive reduction in yield with once a day milking.

10.2.2 Lipolysis and rancidity

Rancidity or lipolysis is brought about when the membrane of the fat globules is damaged. The fat is then attacked by lipase in the milk and split into free fatty acids with undesirable flavours. Current research indicates that the fat globule membrane may be damaged by the shear force associated with any high degree of turbulence or steep velocity profile, such as when milk is forced through an orifice or small pipe, or subjected to excessive beating by the blades of a pump. A similar effect is created when fat globules come into the interface between air and milk. The surface tension acts to split the fat membrane in the same way as shear forces. This effect is accelerated by the presence of foam. The basic requirement for the reduction of lipolysis is the reduction of turbulence and air admission to levels which are consistent with general machine operation. This may be

done by eliminating orifices and restrictions; reducing pipe lengths; increasing pipe diameters and avoiding plugging; eliminating leaks from liners, rubber tubing, and pipe joins; and preventing the operation of "starved" pumps (ie, when there is insufficient milk to fill it).

10.3 THE MILKING MACHINE

10.3.1 Basic operation

A schematic layout of a basic milking plant is shown in *Figure 10.2*. The machine works as follows: a teat cup is placed on each teat of the cow. Inside the cup is a rubber sleeve or liner which fits snugly around the teat forming a moderately air tight seal. A vacuum is applied to the inside of the liner which draws milk through the milk line to the receiver. A pump then draws the milk from the receiver and delivers it through a plate milk cooler to the storage vat.

the liner and the milk flow is temporarily halted (the *Squeeze Phase*). Thus the teat is alternately squeezed and released about once per second; this action promotes circulation in the teat and prevents discomfort. The pulsation cycle is under the control of the pulsator. All the air which is allowed into the chamber must be pumped out again by the vacuum pump.

The general layout of the shed depends on the particular design chosen. In some designs it is necessary for the milk and vacuum pipes to be installed above the milker and/or the cows. This is called a *High Line* system. If these pipes are lower than the cows, then this is called a *Low Line*.

Milking machines must be tested regularly, since any improper operation can harm the stock, cause disease, reduce yields, and reduce milk quality. Milking machine testing is a complex and precise procedure, and should be carried out by a qualified tester

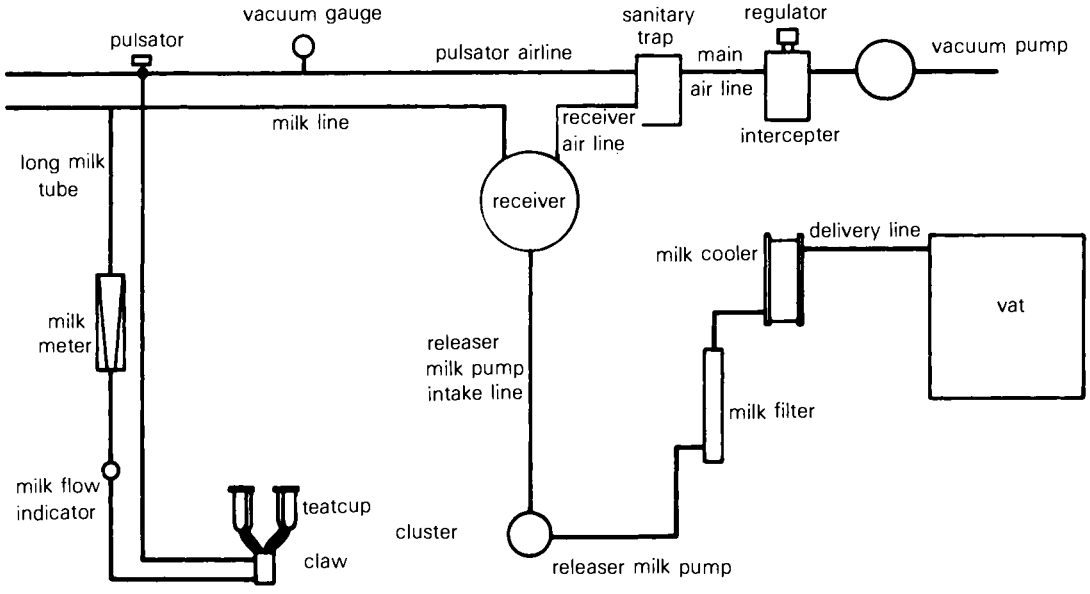


Figure 10.2 Layout of a milking machine.

The actual milking process is governed by continuously switching (pulsating) the pressure in the space between the liner and the teat cup cover between vacuum pressure and atmospheric pressure. When this outer chamber is under vacuum the milk can flow (the *Release Phase*), but when it is at atmospheric pressure the teat is squeezed by

from the MAF or Farm Machinery Association.

10.3.2 Teat cups, liners, and rubberware

As far as the cow is concerned the teat cup is the milking machine. The soft rubber liner fits inside the rigid teat cup and is in direct contact with the cow's teat (*Figure 10.3*). The

liner is required to change its shape drastically about once per second during milking, which works out at about 2.6 million flexes over a period of six months! The requirements for a good liner are that it must be soft and flexible to allow teat massage, it must be hygienic (ie, it must not contaminate the milk or harbour infections), and it must make a vacuum seal when fitted in the teat cup. The important dimensions of the liner are its internal diameter at the mouth, and its length. If the internal diameter is too large, excess air will leak by and the cup tends to fall off. If it is too small the liner pinches the teat and restricts the downward movement of the milk. The liner must also be long enough to accommodate the cow's teat (noting that a cow's teat will extend during milking).

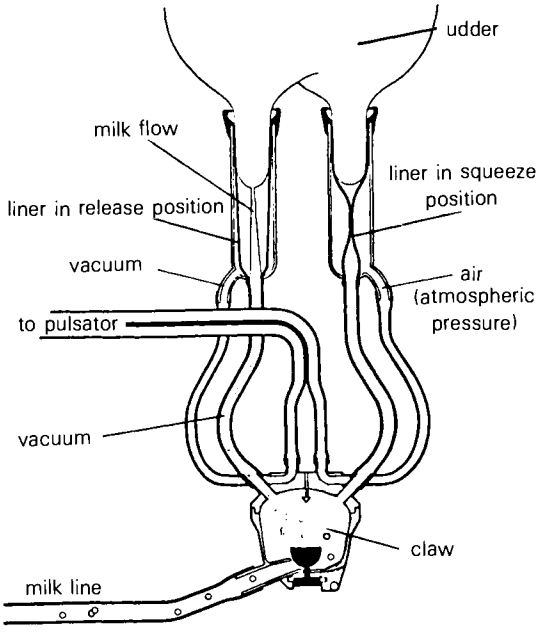


Figure 10.3 Teat cups and cluster (for convenience the cup on the left is shown in the release phase, while the right cup is in the squeeze phase).

Sunlight, grease, fat, and chlorine accelerate the deterioration of rubber. In addition rubber under constant stress develops fine surface cracks. Efforts should be made to avoid "kinking" tubes and other permanently stressed parts. Rubber cuts easily, particularly when wet, and inflations should be checked regularly for any signs of cutting due to sharp nipples and joins onto metal connections. Hard brushes may cut or roughen the rubber and should not be used. Claw tubes and liners should be changed at least once a year, while the long milk and air pulsator tubes should be changed every two years. Rubber parts which show signs of stress cracking should be changed immediately as the cracks are liable to harbour infection.

10.3.3 The claw and the cluster

The claw is the union for the various tubes from the teat cups, the milk line and the pulsator air line (*Figure 10.3*). It includes a chamber for receiving the milk from the liners. The short milk tube connections (ie, the connections to the liners) are usually bevelled outwards. This is so that when the clawpiece is held in the hand the teat cups hang down and cut off the air supply to the short milk tube. Some claws have valves designed for automatic operation, so that if the cup falls off the vacuum supply to the liner is cut off.

Modern claws include a relatively large milk receiving chamber at the base. These claws handle larger milk flows and reduce the occurrence of transfer of milk particles between quarters (thus reducing cross-infection). Some claws employ elaborate spiral milk flowpaths to further reduce milk transfer between quarters. Experiments have shown that a small jet of milk can squirt back onto the teat at the start of the release phase. This jet can penetrate the sphincter and cause cross-infection between quarters and between cows. Several methods have been developed to minimise this effect. In some claws special one way ball valves have been used, while in other designs, circular deflection discs have been included.

Air is admitted to the milk line at the claw through a small hole (normally 0.8-1.0 mm in diameter). This ensures that the milk is transported as small plugs of milk interspersed with air, so that the fluctuations in vacuum within the claw are minimised. A volume of air approximately ten times as great as the volume of milk is admitted. While some air admission is essential, it is inevitably infected to a greater or lesser extent with dust and organisms, so that the quantity admitted should be kept to a minimum. It is important that the air hole does not get blocked and that the correct hole size is maintained.

The assembly comprising the teat cups and

claw is called the Cluster. The total weight of this assembly is important, since it offsets the vacuum within the teat cup and counteracts the tendency of the teat cups to "crawl" (ie, to move upwards on the cow's teat).

Some form of milk flow indicator is required to check the effectiveness of the let down and to avoid over-milking. This can be fitted in the claw or to the long milk tube.

10.3.4 Receiver jars

Although not common in New Zealand, in most dairy sheds elsewhere the milk is delivered from the cluster into a receiver or sight jar (*Figure 10.4*). This is a large glass jar with markings on the side to indicate the volume of milk. The milk from each cow is normally collected in this jar, so that a visual check can be made before the milk is mixed with milk from the rest of the herd. Unsatisfactory milk can then be rejected immediately. The sight jar also allows the volume of milk from each individual cow to be recorded, either by manually recording the level before releasing it, or by mounting the jar on a weigh beam so that the weight can be recorded automatically on a computer.

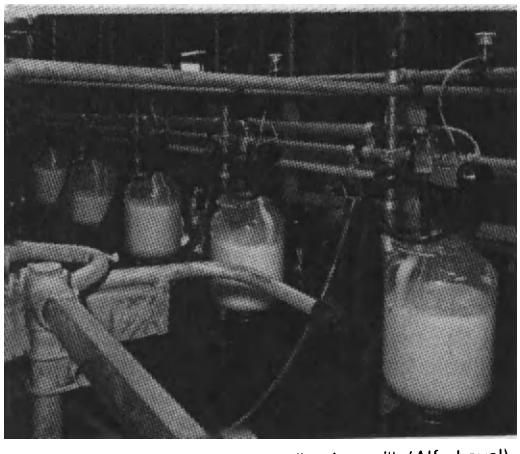


Figure 10.4 Receiver jars for collecting milk (Alfa-Laval).

10.3.5 The Pulsator

Function

There are two main stages in each milking machine cycle, the squeeze phase and the release phase. In the squeeze phase the liner collapses around the teat as air is admitted to the air line (*Figure 10.3*). The squeeze is necessary to massage the teat and maintain good blood circulation. Its absence causes teat damage and trauma. There is no milk flow during this phase. The squeeze may also assist in the initiation and maintenance of milk secretion. During the release (or milking) phase, the inflation moves away from the end of the teat as vacuum is applied to the air line. The removal of lateral forces surrounding the teat, combined with the pressure differential across the sphincter, allows the milk to flow.

The pulsator controls the inlet of air into the outer chamber of the teat cup. It therefore establishes the number of pulsations per minute, the ratio of the duration of the squeeze phase to the milking phase, and the rate at which the squeeze is applied (ie, how fast the pressure in the outer chamber of the teat cup changes to atmospheric pressure). The pulsator also affects the operation of the whole machine. If all pulsators operate in phase there is a tendency for pressure fluctuations to develop in the air line and for instability to occur. This has an adverse effect on the performance of the machine and is uncomfortable for the cow. It is desirable, therefore, to spread the vacuum load by having some form of ripple or sequential control of the pulsators, so that air is admitted by each cup at different instants, to give a steady vacuum level in the machine.

Rate and ratio of pulsation

The rate of pulsation refers to the number of cycles of squeeze and release which occur per minute. One squeeze and one release completes one cycle. The ratio of time between the release (milking) phase and the squeeze phase is known as the *Ratio*. For rapid milking a high pulsation rate and high ratio is desirable (Clough and Dodd, 1956). This is because the peak milk flow rate occurs near the beginning of the release phase. However, too big a ratio will limit the blood circulation within the cow's teat. The ratio is normally measured by dividing the ratio into its four constituent components, as in *Figure 10.5*. In this diagram the time b represents the milking phase and d is the squeeze phase. The machine is functioning incorrectly if b is less than 30% of the total time for the cycle, or if d is less than 15% of the total time. Indications are that a ratio of between 2 : 1 and 3 : 1 at 50/60 pulsations per minute (ppm) is the optimum range bearing in mind all factors including the welfare of the cow.

In order to lift the pressure in the outer

chamber of the teat cup to atmospheric pressure, air is allowed to enter through an orifice (hole) in the pulsator. The rate of air admission controls the "snappiness" of the squeeze. This can normally be varied by altering the size of the orifice, so that a large orifice gives rapid air admission and a snappy squeeze (ie, so that section c in *Figure 10.5* is kept short). When the outer chamber is returned to full vacuum the air must be removed by the machine (section a). The rate at which these processes occur depends on the properties of the liner and the machine.

It should be noted that increasing the pulsation rate increases the air demand and usually decreases the squeeze time. For maximum milking rate and squeeze time a snappy action is desirable on both the fall and rise of pressure (so that sections a and c are kept short), but this may be unacceptably hard on the cow. A snappy squeeze should be avoided as the sudden collapse of the liner onto the teat may build up excessive pressure in the teat, and forcing the milk back into the udder. This can cause physical damage and pain, and will spread infection. If the orifice in the pulsator is blocked, so that the vacuum does not reach the required value quickly enough in the outer chamber, then the pulsation can become choked.

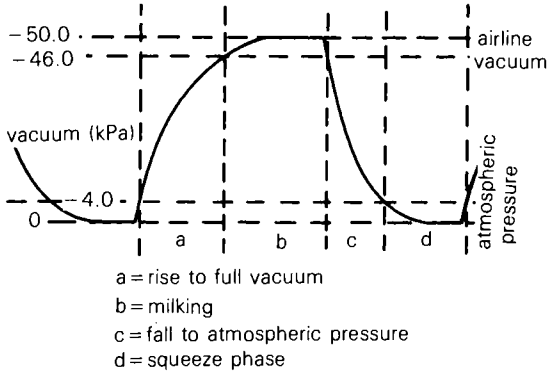


Figure 10.5 Pulsation cycle showing pressure in space between liner and cup.

Pulsator designs

There are several types of pulsator. Mechanical pulsators work from a reciprocating slide, driven by a cam off a rotating shaft running the length of the shed to each pulsator. Sequential operation of pulsators is easily set with the rotating shaft by setting each cam at a different angle of the rotation. Electric pulsators incorporate an electromagnet which energises the pulsation valve. Pulses are produced by either an electronic control panel or a cam and mercury switch mechanism mounted on the end of the vacuum pump shaft. Control of rate and ratio is straightforward.

Self-contained pneumatic pulsators use the vacuum from the pulsator air line. The pulsation rate is determined by the flow of air through a small orifice, and as each pulsator differs slightly from the next due to manufacturing tolerances, in general the pulsators will all operate at different times, smoothing out the air flow. Some pneumatic pulsators are controlled by a master valve which transmits pulses through tubes to valves at each bail.

Various electronic systems are now available. In some the individual electric pulsators are controlled by a central microprocessor. In one such system the ratio may be changed by changing a plastic card in the control unit. Other systems use independent electronic pulsators, where each pulsator has its own control circuit board and there is no master controller.

10.3.6 Releaser milk pump

The object of the releaser is to get milk from the milk line at −50 kPa into the vat at atmospheric pressure. The releaser milk pump fulfils the releasing function simply by pumping the milk up from vacuum to atmospheric pressure (*Figure 10.2*). Diaphragm or centrifugal pumps can be used. Of the two, the centrifugal should be more reliable because of the absence of valves to stick and block. However it does require a non-return valve on the delivery side, to prevent a back flow of air into the plant when it is not filled with milk, or when the float switch control turns it off.

The releaser milk pump is used in conjunction with a *Receiver* (sometimes just a large diameter pipe) which acts as a milk reservoir. From the releaser milk pump, milk is delivered under pressure through the milk filter and cooler to the vat.

10.3.7 Vacuum regulators

The function of the regulator is to maintain the vacuum at the desired level despite wide

variations in air demand. It works by continually allowing excess air to enter the system through the regulator so that the vacuum pump is removing considerably more air than would be required by the plant otherwise. This excess air is called the Reserve. When the vacuum falls suddenly, the regulator immediately restricts the amount of reserve air it is admitting, so that the vacuum is preserved. For design purposes, the reserve air is defined as the difference between the pump capacity and the machine consumption of air. It must be able to cope with any in-rush of air caused by cup changing, or by cups falling off, etc.

Types of regulator

The regulator may be a spring loaded ball or poppet, a deadweight, or a power operated system. It is required to maintain a constant vacuum irrespective of air flow, without oscillation or hunting. These latter defects are particularly common at high flow rates. An advantage of the deadweight type is that they cannot get out of adjustment. Power operated regulators incorporate a sensing line, which senses the vacuum level upstream from the regulator.

It is important that the regulator is in good working order for the milking machine to function properly. It should be cleaned at the beginning of each season and at monthly intervals throughout the season to prevent dust and dirt build-up. After cleaning ensure all parts are replaced as some seemingly insignificant bits can have a major effect on performance!

10.3.8 Vacuum pumps, tanks, and vacuum levels

The vacuum pump

The job of the vacuum pump is to extract air from the machine and thus create a partial vacuum. The most common is the rotary vane type (*Figure 10.6*). The efficiency of the pump depends on the oil layer which forms a seal between the side and the end of the blades. Liquid ring vacuum pumps are also produced which use water rather than oil as a seal.

In too many instances the waste oil expelled outside the milking shed by the vacuum pump exhaust is discharged onto the ground.

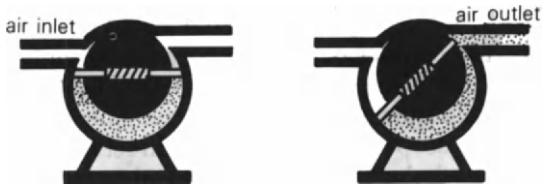


Figure 10.6 Rotary vacuum pump—principle of operation.

There it forms an oily mess with the passage of time. Oil collectors and recirculators are available to prevent this. The exhaust pipe should slope downwards from the pump to avoid moisture running back into the pump when it stops. It is also very important that any contaminants are filtered out before the oil is returned to the vacuum pump.

Vacuum pump performance must be assessed by the quantity of air handled and not the vacuum it can draw. The pump must be correctly sized initially by a specialist, and tested subsequently with an air flow meter.

Vacuum levels can range from -33 to -66 kPa. The effect of increasing the level over this range is to decrease milking time by about 20%. A vacuum gauge should be installed where it can be seen while milking to allow the milker to observe any major changes in vacuum. It must not be installed where it could contact milk as it would be impossible to clean properly.

Interceptor and sanitary trap

The function of the interceptor is to smooth out pump pulsations and to act as a trap for spray and liquid. It should be made from non-corrodible material and have a removable lid for cleaning, a sloping bottom, and a drain plug. It should also have a suitable socket so that an air flow meter can be installed for machine testing. A baffle should be provided to stop entry of spray to the pump. An automatic float to close the outlet to the pump in the event of flooding is also highly desirable. It is important to ensure that there is a regulator or safety relief valve between the float and the vacuum pump to prevent damage should this float valve shut.

In addition to the interceptor, a sanitary trap is fitted between the pulsator and receiver airlines and the interceptor. Its function is to prevent contamination by the transfer of liquids between these parts.

10.4 PIPE SIZES IN MILKING PLANTS

The use of pipes of adequate size for air and milk lines is of considerable importance. Air and milk flowing in a milking machine will suffer a drop of pressure in the direction of flow, and the magnitude of the drop is a function of the flow rate and pipe characteristics (Chapter 5). If the air lines in the machine are too small, the associated pressure losses will prevent the pump maintaining an adequate vacuum at the teat cups, and considerable pressure fluctuations may result. A minimum of 38 mm is advisable. If the milk line is too small plugging may occur; this will result in a loss of vacuum at the cups, vacuum fluctuations, foaming and lipolysis. A milk line of at least 51 mm diameter should be used even in small plants. Vertical sections of pipe should be avoided, but all milk lines should have a slope of at least 10 mm per metre. The long milk tubes which connect the cluster to the main milk line should enter the milk line at the top and tangentially in order to avoid disturbing the flow, and also to minimise any back flow.

10.5 MILKING MACHINE MATERIALS

Stainless steel and approved types of rubber and plastic should be the only materials used which contact the milk. In New Zealand the use of any material in a milking plant must comply with the Dairy Regulations and also with NZS 5121: 1972.

10.6 CLEANING METHODS AND MATERIALS

The basic objects of cleaning are to keep the machine clean, to avoid the build up of milkstone and to kill bacteria. Milkstone is largely a protein and mineral deposit. It is the main source of thermoduric bacteria in milk. Once a milkstone deposit occurs, further layers are built up by protein coagulating and drying out. The three basic cleaning methods are Flush cleaning, Circulation cleaning, and Reverse Flow cleaning. In all cases the cleaning fluid must contact all parts of the machine, and above all there must be sufficient turbulence to provide the mechanical force needed for deposit removal and to prevent the re-deposition of suspended solids. There are a number of approved cleaning options open to the dairy farmer. These include hot, warm, and cold water cleaning systems (eg, refer to articles by Heyes et al (1981), or to local MAF regulations).

Flush cleaning

The cups are placed in a bucket of water or cleaning solution which is then drawn into the plant as if it were milk from the cow. The cleaner flows through the plant and is withdrawn after passage through the cooler in the usual way (*Figure 10.7a*). Disadvantages are that the cleaner only passes through once and is therefore used inefficiently. However, reuse of the cleaning fluid is possible. Velocities and turbulence are low and dirt from the teat cup exteriors may be drawn into the plant with the cleaning fluid.

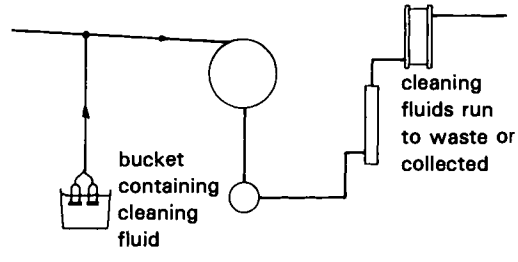


Figure 10.7(a) Flush cleaning.

Circulation cleaning

This method involves recirculation of the cleaning fluid from a container (*Figure 10.7b*). These systems require the use of jetting units. These are stands onto which the cups are plugged and through which the cleaning solution passes. It should be noted that, as the name implies, recirculation involves repeated use of the cleaning solution which is therefore much more efficiently used. The use of buckets is also avoided, as the cleaning solution is drawn from a central tank.

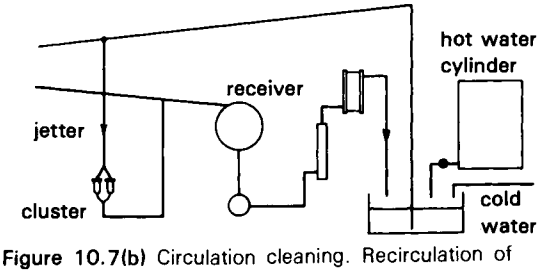


Figure 10.7(b) Circulation cleaning. Recirculation of cleaning fluid.

Reverse flow cleaning

Here the cleaning solutions are pumped through the plant under pressure. The detergents only have a single pass and are discharged onto the ground from the cups. No jetting units are required, and the main cost is the purchase of a suitable pump (*Figure 10.7c*). The addition and metering of the cleaning agents is simple. This may be done with a venturi on the pump delivery or by metering directly into the pump suction.

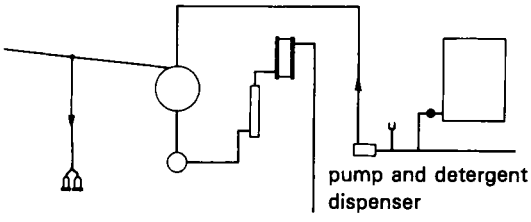


Figure 10.7(c) Reverse flow cleaning.

10.7 THE EFFECT OF THE MILKING MACHINE ON MASTITIS

Mastitis is an inflammation of the mammary gland tissue usually due to a bacterial infection. Mastitis affects milk composition and decreases the quality of the milk. It is prevalent in nearly all dairy herds. A pressure differential of only 0.09 bars is adequate to force milk through the sphincter into the teat sinus (O'Shea and Walsh, 1970), and vacuum fluctuations in the milking machine can allow the transfer of bacteria through the plant into the teat. The pulsation rate has little effect on mastitus levels unless it causes inadequate reserve air or squeeze time. On the other hand a high pulsation ratio can cause an inadequate squeeze which will increase teat sores and give a large increase in mastitis susceptibility. The inflation can also be a source of pathogens if there is inadequate hygiene. Worn or cracked rubber will also encourage bacterial growth.

10.8 COOLERS AND VATS

Heat exchanger milk coolers are common in milking plants. They can achieve an average milk temperature drop of about 16 °C before the milk enters the vat. The milk outlet temperature should be within 3 to 4 °C of the cooling water inlet temperature. Plate coolers are used (*Figure 10.8*). These coolers consist of a series of stainless steel plates sandwiched together in a stack, clearance between adjacent plates being obtained with gaskets. Milk and cooling water both flow in opposite directions between alternate plates. The flow pattern is determined by holes punched at the top and bottom of the plates which act as transfer ports, and by the method of gasketing which transfers the liquid between alternate plates. Cooling water to milk flows are approximately two to one. Plate coolers will acquire deposits of rust on the water side if hard rusty cooling water is used. These deposits can be removed by scrubbing with a 5% phosphoric acid solution.

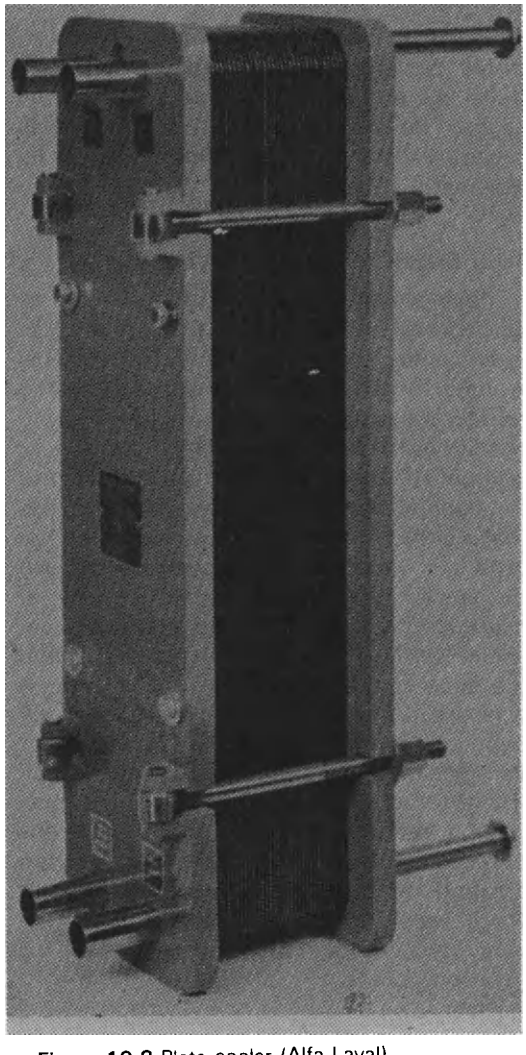


Figure 10.8 Plate cooler (Alfa Laval).

10.8.1 Vats

Farm vats are an integral part of any milking system which relies on tanker collection. The farm vat must store the milk between tanker

collections at 7°C or less, and refrigeration is therefore required. Most New Zealand farm vats utilise a direct expansion refrigeration system. Direct expansion refrigeration systems require that the evaporator is bonded directly to the bottom of the vat and is surrounded by insulation.

In other countries other systems are in common use. The ice-bank system is a system which consists of a refrigeration unit running continuously to produce ice in a large store. At milking time water is sprayed through the ice-bank and cooled to near zero temperature. This water is then used to cool the milk.

All refrigerated vats will include an agitator, which runs continuously, to prevent milk freezing on the bottom. The vat must be cleaned daily or after each milk collection. Cleaning systems can be either manual or by automatic spraying.

10.9 ENERGY CONSERVATION

In dairy sheds the milk must be cooled as quickly as possible down to 7°C or lower. In order to do this heat must be removed. This is done by the heat exchanger and by the refrigerator, and under typical New Zealand conditions the heat removed by these devices is about the same. The heat is transferred to the cooling water in the heat exchanger, so that a large volume of slightly warm water is produced. Some of this can be used to wash the cows' teats, thereby saving the cost of heating this water. Otherwise the heat exchanger heat is wasted. On the other hand the heat extracted by the refrigerator is discharged by the condenser at a relatively high temperature (Chapter 7), and this energy can be used to heat the water which will be required to wash the milking machine. A heat recovery unit is required for this purpose, which fits into the refrigeration circuit between the compressor and the main condenser. These devices work best if the condenser is cooled by water rather than air (Stinson, 1987).

10.10 DEVELOPMENTS IN MILKING SYSTEMS

The system described above represents the most common type of milking equipment in use at the time of writing. Research into new methods continues and alternative systems may render these techniques obsolete. One interesting possibility under study is the concept of airless milking, sometimes called hydraulic milking. In this method the milk is removed in such a way that it does not come into contact with air (Griffin 1985, 1987). The method appears to have some potential as research data indicates that milking rates are increased. In another system, different vacuum levels are set up in the cluster, pulsator and milk transport parts of the machine. Less damage to the milk and time saved are claimed to be the benefits.

10.11 MILKING SHED DESIGN

Common types of shed currently in use are the Herringbone, the Rotary, and to a lesser extent the Walk through and the Step-up (or Angle Park) sheds.

10.11.1 Herringbone sheds (*Figure 10.9*)

For the average size dairy farm the herringbone is the most popular. The milker is in a pit between two rows of cows being milked. It has a very high output per milker. There are two main designs. A "single six" herringbone has provision for six cows on each side of the pit but only one set of cups. The milk and air lines must run down the centre of the pit and over the top of the milker. It is therefore a high line. A low line plant has the same layout but has a separate set of cups for each side, and the milk and air lines are located along the edge of the pit. The cows stand at an angle on each side of the pit in which the milker works. This is normally 0.7 m deep.

A well planned herringbone shed with a power driven backing gate, automatic cup removers and automatic machine washing facilities can provide a high output per hour. In general one person can handle six or seven sets of cups and a typical output would be ten cows per hour per set of cups. The only disadvantage of the herringbone system is the possibility that a slow milking cow can delay release of a batch from the shed, and therefore it may be necessary to segregate such cows. In Europe a triangular herringbone system has been designed, in which the cows move into herringbone type bales on three sides of a central milker's pit.

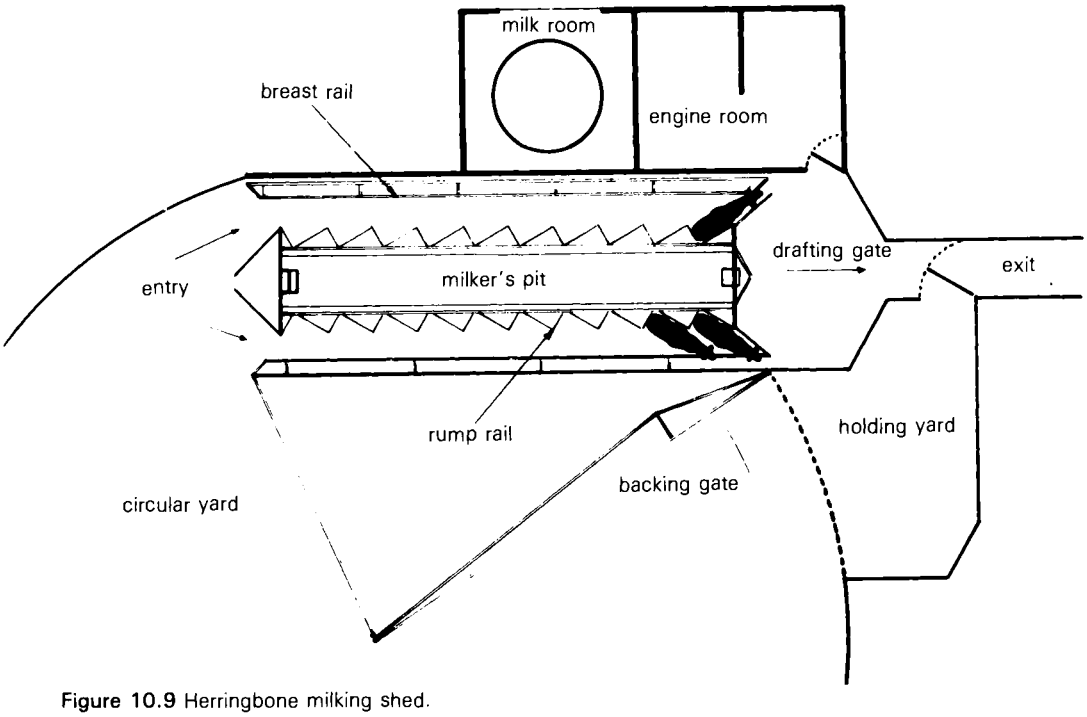


Figure 10.9 Herringbone milking shed.

10.11.2 Rotary milking sheds (*Figure 10.10*)

At present it appears that the rotary milking shed provides the best opportunity for improved working conditions and automation. Since its introduction, a variety of designs have been developed. The platform can be mounted on steel rollers or can float in a large concrete shell of water (see Chapter 5).

Rotary sheds are generally based on either the rotary turnstyle or rotary herringbone design. In the rotary turnstyle system the cows walk onto the platform and are milked with the milker on the outside. When milking is complete the cows back off the platform. The speed of the platform is variable with the rotation time being determined by the stage of lactation (eg, up to seven minutes per revolution). The cows may remain for one or more revolutions. Two milkers are normally required in the system as shown in *Figure 10.10a*. Turnstyles have been installed with between 14 to 64 bails.

In the rotary herringbone design the cows move onto the continuously moving platform at an angle, positioning themselves to face outwards (*Figure 10.10d*). The advantages of this are that all the cups are in easy reach of the milkers. Problems have arisen in getting the cows onto the platform, and positioning them correctly. Typical sizes range from 15

Figure 10.10 Rotary milking sheds.

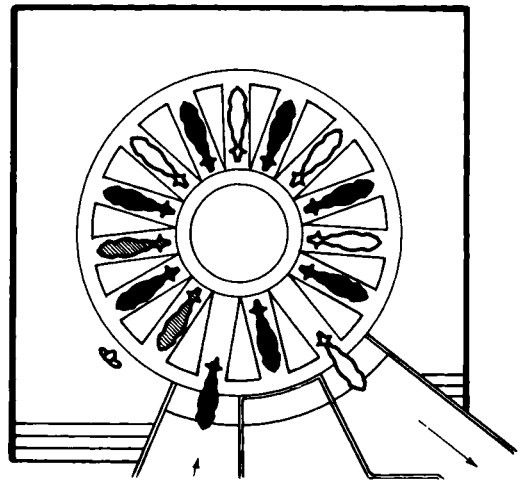


Figure 10.10(a) Rotary shed plan.

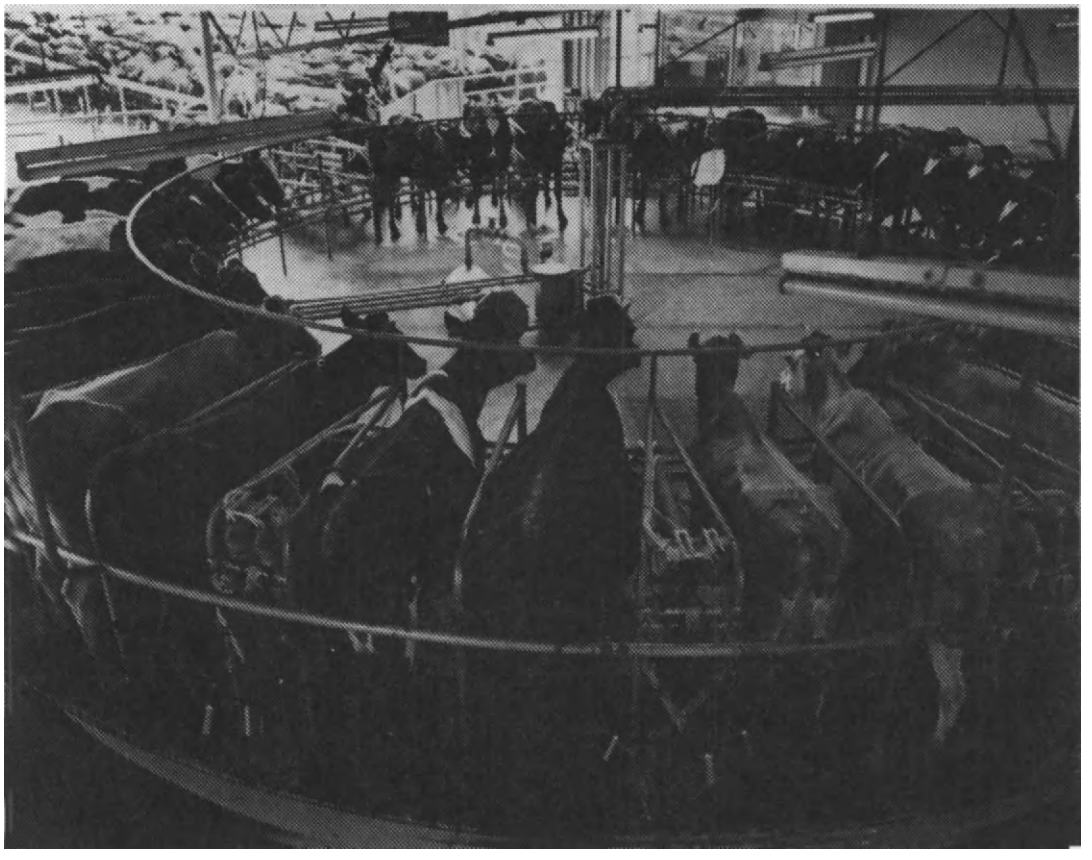


Figure 10.10(b) 36 Bale rotary.

to 64 bails. The largest can milk around 600 cows per hour.

There are several advantages of the rotary system. The milkers are at normal herringbone pit level so they do not have to stoop. The cows move continuously through the system, so there is no break in the flow

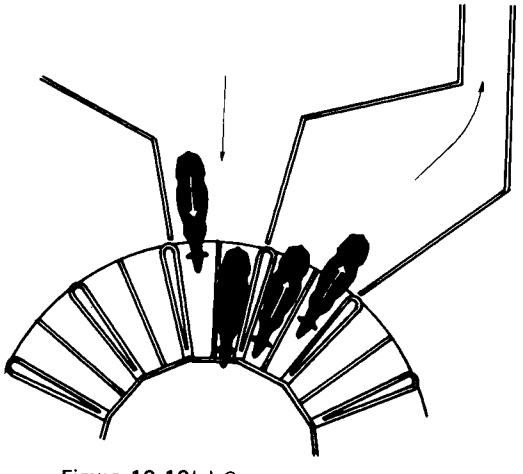


Figure 10.10(c) Cow movement.

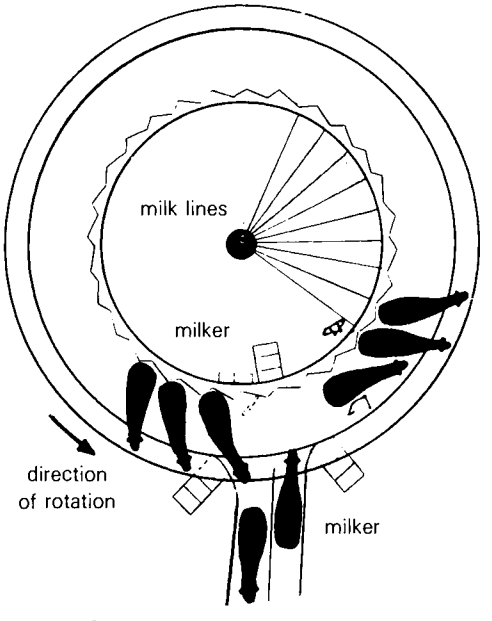


Figure 10.10(d) Rotary herringbone shed.

due to the batching of cows, and milkers do not have to move back and forth down the line of cows. The cows are presented with the

same conditions at every milking, which tends to improve their behaviour. There should be an even milk flow through the plant aiding in pump control and milk cooling. The system also lends itself to semi-automatic milking with the platform providing the driving force for automatic cup removal and recharging of feeding boxes. Disadvantages include the initial cost, and the increased level of sophistication.

10.11.3 Walk through sheds (*Figure 10.11*)

There are two designs, depending on whether there are single or double milking units in each double bail. The single type has the advantage of a very high per cup milking rate. The cups may be transferred from one cow to the next without being hung up. This type of shed is hard to manage. The double unit type enables each cow to be treated individually and, although cup capacity is not as high, the output per milker can still reach one cow per minute.

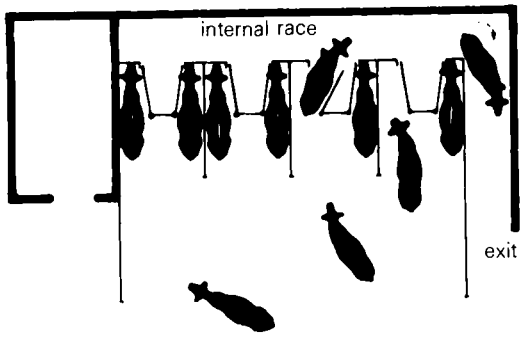


Figure 10.11 Walk through milking shed.

10.11.4 Step-up sheds

In this design the cows have to step-up 0.4 m to 0.5 m onto the milking platform. Once accustomed to this, the cows have little difficulty climbing the step (*Figure 10.12*). The shed has a low capital cost, and allows for individual cow treatment, making it suitable for small herds.

10.12 SITING AND REGULATIONS

A dry sheltered site should be chosen. The buildings should be orientated to take advantage of both the sun and natural shelter.

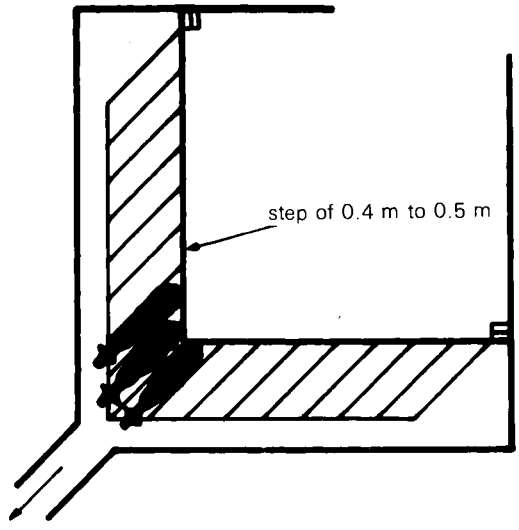


Figure 10.12 Step up shed.

There should be good natural site drainage and the drainage for both washdown water and effluent should be able to be incorporated easily. Gravity provides the cheapest and most efficient system. Effluent must be disposed of at least 45 m from the shed, yards and water supply. The proximity of adequate power and water supplies is a major consideration. The cost of either bringing power to the site or upgrading the existing supply may be considerable.

If possible the shed should be centrally sited in relation to the paddocks for ease of stock access, and to minimise the time stock spend out of the paddock. In New Zealand, sheds must be sited a minimum of 45 metres from any public roads. Tanker access and a roundabout which conform with the milk company's specifications are required. A well planned and co-ordinated layout of farm buildings makes management easier and utilises the services (power, water, drainage, vehicle access) provided more efficiently. A separate room for the vacuum pump, cooler and vat should be provided. The layout chosen must allow for gravity flow from the vat to the collecting tanker.

The farm dairy must comply with all relevant Ministry of Agriculture and Fisheries, Dairy Company and County regulations. Like all other buildings, dairy sheds require a building permit. Dairy effluent to be discharged into a watercourse must be treated. A "right to discharge" should be obtained from the local Catchment Board before the treatment

system is constructed. A water right will also be required before taking water from a stream or well for cleaning and washing down.

10.13 RACES AND YARDS

Often in the planning stages one of the most important factors, the stock, are ignored. For easy milking it is important that there should be a steady but rapid flow of unstressed cows from the paddock, through the shed and back to the paddock. This is affected by the cows' temperament, the milker's animal handling expertise, and the building and yard design.

Smooth, hard surfaced races will enable the cows to move comfortably and quickly to the milking shed. The presence of sharp rocks, uneven surfaces and mud will slow the herd down and increase the amount of hoof injuries and disease incidence. Sometimes bottle necks exist in sections of farm races which markedly reduce cow flow and cause unnecessary stress on animals and fences.

The entrance to the yard should be preceded by a stretch of concrete so that stones picked up in the hooves in the race may be worked out before the cows enter the yard. Small stones on concrete may cause severe bruising. The entrance way and all other concrete surfaces should be finished and cleaned so that they are not slippery. Cows move more rapidly on level surfaces and slight upward grades and so a downward sloping entrance should be avoided. It is preferable that the gate-way is located at the furthest point from the bail entrance so that the cows are facing and walking towards the bails and do not have to turn around (Maguire et al, 1974).

The interaction of cows in a closely confined area is likely to result in injury if the cows are too confined to allow bullied cows to back away from dominant cows, or if the yard surface is slippery. The yard should not have a slope of more than one to two percent as this increases the cow's feeling of insecurity (Kilgour and Dalton, 1984). Sharp edges of any nib walls which protrude into the yard should be rounded off. The shape of the yard does not seem to make any major difference to cow behaviour and movement (Maguire et al, 1974).

10.13.1 Backing gates

A backing gate is a movable gate controlled by the milker (*Figure 10.13*). It moves behind the herd, restricting the area of the yard, and is intended to encourage rather than force cows to move forward into positions from where they can move readily into the bail area. Stimuli such as bells which sound when the gate moves may be used. All the herd soon learn to move forward when the bell sounds, rather than just crushing the cows at the rear against the gate. A noisy gate moved intermittently is preferable to one that creeps round continuously at a slow pace. An electrified wire on the gate can be used but this is likely to produce negative responses in cows towards the milking routine (Kilgour and Dalton, 1984).

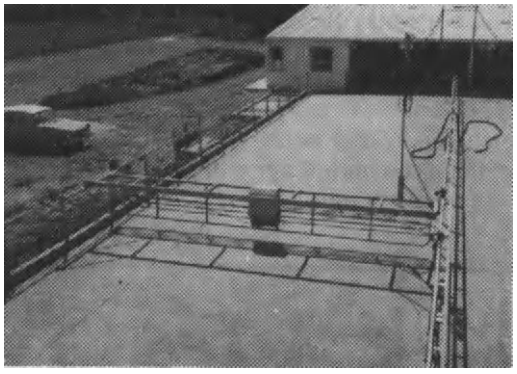


Figure 10.13 Backing gate for large herd.

10.13.2 Other stock considerations

The exclusion of visual disturbances means the cows are more settled in the bail area (Kilgour, 1974). This has been the experience with some farmers using rotary sheds. Turnstyle sheds result in calmer, more relaxed cows as almost all visual disturbance is removed, since they face inwards. One farmer whose rotary herringbone shed had an open side facing pasture had problems with cows jumping off the platform, until the view was excluded!

Cows should not be expected to move in directions where light is directly shining into their eyes, eg, the rising sun. If the exit from the bail area or exit race opens directly into an exposed area the cows will be reluctant to move away from the shelter of the shed. In situations where wind is a continual problem shelter should at least be provided at a distance from the shed sufficient for the build up of cows not to block the exit of the others.

10.14 GENERAL CONSTRUCTION

Concrete floors should not be too highly finished or cows will slip, and the principles discussed in Chapter 9 should be applied. The concrete should be specified as 30 MPa strength, air entrained and wet cured to give good durability and wear resistance.

Adequate slope must be provided for drainage, preferably at right angles to the milk line in high line plants. Drainage slope in the yards should be a minimum of 1:60 and that in the shed 1:40. Adequate provision for sumps and drainage must be made. Concrete races should have a 150 mm nib wall on each side, or washdown water will overflow and produce a quagmire.

Walls must be washable, and can be made from concrete block plastered internally to a height of 1.2 m where contact with the cows is anticipated. The junctions between walls and floors should be finished to a smooth radius throughout. Welded pipe construction is in universal use for bail construction. Normally, 40 mm nominal bore pipe is used for uprights and horizontals, while 25 mm pipe is used for gates and bracing. Zinc rich galvanising paint should be used on non-galvanised surfaces.

10.14.1 Water supply

An adequate water supply for cooling the milk, for udder washing, and for cleaning the equipment and the yard is essential. Water requirements for milk cooling are best estimated on a per set of cups basis. For example, assuming the average milk yield is nine litres per cow per milking, and one set of cups milks ten cows per hour, then the milk flow is approximately 90 litres per set of cups per hour. On a 2:1 cooling water to milk ratio this gives a minimum of 180 litres of cooling water per set of cups per hour.

For shed and yard cleaning a 50 mm hose, reducing to 10 mm in a smoothly tapered nozzle, is required, together with a pump capable of supplying approximately three bar pressure. In some instances automatic yard washing is obtained by mounting a row of nozzles on the backing gate. If water is plentiful, keeping the yard wet during milking makes the washdown quicker and easier. Hoses should be provided at the bails for udder washing. Only small amounts of water are required, and it may be warmed slightly.

10.14.2 Milking plant voltages

It has become evident in recent years that very small stray voltages emanating from backing gates, motor drives and other equipment are in many cases the source of production losses. Cows are very sensitive to even three or four volts, which is well below the levels that humans can detect. Electric shocks suffered by the cow frighten her and block the let down of milk. In some cases indication of teat damage as evidenced by increased cell counts has been detected. The problem may be overcome by providing a net of reinforcing in the floor concrete of the milking area; this reinforcing net should be anchored to a shallow rail around the pit floor and all bailwork thoroughly bonded by welding to this rail. All pipework should in turn be bonded to the bailwork. In this way it is possible to ensure that the concrete on which the cow stands and the teat cups are at earth potential. Tests with a sensitive voltmeter should be carried out from time to time to ensure that there are no stray voltages.

10.15 DISPOSAL OF COW SHED WASTES

This problem has become of particular importance since the passing of the Water and Soil Conservation Act which makes it illegal to discharge waste material in any way which may result in the pollution of natural water. Some farmers still discharge shed effluent into the nearest stream or drain, but the Act is being enforced and farmers who do this will be brought under pressure to provide an alternative waste disposal system. Whilst in some cases it may be feasible to collect washings in a trailer tank for subsequent disposal, this is not generally an economic or feasible system, and either spray disposal on the land or lagoon treatment and discharge must be used. These methods are discussed in Chapter 12.

10.16 AUTOMATION

The aim of automation is to increase the number of cows milked per man-hour whilst maintaining cow performance and udder health. Any area involving significant labour input is an obvious target for automation. These areas will be considered individually.

10.16.1 Automatic teat washing

After milking some form of sanitising solution is often applied to the udder. A suitable automatic system is shown in *Figure 10.14*. The cow walks along the exit race and is detected by a sensor, which triggers a spray from a nozzle in the floor in the direction of the udder. There is some evidence that pre-washing the udder and manual stimulation is unnecessary unless the udder is very dirty (Ridler, 1985).

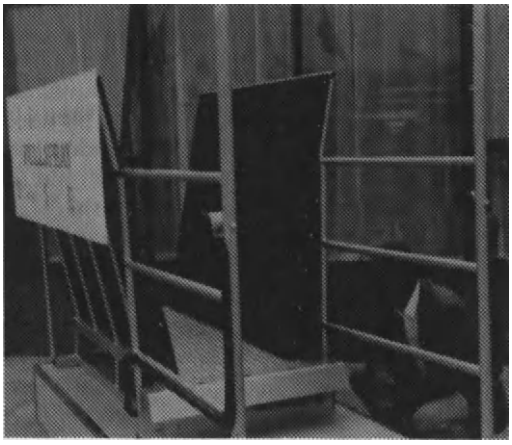


Figure 10.14 Automatic teat sprayer. As the cow walks past, a sensor triggers jets of disinfectant which are sprayed from nozzles located under the cow.

10.16.2 Automatic cow identification and data collection

Electronic identification tags mean that individual animals can be identified by a computer without human assistance. The cow wears a low cost electronic transponder which contains an identification number. This number is read by a detector, which feeds the information into a computer, which in turn can do something useful with the data. In the milking shed each cow's milk yield and weight can be recorded at each milking. The computer can warn the milker of any special messages, or specify attention which the cow needs at that time.

Automatic identification is particularly useful in countries where animals are fed expensive high quality feed supplements throughout the lactation period. This is worth doing because of the need to house stock in winter, which puts a very large premium on the number of stock, and which in turn makes it more economic to maximise the production from each individual cow. Feeding supplements makes this possible, and to optimise the process it is necessary to allocate an individual ration to each animal according to her milk yield. With automation, cows can enter out of parlour feeders between milkings and be identified. Part of the daily ration can then be given so that the intake can be spread over the day.

Transponders usually have a programmable memory chip which contains the identification number. The memory can contain any one of several million different codes so there is no longer any limit to how many animals can be identified. Thus a National recording system can be contemplated. The transponders can be either neck or ear-tag types. Alternatively a miniturised transponder with a battery can be implanted under the skin of the cow. Such devices can include sensors to measure the temperature of the cow, or other vital signs, which could be used for health and productivity checks.

10.16.3 Automatic cluster attachment

At the time of writing, many researchers were working on automatic cluster attachment systems (eg, see IMAG, 1986). The principle of the system is that the cow voluntarily enters the milking bail and is milked if the computer decides she has sufficient milk. The computer will not allow a cow to be milked until at least three hours have elapsed since the last milking. This assumes that the cow wishes to be milked! In the European setting this is easy, because the cow can be rewarded for coming by a feed. In all grass farming systems other suitable inducements are required.

The general principles are as follows: first, the robot milker must be protected from the cow, and vice versa! Next the robot must move a cup quickly to the approximate position of the target teat. One way of achieving this is by recording the precise location of each cow's teats relative to its tail-bone or hip-bone in the memory of the computer. The robot then moves the cup to a position a little below the predicted teat position, which works well as long as the cow does not move during this period. Once the teat cup is close to the teat the final docking is not too difficult and a number of systems have been tested. The

basic principle is to move the cup slowly up onto the teat, making fine adjustments in the process. Some methods involve an array of photo-cells which can locate the teat without touching it. If the cow moves at this stage the robot can usually follow the teat, so the docking is successful.

The robot system must maintain the same hygiene standards as manual systems, and it must also have a reliable means of checking for mastitus or any other new problems. Automatic rejection of inferior milk must be included, and the computer must be able to warn the farmer of any problems.

10.16.4 Automatic cluster removal

Currently available units have a flow sensing unit which is either electrical or mechanical. The cluster must stay on a preset amount of time after a low flow occurs. This prevents the cluster being removed before a second let-down occurs. The cluster removal is powered by a vacuum operated piston.

10.16.5 Electronics for milk quality, animal health and oestrus detection

The checking of milk for unacceptable levels of bacteria is a crucial task for maintaining the quality of a farmer's product. Automatic devices for making these checks continuously were under development at the time of writing. Another area where electronics is showing promise is in the field of health diagnosis and, in particular, in Oestrus detection. A number of studies are in progress, and a range of things are being monitored. Milk temperature has been considered but the results to date suggest that the effect is small (less than 1 °C) and that normal variations in milk temperature swamp the effect.

Other variables include activity, heart rate, and internal temperature. It is likely that no one single factor is likely to be completely reliable for oestrus detection, but a combination of several indicators would be needed to eliminate false positives (IMAG, 1987).

Electronic milk metering and milk quality monitors (eg, fat meters and protein testers) are also coming onto the market. These enable the farmer to monitor the performance of individual cows and to test sub-clinical mastitis.

10.17 EXERCISES

1. Calculate the amount of heat to be removed by the cooling system if milk from 150 cows must be cooled from 34 °C to 7 °C, and each cow produces 15 litres. Take the specific heat of milk as 4200 J kg^{-1} $°C^{-1}$.
2. Using the data from question 1, calculate the water flow rate and volume in a plate heat exchanger to produce a 2:1 flow rate if the milking takes two hours to complete.
3. Using the data from question 1, calculate the temperature of the water leaving the cooler if the effectiveness ratio is 0.8, and the cold water enters at 13 °C.
4. Using the data from question 1, calculate the size of the refrigeration motor required if half the heat is removed by the heat exchanger, and the rest must be removed within three hours of the end of milking. Assume a COP of 2.0 for the refrigeration plant.
5. Make a plan of a dairy shed for 150 cows. Include on your plan a design for the races and yards to avoid congestion and features which would reduce the stock movement.

10.18 AIMS OF THIS CHAPTER

Armed with the information in this chapter, you should be able to:

1. Outline the physiological features of the milking process, and discuss the ways in which milking machines can cause harm to milk and the cow.
2. Describe the main components of a milking machine and how milk is collected and held on the farm.
3. Describe the layouts of rotary, herringbone, walk-through and step up milking sheds, including race and yard designs, and the use of backing gates.
4. Outline current developments in milking system automation.

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Post harvest systems

Chapter 11

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11.1 INTRODUCTION

In this chapter we will look briefly at what happens to horticultural and arable farm products during and after harvest. We will not consider animal products such as meat and wool. Traditionally, the grower has been able to produce crops for a local market, and what happens to them once they have left the farm gate is of no concern to the grower. Nowadays the ways in which products are sold and distributed mean that far more attention must be given to the preparation of the product for a particular market. In addition our knowledge of the deterioration of crops has improved to the extent that we are able to treat crops so that their storage life is much greater. In order to achieve this it is essential to combine a knowledge of crop behaviour after harvest together with the ability to develop equipment which will produce the required treatments. In order to achieve long storage life, several factors need to be considered. In particular, the grower must pay attention to:

a. Harvesting the crop at the correct time,
b. Careful handling to avoid bruising and other damage,
c. Treatments to destroy disease and insects,
d. Other treatments to prolong storage life,
e. Storage under the correct conditions, particularly if the crop must be shipped overseas or stored for lengthy periods before sale or consumption.

11.2 BEHAVIOUR OF CROPS AFTER HARVEST

A horticultural (or arable) crop is a living

product. Potatoes, cereals, seed, and fruit are all active, using up chemical energy stored within them. Although apparently dead, they still interact with their environment. Seeds may remain apparently inactive, showing very little sign of life, until they are triggered into activity by some internal or external stimulus. The activity of fruit is much more apparent, since changes can occur over a period of a few days or hours as the fruit ripens and then deteriorates. Experiments show that fruit is continuing to transpire (ie, give off water) and respire (take in oxygen and emit carbon dioxide and other products).

11.3 POST HARVEST PROCESSING

Fruit, vegetables, cereals and other crops all need to be handled and stored between the farm and the customer in ways which minimise the deterioration of the crop. Some of the key points are outlined here, and the references are provided as sources of further information.

11.3.1 Harvesting

Crops must be harvested in ways which minimise damage. Fruit crops therefore need to be picked to avoid bruising, and frequently hand-picking is still the only satisfactory method of harvesting. Some fruits which are intended for processing can be harvested by machine. Examples here include strawberry and blackcurrent harvesters, which consist of machines with rotating metal fingers which shake the fruit off the tree. Vegetables and cereals are more tolerant to mechanical handling, and a wide range of specialised machinery is manufactured for particular crops (eg, see Culpin, 1986). Machinery is used where it is cost effective, although frequently this results in the loss of jobs for unskilled workers. There is thus a social impact in the introduction of new machinery which needs to be considered. Some products are collected in bulk bins, where the produce is simply placed into a container and transported out of the field. This is fine as long as no damage is done to the crop (see below). Removing the fruit from the bin can be the next problem. This can be achieved by a water dump if the fruit is less dense than water (*Figure 11.1*). If the fruit is slightly denser, salts can be added to the water to raise the water's density.

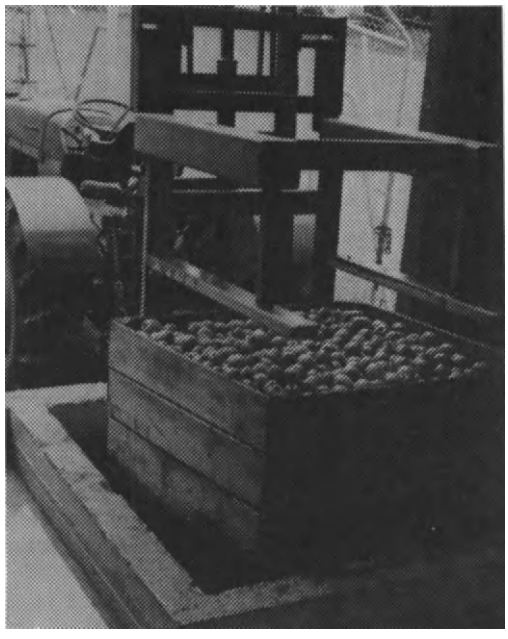
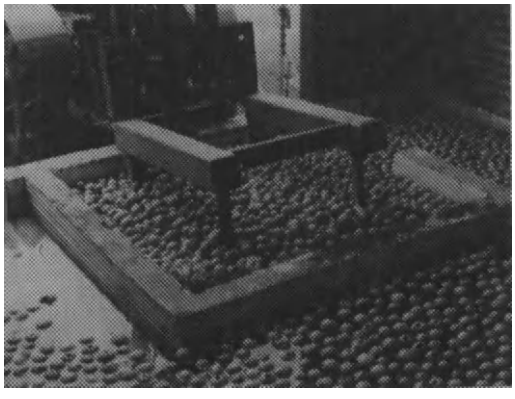


Figure 11.1 Fruit must be handled carefully to minimise damage by impact, rubbing or crushing. A water dump can reduce bruising.



There are very few horticultural crops which will not benefit from being cooled as soon as possible after harvesting. With some leafy crops such as lettuce, immediate cooling to near zero temperatures can improve the freshness of the product in the market. Portable vacuum cooling systems can be used, as described in Chapter 7.

11.3.2 Grading

Most produce needs to be sorted as soon as possible into quality grades. Top grade produce will usually fetch the best market price, and is separated out from the rest. Low grade produce may not be worth selling, and often has to be given away or dumped.

Grading is based on a variety of criteria. These include size and shape, colour, pest damage, bruising, and the presence of any defects. Again, these variables are more critical in fruit than in vegetables. Grading can be done automatically on most of these variables. Optical scanners can determine shape and colour, and to some extent can detect damage or other marks. Weight measurements are straight-forward using electronic load cells. The grading device sorts the produce into the different grades, usually using a conveyor system (*Figure 11.2*). Packaging is often done at this point.

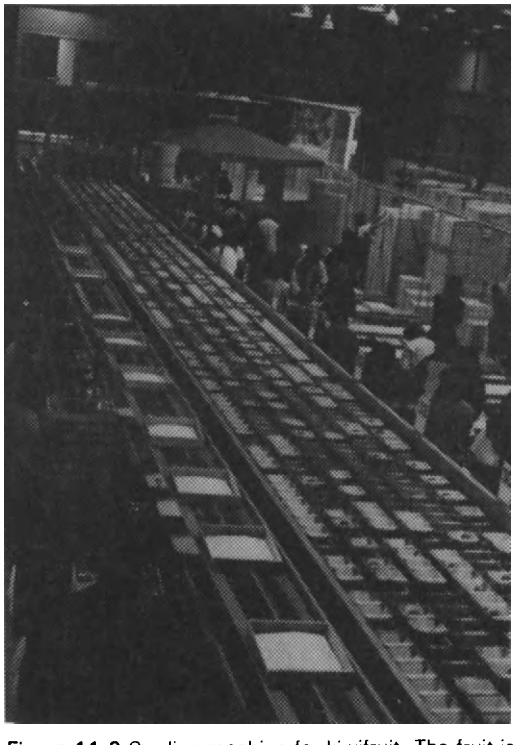


Figure 11.2 Grading machine for kiwifruit. The fruit is weighed, and dropped into the appropriate channel where it is packed manually.



Graders must be designed to be efficient and rapid in operation. They must be designed to deal with the maximum rate at which the crop is likely to be harvested, since it is not advisable to have crops lying around the packing shed waiting to go through the grader, unless it is possible to store the crop without grading first. In some operations a producer may construct a large grading system so that she can pack other grower's crops. Ideally the grader should not damage the crop. In practice some damage seems to be inevitable, especially with bruise sensitive fruits. The grader must be designed so that the fruit does not drop long distances, or bump and rub against other fruit any more than is absolutely necessary (*Figure 11.3*). As well as careful design, it is vital to set the grader up properly if damage is to be minimised.

The design of grading and packing sheds is quite complex. The shed must be designed so that the operators can do their work in comfort and safety, without excessive noise from machinery, and it must be arranged to allow for the movement and storage of produce and packaging material at all times. This means that consideration must be given to the operations which are to be carried out, as well as ensuring that there is sufficient storage space for all the machinery, materials, packaging, pallets, boxes, chemicals, and other equipment which will be required to keep the shed fully operational at peak times (*Figure 11.2*).

11.3.3 Treatment

Harvested crops can contain bacteria, fungi, insects, and insect larvae, which will develop and attack the crop in storage. Worse still, the presence of any of these will cause many crops to be rejected as export items. Many countries have extremely stringent regulations which govern the acceptibility of pests and diseases in imported produce. Quite often the exporting country is responsible for ensuring that the standards are maintained and the discovery of bugs in a shipped consignment can result in the total loss of a market for an entire country. On the other hand consumers are becoming increasingly concerned about the presence of insecticides and other chemicals in the products they purchase, and many countries have



Figure 11.3 Drop on a grading machine—the fruit will impact against other fruit or the rollers.

introduced legislation which limits the acceptable level of a range of chemicals. Thus the producer must provide produce which has no disease, and which also has little trace of any of the chemicals which are needed to achieve this! In spite of these limitations there are some treatments which can be used which are acceptable to the consumer. For example many fruits can be washed, and then sprayed to kill bacteria and insects. They can then be coated with a wax which may be derived from plant or petroleum sources. This wax will enhance the appearance of the fruit, reduce the loss of water in storage (thus reducing shrivelling), and may also contain suitable fungicides.

Nuclear irradiation has also been introduced as a means of eliminating pathogens from crops. Irradiation will extend the shelf life of many products, and at high enough levels will kill most insects at all stages of development. However, it is important to get the level of radiation correct, so that the bug is destroyed without harming the product. In some cases it is only possible to destroy the eggs and young larvae before the dose becomes excessive for the crop. The issue of the safety of irradiation processes is still being debated, and only a few countries have so far allowed irradiated products to be admitted freely. Irradiation is not a particularly cheap process, and in many cases chemical treatments are still far more economic.

Another alternative currently under study to eliminate pathogens is by controlling the atmosphere around the crop. It has been found that some pathogens cannot survive long periods of exposure to low temperature combined with low oxygen and high carbon dioxide levels. As these conditions are suitable for the long term storage of fruits (as discussed below), it is possible that controlled atmosphere storage (CA) may eliminate some of the chemical sprays needed at present.

11.3.4 Drying

Grain and cereal crops are made suitable for storage by removing moisture to below predetermined levels which are around 10 to

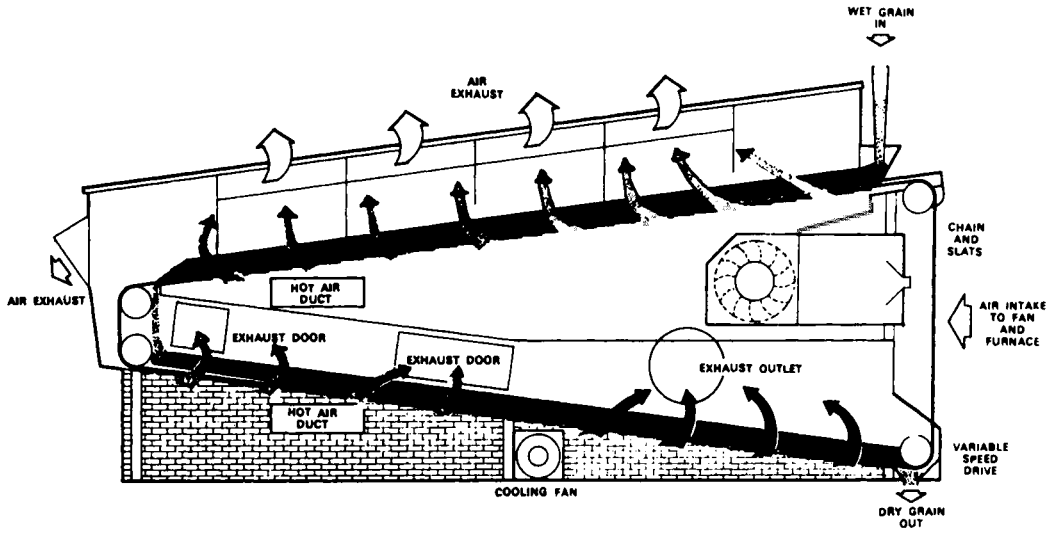


Figure 11.4 Gas fired grain dryer (Alvin Branch Development Co Ltd).

16% moisture content, depending on the seed. This is achieved by harvesting when the crop is as dry as possible, and then by heating in a suitable drier to reduce the moisture content of the crop to storage levels (eg, *Figure 11.4*). There is often a maximum allowable temperature for most crops, which may limit the drying system. The other constraint is economics. If the cost of gas or electrical heating is too high then low temperature air drying may be preferable. Instead of heating, ambient air is passed through to extract the excess moisture. This method takes longer, but can be effective with many crops as long as the humidity of the air is sufficiently low. The air can be heated a little by a solar air heater. This can take the form of the roof of the storage shed (*Figure 11.5*).

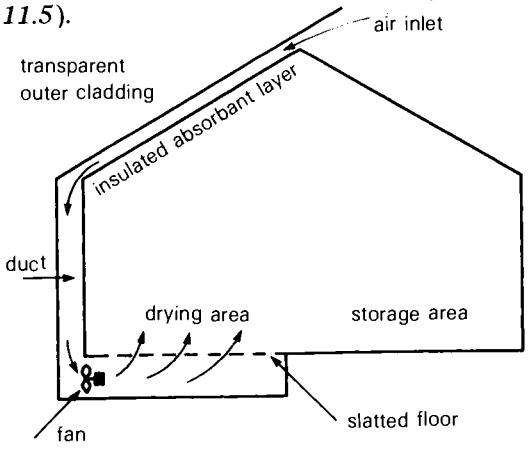


Figure 11.5 Solar assisted drying shed. Air is heated as it is sucked over the inner roof lining, which has been heated by solar radiation.

11.3.5 Packaging and transport

After grading produce must be packaged and transported either to a store, a processing factory, or to market. The packaging system will depend upon the produce. Most vegetables and cereals present no real difficulty, but if the product can be damaged very easily then care must be taken to use the correct type of package and to avoid unnecessary loads of a static or dynamic nature. Some products can be badly damaged if they are carried in a bulk bin on a truck, since the motion of the truck induces movement and crushing of the fruit. Top quality fruit is often packaged in individual trays, so that each fruit is separated from the rest (*Figure 11.6*). This is more expensive, but the reduction in damage and the consequent cash returns for quality produce outweigh the extra cost. The choice of package depends on the particular fruit, and the probable returns. There is little point in packaging second grade fruit in expensive cartons, since the return is likely to be inadequate. The movement of water vapour, air and heat around the individual fruit is affected by the packaging. Thus, if fruit is to be cooled the package must be chosen to allow for an adequate flow of cold air inside the package and around the fruit to extract the heat. The same applies if the produce is to be put into CA storage (see below) or where respiration gases must be removed.

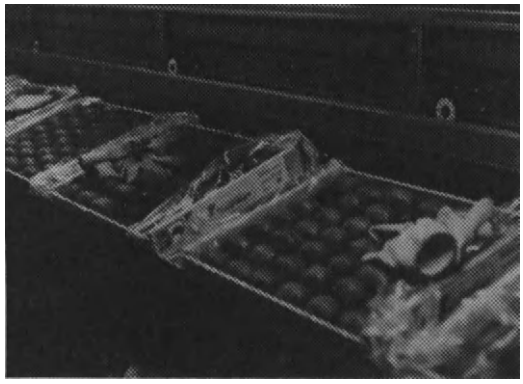


Figure 11.6 Packing fruit in specially designed trays.

11.3.6 Handling damage

There are three ways in which crops can be damaged mechanically, and different crops have different levels of susceptibility to these types of damage. Crops can be damaged by impact, by compression due to (for example) stacking or squeezing, or by abrasion due to rubbing or vibration. For example, plums are susceptible to rubbing, but are resistant to the other two processes, while bananas and peaches are affected by all three. Tomatoes and strawberries are damaged most by compression, while apples are affected by impact or compression in particular. The resistance of produce to mechanical damage can be measured by a variety of tests, including compression and drop impact tests. The threshold for bruising is sometimes determined, or alternatively the bruise volume for a given impact energy is established. Bruising can occur at any point in the harvesting and processing cycle. Some apples can be bruised if the picker in the orchard is too rough, and a great deal of damage can be done if the fruit is transported in a bulk bin over rough tracks by a tractor operator in a hurry! Another major source of damage can be the grading machine, as discussed above.

Bruising damage may not always be evident. Some crops such as potatoes and mangos can be bruised internally by impact, even though the surface appears to be fine. The damage only appears as the cook prepares the product, by which time the producer and transporter have already been paid. However, in the long term the grower will suffer as a result of these problems, because his or her reputation will be lost, and the market price of produce from that enterprise will be affected. Even worse, a group of growers may suffer, or a whole product line may be affected.

Once damaged, the storage life of the product can be seriously affected. In some fruits the damage region decays rapidly, with the production of gases such as ethylene. This gas can accelerate the ripening of the rest of the store, so that an entire consignment can ripen too soon and end up by being rejected at market. Kiwifruit is an example of such a crop, as it is highly sensitive to ethylene.

11.3.7 Pre-cooling for storage

A great deal of agricultural produce will be stored for lengthy periods before being consumed. Such produce is, by definition, biological in nature, and will therefore decay over time. Although not always apparent, all such produce is alive and active. Seed produce such as cereals can be dried, which effectively suspends biological activity. However, eventually these processes lead to senescence and decay. The aim of storage is therefore to provide an environment which slows down the rate at which these decay processes occur. This is usually done by cooling the produce, and by controlling the humidity and composition of the atmosphere in the store. In general it is desirable to cool produce down as soon as possible after harvesting, and to store it thereafter at reduced temperature. Appropriate storage conditions for flowers, fruit and vegetables are listed in (for example) Hardenburg et al, 1986.

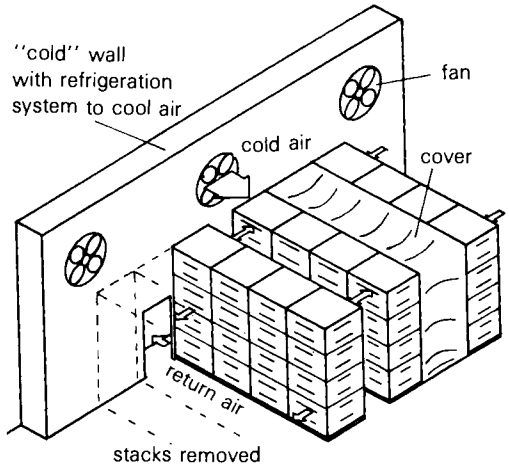


Figure 11.7(a) Schematic.

Crops are cooled in cooling rooms, where refrigeration systems are set up to cool air which is then forced through the produce (eg, *Figure 11.7a*). The air is cooled by a heat exchanger through which the coolant flows, and this is forced through the ducting and into the fruit by the fan. The covers and the configuration of the pallets must be designed so that all the fruit receives a similar flow of cooling air.

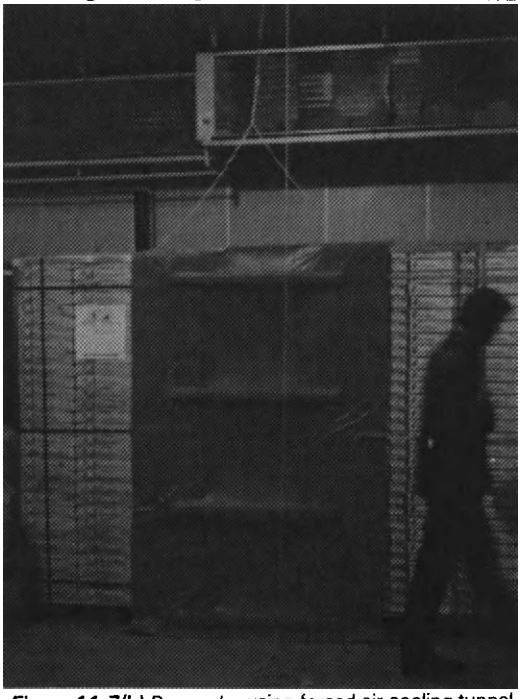


Figure 11.7(b) Pre-cooler using forced air cooling tunnel.

Another method of cooling is known as hydro-cooling. Instead of air the crop is immersed in cooled water. As water has a high specific heat, and because a higher heat transfer coefficient between the water and the crop is possible, hydro-cooling will extract heat from a crop very quickly, so that greater quantities of fruit can be handled in a given time. Vacuum cooling can be used to cool leafy crops such as lettuce, while some crops such as broccoli can be cooled and stored by packing them in crushed ice.

11.4 COOLING CAPACITY CALCULATIONS

Fruit must be cooled as quickly as is economically possible. In order to do this the capacity of the cooling plant needs to be calculated. This requires a knowledge of the internal energy which will need to be removed in the form of heat (in most of the terminology the term heat is used to describe

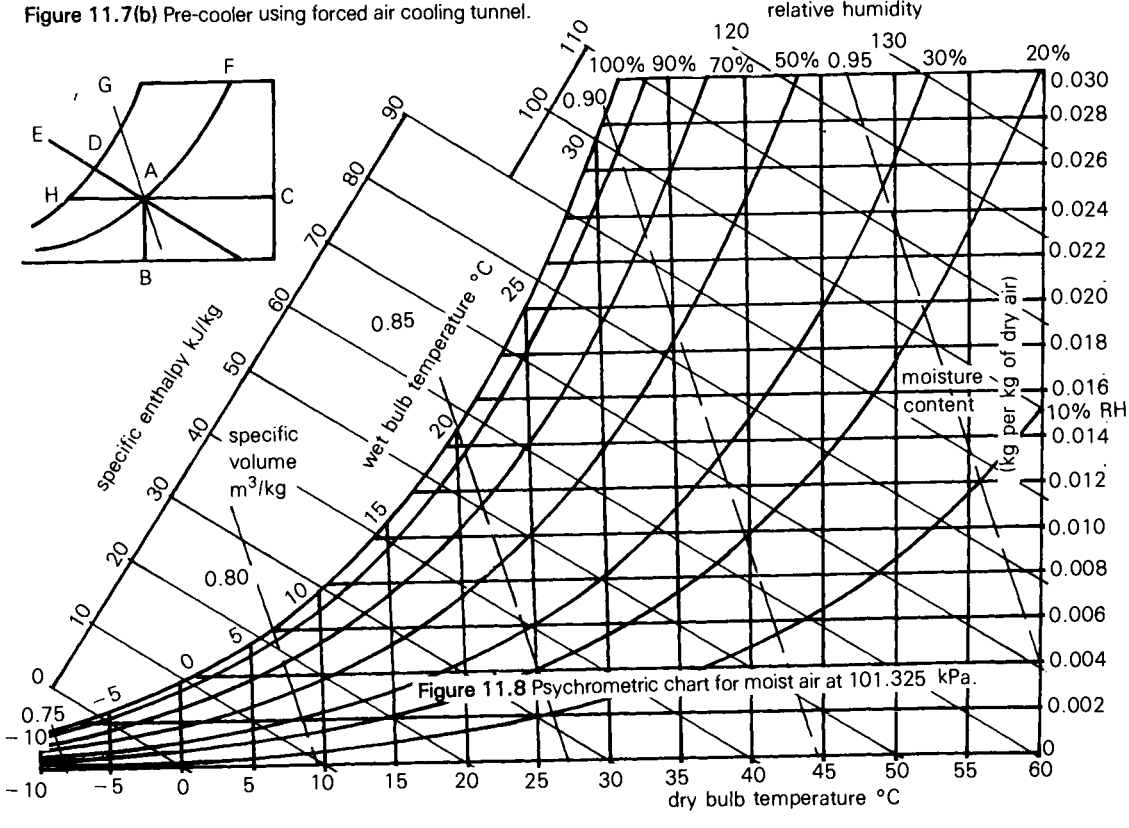


Figure 11.8 Psychrometric chart for moist air at 101.325 kPa.

this internal energy, and we even refer to the specific heat to quantify it. However, it is really the internal energy (ie, the enthalpy) which must be reduced when the fruit is cooled. Heat is what flows out, as we discussed in Chapter 3). The total energy to be removed comes from a variety of sources.

a. Product Load (field heat)

First there is the Product Load E_p (or field heat). This is the energy which must be removed to reduce the temperature of the crop to the desired storage temperature. This will be given by the usual formula:

$$E_p = M\ S\ (T_f - T) \qquad \textbf{Equation 11.1}$$

where E_p is the energy (J), M is the mass of the crop (kg), S is the specific heat capacity (J kg^{-1} $°C^{-1}$), T_f is the temperature of the crop when it enters the cooler, and T is the desired storage temperature. Values of S and T are given in *Table 11.1*. As we are concerned with the size of the refrigeration plant, we will need to consider the rate at which the energy is removed rather than the amount of energy. This is found simply by dividing the energy by the time taken so that the rate of heat removal is given by:

$$P_p = \frac{E_p}{t} \qquad \textbf{Equation 11.2}$$

where P_p is the average rate of removal of heat in watts and t is the total time taken in seconds.

Unfortunately there is a major problem with this model. The heat flow from the product depends upon the temperature gradient, so that as the fruit cools the heat flow will fall. This means that even though the refrigeration unit may have the capacity given by *Equation 11.2*, the time taken to reach the desired temperature will be much longer, since the rate at which the heat flows out will drop as an exponential decay (in theory it will therefore never quite reach the cooler's air temperature!). In practice we must therefore design the system so that the produce is fairly close to the cooler's air temperature after a given period of time. Most designers choose the temperature which is 87.5% of the difference between T_f and T. The time required is then called the *Seven-eighths Cooling Time* t_s. We also now have to design the cooler so that the initial heat flow is much greater than that given by *Equation 11.2*, so that the cooler can extract heat faster at the start. A theoretical analysis shows that the design heat flow should be given by:

$$P_p = B\ M\ S\ (T_f - T) \qquad \textbf{Equation 11.3}$$

$$\text{where } B = \frac{\ln(8)}{t_s} = \frac{2.08}{t_s} \qquad \textbf{Equation 11.4}$$

and where t_s is the seven eighths time in seconds.

At this stage it seems as if we can go ahead with our design, choose the cooling time we want and design the refrigerator size accordingly. However we still may not get what we want! This is because the value of t_s may be limited by the heat transfer properties of the fruit. For a small sized fruit, it cannot be faster than:

$$t_a = \frac{2.08\ m_a S}{A\ h} \qquad \textbf{Equation 11.5}$$

where A is the surface area of the fruit, m_a is the mass of one fruit and h is the surface conductance of the fruit in W m^{-2} $°C^{-1}$.

Even this only works for small fruit. If the fruit is larger, there is a further time lag as the heat flows out of the fruit from its centre to the surface. It then depends on deciding whether it is the temperature of the centre of the fruit that matters, or just the average temperature. However this is getting very complex. In most cases this delays events by only a few minutes.

More importantly, it means that the shortest cooling time is determined by the value of h. As we discussed in Chapter 7, the value of h depends on the fluid boundary layer and how fast it is moving over the surface. For air, values in the range of up to 250 W m^{-2} $°C^{-1}$ can be obtained, while for water values of 15,000 are possible. However, it is crucial that the air can flow freely over the surface of all the fruit, so that the fruit container design and stacking arrangement is critical. The air must be forced through the container, as in *Figure 11.7b*.

In our design calculation, therefore, we need to check to ensure that the value of t_a calculated from *Equation 11.5* is less than the required value of t_s (see example below).

If the produce is to be frozen, then the latent

heat of fusion must be included in the product load. This is given by:

$E_L = M\ L$ **Equation 11.6**

where L is in J/kg and is listed in *Table 11.1*.

$P_r = M\ H$ **Equation 11.7**

where H is the heat given off in W/kg. For precooler design the maximum value, which will be at the initial crop temperature T_f, should be chosen.

Table 11.1 Storage conditions, expected storage life, and heat capacity data

(ASHRAE, 1983; Kutz, 1986; Hardenburg et al, 1986).

	Storage temperature T °C	Relative humidity RH %	Metabolic heat out at 0°C (max) H W kg^{-1}	Approx storage life (max) days	Specific heat (unfrozen) S J kg^{-1} °C^{-1}	Highest freezing point °C	Latent heat of fusion L J kg^{-1}
Apples	−1 to 4	90	0.012	220	3650	−1.1	280
Asparagus	0 to 2	95	0.24	21	3950	−0.6	310
Avocadoes	4 to 13	85	0.07*	30	3010	−0.3	216
Beef (fresh)	0 to 1	90	–	40	3200	−1.7	230
Bread	−18	–	–	100	2000	–	115
Brussel sprouts	0	95	0.07	35	3680	−0.8	284
Cabbage	0	100	0.04	200	3920	−0.9	307
Carrots	0	100	0.046	280	3790	−1.4	294
Cherries	−1	95	0.016	20	3520	−1.8	267
Celery	0	95	0.021	60	3990	−0.5	314
Corn (sweet)	0	95	0.125	8	3320	−0.6	247
Cucumbers	10 to 13	95	0.09*	14	4050	−0.5	320
Grapes	−1 to 0	90	0.008	60	3580	−1.6	274
Kiwifruit	−0.5 to 0	95	0.008	150	3600	−1.6	276
Lettuce	0 to 1	100	0.050	21	4020	−0.2	317
Nuts	0 to 10	75	–	365	1040	–	20
Mushrooms	0	90	0.13	4	3890	−0.9	304
Onions	0	75	0.009	240	3790	−0.8	294
Oranges	0 to 9	90	0.009	90	3750	−0.8	290
Peaches	−0.5 to 0	90	0.009	30	3820	−0.9	297
Pears	−1.6 to −0.5	95	0.020	200	3620	−1.6	277
Potatoes	3 to 10	95	0.009*	240	3450	−0.7	260
Strawberries	−0.5 to 0	95	0.05	7	3850	−0.8	300
Tomatoes (ripe)	7 to 10	90	0.05	7	3990	−0.5	314

* At storage temperature rather than 0°C.

** At higher temperatures the metabolic heat load is higher. As a very rough guide the above values should be doubled at 5°C, trebled for 10°C, and quadrupled for 15°C.

Values are maximum values listed in the references.

b. Respiration Load (P_r)

There are however other "heat" loads. The crop is a living breathing product, and gives off heat as it breathes. The quantity of heat given off depends on the metabolic activity, and drops off with temperature. Values at 0°C are given in *Table 11.1*, and a guide to values at higher temperatures is also included. P_r is given by:

c. Wall gain load (P_w)

The walls, ceilings and floor will transmit some heat, which must be absorbed by the refrigeration plant. This load has been discussed in Chapter 7. The load in watts is given by:

$P_w = U\ A\ (T_a - T)$ **Equation 11.8**

where U is the overall heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$), A is the total outside surface area of the cool store (m^2), and T_a is the outside temperature. If necessary, each wall should be considered separately, and the total added.

d. Air change load (P_a)

Each time the door of the cooler is opened warm air will enter. This will have to be cooled, and any water in it will be condensed. Both processes require the removal of heat. Continuous opening of the doors thus increases the load on the refrigeration plant. It is important to have self-closing doors if people and equipment are often going in and out of cool stores. The air change load is difficult to calculate as it depends upon the type of store and how it is operated. It is given (in W) by:

$$P_a = M_a\ (h_a - h) + M_w\ S_w\ (T_a - T)$$

Equation 11.9

where M_a is the mass of air admitted in kg per second, h_a is the enthalpy of the outside air (J/kg), h is the enthalpy of the air at the conditions inside the cooler, M_w is the mass of water which condenses out (kg/s), and S_w is the specific heat of water. The enthalpy and the mass of water are determined from the psychrometric chart (*Figure 11.8*). This is a chart which gives us the properties of moist air at atmospheric pressure, providing we know the relative humidity and the temperature. From it the mass of water, the enthalpy, the wet bulb temperature, the dew point, and the volume per kg of air can be determined. These terms will be discussed in Chapter 12. The method is described in the example below. The value of M_a can often be found by estimating the number of air changes per hour. The mass can then be found by dividing this volume by the volume occupied by one kg of dry air, which can be read off the chart. M_w can be found by determining the difference in water content from the chart (the inside air will usually be saturated). In practice the second term is small compared to the first term, and can usually be ignored (see the worked example below).

e. Other loads

In this final category we allow for other heat loads produced by fans, motors, people, and lights. These loads are also hard to estimate, and a sensible guess is appropriate. Some fans will be needed to circulate the cooling air through the crop, and so the heat load from these at least can be estimated.

Example

Calculate the size of a refrigeration plant required to cool 15 tonnes of apples to 0 °C from 20 °C in 12 hours, in a pre-cooler. Use the following data: Respiration rate for apples at 20 °C = 0.092 W/kg, U for cooler walls and ceiling = 0.241 $W\ m^{-2}\ °C^{-1}$, outside temperature 29.5 °C, U for floor = 0.35, underfloor temperature 14 °C, size of cooler 9 m × 9 m by 4 m high, humidity of outside air = 70%, assume one air change per hour. Take other data from *Table 11.1*.

Solution: First we will calculate the heat loads, and then find the minimum surface conductance coefficient required to extract the heat from the apples.

a. From *Equation 11.3* the product load is given by:

$$P_p = \frac{2.08 \times 15{,}000 \times 3650 \times (20 - 0)}{12 \times 3{,}600}$$

$$= 52.73\ kW$$

b. The respiration load when the apples are first put in is:

$$P_r = 15{,}000 \times 0.092 = 1.38\ kW$$

When they have cooled to 0 °C the load will be $15{,}000 \times 0.012 = 0.18$ kW. Thus the load will drop as cooling proceeds, and in storage the lower value can be used. However for the pre-cooler, the greatest value is appropriate, ie, 1.38 kW.

c. For the ceiling, walls, and floor respectively, the heat load is:

$$P_{w1} = 0.241 \times 9 \times 9 \times (29.5 - 0) = 576\ W$$

$$P_{w2} = 0.241 \times 9 \times 4 \times 4 \times (29.5 - 0) = 1024\ W$$

$$P_{w3} = 0.35 \times 9 \times 9 \times (14 - 0) = 397\ W$$

The total wall gain is thus the sum of these or 1.997 kW.

d. Calculation of the air change load requires the use of the psychrometric chart. First the volume of air inside the cooler can be found by finding the point representing the moist air at 0 °C and 100% RH, and reading the value of the volume from the near vertical lines (ie, lines parallel to AG in the inset).

From *Figure 11.8*, at 0°C, one kg of dry air occupies a volume of 0.778 m^3. Hence for an air change of 1, the mass of air is:

$$M = \frac{9 \times 9 \times 4}{0.778} = 416.5 \text{ kg}$$

Next the enthalpy can be found. This is obtained by following the sloping lines back to the sloping scale on the left (ie, lines parallel to AE). Thus, at 29.5°C and 70% RH, the enthalpy $h_a = 78.5$ kJ/kg dry air, and at 0°C and 100% RH, h = 9.2 kJ/kg dry air. The mass of water per kg of dry air is found by following the horizontal lines to the right and reading off the scale at C. This gives values of 0.0189 kg and 0.0037 kg respectively. Hence the mass of water which must be condensed is:

$$M_w = (0.0189 - 0.0037) \times 416.5 = 6.33 \text{ kg}.$$

Thus for *Equation 11.9*, the total enthalpy change per second is given by:

$$M_a(h_a - h) = \frac{416.5 \times (78{,}500 - 9{,}200)}{3600}$$

$$= 8.017 \text{ kW}$$

For the water vapour:

$$M_w S_w(T_a - T) = \frac{6.33 \times 4{,}200 \times (29.5 - 0)}{3600}$$

$$= 0.217 \text{ kW only.}$$

Thus in *Equation 11.9*:

$$P_a = 8.017 + 0.217 = 8.234 \text{ kW}$$

In this calculation, the second term, the load due to cooling the condensed water, is only 217 W.

e. We will allow a value of 400 watts for the incidental load.

Thus the total heat load is given by adding these together. Thus:

Total heat load P = 52.73 + 1.38 + 1.997 + 8.234 + 0.40 = 64.7 kW

As can be seen from these figures, the load is dominated by the field heat, so it is evident that a much larger cooler is required to cool the produce than to maintain it once cooled. This is why it is common to put produce through a special pre-cooler before it is placed in the cool store itself. The air change load is the second greatest load in this example.

Now we must ensure that the heat can be removed from the apples. This will be possible providing t_a is less than or equal to t_s. The minimum surface heat transfer coefficient can be calculated from *Equation 11.5*. Assuming a mass of 0.3 kg, and a surface area of 0.025 m^2 for an apple 90 mm in diameter, the minimum value of h is given by:

$$h = \frac{2.08 \text{ M S}}{\text{A } t_s} = \frac{2.08 \times 0.3 \times 3650}{0.025 \times 12 \times 3600}$$

$$= 2.1 \text{ W m}^{-2} \text{ °C}^{-1}$$

This is quite low, so providing the air can flow over the apples the required cooling time should be attainable.

11.5 STORAGE AFTER COOLING

After cooling, the crop is stored in a cool store until required (*Figure 11.9*). For each crop advisors can detail the ideal post-harvest storage conditions (eg, *Table 11.1*). For very sensitive crops, there may be restrictions on the siting of cool stores. For example, a kiwifruit cool store should be sited well away from any main road, because the minute traces of ethylene in car engine exhaust



Figure 11.9 Storage in a cool store at near zero temperatures.

fumes can raise the local air levels sufficiently to cause premature ripening. For the same reasons petrol engines cannot be used inside the store.

Once grain and cereal crops have been dried they must be stored and kept at low moisture levels. Examples of grain silos are shown in *Figure 11.10*. Ambient air can be used to do this. For example the equilibrium moisture content in grain is 14% at 65% relative humidity of the air, so providing the air is below 65% RH, it can be used to keep the grain dry. It is also necessary to ventilate the grain in order to remove heat produced by respiration of the grain. If this is not done biological activity may increase, producing more heat, and fueling the activity. There are other advantages in reducing the temperature of grain in store, since this reduces the risk of mite attack, and other infestations.

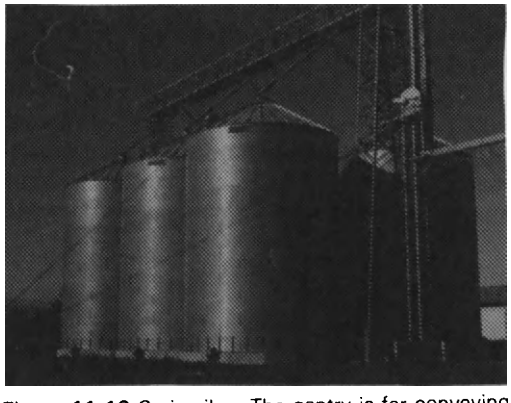


Figure 11.10 Grain silos. The gantry is for conveying the grain into the silos.

Other crops such as potatoes or fruit cannot be dried, since this would destroy their flavour. Instead they are stored at low temperature and high humidity so that the loss of water vapour from the produce is minimised. There are a few crops, such as bananas, which cannot be stored at low temperature without some damage. This is known as chilling injury.

Bulk stores of produce can be very large (*Figure 11.11*). The control of these stores is far from simple. It is necessary to place sensors in appropriate positions throughout the produce, so that the actual behaviour of the environment can be sensed. In this way a rise in temperature in a portion of the store (which indicates biological activity and decay) can be detected and dealt with before it is too late.

The least costly form of storage involves adjusting the physical properties of the air, such as temperature and relative humidity. It should be noted that while temperature is easy to measure and control, relative humidity is less straight-forward. It is difficult to measure high relative humidities (above 95%) accurately, and it is not difficult for the air to become saturated so that water condenses on the crop, and this can be harmful.

11.5.1 Controlled atmosphere (CA) storage

It can be advantageous to control the chemical composition of the air as well. Respiration involves the conversion of oxygen to carbon dioxide, so an increase in CO_2 levels and a decrease in O_2 levels is the logical first step. In practice this works for many crops, although there is usually a limit to the extent that the atmosphere can be altered before



Figure 11.11 Potato store.

undesirable side effects occur. For apples at 5 °C, O_2 levels of 2.5% halve the respiration rate. Increases of CO_2 levels also reduce respiration, but if these are too high then anaerobic effects can occur. Levels differ widely between crops, and some do not respond at all. However where the effect is beneficial, and the market prices for stored produce make it worthwhile, controlled atmosphere storage is an attractive proposition. Computer controlled containers have been developed which enable CA storage on board ships. While the returns are high, the risk of a complete loss is also high, since the CA conditions must be maintained at all times. The introduction of computer watchdog alarm and monitoring systems could improve the situation. Ethylene ripening can be a problem in CA storage, and it may be necessary to remove it using other chemicals such as ozone or potassium permanganate. CA storage conditions are discussed by Hordenburg et al (1986).

11.6 MARKETING

Increasingly the grower is being encouraged to realise that his or her responsibility extends to the consumer, and that presentation of produce and quality affect the returns. This is readily apparent at product markets, where tidily presented produce gets the highest prices. The grower therefore needs to consider how the produce will look in the supermarket if it will be sold straight out of the container. *Figure 11.12* shows some examples of how produce can end up for sale at the market.

Figure 11.12 Packaging can affect market prices.



11.7 EXERCISES

1. Find data for the storage requirements of two or three crops of interest to you. Establish temperature, humidity, and duration of storage details.
2. Calculate the heat to be removed from a ten tonne crop of pears, harvested at 20 °C and to be cooled to −1 °C. If this must be achieved in 24 hours, what cooling capacity would the pre-cooler need? Assume the air outside is at 25 °C and 60% RH, and assume the same data for the pre-cooler as in the example in the text.
3. What refrigeration capacity would a cool store need to have if it had 100 tonne of apples at 0 °C, and measured 100 m × 50 m × 5 m, using the same data for U-values etc as in the previous example.

11.8 AIMS OF THIS CHAPTER

After studying this chapter you should be able to:

1. Describe some of the equipment and processes which are used in the post harvest handling and storage of crops.
2. Discuss the post harvest treatments which are required for quality produce.
3. Calculate the refrigeration requirements for cool stores and pre-coolers.
4. Consider the packaging and presentation of products in terms of market needs and expectations.

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Our environment, its measurement, destruction and protection

Chapter 12

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The environment is the world in which we live. It is beautiful, and in my view, brilliantly designed. It is also fragile, and can be unbalanced by excessive maltreatment. Nature itself causes continuous changes to the environment – in the form of day and night, the weather, the seasons, and more long term cycles. We can describe the environment at a variety of levels: there is the micro-environment immediately surrounding a plant or animal, the local environment in a field, a valley or a city, and the macro-environment which may relate to oceans and continents. Engineers have the ability to modify the environment for good or ill at all these levels. It is therefore particularly important that we should be aware of the environmental consequences of what we do. In this chapter we will therefore pause to consider our environment, how we can monitor it, and how we can avoid destroying it.

12.1 THE ATMOSPHERE

The atmosphere consists of a mixture of gases comprising mostly nitrogen (78%) and oxygen (21%), the balance being carbon dioxide, argon and other rare gases plus water vapour. The atmosphere extends up to a height of 30,000 m for practical purposes although some gases may be found as high as 160 km. The lower layer in which we live is called the *Troposphere*. This generates the weather we know and stretches up to about 10,000 m at the poles and 16,000 m at the equator. Above the troposphere is the *Stratosphere* (strato means stable) where the temperature does not alter. The junction between the two is the *Tropopause* where there is a temperature inversion. The stratosphere is weather-free. Above the stratosphere are other layers such as the Ionosphere about which we need not be concerned.

The sun is the engine which fuels our weather system. A large proportion of the sun's heat is absorbed by the atmosphere. Solar energy falling on the earth's surface on a hot day varies between poles and the equator, but averages approximately 900 W/m^2 at mid-day. Some of this radiant energy is absorbed, and some is reradiated in the infra-red wavelengths. Some of this is in turn absorbed by the atmosphere, rather like a greenhouse. Clouds also absorb or reflect a large proportion of the incoming energy, although some still reaches the earth's surface after scattering even on a cloudy day. Almost 16% of the intercepted solar energy is utilised in evaporating surface and sea water. This represents an enormous amount of energy.

The main factors affecting the world's weather patterns are the inbalance of heat between the poles and the equator, combined with the earth's rotation. Land and sea masses also have a major effect on these flow patterns, resulting in a complex flow of air. Hot air rises and so at the equator there is a band of air which is replaced by cooler air flowing in from the temperate regions. This hot air subsides just poleward of the tropics, returning as easterly trade winds. The subsiding air gives rise to a belt of subtropical high pressure regions. Similar circular flows occur at higher latitudes. The effect of the earth's rotation is to introduce a large component of the air flow in an east-west direction. Wind flows and direction can therefore be vastly different at different altitudes.

Water vapour enters the air as part of the hydrological cycle by evaporation from open water surfaces. As the air rises and its temperature falls it can hold less water and condensation takes place. Fronts occur when a belt of warm moist air rises over the top of a mass of cold air, and rain results. Droplets of water form as clouds or as dew, and rain is formed by coalescing droplets of condensed moisture in cloud. The temperature difference between the rising air and its surroundings determines the shape and appearance. Unstable air and large temperature differences produce cumuliform clouds whereas stable air and small temperature differences produce layer clouds. Layer cloud is most often produced by air rising slowly over a large area. Cloud types can be memorised by reference to a cloud atlas and their recognition is largely a matter of practice. The amount of cloud is specified in "octas" where an octa is one-eighth of the sky area. For example four octas Sc means that half the sky is obscured by stratocumulus.

Hail is formed where rain droplets are carried by upcurrents and circulated above the freezing level until their mass overcomes the upcurrents. Snow is formed by sublimation directly from moisture below freezing point.

Fog is condensation occurring at ground level which greatly reduces visibility. Fog is most commonly caused when the earth loses heat on a clear night by radiation (a radiation fog). If the relative humidity is high enough the air close to the ground is cooled to saturation and fog forms. A very light breeze assists mixing. Otherwise the fog is dense in the first few metres above the ground. Fog is normally dispersed by the heat of the rising sun, although in some cases, cold air may be trapped by rising terrain and a temperature inversion above, in which case the fog will lift to form a low layer of stratus cloud during the day, reforming at night. The name advection fog is given to fog which is formed by moist air moving over a cold surface. Fogs can also be enhanced by pollution of the atmosphere. This phenomenum is common over large cities in winter. London used to be very badly affected by smog but since the introduction of legislation banning open fires the effect has disappeared.

Frosts occur due to cooling of the ground and air by radiation loss. Normally the water vapour in the air in the form of cloud acts as a thermal blanket, absorbing infra-red radiation from the ground. However if the sky is clear, there is nothing to trap the radiation, and so there is a loss of energy. The sky radiation temperature is very low (eg, $-50\,°C$) and so there is little returning radiation to balance the losses. Hence the ground temperature can fall below zero, cooling the air close to the surface, and causing freezing damage to plants. Frost damage can be prevented by keeping plants at $0\,°C$ or higher. This can be achieved by continually spraying orchards with water. The water freezes, but because there is plenty of water still in the liquid state the temperature can fall no further. The plant may be covered with ice but it is perfectly safe thanks to the latent heat of solidification. An alternative method is to mix the air above the crop with the cold air at the surface. This method requires the use of large wind turbines to do the mixing. It will only work if the air above the crop is warmer than the air at ground level!

12.2 ENVIRONMENTAL MEASUREMENTS AND INSTRUMENTS

There are many parameters which can be used to define the environment. We will outline equipment used to measure some of them here. Some specialised devices are required to measure pollution levels, and these will be discussed later.

12.2.1 Temperature

One of the most important and commonly measured variables is temperature. Some devices used to measure it are the following:

a. Liquid in glass thermometer

Liquids expand as they are heated. If a liquid is placed in a small glass bulb, with a capillary tube attached, then as the liquid gets hotter, its level in the tube will rise. By marking the tube a measure of temperature can be attained (*Figure 12.1a*). This method is widely used for domestic and medical purposes, using mercury or alcohol as the liquid. The temperature is easy to read, and the thermometer is simple and inexpensive. It has an accuracy of typically $0.5\,°C$. Disadvantages are that it is fragile, slow, and can only be read manually, so it is no use for automatic recording or control systems. For industrial purposes (and for particularly harsh environments) the liquid can be placed inside a steel bulb. If the tube is replaced by a narrow pipe the expansion of the liquid can be recorded on a Bourdon pressure gauge (Chapter 5), and this can be used for control.

b. Bimetallic strip

If two strips of different metals with different coefficients of thermal expansion (Chapter 3) are rivetted together (*Figure 12.1b*), then as they are heated, the strip must bend because of the difference in thermal expansion. This effect is used to drive a pointer as a measure of temperature. Such bimetallic strips are robust and can be used for automatic control. They have a slow response time (2/3 minutes).

c. Thermocouple

If two wires of different metals are joined at the ends, and each end is at a different temperature, then a voltage is produced between the ends which is proportional to the temperature difference. This effect is used in the thermocouple (*Figure 12.1c*). The voltage is of the order of a few mV only (eg, for $100\,°C$ a Copper–constantin thermocouple

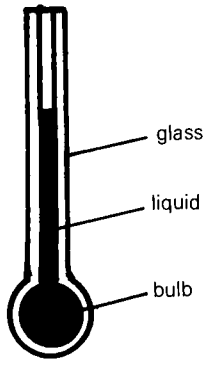


Figure 12.1(a) Liquid in glass thermometer.

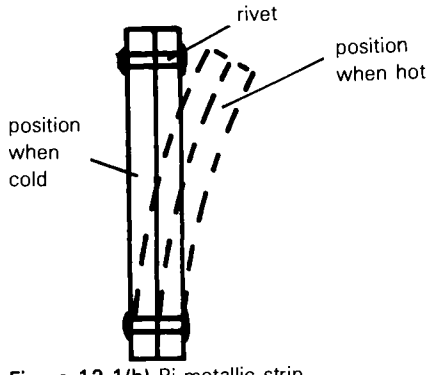


Figure 12.1(b) Bi-metallic strip.

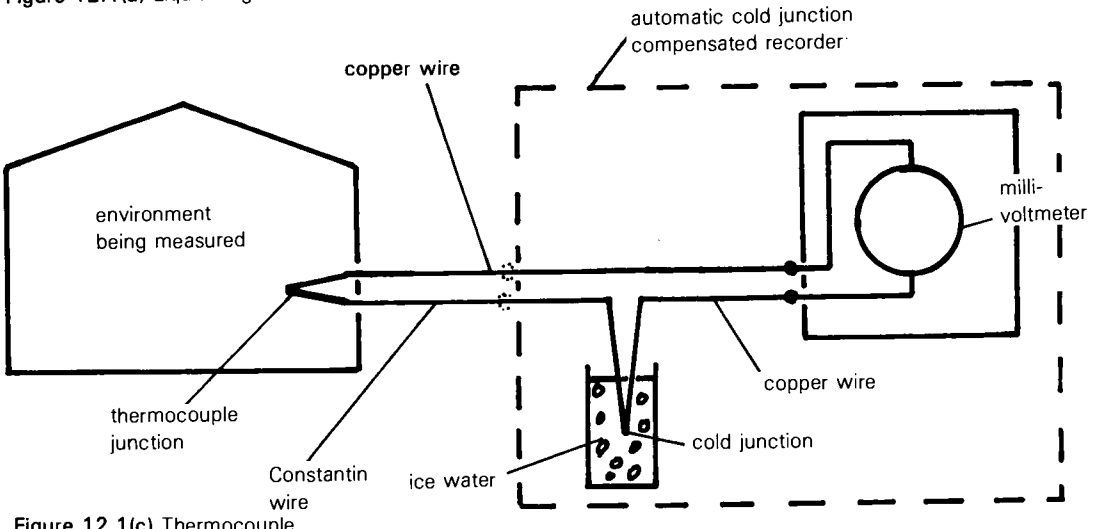


Figure 12.1(c) Thermocouple.

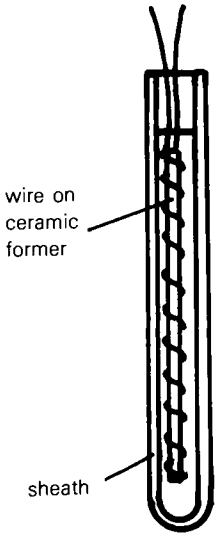


Figure 12.1(d) Resistance thermometer.

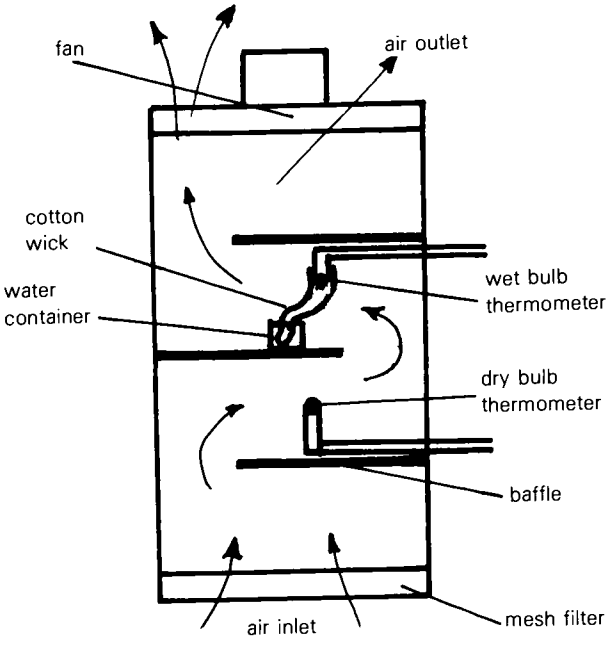


Figure 12.1(e) Humidity sensor inside aspirated screen.

will produce 4.7 mV). However it is reliable, and can be amplified and used for automatic recording. Different types of thermocouples can be used over a very wide range of temperatures, and they are very common in research work. One problem is that a reference cold junction is required. In theory this is achieved by placing the reference junction in an ice–water mixture at 0 °C, but nowadays many recorders and loggers have an electronic circuit which replaces the cold junction completely. This is known as automatic cold junction compensation. If a larger voltage is needed it is possible to join several thermocouples together in series to produce a *Thermopile*. These are used in solar radiation sensors (see below). Thermocouples are inexpensive, small, respond quickly, and because of their small size, are not affected very greatly by direct sunlight or radiation. They can be destroyed by chemical attack, and an amplifier is essential.

d. Resistance thermometer

A fine coil of platinum, copper or nickel wrapped around a small ceramic rod and placed in a metal sheath makes an excellent temperature sensor which is very stable over a long period of time (*Figure 12.1d*). As it warms the resistance changes, and by measuring this with suitable electrical apparatus the temperature can be recorded accurately. Resistance thermometers are often used for control of equipment where long term reliability is important. They can be manufactured to a high degree of accuracy, so that a broken thermometer can be replaced in a control system without the need to recalibrate the system. This can be very useful in practice. They have a slow response.

e. Semiconductors (thermistors and integrated temperature sensor ICs)

The resistance of a semiconductor varies dramatically with temperature. Although the change is non-linear, and the resistance falls as the temperature rises, a semiconductor diode, or Thermistor, can be used to measure temperature quite accurately. To overcome the non-linearity problems integrated circuits have been developed, which convert the resistance change directly into a current which is proportional to the temperature. An example is an AD590, which is a three wire IC in a can, about 5 mm in length and diameter. Since these devices generate a current rather than a voltage as the output signal, they can be operated a long way from the recording instrument without loss of accuracy (if the connecting wires have a significant resistance the device will have to output a higher voltage to maintain the same current in the circuit).

12.2.2 Relative Humidity and dew point

The relative humidity is a measure of the amount of moisture in the air. For our purposes it is defined as the ratio of the mass of water vapour present per unit mass of air to the maximum possible mass of water that the air could contain at that temperature (strictly it is the ratio of the partial pressures). It is measured by a variety of methods. Many wall sensors consist of bundles of horse or human hair which expand as the humidity rises (*Figure 12.2*). This effect is used to drive a pointer. Although this method is not very accurate (5%), it is probably adequate for most purposes. A range of electronic sensors are available now. Some of these consist of a water absorbant plastic dielectric material, whose capacitance changes with humidity. These devices are fairly accurate, but very few produce reliable results if the humidity exceeds 95%. They can all be contaminated easily.

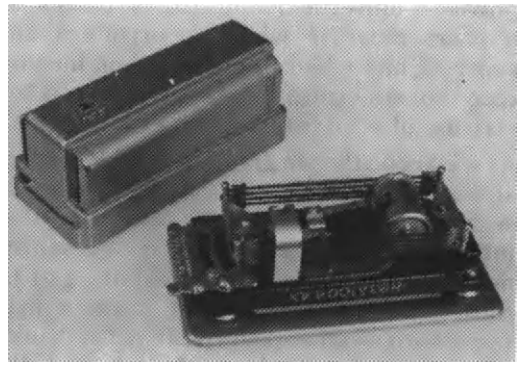


Figure 12.2 Horse hair humidity controller.

The most common and reliable method of measuring humidity is the wet and dry bulb system (*Figure 12.1e*). Two temperature sensors are used. The dry bulb thermometer measures the air temperature. The wet bulb consists of a sensor which is surrounded by a cotton wick. This is kept damp because it

draws water from a small reservoir. As the air flows across the wet bulb, the water evaporates, and this evaporation lowers the temperature of the sensor. The dryer the atmosphere, the greater the drop or depression. By using these two measurements and by referring to the psychometric chart, the relative humidity can be determined (by following the lines from B and D to A in *Figure 11.8* and reading the value of the curve AF). In order for wet and dry bulb sensors to be accurate, the air flow over the wet bulb must be at least 3 m/s. This is rarely accomplished in practice and the result is that the sensor over-estimates the humidity. The sensors must be enclosed in a suitable box with a fan which extracts air, thus drawing air in over the sensors (*Figures 12.1e* and *8.28*).

Another measure of moisture content is the dew point. This is the temperature to which the air must be cooled to become saturated so that dew forms on a cold surface at that temperature. It can also be determined from the psychrometric chart (point H in *Figure 11.8*).

12.2.3 Barometric pressure

Atmospheric pressure is measured with a mercury barometer or anaeroid (Chapter 3), the former being used for accurate measurement. Meteorological station readings are reduced to sea level pressure to provide a universal datum. The barograph is a chart recorder which incorporates an anaeroid and which provides a continuous record of atmospheric pressure. This can be very useful as an indicator of weather trends.

As we know, the weight of air in the earth's atmosphere creates a pressure at the earth's surface of approximately one bar. In meteorology, the unit of pressure measurement is the millibar (mb). Atmospheric pressure is not constant but varies with weather patterns. In general, low pressure brings bad weather, and high pressure is normally associated with good weather. While the International Standard Atmosphere is 1013 mb, the normal range of pressure variation is from about 975 to 1035 mb.

12.2.4 Wind and airflow

Wind direction and velocity are both very important measurements. Direction is measured with a wind vane in degrees from north, while velocity should be measured with a pitot tube. In practice a rotating device consisting of three cups rotating about a vertical axis is often used. Often only the total number of revolutions is recorded, and this is known as the wind run. Devices for wind measurement are known as Anemometers. An anemomograph combines velocity and direction. It provides a constant record, including gusts and directional variation. A scale known as the Beaufort Scale has been widely used in the past. This grades wind velocity by number up to 12 and relates to the physical effect that the wind has on land or on the surface of the sea.

The measurement of small air movements (such as inside a greenhouse or a livestock shelter) is not easy. A sensitive turbine flow meter can be used if the flows are strong, but for accurate measurement of low flows a hot wire anemometer or a hot bulb device is needed. These operate on the principle that as the air flows over the wire or bulb, cooling occurs, so that the resulting temperature is a measure of the air speed. These devices are expensive and delicate.

12.2.5 Evaporation

Evaporation of water is measured by the drop in water level in mm from an open tank or pan. The size of the pan is specified by national standards, and measured values are often published in local newspapers. These can be used as a guide for timing irrigation (Chapter 5).

12.2.6 Measurement of rainfall

Rainfall is measured with a rain gauge comprising a calibrated funnel and measuring cylinder. If a tipping mechanism is incorporated, so that each cubic centimetre of water collected toggles a counter as it passes through, the device can record the rate of rainfall on a chart.

12.2.7 Sunshine recorders

These devices basically consist of a glass ball which directs and focuses direct sunlight onto a chart made from a special paper. When the sun is shining the focussed rays burn a trace on the paper. The length of the burnt strip is a measure of the sunshine hours.

12.2.8 Solar radiation

The actual level of solar radiation can be determined continuously with a Solarimeter. This consists of a blackened surface which is protected by one or two glass domes, and which heats up as the solar radiation falls upon it (*Figure 12.3*). A thermopile under the surface measures the temperature, and this is calibrated in terms of the solar radiation in Watts per square metre. The glass cover does not transmit infra-red radiation so if this is of interest the glass must be replaced by a thin polythene cover. Some sensors use a silicon solar cell to measure the radiation. These do not detect radiation at wavelengths longer than red light, and they are usually calibrated to correct for this deficit, using solar radiation wavelength distribution curves. They are therefore only accurate for recording outside radiation levels. They are not necessarily calibrated correctly for use inside glasshouses, for example.

If the main concern is the measurement of sunlight which is useful to plants, a Quantum Recorder can be used. This has a special filter which blocks out radiation outside the photosynthetically important region, and compensates for the differences in energy between blue and red light, to give a measure which is proportional to the number of light quanta striking the sensor.

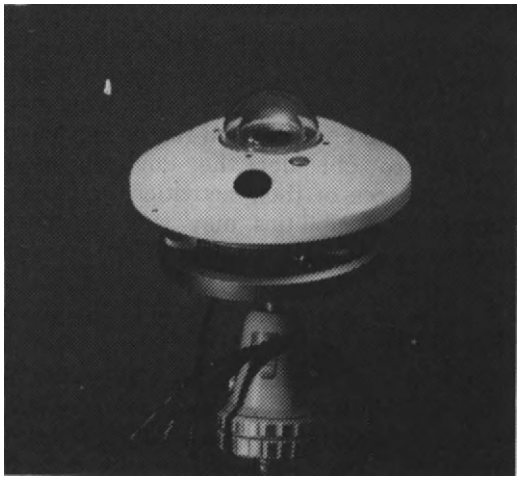


Figure 12.3 Solarimeter (Swissteco instruments).

12.3.9 Upper air observations

Measurements in the atmosphere are regularly made with special balloons. These balloons carry instruments to measure pressure, temperature and humidity as well as a small transmitter to send the results back to a recorder at the ground station. Once used, the instruments are not normally recovered. To measure wind speeds in the upper atmosphere, a hydrogen filled balloon can be used. This is tracked with a theodolite or by radar, and allows the direction and velocity of upper winds at all levels to be determined. Satellites are now used widely for meteorological monitoring.

12.3 ENVIRONMENTAL POLLUTION

> "Pollution comes from getting rid of wastes at the least possible cost"
>
> Fraser Darling, Reith Lectures, 1969

In 1986 a sharp rise in nuclear radiation levels was detected in the air in monitoring stations in Sweden. Some days later the world became fully aware of a small town in the heart of the Ukraine. At Chernobyl a major nuclear accident had resulted in the release into the atmosphere of several tons of highly radioactive nuclear materials. The resulting cloud was carried by the prevailing winds over most countries in Northern and Central Europe. Around Chernobyl thousands of people were hurriedly evacuated, and the farmland became totally unusable. In Finland and Norway the nuclear fallout made grass unsafe, and grazing stock were declared inedible, possibly for decades, with major consequences for the Laps and other farming communities. In England fallout was concentrated in areas where rainfall occurred as the cloud passed overhead. Vegetables and milk were contaminated and had to be destroyed. Roughly forty people died of radiation sickness within a few days, and estimates of the total death toll due to long term effects varied from one to ten thousand people.

This disaster is an extreme example of the consequences of the failure of a producer to control the waste emanating from their enterprise. The consequences of a single nuclear accident are immediately obvious and on a large scale. Far more insidious damage may be occurring to our environment due to the continuous deposition of waste from industries, farms, and municipalities, together with the overall ecological effects of intensive agricultural systems. In Europe and

America the term Acid Rain is used to describe one form of pollution of the atmosphere by factories and farms. The presence of sulphates and nitrates in the air reduces the pH of the moisture in the air as it forms rain droplets. Wherever the rain falls trees, plants and lakes suffer. Major forests are apparently dying as the acid rain reduces the pH levels in the soil. Neither is the phenomenum of air pollution new: for decades, industrial pollution has meant that galvanised iron has a very limited lifetime in Europe and is therefore rarely used as a roofing material. Some lakes will no longer sustain life due to the pollution from chemical wastes. Carbon dioxide levels worldwide have increased from 300 parts per million to 330 in the last 20 years, while there is increasing concern about the effects of chemicals on the ozone layer, which protects us from the deadly ultra-violet radiation from the sun.

More and more people are beginning to realise that the earth is a finite size, and that there are limits to the amount of waste or the disturbance of the ecosystem that can be absorbed or recycled by nature. We have also learnt that some products such as glass, organo-chlorines (dieldrin, DDT, and its main residue, DDE), and poly-chlorinated biphenyls (PCBs, which have been used as additives to paints, plastics, and electrical components) are only marginally degradable. Indeed because DDE and PCBs are soluble in body fats, they accumulate in them, resulting in a steady rise in concentration of these chemicals in the food chain. Although the bulk of the problems arise from high population levels and heavy industries, the farming sector also has a major responsibility for the environment. There is some evidence that intensive livestock systems make a significant contribution to localised acid rain levels, and fertiliser run off and the dumping of untreated waste can cause major problems in waterways. Farming practices also affect the landscape. Bad cultivation methods, the removal of trees and hedgerows, and continuous mono-culture can result in serious soil erosion, slips on hill sides, and the deterioration of the soil structure and fertility.

The Chernobyl tragedy, coupled with the other environmental problems, has forced many engineers, along with others involved with increasing agricultural productivity, to rethink their role. There has been a growing awareness that increasing production results in increasing waste problems, which in turn is likely to have an adverse effect on the environment. For example, in The Netherlands, the most densely populated country in Europe, and in agricultural terms certainly one of the most productive, particularly difficult problems have arisen in dealing with agricultural and horticultural wastes.

A large amount of work has gone into ways of dealing with agricultural waste. Future research into new techniques must not only consider the economics of a proposed development, but should also consider the environmental implications. For example, rock wool is a very nice material to grow plants in. It is relatively cheap, disease free when new, and it is an ideal medium to grow roots in. This is fine for the first year or two, but eventually it will carry too many trace chemical residues from the fertigation water, and will contain a few diseases. It is clearly time to renew the medium but now what do you do with the waste? It is really not very suitable for anything and costs would eliminate some of the possible options. The local tip may be able to handle some, but it is not the best material for fill, and when 30% of your nation's crops are growing in it, you have a problem of your own creation.

For the purposes of this book, our interest in pollution will be in ways of controlling and dealing with waste in order to meet water quality regulations and practical problems. However the engineer and the farmer have a duty to consider the environmental consequences of their activities, and their moral responsibilities may well be more demanding than their legal duties.

12.4 TYPES OF POLLUTION

Pollution is that which destroys the purity of the environment. It can occur as the result of human activity in a variety of ways. Apart from the obvious chemical and nuclear pollution there are also physical and biological pollutants.

12.4.1 Physical pollution

Physical pollution is caused by the addition of inactive materials or other products to the environment, whose presence disturbs the

physical features of the environment. The cooling water from a large power station or factory can cause the water temperature in a river to rise by several degrees centigrade for some distance downstream of the discharge point. Even though the discharge is chemically clean, the temperature rise causes a reduction in the oxygen level in the water. Unfortunately increased temperatures result in an increase in biological activity, with a corresponding increase in oxygen requirements. The net result is that under some conditions aquatic life may be unable to survive.

Streams and rivers can also become polluted with large quantities of suspended solids. They become turbid, since sunlight cannot penetrate the water to any significant depth, and this interferes with the natural biological processes. The silting of dams, river mouths, and drainage channels is another form of pollution. Although this process occurs naturally over a long period of time, it is frequently accelerated by human activity. Thoughtless removal of trees and natural vegetation can lead to a drastic increase in rain water run off, which takes with it large quantities of soil. This ends up as silt in the river-bed. If heavy rainfall occurs, the resulting flooding is made worse, and the problem of silt removal from flooded farm land once the water has receeded can be as bad as the problems caused by the water itself.

Other physical pollution occurs as dust and other fine solids are discharged into the air and waterways by industrial plants such as stone crushing or cement works. Smoke and dust cause reductions in light levels, deposits on greenhouses and other sun dependant systems, and in bad conditions they cause smog. This is dangerous to health. It also reduces visibility which generates further hazards for transport. In very bad cases dust in the atmosphere will reduce sunlight levels to the extent that the air temperature falls on a national or global scale. Evidence for this effect has come from studies of the world climate after major volcanic eruptions, and has lead to the realization that a nuclear conflict could cause a world wide fall in temperature of several degrees lasting several months or even years (the nuclear winter concept).

12.4.2 Chemical pollution

Chemicals discharged in waste water or even in storm water and normal run off are a major cause of concern in highly populated countries. There are three main types of chemical pollution, namely elemental, inorganic compounds and organic compounds. Elemental pollutants include the heavy metals, arsenic, lead, and sulphur. Heavy metals form soluble organic compounds such as methyl mercury which are absorbed by fish in polluted water. Humans eat either the fish, or birds which have preyed on the fish, and we therefore absorb the pollutants. These chemicals can have serious effects on humans, even in very small quantities, since they affect the central nervous system and the brain. Some industries produce large quantities of these wastes. For example, mercury is a waste product of the paper and pulp manufacturing industry. Sulphur and other residues from combustion are released into the atmosphere from chimneys, and react with water to produce sulphuric acid, one constituent of acid rain. Most companies will go to some lengths to ensure that they do not pollute the environment, by installing expensive treatment systems.

Inorganic compounds include fertilisers used in agriculture. If too much fertiliser is applied to the soil at any one time, then the excess will be washed out by storm water and will end up in rivers and lakes. These nitrates and phosphates cause weeds and plants in the waterways to thrive. Unfortunately this disturbs the natural ecosystem and the waterways become choked and blocked by excessive quantities of weed, and in addition sunlight levels are reduced resulting in excessive eutrophication of the water. Another major pollutant causing serious concern is the group of fluorocarbons. These chemicals are used in domestic sprays as a propellant, and also in refrigerators. Although almost totally inert, they act as a catalyst to break down ozone molecules (O_3) into oxygen (O_2). There is considerable concern that they are collecting in the earth's atmosphere and destroying the protective ozone layer.

Some pesticide sprays are also dangerous to humans if absorbed while they are still active. Most approved sprays are biodegradeable, ie,

they break down rapidly when deposited in the environment. The withdrawal of DDT as a spray against insects was done mainly because the chemical did not decompose, and although it is apparently harmless to humans, the knowledge that we all carry minute quantities of this insecticide in our bodies nowadays is worrying to some. There have been serious disasters when such chemicals as dioxin have been released from factories manufacturing pesticides and other chemicals.

Organic compounds include fats, oils, and synthetic organic compounds. Sometimes discharged in large quantities by accident, these are very hard to treat. Some float on water and are a hazard to marine and bird life. Detergents assist in breaking up the fat and oil, but these are yet another chemical to pollute the water.

12.4.3 Biological pollution

When bacteria and other micro-organisms are released into a waterway and exposed to sunlight and oxygen, they absorb oxygen from the water as they react or breed, further increasing the demand for available oxygen.

In addition the environment can be polluted by discharges of pathogens, bacteria, viruses, protozoa, parasites and other microbes which are dangerous to stock and humans. Common bacterial diseases include typhoid (Salmonella typhosa), cholera (Vibrio comma) and dysentery (Shingella dysenteriae). Amoebic dysentery is one of the most common protozoal infections, while amoebic meningitis is a lethal illness caused by a protozoa which can survive only in hot water as is found in thermal pools. Bilharziosis is a parasitic disease caused by worms which infest the internal organs of human beings. Infection is only possible by contact with contaminated water, and water can be contaminated only by the discharge of human body wastes into water containing snails, which then act as a host for the eggs of the parasite while in the water. Infectious hepatitis is an example of a viral infection which can affect many people in a community without warning. The effects of this and other viruses can be very serious.

12.4.4 Levels of oxygen in water

The level of dissolved oxygen has a major affect on the functioning of a waterway. For example, under normal conditions many species of fish require at least three milligrammes per litre (mg/l) of dissolved oxygen to survive. However bacterial activity and other processes involving the removal of dissolved oxygen will still occur down to one or two mg/l of dissolved oxygen. As water under normal conditions can contain no more than nine mg/l of dissolved oxygen, it is clear that even small concentrations of active waste can remove the oxygen, killing the aquatic life.

12.5 MEASUREMENT OF POLLUTION

A number of terms need to be used in order to specify the level of pollution. Measurements are essential if any control is to be achieved over waste discharges, and the following terms are at least realistic measures of the extent to which a waterway is polluted. Unfortunately the extent to which a discharge pollutes a waterway depends upon how much the waste is diluted as it enters, and the quality of the water beforehand. Effective measurement is therefore rarely easy.

12.5.1 Biochemical oxygen demand (BOD)

This is the amount of oxygen a sample of polluted water requires to oxidise the biodegradeable waste present in the sample completely, in milligrammes per litre (mg/l). It is measured by taking a sample and diluting it with clean fully aerated water containing trace nutrients, so that there will be sufficient oxygen in the sample to allow all the active waste to oxidise (in practice this means that the BOD of the diluted sample will need to lie between 1.5 and 7.5 mg/l). The dissolved oxygen concentration is then measured, and in the five day test, the sample is sealed up and stored for five days at 20°C. At the end of this period the dissolved oxygen level is again measured and the amount which has been used up found by subtraction. A control containing the aerated clean water is also incubated as a check. The test is accurate to around five percent if done properly. Its major disadvantage is the time required.

12.5.2 Chemical oxygen demand (COD)

This is the amount of oxygen required to oxidise the non-biodegradeable waste. The measurement involves oxidising the sample with a chemical oxidant such as potassium

dichromate. This is boiled in a solution of concentrated sulphuric acid using a silver catalyst for two hours. Potassium permanganate is also used at 27 °C for four hours. The test gives relatively fast results and is repeatable. However chemicals which resist biological breakdown do not necessarily create an oxygen demand in natural waterways, so the measurement does not indicate the behaviour of the pollutant in practice.

12.5.3 Solids

The concentration of total solids can be established by drying a sample in an oven at 105 °C. Alternatively the separate constituents of the total solids can be determined. The suspended and soluble solids can be found by filtration. Suspended solids are those which are retained on a filter paper, while dissolved solids are those which are truly dissolved and pass through. In practice the latter is often taken to include particles of less than one micron, and can be measured by using millipore filter paper of the required size, which is more accurate. The proportion of settleable solids can be measured by placing the sample in a graduated inverted cone (an Imhoff Cone), and allowing the solids to settle over a period of up to one hour. This gives an indication of the proportion of the waste which can be removed by sedimentation. The volatile (organic) solids component can be determined by heating in a furnace at 550 °C, which is sufficient to burn the organic compounds off as gases.

12.5.4 Nitrogen and phosphorus

Fertiliser and agricultural wastes frequently contain large quantities of nitrogen and phosphorus, present in both soluble and insoluble forms. Nitrogen analysis requires a number of separate tests. Dissolved nitrogen is measured through a reaction with phenoldisuphoric acid, from which the nitrate level is measured by comparing the colour of the solution with a standard colour card. Organic nitrogen and nitrogen in the form of ammonium (NH_4) is measured by a process in which it is converted to free ammonia by an alkali solution, and then converting back to NH_4 using an acid. The volume of acid required then determines the original concentration of nitrogen.

There are several ways of measuring phosphorus levels. Organic forms are converted to soluble fractions by acid digestion. One of the commonest methods involves the use of ammonium molybdate and stannous chloride to give a blue colour which is measured spectrophotomically.

12.5.5 Bacteria and pathogens

Laboratory tests for pathogenic bacteria are difficult to perform, and are generally not reproducible quantitatively. Furthermore because, say, the Salmonella virus is absent, there is no guarantee that Shigella, Vibrio, or other disease producing viruses will also be absent. The bacteriological quality of water is therefore checked by testing for non-pathogenic indicator organisms, mainly of the coliform group. The reason for this is as follows: Coliform bacteria, such as Escherichia coli, and fecal streptococci, reside in the intestinal tracts of man and animals and are excreted in large numbers (typically around 50 million coliforms per gramme). Pathogenic bacteria and viruses originate from the same source (the fecal discharge of diseased animals), and so water found to contain coliform bacteria from fecal discharges is identified as being potentially dangerous.

The test for coliforms involves a preliminary test followed by a confirmation test where the first test is positive. The screening test relies on the fact that the coliform group will cause the fermentation of lactose, producing a gas which can be collected in an inverted gas tube. This gives an estimate of the number of E coli present. The confirmation test requires the culturing of the bacteria on a selective agar medium. Colonies can then be identified and the numbers can be related to the populations in the original.

12.5.6 Dissolved oxygen and pH

These two quantities are frequently required in order to assess the quality of a waterway. Dissolved oxygen can be measured electrically or chemically. As discussed earlier, the maximum level of dissolved oxygen is around nine mg/l. The acidity of a solution is measured by determining the pH. This is a measure of the number of ions of Hydrogen that are free in the solution. A neutral solution has a pH of seven. A very

acidic solution has a low pH, while an alkaline solution has a high value (up to 15). Acceptable ranges for pH are relatively small (eg, 6.0 to 8.5 for drinking water).

12.6 METHODS OF TREATMENT

Agricultural and horticultural wastes can contain all types of waste materials. *Table 12.1* gives values of the levels of waste from livestock.

Fortunately the major component of the waste is usually organic and biodegradeable waste, which can be treated fairly efficiently on the farm. In some cases the solid and liquid waste components can be separated out. This can be done using a vibrating screen or a filter. In *Figure 12.4* the liquid passes through the stainless steel screen and drains into a tank to the side of the photograph, while the solids are caught on the screen and fall into the trailer underneath. The liquid is then

Table 12.1 Approximate daily waste production levels from livestock (per animal per day)

	volume litres	total BOD kg	total COD kg	total solids kg
Cow (400 kg) (Total waste)	40	0.8	2.6	6.0
Cow (400 kg) (Yard wash-down water*)	Up to 100 l	0.09	0.3	0.5
Pig (45 kg)	8.5 (25**)	0.14	0.4	0.4
Poultry (2.3 kg bird)	0.14	0.008	0.03	0.04

* Assuming the herd is in the dairy shed and yard area for two hours per day.
** Allowing for wash-down water.

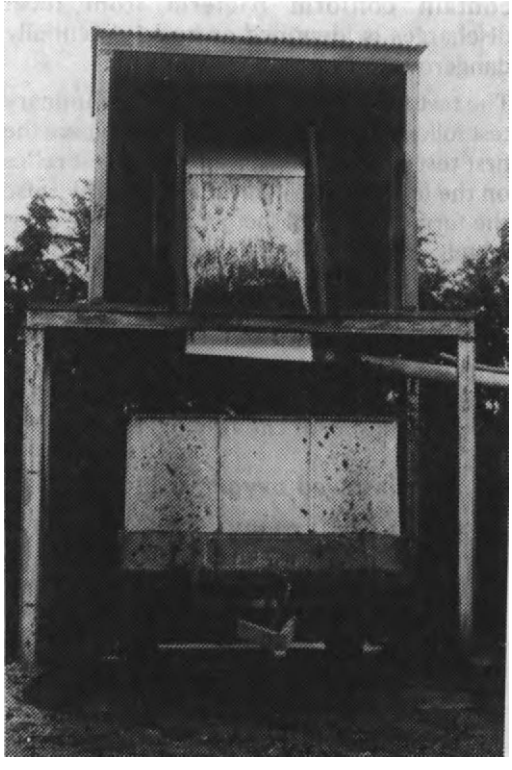


Figure 12.4 Screen to separate liquid and solid waste (used on a piggery).

sprayed onto the paddocks, while the solids are treated separately. Larger particles such as stones and gravel can be removed by a simple sump trap, providing this can be cleaned out at regular intervals. Settling tanks can also be used to remove the bulkier solids. After this primary treatment the farmer has a number of options for disposing of the waste, as outlined below.

12.6.1 Do nothing

Simply discharging waste into the environment can result in health risks and pollution. It is not only anti-social but in most countries it is illegal. Fines can amount to several thousand dollars per day.

12.6.2 Tanker disposal

This method is common in many countries, particularly for intensive livestock situations, or where there is a large solids content to the waste. A tanker (or "honeywagon") is filled with the waste, and it is taken out on the farm so that the waste can be spread over a paddock. The method is time consuming and cumbersome, and as the tanker is heavy, can be awkward on soft soils in wet conditions.

In practice the spread of waste is usually uneven, and this can result in damage to the pasture. Pathogens will be spread over the paddock, and although these are mostly killed off by ultraviolet radiation in sunlight, there could be an increased health risk with this method, if stock have access to the area too soon after treatment. There will often be an odour problem for a few days after spreading, which may cause problems with neighbours. Ploughing the paddock can improve matters. The waste does have some useful fertiliser value.

12.6.3 Soil injection

It is possible to obtain equipment which can be used to inject the waste into the soil. This eliminates many of the problems associated with land application, but is more costly in time and equipment.

12.6.4 Spray disposal

In this method the waste is pumped away from the source through pipes and sprayed onto farmland. The system is worth consideration where large volumes of dilute waste are involved, such as the waste from a milk shed, or the water used to clean out buildings and working areas. A typical arrangement is shown in *Figure 12.5*. In this method a good silt trap is essential to protect the pump. A screen is also needed to ensure that the nozzle of the sprayer does not get blocked. The pump is controlled by a float switch, which switches the pump on whenever the level of effluent reaches a predetermined height in the sump. The system requires continual attention. The silt trap must be cleaned regularly, and the sprinklers and spray lines must be kept clear of blockages. The fluid being pumped in this system is a particularly unpleasant type and clearing a blockage is a job which should need to be done as infrequently as possible. A pump failure can have serious consequences almost straight away, and it is important to ensure that the entire system is well designed and built from reliable equipment. Unblocking a spray nozzle can be a very risky task, especially if the float switch turns the pump on in the middle! Unless the system is well designed and extensive enough, the sprinklers will need to be moved frequently to spread the waste around the farm.

In addition to hydraulics, the design of a system must take into account the quantity and quality of waste which will be produced, and also the ability of the soil to receive it without there being any undesirable side effects to stock, crops, or humans. There is a limit to both the volume which should be applied at any one time and the rate at which it should be applied. There should be an interval of between three and five weeks between applications. Design figures have been produced and some approximate

Table 12.2 Maximum application rates for land

Soil type	Application rate		Application volume			
			Dry weather		Wet weather	
	Flat to 8% slope	Slope over 12%	well drained	poorly drained (600 mm deep soil*)	well drained	poorly drained (600 mm deep soil*)
	mm/hr	mm/hr	mm	mm	mm	mm
Coarse sand	32	20	300	127	280	100
Deep sands, light sandy loams	32	20	200	91	180	60
Sandy loams, 600 mm deep	20	13	90	60	60	50
Silt loams, sandy clays	16	10	90	60	60	30
Clay loams	13	8	51	33	25	0
Clays	6	4	25	15	0	0

* For shallower top soils the application volumes should be reduced in proportion. In wet weather application volumes in shallow soils should be even lower or zero.

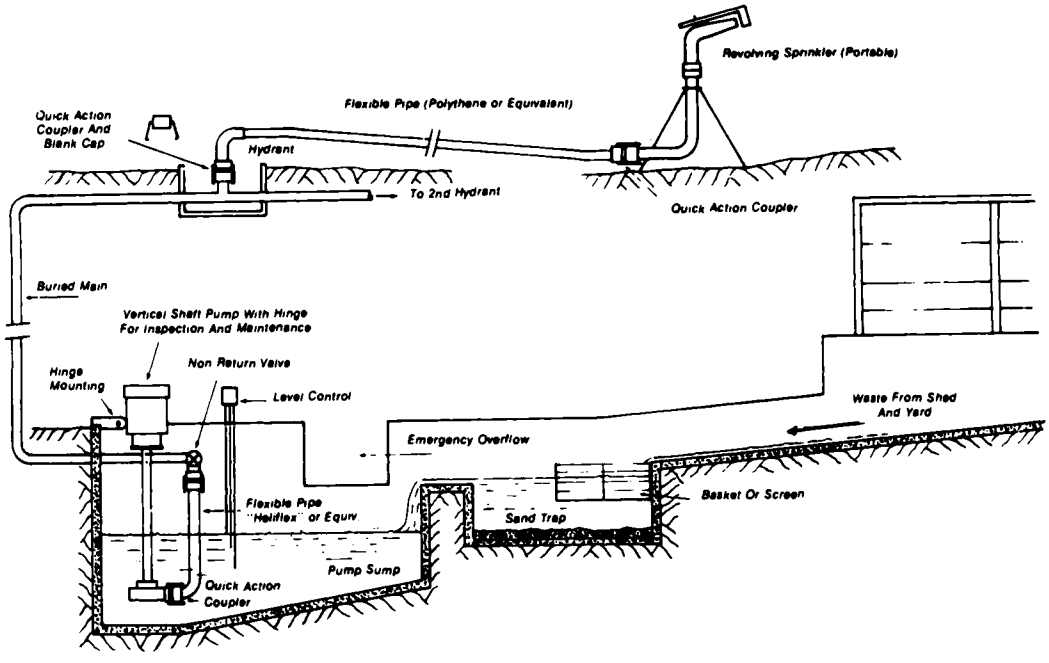


Figure 12.5(a) Layout of spray disposal system (Clarke).

maximum application rates and volumes are listed for various soils in *Table 12.2*. There is clearly a very large variation depending on the soil type, the slope of the ground, and the prevailing weather conditions.



Figure 12.5(b) Sprinkler.

If we take the example of a dairy shed, about 40 litres of diluted waste is produced on average per cow per milking, although this figure will vary considerably. As a general guide, in this case the frequency of application should not exceed once every 20 days, although this figure varies widely according to soil type, climate, and drainage characteristics. The resting period between applications should be long enough to allow the pasture to dry, and for the solids to break down. It must also allow for a decrease in disease levels of pathogens and allow the pasture to recover its palatability as far as stock are concerned. The final selection of the application rate, the area required for spraying, and the frequency of sprinkler shifting, must be made with care as it will involve capital expenditure, labour input to shift the sprinklers, and changes and adjustments to the stocking management. In addition there will be some maintenance and running costs for the pumps and nozzles which may be quite large.

The spray equipment required comprises a sump, a suitable sump pump with float or probe switches, a rigid mainline of a size to ensure velocities of not less than 0.75 m/sec (to give a continual cleaning action), and a

portable spray line and sprinkler equipped with a rubber nozzle not less than 12 mm in diameter. The sump should have a capacity equal to approximately one half the liquid to be disposed of per milking together with an easily cleaned sand and grit trap and a screen to exclude hay or coarse material. Adequate provision for overflows must be made. The pump chosen must be selected with care to ensure that it has both the necessary head and capacity to operate the sprinkler over the desired radius after allowance for head loss in the pipes. It should also be designed to handle the suspended solids in the effluent. If a centrifugal pump is used, the impeller will probably need to be a semi-open or fully open type, to avoid blocking. In setting out the position of sprinklers care should be taken to ensure that there is no significant overlap between different sprinklers or new positions, so that no area receives excessive spray from two sprayer positions. This means that there will be a wasted area between the spray circles. The excess area which is not used is specified by the unsprayed area factor F which is the ratio of the total area to the sprayed area. Simple geometry shows that for a regular rectangular distribution of fixed nozzle positions this is given by:

$$F = \frac{4\ S\ T}{\pi\ d^2} \qquad \text{Equation 12.1}$$

where S is the spacing between sprinkler rows, T is the spacing between positions along the row, and d is the spray diameter. If the spray is uniform over the sprayed area, then the total area required will be given by:

$$A = \frac{V\ t\ F}{k} \qquad \text{Equation 12.2}$$

where V is the daily volume of effluent (m^3 per day), t is the resting period in days, and k is the depth of effluent allowed per application in metres. The area must be split amongst separate paddocks to allow for resting and grazing. The spray diameter can be chosen to allow for some overlap where the sprinkler distribution pattern falls off at the edge of the sprayed area providing the maximum allowed levels are not exceeded.

Rates of application may vary with soil, climatic conditions, time of year (*Table 12.2*). Excessive application will damage and pollute the pasture, which will then be avoided by animals, or may cause disease problems. If stock are put into the paddock then the wet conditions will cause them to pug the soil, destroying its structure. Subsequently grass growth will be severely retarded. Some of the excess may run off and pollute nearby waterways, or percolate through to pollute the ground water.

The advantages of the system are that it may have the potential to overcome or reduce the problem of water pollution and in addition it returns the valuable manure fraction in the waste to the land. It should be emphasised, however, that in many countries insufficient research has been carried out to date to determine the long term effect on the soil structure.

12.6.5 Lagoons

Lagoons are probably the simplest method of biological waste treatment. The major advantages of lagoons are that they require relatively little maintenance, and there are few things which can go wrong with them. The main disadvantages are that useful farmland must be taken out of production permanently, there can be a slight odour problem, and the initial costs can be high. The aim of the system is to provide a basic treatment for the effluent so that it may be discharged with reasonable safety into a fast moving water course. There are three main principles which should be kept in mind. First, as far as possible the farmer should try to minimise all volumes; this not only decreases the size of plant required, but also increases the rate of breakdown in the treatment plant due to the increased concentration. Second, it is usually an advantage to keep different types of waste separate. Thus solids and liquids may be better handled separately, while unpolluted storm water should not enter the lagoons, but should be piped directly into the storm water drains. Third, the system should be designed for each farm.

An anaerobic/aerobic treatment combination appears to be the best. The basic requirements of such a system are two main lagoons, one which is deep, called the *Anaerobic Lagoon*, and the other with a large surface area known as the *Aerobic Lagoon* (*Figure 12.6*).

From the source the effluent flows first to the anaerobic lagoon. Here "bugs" which work in

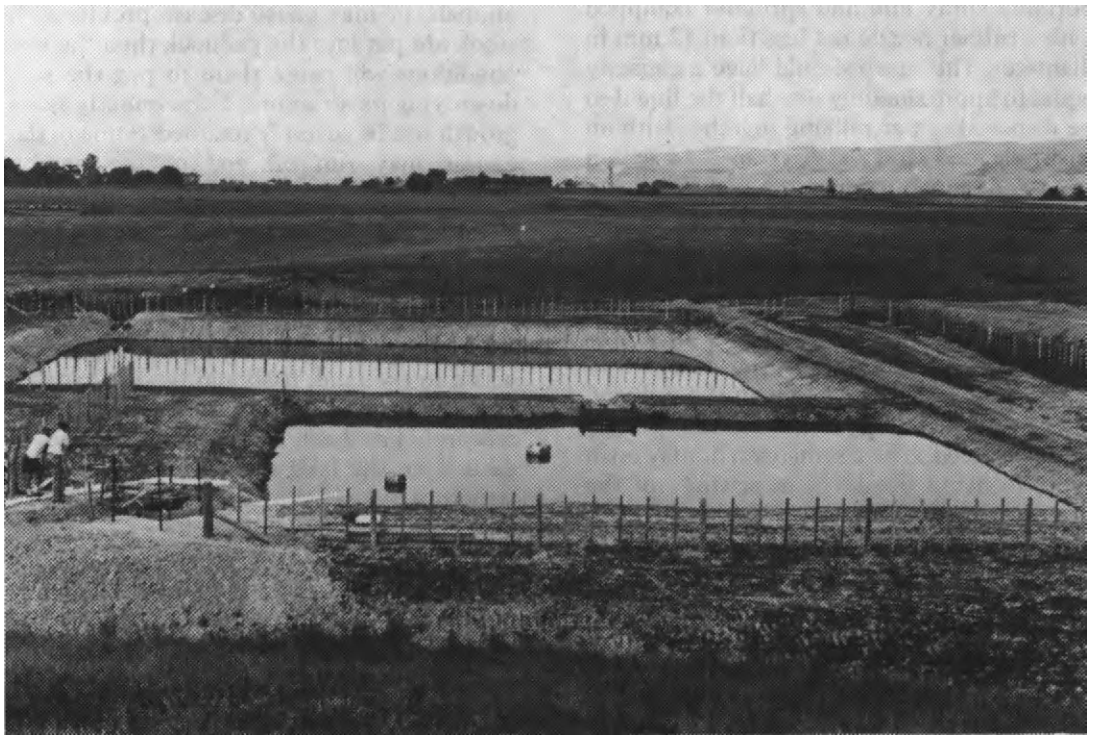


Figure 12.6 Lagoons. The Anaerobic lagoon is in front.

the abscence of oxygen attack the effluent. The organic matter is first broken down by acid forming bacteria (liquefaction). Next the products are absorbed by the acid bacteria in an acid fermentation process, producing volatile fatty acids such as acetic, proprionic and butryic acid. Finally other bacteria consume these acids producing methane gas (methanogenesis). As a result of these reactions a scum can form on the top of the lagoon, methane gas can be given off, and a sludge is deposited on the floor of the lagoon. The reactions are relatively slow, the rate depending upon the temperature, with optimum values around 37°C. The lagoon should have a holding capacity of about 20 to 30 days effluent to allow for complete treatment. The pond should be as deep as possible, so that heat losses (which will depend upon the surface area) are minimised.

For dairy farms using an all grass grazing system (where the effluent comes only from hosing the yard and cleaning the milk shed after each milking) approximate design figures are a depth of 3 to 5 metres, and a volume of 3.7 m^3 per cow (cf for example with 6.3 m^3 per pig). The exact value depends on the local climate: in New Zealand the range varies from 3.2 m^3/cow for the warmer north, to 4.5 m^3/cow for the south.

The lagoon should be roughly square in shape. The freeboard (i.e., the height of the bank above the normal maximum water level) should be at least 0.4 metres, to prevent any possible overflow in windy conditions. These are only rough guide lines, and more detailed design guides should be consulted. The slope of the sides (the batter) should be about 2:1, and the banks should be sufficiently wide to allow for access by vehicles for cleaning out the sludge (*Figure 12.6*). This will be required at intervals of three to four years, depending on the nature and volume of the solids component. It is estimated that the solids will accumulate at the rate of about 0.67 m^3 per year per cow, but in any event the lagoon should be cleaned before the solids occupy half the total volume. The inlet to the lagoon should be through a downward sloping pipe to the centre, as this helps to ensure that the new waste just entering stays as long as possible in the anaerobic lagoon. For intensive systems the BOD and COD loadings need to be considered as well as the solids.

From the anaerobic lagoon the liquid effluent

discharges to an aerobic lagoon. The outlet is just a pipe connecting the two lagoons together. It should be placed a little below the surface of the lagoons, to eliminate the possibility of the solid crust on the anaerobic lagoon blocking it up. It should also have a screen to prevent any sludge passing through into the aerobic lagoon. The aerobic lagoon is shallow, so that light can penetrate through the volume of the water to encourage biological activity, and so that as much oxygen as possible can be absorbed from the air. In the aerobic lagoon algae use the waste nutrients and solar energy to produce oxygen by photosynthesis. Some bacterial activity also takes place, particularly at the bottom of the lagoon. These reactions reduce the biological oxygen demand (BOD) of the fluid, so that it can be discharged into local drainage channels without harming them. The end-products are carbon dioxide and water, which usually contains some dissolved oxygen. The reaction is faster than the earlier processes and the conditions are less critical.

Design figures for the aerobic lagoon, assuming 60% removal of harmful products in the anaerobic stage, are a depth of 0.9 to 1.2 m (plus 0.4 m freeboard), and a surface area of 3.2-4.2 m^2/cow. In winter conditions the lagoon can become slightly anaerobic for short periods of time, but the effect is self-correcting. Aerobic lagoons are best suited to treating dilute effluent, such as that output from an anaerobic lagoon. They can be used alone, but they are less effective, and the surface area required for adequate treatment is much larger.

Legal and environmental requirements must also be considered. For example, lagoons must be sited at least 45 m from a shed, and at least 300 m from a neighbour! They must not pollute local water courses. The proximity of water courses and the height of the water table must therefore be considered. Prevailing winds and possible effects on neighbours must also be considered very carefully, as the anaerobic lagoon often gives off an unpleasant odour. It is essential that the lagoons are fenced in properly, so that stock and humans cannot fall in by accident. This is particularly important if young children are likely to be in the area, as the anaerobic lagoon is deep, and the sides are very slippery. It is doubtful if even a strong adult could get out easily without assistance. A permit to discharge the outlet from the lagoons will be required from the local water authority.

The disadvantages of lagoons are that an area of land must be taken out of production, the solids in the anaerobic lagoon must be removed periodically, typically every three to four years, and the lagoons are a danger to stock and people, and must be securely fenced. A further problem arises if insoluble phosphates are discharged into them, since the lagoons convert them into soluble forms which can then cause increased eutrification of the waterway. The low maintenance requirements are the major advantage of the system.

12.6.6 Long ditches

Some dairy farmers discharge the effluent into a ditch rather than a lagoon. Providing these are properly designed and of adequate size, the biological processes are the same as in the lagoon treatment. Baffles are required at intervals to enable the ditches to retain solid deposits. The first sections then act as settlement areas, while in the latter sections aerobic and anaerobic processes take place. Stormwater can reduce the effectiveness of the treatment, especially if the drain discharges into a natural waterway, and the ditches will generally need to be separated from the normal farm drainage system.

12.6.7 Septic tanks

One of the most common forms of human effluent treatment in widespread use, where no community scheme is available, is the septic tank. The tank works on similar principles to the anaerobic lagoon, followed by a soil filtration process in the soakage field, which deals with the supernatant (that which floats on the surface). Such systems operate on a small scale, and are dealt with by the local health authority.

12.6.8 Legal obligations

Before installing any treatment system the design should be checked with the local authorities. This may include the local catchment board who administer any water and soil conservation regulations, the local farm dairy inspector responsible for administering the milk production and supply regulations, and any local bodies who control regional planning.

12.7 PROBLEMS IN DENSELY POPULATED COUNTRIES AND COLDER CLIMATES

While the problem of pollution may not seem too important to countries where there is a low population density, and where agricultural land is plentiful, in other parts of the world land is scarce. In these countries the available waste land is already badly polluted, and the problem is getting worse. Serious health problems have arisen in parts of the world where indescriminate dumping has been allowed on sites which have not been prepared properly or were close to inhabited areas. To site one example, in the United States a canal (the Love Canal) was partially constructed in the early part of this century, but was never completed. Subsequently the excavation was used to dump chemical waste. The chemicals seeped into the local water courses, causing widespread pollution that has been extremely difficult to contain and deal with.

We have already mentioned the problem of rock wool disposal from horticultural enterprises. In many countries, animals are housed for a large part of the year. This creates a much larger waste problem, since not only must the entire daily waste from the herd be dealt with, but in addition any straw or bedding material must also be removed periodically and dumped. In these cases, sophisticated treatments are required and the methods outlined above require substantial modification. In many countries the waste is normally spread over the land, which sounds a satisfactory ecological solution until the volumes involved reach the proportions experienced in many European countries. Even worse, what do you do if the land is frozen when you have a large mass to dispose of? Some governments have introduced legislation which restricts the quantity of various elements which can be spread in any given period. This type of legislation can cause considerable problems not only to the farmer, but also to whoever has to police the scheme.

In relatively clean, young and developing countries, one is tempted to ask to what extent they may, in the future, be encouraged to become the recipient of other people's waste. In a very round about way, this is what intensive production is all about; one receives inputs in the form of cash and raw materials; one then processes the materials to generate the required product which is then exported, leaving the waste from the process and hopefully a decent profit. Who knows, this may be a good marketing strategy for the 1990's. If so it would be a tragedy for these countries, unless they can learn the lessons from developed countries. Surely, ultimately, production systems need to be developed which restrict pollution to levels which the natural ecosystem can cope with. Pollution seems to be one more result of mankind's selfishness and lack of concern for others. Perhaps if each one of us is just a little bit more thoughtful about what our actions are doing to the environment, there may be cause to hope that we may yet be able to create a world that is fresh, clean, healthy, and free for everyone.

12.8 EXERCISES

1. Choose a suitable building or room such as a greenhouse or office. Establish how the environment is controlled and find the location of the sensors and their type. If possible use other sensors to compare the accuracy of the installed devices.
2. Discuss the selection of a temperature sensor for a greenhouse or a piggery. Consider where it should be located and what problems could arise due to the nature of the work and the environment, which could impair the accuracy of the sensor.
3. Design a lagoon system for a dairy farm with 250 cows, using the upper limits of the values in the text.
4. Select a product. Starting with the farm inputs, consider all the consequences to the environment of that product, on the farm. Then consider the environmental effects of the processes which go into producing the materials used on the farm (remember the fuel input and the fertiliser requirements), and the effects of the processes which take place after the product has left the farm. Consider how some of these effects could be minimised or eliminated.

12.9 AIMS OF THIS CHAPTER

Having read this chapter you should be able to:

1. Describe the atmospheric environment.
2. Explain methods of measuring environmental variables, including temperature, relative humidity, wind and radiation.
3. Be more aware of the nature and causes of pollution.
4. Describe methods of treating biological farm wastes, and make calculations to estimate the sizes and design of some disposal systems.
5. Be a little more willing to care for your environment.

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Appendix

Converting Units

1.1 UNITS, MULTIPLES, AND CONVERSION BETWEEN SYSTEMS OF UNITS

Any physical variable has units. You weigh 70 kg, have two eyes, and drive your car around town at 50 km per hour. Missing out the units on any of these terms can cause considerable confusion ("I was only doing 50, M'Lud").

It is essential to state the units of any anything you calculate, and to be able to convert between units. For example, many farmers know how much fertilizer to put on in cwt/acre, (or bags per acre) but when it is sold in kg, some may be unsure exactly how much to buy.

Most countries are committed nowadays to the metric system, so that units such as inches (in), feet, yards, acres, pounds (lb), hundredweight (cwt) and tons may eventually disappear. However, many agriculturalists still use the old Imperial units. This appendix (see *Tables 1* and *2*) lists the conversion factors, and also gives you a method of converting without making mistakes.

Table 1 Internationally agreed multiples and sub-multiples

Factor by which the unit is multiplied		Prefix	Symbol ***	Typical examples
One thousand million million	10^{15}	Peta	P	Petajoule (PJ)
One million million (billion**)	10^{12}	Tera	T	Terajoule (TJ)
One thousand million	10^{9}	Giga	G	Gigahertz(GHz)
One million	10^{6}	Mega	M	Megawatt (MW)
One thousand	10^{3}	kilo	k	kilometre (km)
(One hundred*)	(10^{2})	(hecto)	(h)	hectometre (hm)
(Ten*)	(10^{1})	(deca)	(da)	decagramme (dag)
Unity	10^{0}	–	–	metre (m)
(One tenth*)	(10^{-1})	(deci)	(d)	decimetre (dm)
(One hundredth*)	(10^{-2})	(centi)	(c)	centimetre (cm)
One thousandth	10^{-3}	milli	m	milligramme (mg)
One millionth	10^{-6}	micro	μ	microsecond (μs)
One thousand millionth	10^{-9}	nano	n	nanosecond (ns)
One million millionth (one billionth**)	10^{-12}	pico	p	picofarad (pF)
One thousand million millionth	10^{-15}	femto	f	femtojoule (fJ)
One million million millionth	10^{-18}	atto	a	attojoule (aJ)

* Not recommended multiples.

** European billion. USA billion is 10^{9}. For this reason the word billion is not recommended.

*** Note that it matters whether or not the symbol is a capital letter or a lower case letter. Thus P = Peta = 10^{15}, while p = pico = 10^{-12}.

Table 2 Conversion of units to SI

Length	
1 inch	= 0.0254 m
	= 25.4 mm
1 foot	= 0.3048 m
1 yard	= 0.9144 m
1 mile	= 1.60934 km
Area	
1 square inch	$= 6.45 \times 10^{-4}$ m^2
1 square foot	$= 9.29 \times 10^{-2}$ m^2
1 square yard	= 0.836 m^2
1 square mile	$= 2.59 \times 10^6$ m^2
	= 2.59 km^2
1 acre	$= 4.047 \times 10^3$ m^2
	= 0.4047 ha
1 hectare	$= 10^4$ m^2
	= 2.47 acres
Volume	
1 cubic inch	$= 1.6387 \times 10^{-5}$ m^3
	= 0.00164 litres
1 cubic foot	= 0.0283 m^3 = 28.3 litres
1 gallon (UK)	$= 4.54609 \times 10^{-3}$ m^3
	= 4.546 litres
	= Volume of 10 lb of water
1 gallon (USA)	$= 3.78544 \times 10^{-3}$ m^3
	= 3.785 litres
	= 0.83268 gallon (UK)
1 cubic yard	= 0.7646 m^3
1 bushel	= 36.37 litres
	= 8 gallons (UK)
Velocity	
1 mph	= 0.4470 m s^{-1}
1 foot per second	= 0.3048 m s^{-1}
1 knot	= 0.5144 m s^{-1}
Mass	
1 lb	= 0.4536 kg
1 ton (Imperial)	= 1016 kg
1 slug	= 14.59 kg
1 tonne (metric)	= 1000 kg
Density	
1 lb/cu ft	= 16.02 kg m^{-3}
1 lb/cu inch	$= 2.768 \times 10^4$ kg m^{-3}
1 lb/gallon	= 0.0998 kg/litre
Force	
1 pound force	= 4.448 N
1 dyne	$= 10^{-5}$ N
1 poundal	= 0.138 N
Pressure	
1 psi	$= 6.895 \times 10^3$ N m^{-2}
	= 6.895 kPa
1 Atmosphere	$= 1.01325 \times 10^5$ N m^{-2}
1 bar	$= 10^5$ N m^{-2}
1 Atmosphere	= 760 mm Hg
	= 29.92 ins Hg
1 N m^{-2}	= 1 Pascal (Pa)
1 metre head of water	$= 9.81 \times 10^3$ N m^{-2}
Work and Energy	
1 Kilowatt hour (kW h)	$= 3.6 \times 10^6$J = 3.6 MJ
1 BTU (British Thermal Unit)	= 1055 J
	= Energy to raise 1 lb of water 1°F
1 erg	$= 10^{-7}$ J
1 electron volt	$= 1.602 \times 10^{-19}$ J
1 CHU (Centigrade Heat Unit)	= 4186 J
	= Energy to raise 1 kg of water 1°C
1 ft lb	= 1.356 J
1 Calorie	= 4.186 J
Power	
1 Horse-power (HP)	= 746 W
1 ft lb/sec	= 1.356 W
1 J s^{-1}	= 1 W
Temperature	
1°F (Fahrenheit)	= 0.555556°C
	= 5/9°C
Temperature (°C)	= 5/9 (Temperature (°F) − 32)
1°K (Kelvin)	= 1°C
Temperature (°K)	= Temperature (°C) + 273.16

Other Combined Units

1 cwt/acre = 125.53 kg/ha

1.2 A METHOD FOR CONVERTING UNITS

Sometimes it can be hard to remember whether to multiply or divide by a conversion factor. The method below is a foolproof method of ensuring that the conversion is done correctly.

The trick is to multiply by one!

It works like this: Suppose we wish to convert 15 inches (in) to cm. We know that there are 2.54 cm in one inch. To convert a length of 15 inches to cm we first write:

$$\frac{2.54 \text{ cm}}{1 \text{ in}} = 1 \text{ and } \frac{1 \text{ in}}{2.54 \text{ cm}} = 1$$

Now, we multiply by 1, choosing either the first or second fraction so that the dimension (ie the inches) term we want to remove cancels. Thus:

$$15 \text{ in} = 15 \text{ in} \times \frac{2.54 \text{ cm}}{1 \text{ in}} = 28.1 \text{ cm}$$

This looks like a difficult way of doing something easy. For a very simple conversion like this it is! However, the method works for more difficult conversions too. For example, when there is more than one unit to be converted a series of factors may be used so that all the old units are eliminated. For example: convert 60 mph (miles per hour) to metres per sec.

From conversion tables

$$1 = \frac{1.609 \text{ km}}{1 \text{ mile}} = \frac{1 \text{ mile}}{1.609 \text{ km}} = \frac{1 \text{ hour}}{3{,}600 \text{ s}}$$

$$= \frac{3{,}600 \text{ s}}{1 \text{ hour}} = \frac{1{,}000 \text{ m}}{1 \text{ km}} = \frac{1 \text{ km}}{1{,}000 \text{ m}}$$

Choosing the appropriate unity terms

$$60 \text{ miles/hour} = \frac{60 \text{ miles}}{1 \text{ hour}} \times \frac{1.609 \text{ km}}{1 \text{ mile}} \times \frac{1{,}000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ hour}}{3{,}600 \text{ secs}}$$

$$= \frac{60 \times 1.609 \times 1{,}000}{3{,}600} \frac{\text{m}}{\text{s}}$$

$$= 26.8 \text{ m s}^{-1}$$

1.3 AREA FORMULA

Triangle, sides a, b, c (see figure):

Area = 0.5 × Base × Height

or $A = 0.5 \times b \times h$

Alternatively,

$$A = (s(s-a)(s-b)(s-c))^{1/2}$$

where $s = \frac{1}{2}(a+b+c)$

Circle, radius r, diameter d:

$$A = \pi r^2 = \frac{\pi d^2}{4}$$

Trapezium, sides y_1, y_2, width d:

$$A = 0.5 \text{ d } (y_1 + y_2)$$

Irregular Area (eg, PQRS in Figure A1.1):

(a) *Trapezium formula:*

$$A = d\left(\frac{y_1 + y_n}{2} + y_2 + y_3 + y_4 + \ldots + y_{n-1}\right)$$

This is called the trapezium formula. The area must be divided up into a series of sections of equal width, and the distances shown in the figure must be measured. Note that y_1 and y_n are the first and last measurements at the very ends of the base line. They may be zero, but should still be labelled and counted.

(b) *Simpson's formula*

This gives a more accurate answer. The area is the sum of the end ordinates (y_1 and y_n), plus four times the sum of the even ordinates (y_2, y_4, y_6, etc) plus two times the odd ordinates (y_3, y_5, y_{n-2}), all multiplied by d and divided by three. There must be an odd number of ordinates for this formula to be used.

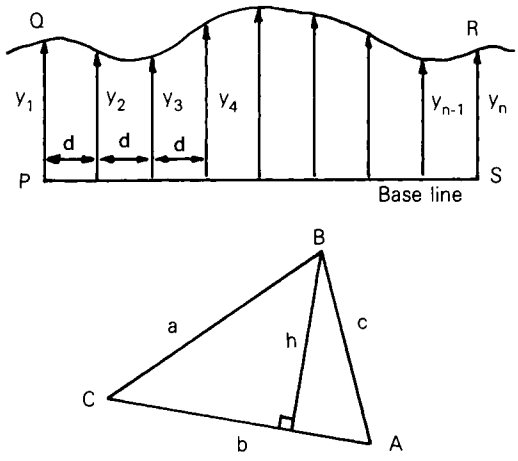


Figure A1.1 Area calculation for triangles and irregular areas.

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