Engineers' Data Book

Institution of
MECHANICAL
ENGINEERS

Engineers' Data Book

Fourth Edition

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Foreword

This book is an essential tool to help you as you embark on your career in mechanical engineering, providing a wide range of useful information you will need during your studies, and later as a professional engineer.

The Institution of Mechanical Engineers (IMechE) is your dedicated partner throughout your career and we are committed to supporting you through your studies to graduation and beyond. Home to 98,000 engineering professionals working in the heart of the country's most important and dynamic industries, we will ensure that you have the skills, knowledge, support and development advice you need at every stage of your career.

Because we set the standard for professional excellence in mechanical engineering our members are recognised for their professional competence and enjoy enhanced career opportunities as a result. To achieve this recognition of your skills and to manage your career development, it is important that you maintain your membership of IMechE and take advantage of the opportunities available to help you fulfil your potential.

As an Affiliate member, during your studies you will benefit from career advice and support as well as regular information about engineering and how to get involved in your local IMechE community. By becoming a member, you also have access to Career Developer, our suite of online reporting tools, enabling you to record your professional experience as soon as you start your industrial placement.

Upon graduation you can apply to become an Associate Member of IMechE and begin the journey towards professional registration. With appropriate work experience and support from IMechE to develop your skills and knowledge, you can apply for registration as an Incorporated or Chartered Engineer. Your membership of IMechE will bring ongoing support for your continued professional development, through a range of member resources, events and activities. Engineers need to continue their professional development to keep their skills fresh and progressive, so we will help you stay up to date, broaden your knowledge and deepen your understanding of your chosen industry.

We hope that your relationship with IMechE will be a lifelong one that supports you throughout your career. As you join this exciting and essential profession, we wish you luck and look forward to helping you stay ahead in an increasingly varied, dynamic and rewarding industry.

Preface

This significantly updated 2012 edition of the *Engineers'Data Book* replaces the three successful previous editions published in 1998, 2000 and 2004. Since the data book's inception, feedback from engineers and students has indicated that, despite the proliferation of technical information in published and electronic format, there is still a need for a source of core mechanical engineering information in a readily available form. The 2012 data book has increased in content by approximately 60 percent compared to the first edition. As well as an increase in the coverage of basic units, data, and engineering rules, the content has gradually been extended to cover vital aspects of structural integrity and reliability of engineering components: these are important current issues in the engineering business.

Finally, it is important that the content of this data book continues to reflect the information that is needed and used by student and experienced engineers. If you have any suggestions for future content (or indeed observations or comment on the existing content) please let me know on: enquiries@matthews-training.co.uk

Clifford Matthews

Introduction

The Role of Technical Standards

What role do published technical standards play in mechanical engineering? Standards have been part of the engineering scene since the early days of the industrial revolution when they were introduced to try to solve the problem of sub-standard products. In these early days they were influential in increasing the availability (and reducing the price) of basic iron and steel products.

What has happened since then? Standards bodies have proliferated, working more or less independently, but all subject to the same engineering laws and practical constraints. They have developed slightly different ways of looking at technical problems, which is not such a bad thing – the engineering world would be less of an interesting place if everyone saw things in precisely the same way. Varied though they may be, published standards represent good practice. Their ideas are tried and tested, rather than being loose – and they operate across the spectrum of engineering practice, from design and manufacture to testing and operation.

The current trend in Europe is towards harmonization of national standards into the Euronorm (EN) family. Whether you see this as rationalization or simply amalgamation is not important – the harmonized standards will have significance for the mutual acceptability of engineering goods between companies and countries. Some recent 'standards', such as the Machinery Directive and Pressure Vessel Directive have real statutory significance, and are starting to change the way that mechanical engineers do things. They may be written by committees, but they are not without teeth.

Since the first edition of the Data Book, the number of EN harmonized engineering standards has increased significantly. However, their influence is still to be felt in many areas.

Engineering companies that have been used to working to existing British and US standards can be reluctant to change, with the result that many companies still prefer to work to superseded standards. In some disciplines (pressure equipmentis a good example) the amount of equipment being manufactured to the new EN standards is quite small. Things are changing, but slowly.

Technical standards continue to be an important model for technical conformity in all fields. They affect just about every mechanical engineering product from pipelines to paperclips. From the practical viewpoint it is worth considering that, without standards, the design and manufacture of even the most basic engineering design would have to be started from scratch.

Section 1

Engineering Careers

1.1 Introduction: what is an engineer?

You can hear, and read, long opinionated, but largely inconclusive, arguments as to what the title 'engineer' actually means. For every view that the title should be limited to those with a certain level of qualifications, or have attained a prescribed level of Institution membership, there is a contrary view that says it should relate equally to those who can prove a level of practical or craft skill, or demonstrate so many years of vocational experience.

Unlike some countries, where the designation is better defined, the situation in the UK remains liberal and self-regulated. In many industries the titles 'engineer' and 'technician' are used freely and interchangeably, without causing too much chaos. Older, more traditional industries often have more a definitive intenal understanding of what the titles mean to them. This owes as much, or more, to their own hierarchical structure and heritage, however, as to any technical interpretation they really ascribe to the terms. This older view of the world, whether you are called 'technician' or 'engineer', paints to them a picture of whether or not you sit in an office or get your hands dirty, what you wear, and how much you get paid.

Looking back in time to the start of it all, it becomes clear that job titles and delineations are much more artificial than they appear. The earliest engineers conceived the ideas, designed their innovative steam engines, bridges and ships, raised the funds, and did many of the jobs themselves. This was born of necessity, because there were no ready-trained technicians waiting to take on the engineers' concepts and turn them into reality. Once under way, however, industry matured quite quickly and separate job roles soon started to crystallize out,

Engineers' Data Book, Fourth Edition. Clifford Matthews.

driven by people's preference to concentrate on things that they naturally did best.

Over the last 100 years or so, with increased maturity of the industrial society, the division of labour has continued, each engineering specialism soon fragmenting into several subspecialisms of its own, and so on. This is why the argument as to what exactly delineates an *engineer* from a *technician* has no real answer, and probably never will have. It is simply too difficult to draw a line in the sand, within such a large and varied continuum of skills, on which everyone will agree.

Assuming that you have no wish to spend the next forty or so years worrying about a question to which you know there is no answer, here is another way to look at it. Think of engineers and technicians as all being part of the wide spectrum of engineering. A spectrum has no gaps between its colours, each one leads seamlessly on to the next. Now think what it would look like viewed in black and white rather than colour – they are now all the same colour (grey) differentiated from each other only by the depth of their shade of grey.

What if the shades of grey represented *technical difficulty*? The light grey shades would represent job roles that are easier to learn, with the dark ones being progressively more difficult. Difficulty might also be associated not only with the technical depth of the subject or role but also with the *time* it would take to learn to do it well. At no point in this continuum from white (easy) to black (difficult) could we draw a definitive line dividing 'light' from 'dark', all we can say is that the spectrum consists of varying degrees of lightness and darkness and that every shade forms part of the complete picture. So this is our conclusion:

- Generic job titles such as 'engineer' and 'technician' cannot, realistically, be accurately defined – they are simply parts of the continuous spectrum of job roles in the engineering industry. However . . .
- One way to view the difference in roles is to consider how *difficult* each one is, and how long it would take to master it (properly!).

1.2 A rough guide to industry breakdown

There are many hundreds of different industry types, roles, job descriptions and specialisms in the world of mechanical engineering, all of which are spread over a multitude of different industry sectors. There are various systems that attempt to categorize these into standard industry classifications (SICs) using code numbers or letters, but they are complicated and do not always fit well with each other.

Simplistically, you can think of the engineering industry, and the job roles within it, as a matrix. To keep this matrix to any sort of manageable size means that it needs to be generalized – providing an overall picture rather than a detailed or comprehensive analysis.

Figure 1.1 shows the matrix. The more basic industries lie near the bottom, rising to the increasingly complex and technologically advanced ones towards the top. Although pure science elements exist at all these levels they become more prevalent (and are used in greater detail) in those industries near the top of the matrix. There is no implication of value or worth to industry in the position of any entry in the vertical scale, it is just a crude grading based on the overall complexity and resultant difficulty of the subject. The horizontal axis of the matrix is different. This shows the basic allocation of job roles which is equally applicable to all the industry sectors in the vertical scale. There may be a few differences, but the basic breakdown is much the same for all. The horizontal axis is based on a chronological (time) scale, running left to right. Unlike the vertical axis, the differences in complexity and difficulty are less well spread across the horizontal axis. Product conception and design fit naturally together as a discrete skill-set, but the others are fairly well separated out, representing discrete and identifiable job roles.

The left-hand end – conception and design – suits those people with high levels of innovation and conceptual skills. They can spot an idea, visualizing its final function and form, but lack a full set of skills suited to turning it into hard engineering reality. At the right-hand end, plant operators and technicians have the business and practical skills to operate a

DISCIPLINE AREA	ROLES			
	Conceptual design	Manufacture	Installation/ commissioning	Operation
Pharmaceutical production	x	x	x	x
Medical / Optics engineering	x	x	x	x
Aerospace	x	x	x	x
Weapons engineering	x	x	x	x
Process engineering design	x	x	x	x
Metallurgy	x	x	x	x
Production engineering	x	x	x	x
Power generation	x	x	x	x
Automotive/marine engineering	x	x	x	x
Consumer products	x	x	x	x
Paint/coatings	x	x	x	x
Forging/casting	x	x	x	x
Structural engineering	x	x	x	x
Fabrication manufacture	x	x	x	x
Domestic services, heating etc	x	x	x	x

Figure 1.1

plant or a range of products on a commercial basis, but lack the skills to conceive, design and build a plant or product range from scratch. They need others to provide those skills.

You can use this rough matrix to plot your current position in the industrial landscape, or to plan where you might like to be in the future. It is neither complete nor exhaustive (there would need to be 40+ vertical categories to accomplish that), but as a broad career route map it is not a bad place to start.

1.3 Training and professional development

Whatever you do, don't confuse these two. It is best to think of *training* as your initial academic qualification: craft training or whatever – an activity whose prime purpose is to get you into your first engineering job. It also provides essential (and useful) technical background to get you onto the doorstep of your subject, but does not yet provide you with any of the full skill sets you need to move forward. This training is a benchmark, slotted into the system to differentiate between those who have it and those who do not.

Professional development is the next step. This is any training activity that has a specific job-related objective or purpose. It is often mistakenly seen as comprising mid-career courses in generalized disciplines such as marketing, finance, QA, project management skills and similar. Such-temptingly-named courses are really not what it is about. Whilst they may look and sound good, they lack cutting edge in differentiating those people with real ability in the core skills of the industry from those who do not. They are too general, too short, and woefully lacking in core skills, technical content and bite.

Productive professional development must be centred on the core skills of your particular industry. To possess the quality of being able to differentiate between its participants, productive professional development has to be structured to have a pass or fail criteria, with a pass mark high enough (and overall pass rate low enough) to buy it credibility and give it some teeth.

The best time to start productive professional development is as *soon as possible* after your initial training is complete. For best effect try to run it in parallel with a role that gains you practical hands-on experience of the discipline in which you are employed. This will force the productive and professional elements to complement each other, multiplying the effect of them both. Coupled with sound initial training and a bit of hands-on experience, the way in which you choose to pursue professional development activities in the early career years seems to be one of the clear factors in determining those who progress quickly up the technical jobs hierarchy and those who do not.

1.4 Degrees of (engineering) excellence

You have probably decided that getting a degree is a good idea – or why would you be reading this book? The reason why any high-level qualification is required is always a good talking point. Opinions differ about why it is necessary, and what is the point of it all.

The time-honoured explanation you will be given is that it is all about training your mind. Engagement in the apparently endless carousel of mathematical examples, laboratory reports, descriptions and discussions will train your grey cells to address similar, even unrelated, problems in your future career – and all will be well.

This is interesting but, of course, untrue. Your mind is now as trained as it will ever be. It is at the pinnacle of its absorptive, innovative and recuperative powers – loaded, primed and ready to go. You are sitting at the end of 400,000 to 500,000 years of human development, a continuum of innovation, forward thinking and trial-and-error that turned the world from stone age caves and forests to what you see today. Most of the steps and discoveries were made by people under the age of 25, without any qualifications at all – which is a very recent development.

If we set the above aside as an illusion disproven by history, we find that the need for an engineering degree today is based on *four* main criteria. Consider them of equal weight: complementary criteria that naturally exist as part of a set, and each of which has little resonance or effectiveness without the assistance of the others.

1.4.1 A degree is a benchmark

As a benchmark for industry, degrees work reasonably well without being spectacular. Industries seem to like benchmarks, as it gives them something to aim for, or against which they can measure their success. Engineering companies use them as part of their recruitment policy, giving them some idea of whom to invite to interviews.

One of the strange properties of benchmarks is that they cannot be usefully produced by the part of organization that sees the benefit in using them. The profit-making parts of any engineering business (consisting of those people and groups that actually know how things work) are far too busy trying to extract profit from the market – whilst supporting the rest of the organization and its hangers-on – to get involved in recruitment policy, skill-sets or this week's current incarnation of the education system. The result is that recruitment policy and practices are administered by those on the *edge* of an organization rather than at its profit-making core. This fosters the practice of grabbing at plausible-sounding requirements that can be put in recruitment adverts, and slid into the candidate assessment procedure.

The actual detailed content of degree courses can (and do) remain a bit of mystery to many recruiters. The content of most benchmark qualifications are set in academia rather than by the 'customer' organizations because, as we know, they are simply too busy. Some comfort is offered by various third-party accreditations of degree courses and this, accompanied by a few subjective recollections of the reputation and specialisms of some educational institutions and courses, is usually good enough. The end result is that an engineering degree becomes a prerequisite for entering the recruitment and interview process of any engineering company.

1.4.2 A degree is a filter

This one works for you. The time and effort required to achieve an engineering degree gives you the opportunity to see if you like the subject. If it proves to be unsuitable for you, then it's best to find out sooner rather than later, to prevent your career becoming a necessary daily chore. If you decide that it is something you would like to do, then you will gain:

- The opportunity to make engineering your career.
- Access to the answers to the vast array of engineering questions that 99% of the general population can't answer.
- A guarantee (well, almost) of long-term employability – if you are any good. This may, or may not, offer good financial reward depending on which area of the subject you end up in. There are a few stratospheric salaries in engineering, a lot of good ones and some where you would earn as much driving a taxi. Your eventual destination will be decided by the sum total of your ability, willingness to seek knowledge, and the choices you make along the way.

The degree process filter acts as a long filter, rather than a particularly severe or fine one – but it works quite well.

1.4.3 A degree is a first step in the career race

Career progression is nothing more than a race against the clock. As you progress, the winning post either gets closer or recedes into the unobtainable distance, depending on where you have set it.

In any race, the first step is ***not*** the winning post. Sadly, you cannot *enter* any race without a first step, so the sooner you take it the better. Think of this first step as a mechanistic process, with the objective being its *completion*, rather than demonstrating a shining example of success. A degree is a sound first step, but it is not the winning post, which is where the prizes are awarded.

1.4.4 A degree gives you knowledge feedstock

The biggest advantage of an engineering degree is the knowledge feedstock it provides. It may be surrounded by the usual doubtful skills of management, sales, communication, and the like, but strip these away and it is an almost perfectly technical subject. You cannot progress without a critical mass of this technical information, much of which is packaged in the engineering degree syllabus.

Which degree is the best?

This matters less than you think. The number of engineering degrees available in the UK alone now runs into hundreds, each one comprising different combinations and permutations of pure or applied subjects and claiming to be shorter, more effective, or more (or less) intensive than the others.

Relax. With a few exceptions – all this creation is largely artificial. It proliferates from the needs of educational establishments to increase their numbers of student 'customers' rather than from the segmented technical needs of the industries they ultimately serve. At this level, all engineering has a fairly stable core of mathematics, chemistry and physics: equations, concepts and techniques that describe the engineering-related parts of the natural world. The multiple variation of degree subject combinations are nothing more than different patterns of the DNA of the subject, not different DNA.

The pattern of technical subjects learned will really only become useful to you when you are in about Year 4 of your post-graduate career. Before this, in Years 1, 2 and 3, the pattern of knowledge 'feedstock' amassed during your degree course will feature in only about 5% of the things in which you are involved. The rest will, for the moment, be forgotten. Sadly, it is impossible to know in advance exactly which 5% of your initial knowledge upload you will need, so you more or less have to learn it all.

In about Year 4 of a post-graduation career, everything changes. Only about 20% of graduates will still be with their initial role or employer and the demand will now almost certainly be for a completely different pattern of knowledge than the 5% you used when you first started. The new pattern of knowledge required will now start to present itself to you. The percentage of the core engineering subjects you use will start to rise, and any synthetic combinations of syllabus content of your original degree will quickly lose its significance. This will be followed in close pursuit by the title of your degree, its artificially created specialisms, and the name of the hallowed institution from whence it came.

Now the race is on.

1.5 Degrees and how to pass them

Passing a degree is more or less a mechanistic procedure. Assuming that you have been preprogrammed with the necessary basic education, and are blessed with an average-to-good mental processing ability, passing a degree comprises a fixed equation of 5% flair and natural ability, 5% chance, and 90% predictable, mechanistic procedure. Engineering degrees are no exception to this – in fact they fit the formula better than most. Here is the procedure:

- Step 1: Decide your target, C, B or A.
- Step 2: Get the syllabus, so that you know what's coming.
- Step 3: Weed out the syllabus so that you can manage it.
- Step 4: Establish a learning method.
- Step 5: Follow your learning method, tailored to the C, B or A decision target you have set.

This five-step methodology has always worked well, and its effectiveness is actually increasing owing to the recent proliferation of degree courses and increases in undergraduate numbers. It is helped along by the increasing contemporary assumption that most candidates should succeed, surrounded by a sparkling array of assessment structures, grades and subgrades. Here is Step 1 (the most important one) in a little more detail.

Decide your target: C, B or A

Which of these three targets you choose will set the agenda for all the time you spend on your degree course. They are equally applicable to full or part time courses – they relate purely to the target you set yourself, and are therefore independent of the name, content or length of the course. One of the inherent properties of these targets is that if that you don't consciously choose one of the three, one will always choose itself *for you,* attaching itself to you without your knowledge. It is therefore best to choose one for yourself, so that you know what it is, and can fit in with it.

Target C

If you choose target C you have decided to do *just enough* to pass all the parts of the syllabus that you need to get your degree. Grade is not important to you, and you are happy to rely on a bit of luck to, hopefully, get better than you deserve. In submitting reports, dissertations and projects, and sitting exams, you are happy with recital rather than real understanding – indeed you may not know the difference. There is no need to feel isolated if you have chosen target C (or if it has chosen you) because about 50% of your fellow undergraduates will do exactly the same.

Target B

Target B undergraduates are target C ones in urbane disguise. Whilst fundamentally sharing the target C views, they have identified that the business of passing qualifications must have some *error margin* floating around. Aiming just to pass could mean that with a bit of bad luck, unplanned absence or misreading of exam questions, it might just be possible to fall victim to this error margin, and fail. Opinions differ on how big this error margin actually is, but intuitively it falls somewhere between 5 and 15%.

Target B undergraduates aim to try that little bit harder, to ensure that they place themselves firmly in the pass zone, cleanly above the error band. They intend to do this mainly in the continuous assessment or project work elements of the degree course – hoping that the examined parts (which are just that bit harder) will look after themselves. To help their chances in the continuous assessment modules, target B undergraduates tacitly accept that they will need to bring a little structure and organization to their work. This, however, will be largely *reactive* – they will do it when chased, or when they think they have to. On balance they are still (knowingly or unknowingly) being *managed by* the degree syllabus that is thrust upon them, occasionally being surprised when it goes too fast, too slow or when it suddenly expands to a depth that catches them out. When it does, they will discuss this apparent unfairness with some of the 35% of undergraduates who have chosen the same target B path.

Target A

Target A is *not* necessarily about getting the top marks in the class, grade A+ or A++ with gold and platinum star. These awards, say the 15% target A group, are for the birds – merely a crude and ephemeral illusion of early-career grandeur, rather than success in itself.

The real secret of target A lies in the *predictability* it brings to the whole affair. Target A undergraduates analyse the content, structure and timing of the course in advance. In this way, as they progress through the months and years of the course, they always know what is coming next, and can put the past and forthcoming parts of the syllabus in the context of the final examinations. Later parts of the syllabus come as no surprise and three notable things play a big part in this:

- Full familiarity with the basic ‘ball skills’ of the course subjects. To hit target A requires complete mastery of basic maths routines and its differentiation and integration methods until they become second nature. Recognizing mathematical formats and equation types is a requirement of many degree subjects so this will pay itself back in benefits many times.

Once you have achieved this mastery you will find yourself *attracted* to classroom and homework examples that contain them, rather than imaginatively avoiding them – which is what the target B and C groups do.

- Asking ***'why?'*** and ***'what else can I find out?'***. The target A philosophy does not end with doing the ten questions or examples you are given on any particular subject. Think of this as being about two-thirds of the journey – when you've done them, make an active attempt to find some different examples (harder, not easier ones), and do them as well. For qualitative, or description information and concepts, then ask *why?* two or three times, and search until you find the answer. You are constantly making things hard for yourself – but that is the environment of target A.
- *Planning and time management* is the bedrock of target A territory. You need to get the course syllabus in advance, see how long each part takes, make plans for doing it, learning it, revising it, sorting out your problems with it and then anticipating the way that its content will be slid into the examinations. None of this is random – it is all planned in advance so that ultimately there are no surprises. You are managing *it*, rather than it managing you.

Summary: Your choice of target

Seen from a distance, there is no single more important part of passing an engineering degree course than the target C, B or A, that you choose. Throughout the course it will determine;

- What you do
- How you do it
- When you do it
- How much effort you put in
- Whether you pass or fail – and what grade you get

1.6 Do you have any . . . experience?

Nature has thoughtfully provided you with a mental processing power. Your degree will give you the named folders in which to store the next four decades of accumulated data. All you need now is the universal tool for sifting the wide datastream that will be heading in your direction, from which you have to separate out the relevant information from the unnecessary, the illusion and the noise.

This tool is called *experience*. Whilst it may not be the only tool in the box, it has an impressive record of success. Almost everything gets easier with experience – seemingly insurmountable problems become straightforward, once you have seen the solution before. Intractable barriers turn to straw in the sunlit field of hindsight and straight-thinking gradually replaces the previous patterns of circle and spirals that, you have painfully discovered, lead nowhere.

As with all things of value, experience has a scarcity about it. To graduates it is *elusive*. All employers would like it, quizzing you to see if you have it, as you wonder exactly where you are supposed to have got it from. To employers, it is a *scarce* resource – graduates with experience, particularly relevant experience, are rare enough to foster competition amongst employers for their services. It would be even better if these graduates came prepacked ready for use, their experience having been thoughtfully provided by the time and expense of someone else.

To get round this situation, you need to get hold of this experience *quickly*. As experience is basically about you absorbing relevant parts of the datastream, the secret is to ensure that you embark on a process of *accelerated* data transfer. This won't happen by itself, you need to consciously make it happen.

Forget the clock and calendar as a frame of reference, because accelerated data (experience) time is not real time. Real time is far too slow. Graduates who process the datastream in real time are controlled *by* the datastream, rather than exerting their will *upon* it – and the following risks lie in wait.

- In four years, you may have not necessarily accumulated four years of experience data transfer – only four months of transfer, repeated 12 times. You have achieved an experience efficiency of one-twelfth, or 8.3%.
- You have processed 12 × 4 month datastreams which, although aesthetically and technically different, actually only

trigger the same experience 'locks'. The result is much the same. Congratulations: 8.3%.

Note that the above has little to do with your mental processing power (to solve problems, write specifications, understand drawings or whatever). Everyone is a bit different at that but these differences have little effect compared to the results if the correct (experience) datastream does not arrive at you in the first place.

To summarize *– The key thing is to accelerate the (experience) datastream that you are exposed to*. Once it is there, your brain will process it for you without you needing to try very hard.

How to accelerate your input datastream

Choose your poison from the recipe in Fig. 1.2. The list shows the datastream (experience) efficiency that each of the entries will give you. None has an efficiency greater than 100%, so you can't accelerate calendar time chronologically, but anything over about 40% will place you above the average, and you will effectively exceed real time.

Conversely, if you rely on activities below 40%, then your experience clock slows below real time and you will fall behind. Unfortunately, the activities offering the greatest experience return are always the least comfortable, and have an unerring ability to hide away until you look for them. Comfort resides at the bottom left of the list, waiting to catch you.

How long is this list valid for?

It remains in force, unchanged, for your whole career, if your care to read it. By about 10 years after graduation however, you will have chosen your place on the list and are caught. You will find it just about impossible to move up the list, no matter how hard you try.

1.7 Final cut – job interviews

Job interviews are, by their nature, awkward affairs. As a bit of office theatre they are difficult to better, with multiple facets depending on whether you are looking at it from the viewpoint of employer or applicant. Running the whole show is, of course,

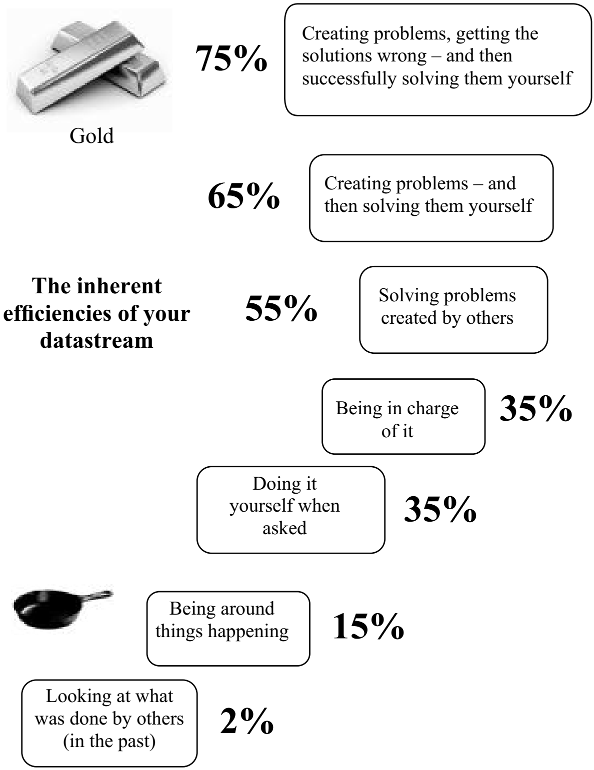

Figure 1.2 Engineering experience and how to get it

the generation gap between interviewer and interviewee. It provides both with significant challenges and generally makes for an interesting mixture of optimism, misunderstanding and general unease.

On balance, engineering interviews are more difficult for the intervie*wer* than the intervie*wee*. Rather than being active searches for the *strong points* of applicants, it more often turns into a procession of questions and verbal exercises to see who has the fewest *weak points* amongst these being interviewed. This is actually good news from the applicant's point of view, as these perceived weak points are smaller in number than strong points ever can be and are, within a fairly small tolerance band, almost perfectly predictable. Here they are;

- ***Limited technical knowledge?*** The headline purpose of an engineering job interview is generally to find out whether an applicant's technical knowledge base reflects an aptitude for, and an interest in, the subject of engineering, or whether all they can do is recite in parrot fashion what they remember from their assembled college courses. About 70% of applicants fit into the second category, and are easy to spot.
- ***Lack of interest in practical skills?*** Don't confuse this with being questioned on your physical experience of practical skills – that will be quite clear from your age and the activities shown on your CV. The issue is your *interest* in the practical aspects. You can fall foul of this one by talking too much about computer skills and spreadsheets – because familiarity with these is not in short supply.
- ***Browser dependency?*** Nothing is better than this at chiselling the interview generation gap into a form that won't help you. In the ageing eyes of your interviewers the answers to technical questions are *not* found in the depths of Gurglepedia or any other epic destinations of your browser. They may of course be wrong, but *they* are running your interview.
- ***Dependence and indecisiveness?*** Interviewers are permanently twitchy about applicants who seem to have plenty of technical knowledge but would rather let someone else make all the decisions for them. Reasons for this range from not wishing to be seen to get something wrong, to saving face, to an overall attitude of indecision and procrastination upon which some people base their life. Neither provides very good value for money from an employer's point of view. If, perish the thought, your interviewer also suffers from even a little of this, he or she will strangely not welcome seeing it in you. That's just how it works.

This, therefore, is the formula: if you can formulate an interview technique to get round these perceived weak points first, you can then get on with the easier business of letting your strong points shine through.

To help you, our website provides further guidance on the answers to more specific interview questions. Try the quizzes and take a look at the sample answers that employers are looking for. They all work.

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When prompted, use the password: Matthewsdatabook2012.

Section 2

Units

2.1 The Greek alphabet

The Greek alphabet is used extensively to denote engineering quantities. Each letter can have various meanings, depending on the context in which it is used.

Table 2.1 The Greek alphabet

Name	*Symbol*		*Used for*
	Capital	*Lower case*	
alpha	A	α	Angles, angular acceleration
beta	B	β	Angles, coefficients
gamma	Γ	γ	Shear strain, kinematic viscosity
delta	Δ	δ	Differences, damping coefficient
epsilon	E	ε	Linear strain
zeta	Z	ζ	
eta	H	η	Dynamic viscosity, efficiency
theta	Θ	θ	Angles, temperature
iota	I	ι	
kappa	K	κ	Compressibility (fluids)
lambda	Λ	λ	Wavelength, thermal conductivity
mu	M	μ	Coefficient of friction, dynamic viscosity, Poisson's ratio
nu	N	ν	Kinematic viscosity
xi	Ξ	ξ	
omicron	O	o	
pi	Π	π	Mathematical constant
rho	R	ρ	Density
sigma	Σ	σ	Normal stress, standard deviation, sum of
tau	T	τ	Shear stress
upsilon	Υ	υ	
phi	Φ	φ	Angles, heat flowrate, potential energy
chi	x	χ	
psi	Ψ	ψ	Helix angle (gears)
omega	Ω	ω	Angular velocity, solid angle

Engineers' Data Book, Fourth Edition. Clifford Matthews.

2.2 Units systems

Unfortunately, the world of mechanical engineering has not yet achieved uniformity in the system of units it uses. The oldest system is that of British Imperial units – still used in many parts of the world, including the USA. The CGS (or MKS) system is a metric system, still used in some European countries, but is gradually being superseded by the Systeme International (SI) system. Whilst the SI system is understood (more or less) universally, you will still encounter units from the others.

2.2.1 The SI system

The strength of the SI system is its *coherence*. There are four mechanical and two electrical base units, from which all other quantities are derived. The mechanical ones are:

Length:	metre (m)
Mass:	kilogram (kg)
Time:	second (s)
Temperature:	Kelvin (K)

Remember, other units are derived from these; e.g. the Newton (N) is defined as $N = kg\ m/s^2$.

2.2.2 SI prefixes

As a rule, prefixes are applied to the basic SI unit, except for weight, where the prefix is used with the unit gram (g), not the basic SI unit kilogram (kg). Prefixes are not used for units of angular measurement (degrees, radians), time (seconds), or temperature (°C or K).

Prefixes should be chosen in such a way that the numerical value of a unit lies between 0.1 and 1000.

For example	28 kN	rather than	2.8×10^4 N
	1.25 mm	rather than	0.00125 m
	9.3 kPa	rather than	9300 Pa

Table 2.2 SI prefixes

Multiplication factor	*Prefix*	*Symbol*
1 000 000 000 000 000 000 000 000 = 10^{24}	yotta	Y
1 000 000 000 000 000 000 000 = 10^{21}	zetta	Z
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a
0.000 000 000 000 000 000 001 = 10^{-21}	zepto	z
0.000 000 000 000 000 000 000 001 = 10^{-24}	yocto	y

2.2.3 Conversions

Units often need to be converted. The least confusing way to do this is by expressing equality:

For example: to convert 600 mm H_2O to Pascals (Pa)

Using 1 mm H_2O = 9.80665 Pa
Add denominators as

$$\frac{1\,\text{mm}\,H_2O}{600\,\text{mm}\,H_2O} = \frac{9.80665\,\text{Pa}}{x\text{Pa}}$$

Solve for x

$$x\,\text{Pa} = \frac{600 \times 9.80665}{1} = 5883.99\,\text{Pa}$$

Hence 600 mm H_2O = 5883.99 Pa

Setting out calculations in this way can help avoid confusion, particularly when they involve large numbers and/or several sequential stages of conversion.

2.3 Units and conversions

2.3.1 Force

The SI unit is the Newton (N) – it is a derived unit.

Table 2.3 Force (F)

Unit	*N*	*lb*	*gf*	*kgf*
1 Newton (N)	1	0.2248	102.0	0.1020
1 pound (lb)	4.448	1	453.6	0.4536
1gram-force (gf)	9.807×10^{-3}	2.205×10^{-3}	1	0.001
1 kilogram-force (kgf)	9.807	2.205	1000	1

Note: Strictly, all the units in the table except the Newton (N) represent weight equivalents of mass, and so depend on g. The true SI unit of force is the Newton (N) which is equivalent to 1 kg m/s^2.

2.3.2 Weight

The true weight of a body is a measure of the gravitational attraction of the earth on it. Since this attraction is a force, the weight of a body is correctly expressed in Newtons (N).

Mass is measured in kilogram (kg)
Force (N) = mass (kg) × g (m/s^2)

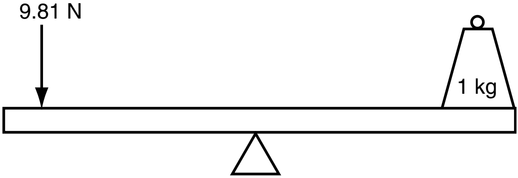


Figure 2.1

1 kg = 2.20462 lbf
1000 kg = 1 tonne (metric) = 0.9842 tons (imperial)
1 ton (US) = 2000 lb = 907.185 kg

Table 2.4 Density (ρ)

Unit	*kg/m³*	*g/cm³*	*lb/ft³*	*lb/in³*
1 kg per m^3	1	0.001	6.243×10^{-2}	3.613×10^{-5}
1g per cm^3	1000	1	62.43	3613×10^{-2}
1 lb per ft^3	16.02	1.602×10^{-2}	1	5.787×10^{-4}
1 lb per in^3	2.768×10^4	27.68	1728	1

2.3.3 Pressure

The SI unit is the Pascal (Pa).

$1 \text{ Pa} = 1 \text{ N/m}^2$
$1 \text{ Pa} = 1.45038 \times 10^{-4} \text{ lbf/in}^2$ (i.e. psi)

In practice, pressures are measured in MPa, bar, atmospheres, torr or the height of a liquid column, depending on the application.

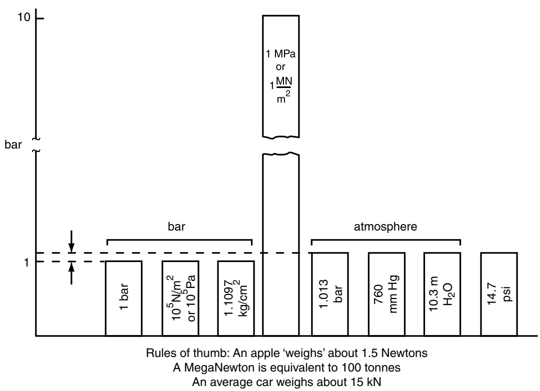


Figure 2.2

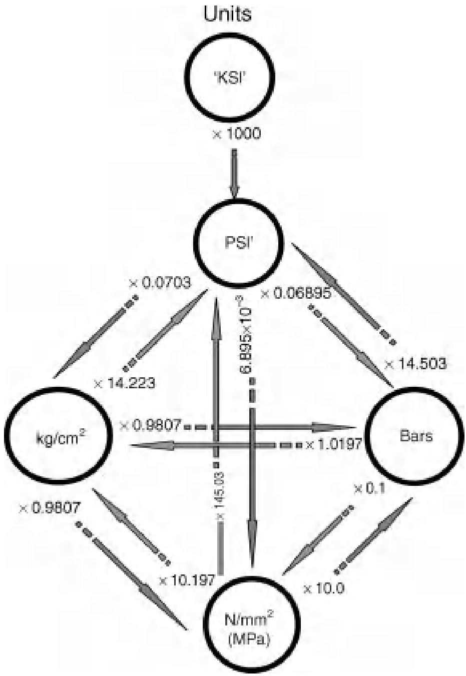


Figure 2.3

Table 2.5 Pressure (*P*)

Unit	*Atm*	*in H_2O*	*cm Hg*	*N/m^2(Pa)*	*lb/in^2(psi)[a]*	*lb/ft^2*
1 atmosphere (atm)	1	406.8	76	1.013×10^5	14.70	2116
1 in of water at 4°C	2.458×10^{-3}	1	0.1868	249.1	3.613×10^{-2}	5.02
1 cm of mercury at 0°C	1.316×10^{-2}	5.353	1	1333	0.1934	27.85
1 N per m^2	9.869×10^{-6}	4.015×10^{-3}	7.501×10^{-4}	1	1.450×10^{-4}	2.089×10^{-2}
1 lb per in^2 (psi)	6.805×10^{-2}	27.68	5.171	6.895×10^3	1	144
1 lb per ft^2	4.725×10^{-4}	0.1922	3.591×10^{-2}	47.88	6.944×10^{-3}	1

[a] Where $g = 9.80665\ m/s^2$.

[b] Note that the United States unit ksi ('kip' per square inch) may be used. 1 ksi = 1000 psi, not 1 kg/square inch.

And for liquid columns:

1 mm Hg = 13.59 mm H_2O = 133.3224 Pa = 1.333224 mbar
1 mm H_2O = 9.80665 Pa
1 torr = 133.3224 Pa

For conversion of liquid column pressures; 1 in = 25.4 mm.

2.3.4 Temperature

The SI unit is degrees Kelvin (K). The most commonly used unit is degrees Celsius (°C).

Absolute zero is defined as 0 K or −273.15 °C, the point at which a perfect gas has zero volume.

The imperial unit of temperature is degrees Fahrenheit (°F).

$°C = {}^5/_9\ (°F - 32)$
$°F = {}^9/_5\ (°C) + 32$

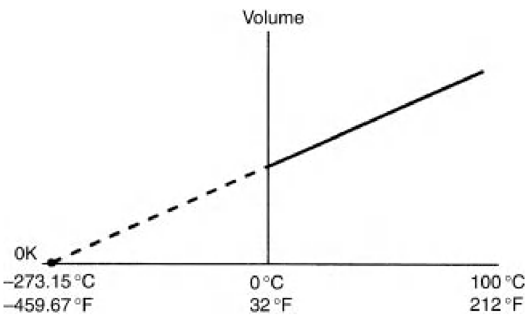
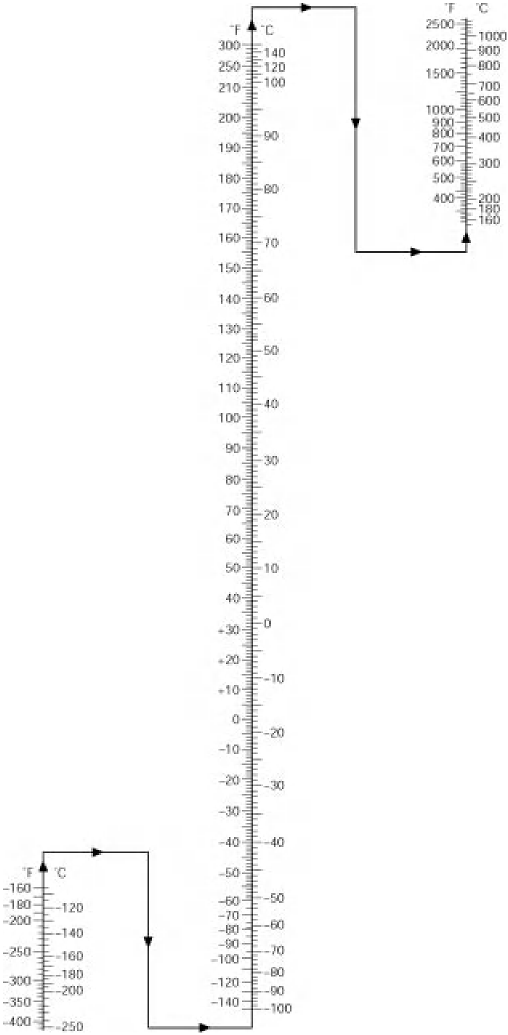


Figure 2.4


°F °C
2500
2000
1500
1000
900
800
700
600
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400
1000
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180
160
°F °C
300
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-80
-90
-100
°F °C
-160
-180
-200
-250
-300
-350
-400
-120
-140
-160
-180
-200
-250

Figure 2.5

2.3.5 Heat energy

The SI unit for heat energy (in fact all forms of energy) is the Joule (J).

Table 2.6 Heat energy

Unit	*J*	*Btu*	*ft lb*	*hph*	*Cal*	*kWh*
1 Joule (J)	1	9.481×10^{-4}	0.7376	3.725×10^{-7}	0.2389	2.778×10^{-7}
1 British thermal unit (Btu)	1055	1	777.9	3.929×10^{-4}	252	2.93×10^{-4}
1 foot-pound (ft lb)	1.356	1.285×10^{-3}	1	5.051×10^{-7}	0.3239	3.766×10^{-7}
1 horsepower-hour (hph)	2.685×10^{6}	2545	1.98×10^{6}	1	6.414×10^{5}	0 7457
1 calorie (cal)	4.187	3.968×10^{-3}	3.087	1.559×10^{-6}	1	1.163×10^{-6}
1 kilowatt hour (kWh)	3.6×10^{6}	3413	2.655×10^{6}	1.341	8.601×10^{5}	1

Specific energy is measured in Joules per kilogram (J/kg).

$$1\ \text{J/kg} = 0.429923 \times 10^{-3}\ \text{Btu/lb}$$

Specific heat capacity is measured in Joules per kilogram Kelvin (J/kg K).

$$1\ \text{J/kg K} = 0.238846 \times 10^{-3}\ \text{Btu/lb}\ ^{\circ}\text{F}$$
$$1\ \text{kcal/kg K} = 4186.8\ \text{J/kg K}$$

Heat flowrate is also defined as power, with the SI unit of Watts (W).

$$1\ \text{W} = 3.41214\ \text{Btu/h} = 0.238846\ \text{cal/s}$$

2.3.6 Power

The Watt is a small quantity of power, so kW is normally used.

Table 2.7 Power (*P*)

Unit	*Btu/h*	*Btu/s*	*ft-lb/s*	*hp*	*cal/s*	*kW*	*W*
1 Btu/h	1	2.778×10^{-4}	0.2161	3.929×10^{-4}	7.000×10^{-2}	2.930×10^{-4}	0.2930
1 Btu/s	3600	1	777.9	1.414	252.0	1.055	1.055×10^{-3}
1 ft-lb/s	4.628	1.286×10^{-3}	1	1.818×10^{-3}	0.3239	1.356×10^{-3}	1.356
1 hp	2545	0.7069	550	1	178.2	0.7457	745.7
1 cal/s	14.29	0.3950	3.087	5.613×10^{-3}	1	4.186×10^{-3}	4.186
1 kW	3413	0.9481	737.6	1.341	238.9	1	1000
1 W	3.413	9.481×10^{-4}	0.7376	1.341×10^{-3}	0.2389	0.001	1

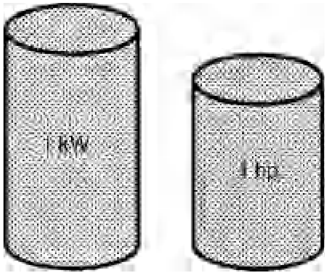


Figure 2.6

Figure 2.7 Comparative power outputs

2.3.7 Flow

The SI unit of volume flowrate is m^3/s.

1 m^3/s = 219.969 UK gall/s = 1000 litres/s
1 $m^3/h = 2.77778 \times 10^{-4}$ m^3/s
1 UK gall/min $= 7.57682 \times 10^{-5}$ m^3/s
1 UK gall = 4.546 litres

Figure 2.8

The SI unit of mass flowrate is kg/s.

1 kg/s = 2.20462 lb/s = 3.54314 ton (imp)/h
1 US gall = 3.785 litres

2.3.8 Torque

The SI unit of torque is the Newton metre (N.m). You may also see this referred to as 'moment of force'.

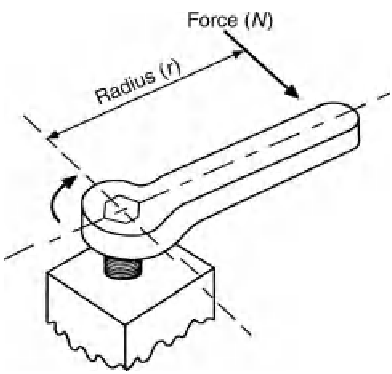


Figure 2.9

1 N.m = 0.737 lbf ft (i.e. 'foot pounds')
1 kgfm = 9.81 N.m

2.3.9 Stress

Stress is measured in Pascals – the same SI unit used for pressure, although it is a different physical quantity. 1 Pa is an impractical small unit so MPa is normally used.

$1\ \text{MPa} = 1\ \text{MN/m}^2 = 1\ \text{N/mm}^2$
$1\ \text{kgf/mm}^2 = 9.80665\ \text{MPa}$

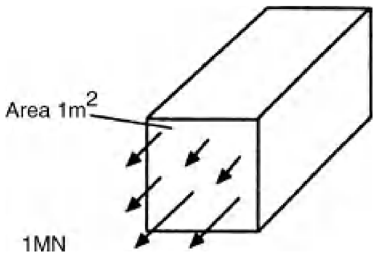


Figure 2.10

2.3.10 Linear velocity (speed)

The SI unit is metres per second (m/s).

Table 2.8 Velocity (*v*)

Unit	*ft/s*	*km/h*	*m/s*	*mile/h*	*cm/s*
1 ft per s	1	1.097	0.3048	0.6818	30.48
1 km per h	0.9113	1	0.2778	0.6214	27.78
1 m per s	3.281	3.600	1	2.237	100
1 mile per h	1.467	1.609	0.4470	1	44.70
1 cm per s	3.281×10^{-2}	3.600×10^{-2}	0.0100	2.237×10^{-2}	1

2.3.11 Acceleration

The SI unit of acceleration is metres per second squared (m/s^2).

$1\ \text{m/s}^2 = 3.28084\ \text{ft/s}^2$

Standard gravity (g) is normally taken as $9.81\ \text{m/s}^2$.

2.3.12 Angular velocity

The SI unit is radians per second (rad/s).

1 rad/s = 0.159155 rev/s = 57.2958 degree/s

The radian is the SI unit used for plane angles.

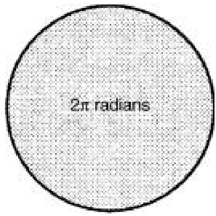


Figure 2.11

A complete circle is 2π radians
A quarter-circle (90°)is $\pi/2$ or 1.57 radians
1 degree = $\pi/180$ radians

2.3.13 Volume and capacity

The SI unit is cubic metres (m^3), but many imperial units are still in use.

$1\ m^3 = 35.3147\ ft^3 = 61\ 023.7\ in^3$

2.3.14 Area

The SI unit is square metres (m^2) but many imperial units are still in use.

Table 2.9 Area (*A*)

Unit	*sq in*	*Sq ft*	*Sq yd*	*sq mile*	*cm²*	*dm²*	*m²*	*A*	*ha*	*km²*
1 square inch	1	–	–	–	6.452	0.06452	–	–	–	–
1 square foot	144	1	0.1111	–	929	9.29	0.0929	–	–	–
1 square yard	1296	9	1	–	8361	83.61	0.8361	–	–	–
1 square mile	–	–	–	1	–	–	–	–	259	2.59
1cm²	0.155	–	–	–	1	0.01	–	–	–	–
1dm²	15.5	0.1076	0.01196	–	100	1	0.01	–	–	–
1m²	1550	10.76	1.196	–	10000	100	1	0.01	–	–
1a	–	1076	119.6	–	–	10000	100	1	0.01	–
1ha	–	–	–	–	–	–	10000	100	1	0.01
1km²	–	–	–	0.3861	–	–	–	10000	100	1

Other metric units of area:

Japan:	1 tsubo	$= 3.306\,m^2$
	1 se	$= 0.9917\,a$
	1 ho-ri	$= 15.42\,km^2$
Russia:	1 kwadr. archin	$= 0.5058\,m^2$
	1 kwadr. saschen	$= 4.5522\,m^2$
	1 dessjatine	$= 1.0925\,ha$
	1 kwadr. werst	$= 1.138\,km^2$

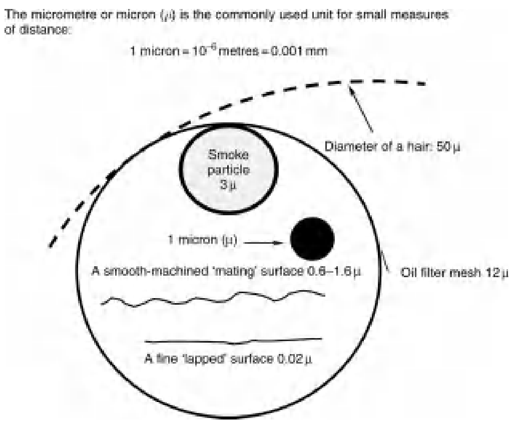


Figure 2.12 Making sense of microns (μ)

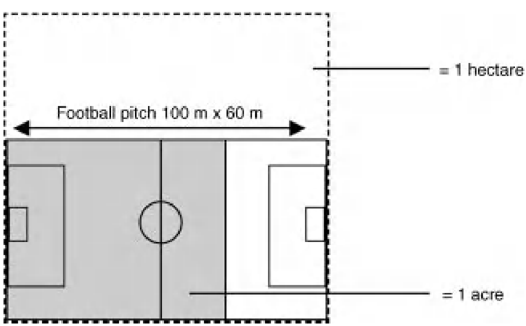


Figure 2.13

2.3.15 Viscosity

Dynamic viscosity (μ) is measured in the SI system in Pascal seconds (Pa s).

$$1 \text{ Pa s} = 1 \text{ N s/m}^2 = 1 \text{ kg/m s}$$

A common unit from another units system is the centipoise (cP), or standard imperial units may be used:

Table 2.10 Dynamic viscosity (μ)

Unit	*Centipoise*	*poise*	*kgf-s/m²*	*lb-s/ft²*	*kg/m-s*	*lbm/ft-s*
1 centipoise	1	10^{-2}	1.020×10^{-4}	2.089×10^{-5}	10^{-3}	6.720×10^{-4}
1 poise	100	1	1.020×10^{-2}	2.089×10^{-3}	0.100	6.720×10^{-2}
1 N-s per m^2	9.807×10^3	98.07	1	0.2048	9.807	6.590
1 lb (force)-s per ft^2	4.788×10^4	4.788×10^2	4.882	1	47.88	32 174
1 kg per m-s	10^3	10	0.1020	2.089×10^{-2}	1	0.6720
1 lb (mass) per ft-s	1.488×10^3	14.88	0.1518	3.108×10^{-2}	1.488	1

Kinematic viscosity *(ν)* is a function of dynamic viscosity.

Kinematic viscosity = dynamic viscosity/density, i.e. $\nu = \mu/\rho$ The SI unit is m^2/s. Other imperial and CGS units are also used.

$$1 \text{ m}^2/\text{s} = 10.7639 \text{ ft}^2/\text{s} = 5.58001 \times 10^6 \text{ in}^2/\text{h}$$
$$1 \text{ Stoke (St)} = 100 \text{ centistokes (cSt)} = 10^{-4} \text{ m}^2/\text{s}$$

2.4 Consistency of units

Within any system of units, the consistency of units forms a 'quick check' of the validity of equations. The units must match on both sides.

Example:

To check kinematic viscosity (ν)= $\dfrac{\text{dynamic viscosity}(\mu)}{\text{density } (\rho)}$

$$\frac{m^2}{s} = \frac{Ns}{m^2} \times \frac{m^3}{kg}$$

Replacing N with kgm/s^2

$$\frac{m^2}{s} = \frac{kgm\,s}{s^2m^2} \times \frac{m^3}{kg}$$

Cancelling gives

$$\frac{\text{m}^2}{\text{s}} = \frac{\text{m}^4\text{s}}{\text{s}^2\text{m}^2} = \frac{\text{m}^2}{\text{s}}$$

OK, units match.

2.4.1 Foolproof conversions: using unity brackets

When converting between units it is easy to make mistakes by dividing by a conversion factor instead of multiplying, or vice versa. The best way to avoid this is by using the technique of unity brackets.

A unity bracket is a term consisting of a numerator and denominator in different units which has a value of unity.

$$e.g. \left[\frac{2.205 \text{ lbs}}{\text{kg}}\right] \text{ or } \left[\frac{\text{kg}}{2.205 \text{ lbs}}\right] \text{ are unity brackets}$$

$$\text{as are } \left[\frac{25.4 \text{ mm}}{\text{in}}\right] \text{ or } \left[\frac{\text{in}}{25.4 \text{ mm}}\right] \text{ or } \left[\frac{\text{Atmosphere}}{10\,1\,325 \text{ Pa}}\right]$$

Remember that as the value of the bracket is unity it has no effect on any term that multiplies.

Example: Convert the density of steel $\rho = 0.29$ lb/in^3 to kg/m^3

Step 1: State the initial value: $\rho = \dfrac{0.29 \text{ lb}}{\text{in}^3}$

Step 2: Apply the 'weight' unity bracket:

$$\rho = \frac{0.29 \text{ lb}}{\text{in}^3}\left[\frac{\text{kg}}{2.205 \text{ lb}}\right]$$

Step 3: Then apply the 'dimension' unity brackets (cubed):

$$\rho = \frac{0.29 \text{ lb}}{\text{in}^3}\left[\frac{\text{kg}}{2.205 \text{ lb}}\right]\left[\frac{\text{in}}{25.4 \text{ mm}}\right]^3\left[\frac{1000 \text{ mm}}{\text{m}}\right]^3$$

Step 4: Expand* and cancel:

$$\rho = \frac{0.29\,\cancel{lb}}{\cancel{in}^3}\left[\frac{kg}{2.205\,\cancel{lb}}\right]\left[\frac{\cancel{in}^3}{(25.4)^3\cancel{mm}^3}\right]\left[\frac{(100)^3\cancel{mm}^3}{m^3}\right]$$

$$\rho = \frac{0.29\,kg(1000)^3}{2.205(25.4)^3 m^3}$$

$$\rho = 8025.8\,kg/m^3 : \text{Answer}$$

* Take care to use the correct algebraic rules for the expansion. For example:

$$(a.b)^N = a^N.b^N \; not \; a.b^N$$

So, for example, $\left(\frac{1000\,mm}{m}\right)^3$ expands to $\frac{(1000)^3.(mm)^3}{(m)^3}$

Unity brackets can be used for all unit conversions provided you follow the rules for algebra correctly.

2.4.2 Imperial-metric conversions

Table 2.11 Imperial–metric conversions

Fraction (in)	*Decimal (in)*	*Millimetre (mm)*
1/64	0.01562	0.39687
1/32	0.03125	0.79375
3/64	0.04687	1.19062
1/16	0.06250	1.58750
5/64	0.07812	1.98437
3/32	0.09375	2.38125
7/64	0.10937	2.77812
1/8	0.12500	3.17500
9/64	0.14062	3.57187
5/32	0.15625	3.96875
11/64	0.17187	4.36562
3/16	0.18750	4.76250
13/64	0.20312	5.15937
7/32	0.21875	5.55625
15/64	0.23437	5.95312
1/4	0.25000	6.35000
17/64	0.26562	6.74687

Table 2.11 (Cont.)

Fraction (in)	*Decimal (in)*	*Millimetre (mm)*
9/32	0.28125	7.14375
19/64	0.29687	5.54062
15/16	0.31250	7.93750
21/64	0.32812	8.33437
11/32	0.34375	8.73125
23/64	0.35937	9.12812
3/8	0.37500	9.52500
25/64	0.39062	9.92187
13/32	0.40625	10.31875
27/64	0.42187	10.71562
7/16	0.43750	11.11250
29/64	0.45312	11.50937
15/32	0.46875	11.90625
31/64	0.48437	12.30312
1/2	0.50000	12.70000
33/64	0.51562	13.09687
17/32	0.53125	13.49375
35/64	0.54687	13.89062
9/16	0.56250	14.28750
37/64	0.57812	14.68437
19/32	0.59375	15.08125
39/64	0.60937	15.47812
5/8	0.62500	15.87500
41/64	0.64062	16.27187
21/32	0.65625	16.66875
43/64	0.67187	17.06562
11/16	0.68750	17.46250
45/64	0.70312	17.85937
23/32	0.71875	18.25625
47/64	0.73437	18.65312
3/4	0.75000	19.05000
49/64	0.76562	19.44687
25/32	0.78125	19.84375
51/64	0.79687	20.24062
13/16	0.81250	20.63750
53/64	0.82812	21.03437
27/32	0.84375	21.43125
55/64	0.85937	21.82812
7/8	0.87500	22.22500
57/64	0.89062	22.62187
29/32	0.90625	23.01875
59/64	0.92187	23.41562
15/16	0.93750	23.81250
61/64	0.95312	24.20937
31/12	0.96875	24.60625
63/64	0.98437	25.00312
1	1.00000	25.40000

2.5 Dimensional analysis

2.5.1 Dimensional analysis (DA) – what is it?

DA is a technique based on the idea that one physical quantity is related to others in a precise mathematical way.

2.5.2 What is it used for?

It is used for:

- Checking the validity of equations;
- Finding the arrangement of variables in a formula;
- Helping to tackle problems that do not possess a complete theoretical solution – particularly those involving fluid mechanics.

2.5.3 Primary and secondary quantities

These are quantities which are absolutely independent of each other. They are:

M Mass
L Length
T Time

For example: Velocity (v) is represented by length divided by time, and this is shown by:

$$[v] = \frac{L}{T}$$

Note the square brackets denoting the 'dimension of'.

Table 2.12 Dimensional analysis – quantities

Quantity	*Dimensions*
Mass (m)	M
Length (l)	L
Time (t)	T
Area (A)	L^2
Volume (V)	L^3
First moment of area (I)	L^3
Second moment of area (I)	L^4
Velocity (v)	LT^{-1}
Acceleration (a)	LT^{-2}

Table 2.12 (Cont.)

Quantity	*Dimensions*
Angular velocity (v)	T^{-1}
Angular acceleration (α)	T^{-2}
Frequency (f)	T^{-1}
Force (F)	MLT^{-2}
Stress (Pressure) (σ, p)	$ML^{-1}T^{-2}$
Torque (T)	ML^2T^{-2}
Modulus of elasticity (E)	$ML^{-1}T^{-2}$
Work (W)	ML^2T^{-2}
Power (P)	ML^2T^{-3}
Density (ρ)	ML^{-3}
Dynamic viscosity (μ)	$ML^{-1}T^{-1}$
Kinematic viscosity (ν)	L^2T^{-1}

Hence velocity is called a secondary quantity because it can be expressed in terms of primary quantities.

2.5.4 An example of deriving formulae using DA

To find the formulae for periodic time (t) of a simple pendulum we can assume that t is related in some way to m, l, and g, i.e.

$$t = \Phi\{m, l, g\}$$

Introducing a numerical constant C and some possible exponentials gives:

$$t = \mathrm{C}m^a l^b g^d$$

C is a dimensionless constant so, in dimensional analysis terms this equation becomes

$$[t] = [m^a l^b g^d]$$

Substitute primary dimensions gives:

$$\begin{aligned} \mathrm{T} &= \mathrm{M^a L^b (LT^{-2})^d} \\ &= \mathrm{M^a L^{b+d} T^{-2d}} \end{aligned}$$

In order for the equation to balance

For M, a must = 0
For L, b + d = 0
For T, −2d = 1
Giving $b = {}^1/_2$ and d $= -{}^1/_2$

So we know the formula is now written:

$$t = \mathrm{C}l^{1/2}g^{-1/2}$$
$$\text{or} \quad t = \mathrm{C}\sqrt{\frac{l}{g}} : \text{the answer}$$

Note how dimensional analysis can give you the 'form' of the formula but not the numerical value of the constant C.

Note also how the technique has shown us that the mass (m) of the pendulum bob does not affect the periodic time (t) (i.e. because a = 0).

2.6 Essential engineering mathematics

2.6.1 Powers and roots

$$a^n.a^m = a^{n+m} \quad \frac{a^n}{a^m} = a^{n-m} \quad ab^n = a^n b^n \quad \left(\frac{a}{b}\right)^n = \frac{a^n}{b^n}$$

$$(a^n)^m = (d^m)^n = a^{nm} \quad (\sqrt[n]{a})^n = a \quad a^{\frac{1}{n}} = \sqrt[n]{a}$$

$$a^{n/m} = \sqrt[m]{a^n} \quad n\sqrt{ab} = n\sqrt{a}.n\sqrt{b}$$

2.6.2 Logarithms

$$\log_a a = 1 \quad \log_a 1 = 0 \; (\log_a M)N = \log_a M + \log_a N$$

$$(\log_b N) = \frac{\log_a N}{\log_a b} \quad \log_b b^N = N \quad b^{\log_b N} = N$$

2.6.3 The quadratic equation

A quadratic equation is one in the form ax^2 + bx + c = 0 Where a, b, and c are constants.

$$\text{The solution is : } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

2.6.4 Trigonometric functions

$\sin\alpha = \frac{y}{r}$

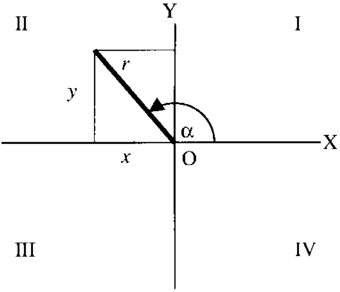
$\cos\alpha = \frac{x}{r}$

$\tan\alpha = \frac{y}{x}$

$\cot\alpha = \frac{x}{y}$

$\sec\alpha = \frac{r}{x}$

$\operatorname{cosec}\alpha = \frac{r}{y}$



The signs of these functions depend on which quadrant they are in:

Quadrant	*Sin*	*Cos*	*Tan*	*Cot*	*Sec*	*Cosec*
I	+	+	+	+	+	+
II	+	−	−	−	−	+
III	−	−	+	+	−	−
IV	−	+	−	−	+	−

2.6.5 Trig functions of common angles

	0°	*30°*	*45°*	*60°*	*90°*
Sin	0	$\frac{1}{2}$	$\sqrt{2}/2$	$\sqrt{3}/2$	1
Cos	1	$\sqrt{3}/2$	$\sqrt{2}/2$	$\frac{1}{2}$	0
Tan	0	$\sqrt{3}/3$	1	$\sqrt{3}$	∞
Cot	∞	$\sqrt{3}$	1	$\sqrt{3}/3$	0
Sec	1	$2\sqrt{3}/3$	$\sqrt{2}$	2	∞
Cosec	∞	2	$\sqrt{2}$	$2\sqrt{3}/3$	1

$$\sin\alpha = \frac{1}{\operatorname{cosec}\alpha} \quad \cos\alpha = \frac{1}{\sec\alpha} \quad \tan\alpha = \frac{1}{\cot\alpha} = \frac{\sin\alpha}{\cos\alpha}$$

$$\sin^2\alpha + \cos^2\alpha = 1 \quad \sec^2\alpha - \tan^2\alpha = 1$$
$$\operatorname{cosec}^2\alpha - \cot^2\alpha = 1$$

2.6.6 Differential calculus

Derivatives	*Integrals*
$\frac{d}{dx}(u \pm v \pm \ldots) = \frac{du}{dx} \pm \frac{dv}{dx} \pm \ldots$	$\int df(x) = f(x) + C$
$\frac{d}{dx}(uv) = \frac{u\,dv}{dx} + \frac{v\,du}{dx}$	$d\int f(x)dx = f(x)dx$
$\frac{d}{dx}\left(\frac{u}{v}\right) = \frac{1}{v}\frac{du}{dx} - \frac{u}{v^2}\frac{dv}{dx}$	$\int af(x)dx = a\int f(x)dx$ (a = constant)
$\frac{d}{dx}(u^n) = nu^{n-1}\frac{du}{dx}$	$\int u\,dv = uv - \int v\,du$
$\frac{d}{dx}(\ln u) = \frac{1}{u}\frac{du}{dx}$	$\int u^n du = \frac{u^{n+1}}{n+1} + C \quad (n \neq -1)$
$\frac{d}{dx}(\tan u) = \sec^2 u \frac{du}{dx}$	$\int \frac{du}{u} = \ln u + C$
$\frac{d}{dx}(\sin u) = \cos u \frac{du}{dx}$	$\int e^u du = e^u + C$
$\frac{d}{dx}(\cos u) = -\sin u \frac{du}{dx}$	$\int \sin\,du = -\cos u + C$
	$\int \cos u\ du = \sin u + C$
	$\int \tan u\,du = -\ln\cos u + C$

2.7 Maths and the real world?

2.7.1 What's it all about?

'Please sir, what use is this?' Fair question. Most people who are forced to use maths have little idea what it is really about. This also applies to people who are quite good at it and to many who teach it, or do little else. To them all, it is seen as an obscure and rather tiresome series of symbols and enforced equations surrounded by a bewildering number of different ways to put various numbers in to obtain (sometimes) the answer that you are supposed to get.

Good news. The reason you find maths awkward is simply because it is *abstract*. There's no reason to be surprised at this – lots of things are – language, for example, is abstract, and you use it all the time. Think about this explanation.

- Maths is an abstract depiction of *nature*.

Thinking of it as a depiction of nature is the first essential step. Think of the other way of doing it – Art, which is also a depiction of nature, and you might find it easier. These two systems are all there are, it's just that most people have little problem with accepting that a painting of a tree represents a tree, but find it more difficult to conceive that a jumble of numbers, symbols and equations can equally represent what a tree is, and does. This is the difficulty with maths – your mind is better tuned to looking at pictures and images and things rather than equations, because it is easier.

Why does maths depict nature?
Because nature is a 100% rule-based game. Everything that exists, and happens, does so because it has passed the test of compliance with an unbreakable set of rules, as they stand. Anything that doesn't comply can't exist, or happen, so simply looking around you provides first-hand evidence that enough things comply with these rules to result in all the things you can see, hear and feel.

How many of these rules are there?
Millions of millions without a doubt. Some are simple and others are almost infinitely complex. Think of them as the rules of a complex game, like rugby or cricket. The simpler rules are quite adequate at deciding that when a cricket ball is caught before it hits the ground the batsman is out. More complex rules conclude what should happen if the umpire's hat falls off and knocks over the stumps assisted, or not, by a disoriented pigeon. The game functions under these rules, hence proving their existence and effectiveness.

The rules of nature are a little more complex. They have to be good for billions of items and trillions of actions. They have to cover genetics, mechanics, acoustics, optics, aesthetics (that's an interesting one) and all the others, acting as an immutable, always-correct lowest common denominator of the world as it is.

How do we know that these rules involve maths?

Because the simplest ones, that we can observe directly, seem to work. Two boxes, each containing three apples spookily always results in a total of $2 \times 3 = 6$ apples. This is the simple test that proves the relationship – count the apples and you get 6, then multiple 2×3 and you get 6. See? It works. The rules are not all that simple of course, but the matching continues:

- Atoms and molecules arrange themselves, without help or persuasion, into patterns that can be described by fairly simple formulae. This is encouraging – success at this lowest scale probably means that bigger and more complex things will be the same.

Throw a ball in the air and, before very long, it will stop and come down. By applying our previous logic chain, it happens, so the rules must allow it. Maths is an abstract depiction of the rules, so there *must* be a mathematical way to describe what is happening. All you have to do is find it. Once you have found it think of the advantages: it will tell you what will happen if the ball is twice as heavy, thrown twice as high, or at an angle, so there will be no need to waste time trying it out in practice.

Now it's time for the big step. Once you accept that all the rules of everything can be depicted by maths you are ready to use it to find out things that are impossible to find out in any other way. You can predict what will happen in things too small to see, or in places to which you have no access (the planets, the sun and other suns). You have the tools to manage invisible things such as electromagnetic waves (radio, ultraviolet, infrared and the rest). Once you know the rules they follow, they are under your control (oh, don't forget, the rules are governing you, as well).

Where is this book containing all the rules?

There isn't one. The discovery of the rules is ongoing – it's doubtful if we've discovered 0.00001% of them, but its a standing target, because they are all there, static and unchanging, waiting to be discovered.

Ok, how do I use the rules?

Maths is used for everything that involves any of the 'big four' parameters shown in Fig. 2.14.

- Quantity
- Structures
- Space
- Change

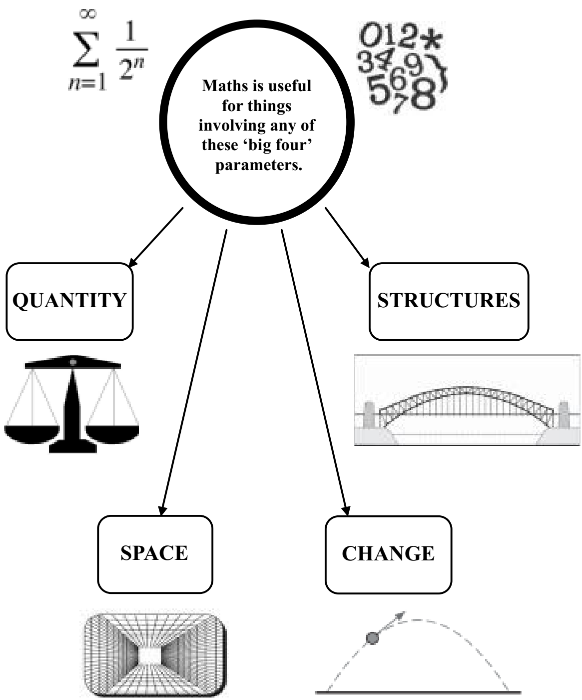


Figure 2.14 The main uses of maths

It won't give you a guaranteed answer to everything, because it is an abstract depiction of reality rather than a perfect one. It is perfect at its rule-based core but it is our use of it that brings the imperfection, because we didn't write the rules. Pure maths is more important than applied maths because there couldn't be the second without the first. Applied maths is used in engineering throughout the world as an essential tool in the design of things and processes, and therefore is practically more useful. This is why maths is in your degree syllabus.

2.7.2 Why bother with calculus?

Let's be honest, 99.999% people in the world don't understand the first thing about calculus – nor do they need to. Moving on to the mechanical engineering world where the percentage is a bit higher (but not much) you soon find that using it (mainly to pass exams) is an altogether different thing from actually understanding what it is all about.

In an engineering career, perhaps the only reason for getting involved with calculus is that you have to. Fortunately, most engineers won't need to. It is only in the higher echelons of engineering technology (fundamental design, for example) that you will need it. In this top 1% of the industry it becomes an issue – leaving the remaining 99% (which of course is most of it) to continue without it, once the necessary exams have been passed and forgotten.

Does all maths involve calculus?

Certainly not – most of it doesn't. It is difficult to put an accurate value on it but perhaps 70–80% of maths does not need calculus in any major way. Trigonometry for example, being mainly concerned with lengths, distances and angles between objects, doesn't require much calculus in the mainstream 80% of the subject.

Contrast this with the fact that virtually all engineering-based exams feature calculus heavily. Students are left with little choice but to study it in some considerable depth. Derivatives and integrals are memorized and regurgitated, elaborate solutions rehearsed for line-by-line presentation and the (hopefully correct) answers presented, with a flourish, at the end.

So what *is* calculus all about?

Easy, you need calculus to understand things that *change*. One of the most common types of change is physical movement – the distance from a moving object to some static point changes with time, so there is a change.

As you would expect, simple movement patterns (in a straight line or circle for example) are not too difficult to understand but it gets more difficult when you try to describe the curved path taken when you throw a ball, or the path of the earth round the sun, or the movement of atoms in a metal, as you heat it up.

Things don't have to *physically* move for the concept of 'movement' to be involved. Look at the shape in Fig. 2.15. As it is a 3-dimensional shape, it is not easy to calculate the volume of such a strange shape. The answer lies in thinking of it as a simple 2-dimensional flat shape rotated about the axis *y–y*. This will produce the 3-D volume. Note that, physically, nothing has actually been rotated (there has been no movement that you could watch), the movement has taken place conceptually.

Here's another type of movement that is non-real. How would you solve this problem?

$$3+2 \times 6 = ?$$

You would do it, knowingly or unknowingly, in steps. From the 'BODMAS' rules of maths (i.e. Brackets – Other operations – Division – Multiplication – Addition – Subtraction) you would do it in the following steps:

Step 1: Rewrite it as $3 + (2 \times 6) = ?$
Step 2: Calculate the terms in brackets $3 + 12 = ?$
Step 3 Do the sum: $3 + 12 = 15$ [*answer*]

See how you moved through the steps? – that's the *movement*. Nothing physical, but movement just the same.

Suspend belief for a moment and imagine that moving forward through steps 1 to 3 is called something special but meaningless (*differentiation*) – that's just the name we have given to the idea of moving forward. If you always want to go only from step 1 to step 3, that's all you need. Now turn things around – suppose you already had the answer of 15 but were

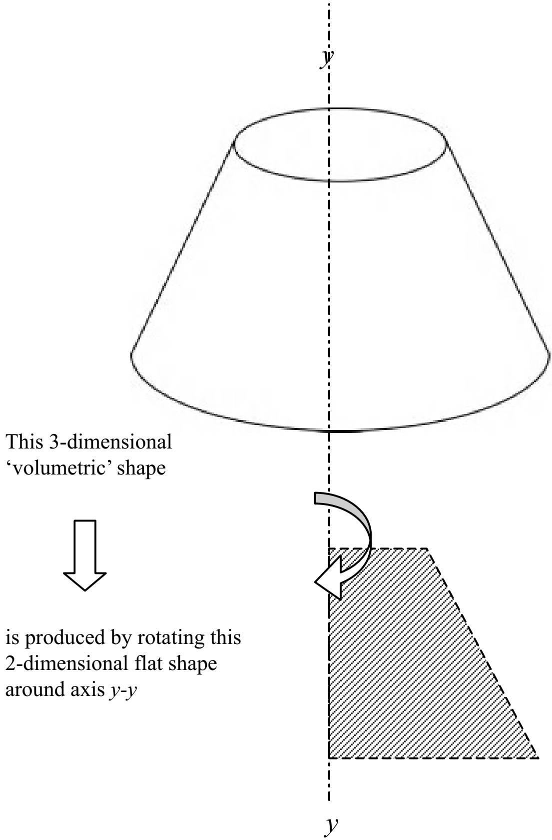


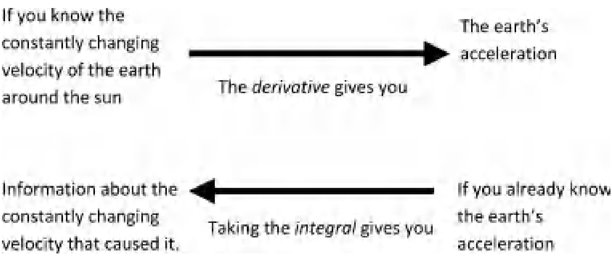
Figure 2.15 Volumes of revolution

curious as to where it came from. Your interest may be driven by the urge to have this answer again (if you liked it) or to stop it appearing again, if it causes you problems. You know that it is linked to other numbers but need to know which ones, and how. To do this you would need to move backwards. Once again, we'll give this a random name – call it *integration* – the opposite of differentiation, the name we gave to moving forward.

In the final act – combining the two concepts of dealing with rates of change with the two main and opposite options of moving forward or backwards – we have it. This is calculus. Catch it before it slips away:

- You have a constantly changing function and want to find out about its rate of change. This is the *derivative*.
  OR
- You already know the rate of change of a system and want to find the given values that describe the system's input. You get this by working backwards – called *integration*.

Or, perhaps examples will explain it better:



Very clever – how does it do that?

Put formally, it relies on the fact that you can get the answer to something by using a set of approximations of increasing accuracy. Sounds convincing, but how does this translate into practice? The whole thing is based on the concept that anything can be broken into infinitesimally small pieces and that these pieces, as they are small, must be simple. Although this is the basis of calculus, it disappears rapidly from sight as soon as you start actually doing it. It is easy to forget about it, but it lives behind the scenes, controlling everything.

How small is infinitesimal?

Almost infinitely small. On a scale of 93 million miles between the earth and the sun, one of the infinitesimal distances could be the thickness of a hair. It is this smallness that makes the whole thing work. On the scale of infinitesimal smallness, irregular shapes (that are difficult to deal with) can be approximated by regular ones which *can* be dealt with. By adding all the small regular shapes together to make the larger shape, the large shape suddenly becomes manageable. Figure 2.16 shows the idea.

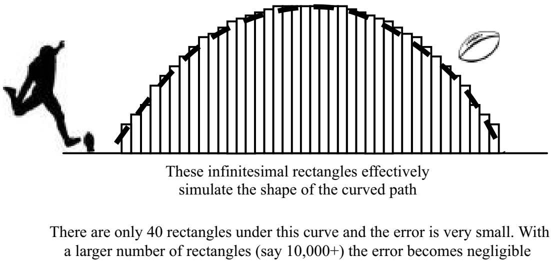


Figure 2.16 A curve described by multiple rectangles

If you think of the large irregular shape as being caused by something in the real world that continually changes direction with time, such as the path of a cannonball fired off a cliff at a passing ship, then you can see the advantages.

Being human, we like to have things expressed as real numbers before we can deal with them. The thing that does this is the concept of *limits*. Limits capture the small-scale behaviour of infinitesimal points of a curve, for example, whilst translating it into real numbers. Think of this when you see the limits on an integration (at the top and bottom of the squiggly line) – that is what the integral sign is doing. You don't see this change from 'real-world things' to 'real-world numbers' when you are finding a derivative, but it is there, just the same, hiding behind the symbols.

Reminder – why do we need calculus?

We need calculus to deal with anything that involves a system that is in a state of constant change. Without calculus it is impossible to predict how that system has previously changed to reach its present state or the state it will adopt in the future.

Section 3

Engineering Design – Process and Principles

3.1 Engineering problem-solving

Engineering is all about solving problems. Engineering design, in particular, is a complex series of events that can involve logic, uncertainty, and paradox, often at the same time. There are a few 'common-denominator' observations that can be made about problems in general.

Engineering problems are:

- *Multi-disciplinary* Discipline definitions are largely artificial; there are no discrete boundaries, as such, in the physical world.
- *Nested* Every part of an engineering problem contains, and is contained within, other problems. This is the property of *inter-relatedness*.
- *Interactive* The final solution rarely arrives at once. The solution process is a loop.
- *Full of complexity* So you can't expect them to be simple.

3.2 Problem types and methodologies

Engineering problems divide into three main types, each with their own characteristics and methodology for finding the best solution. A methodology is a structured way of doing things. It reduces the complexity of a problem to a level you can handle.

3.2.1 Type 1: Linear technical problems

These consist of a basic chain of quantitative technical steps (Fig. 3.1), mainly calculations, supported by robust engineering and physical laws. There is substantial 'given' information in a form that can be readily used. Note how the problem-solving process is *linear* – each quantitative step follows on from the last

Engineers' Data Book, Fourth Edition. Clifford Matthews.

and there are few, if any, iterative or retrospective activities. The solution methodology involves rigorous and accurate use of calculations and theory. Rough approximations and 'order of magnitude' estimates are not good enough.

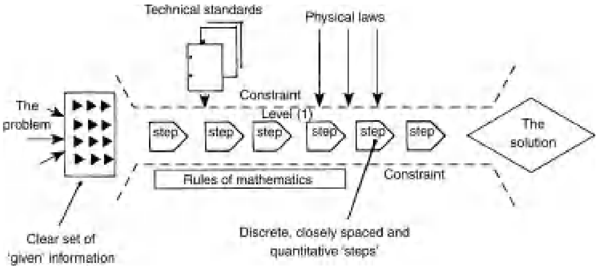


Figure 3.1

3.2.2 Type 2: Linear procedural problems

Their main feature is the existence of procedural constraints controlling what can be done to further define the problem and then solve it. Don't confuse these with administrative constraints; they are established procedural constraints of the *technical* world (Fig. 3.2). The methodology is to use procedural techniques to solve the problem rather than approaching it in an overly technical way. The problem is still in linear form, so you have to work through the steps one-by-one, without being retrospective (or you will lose confidence).

3.2.3 Type 3: Closed problems

These look short and simple but are crammed with hidden complexity. Inside, they consist of a system of both technical mini-problems and awkward procedural constraints (Fig. 3.3).

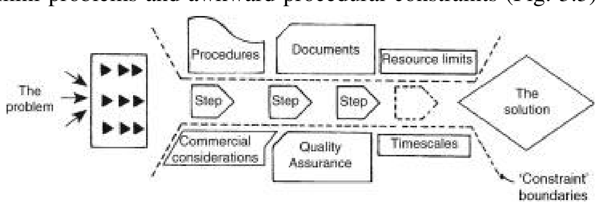


Figure 3.2

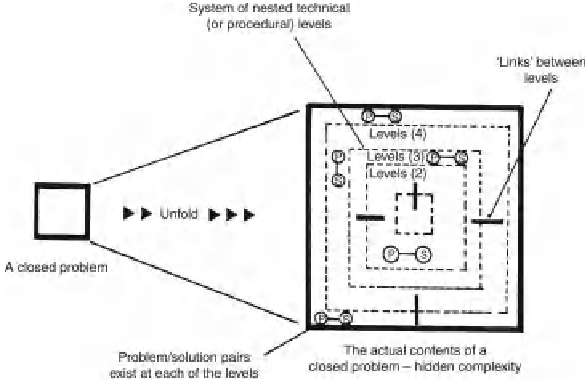


Figure 3.3

The methodology involves 'opening-up' the problem to reveal its complexity before you can solve it. Some hints are:

- Look for *common* nesting levels – you can anticipate these with practice.
- List the *variables and technical parameters* that you feel might be involved – then think for yourself in a pro-active way.
- Think *around* the problem, looking hard for the complexity (you will be revealing it, not introducing it because it is there already).
- Use *group input* – closed problems do not respond well to an individual approach. A group of minds can form a richer picture of a problem than can one.

Remember the golden rule: decide what type of problem you are looking at before you try to solve it.

3.3 Design principles

Engineering design is a complex activity. It is often iterative, involving going back on old ideas until the best solution presents itself. There are, however, five well-proven principles of functional design that should be considered during the design process of any engineering product.

- *Clarity of function* This means that every function in a design should be achieved in a clear and simple way, i.e. without redundant components or excessive complexity.
- *The principle of uniformity* Good functional design encourages uniformity of component sizes and sections. Any variety that is introduced should be there for a *reason*.
- *Short force paths* It is always best to keep force paths short and direct. This reduces bending stresses and saves material. Local closure (in which forces cancel each other out) is also desirable – it reduces the number of 'wasted' components in a design.
- *Least constraint* This is the principle of letting components 'go free' if at all possible. It reduces stresses due to thermal expansions and unavoidable distortions.
- *Use elastic design* Good elastic design avoids 'competition' between rigid components which can cause distortion and stresses. The idea is to allow components to distort in a natural way, if that is their function.

3.4 The engineering design process

The *process* of engineering design is a complex and interrelated set of activities. Much has been written about how the design process works both in theory and in practice.

There is general consensus that:

Design is the use of:

- Scientific principles

  +
- Technical information

  +
- Imagination

Designs are hardly ever permanent. All products around us change – sometimes gradually and sometimes in major noticeable steps – so the design process is also *continuous*. Within these points of general agreement there are various schools of thought on how the process works.

3.5 Design as a systematic activity (the 'pugh' method)

This is a well-developed concept – one which forms the basis of UK degree-level design education. It conceives the process as a basically linear series of steps contained within a total context or framework (see Fig. 3.4).

A central design core consists of the key stages of investigation, generating ideas, synthesis, manufacture, and evaluation. The synthesis stage is important – this is where all the technical facets of the design are brought together and formed into a final product design specification (known as the PDS). The design core is enclosed within a boundary, containing all the other factors and constraints that need to be considered. This is a disciplined and structured approach to the design process. It sees everything as a series of logical steps situated between a beginning and an end.

3.6 The innovation model

In contrast, this approach sees the design process as being circular or cyclic rather than strictly sequential. The process (consisting of basically the same five steps as the 'Pugh' approach) goes round and round, continually refining existing ideas and generating new ones. The activity is, however, innovation-based – it is *creativity* rather than rigour that is the key to the process.

Important elements of the creative process are:

- *Lateral thinking* Conventional judgement is 'put on hold' while creative processes such as brainstorming help to generate new ideas.
- *Using chance* This means using a liberal approach – allowing chance to play its part (X-rays and penicillin were both discovered like this).

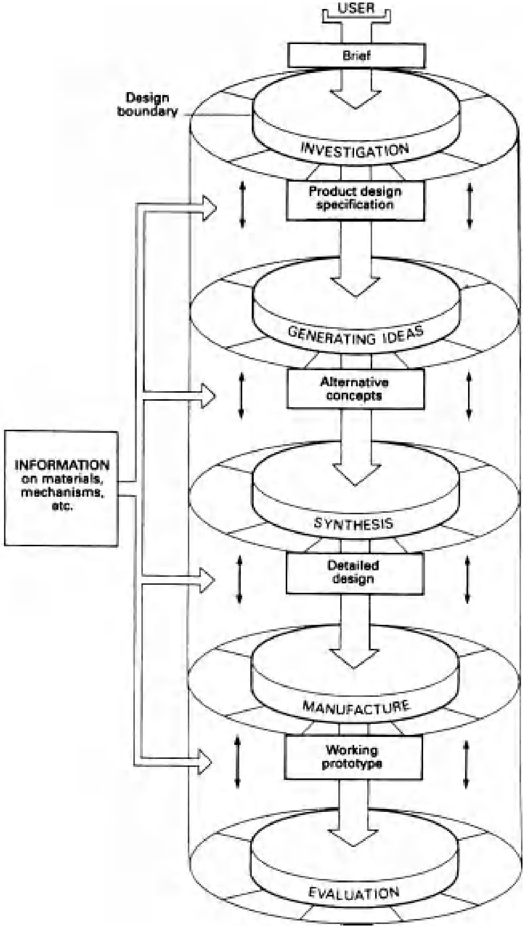


Figure 3.4 Design systemic activity model (overall concept adapted from the model used by SEED in their Curriculum for Design publications)

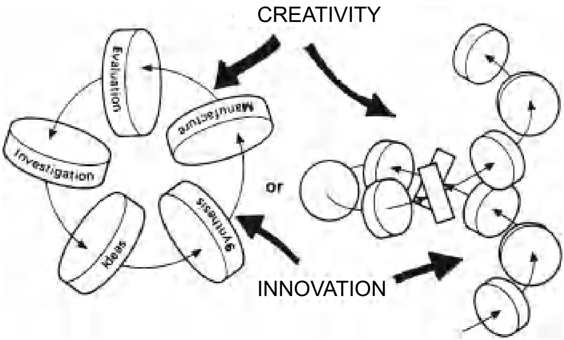


Figure 3.5

- *Analogy* Using analogies can help creativity, particularly in complex technical subjects.

Both approaches contain valid points. They both rely heavily on the availability of good technical information and both are *thorough* processes – looking carefully at the engineering detail of the design produced. Creativity does not have to infer a half-baked idea, or shoddiness.

3.6.1 Design and develop (or not)

It is a strange property of the engineering world that those people or teams that design a product rarely seem very good at developing it. Take any large complex product – a cutting-edge fighter aircraft, an intricately designed medical monitor, or a process flow system of high complexity – and you can see this principle in action. Group necessity spawns the need for the product and individual ingenuity provides the spark that sets the design process in motion – until the combined weight of multiple minds in the design and project team takes over, steamrolling it to its final (hopefully complete) solution.

Now the product is finished, its creators marvel in its complexity, swimming in self-congratulation of the intricacy of its interlocking parts, its form and structure, and the overall purity of its design. The product goes to market, customers are satisfied, and further orders will hopefully follow.

Now the problems start. Within a very short time customers' requirements refine themselves. Paradoxically, the more successful the product, the more extensively it is bought and used, and the quicker the customers' feedback loop works. Almost immediately customers discover nice little improvements that would be desirable – an extra access door here, or a more robust switch there, or a part that is redundant and could be safely omitted. Outside pressures of regulations, design codes and standards change through time, and big customers change their purchasing preferences, or leave the market altogether, to be replaced by others with bigger or more specific ideas about what they want.

Now the competition starts. Successful products breed almost immediate competition. In a well-rehearsed series of events, competitors 'cluster around' the successful product or design, copying its radical ideas, simplifying its design or changing its manufacturing methods to reduce the price. This goes on for a while – the weaker and 'out of their depth' ones soon drop out, leaving a hard core of competitors. And so the market settles.

For the original design team the solution would seem obvious – improve the design using the same initiative, engineering understanding and flair that produced the design in the first place. Surprisingly, this very often proves almost impossible. It is easy to start, and try, but real success is rare. It is as if the technical blinds come down, barriers of various types rise from the twilight of the previous success, and the old flair cannot seem to quite apply itself to improving its own previous creations. There is no simple explanation, but it is a combination of:

- entrenched thinking;
- self-denial that the original can be improved, by anyone;
- belief that the new customers are wrong, and they will eventually realize it and revert to wanting the original product;
- the overall fact that development and iterative improvement of a product is a completely different business to making one

from scratch, best suited to different people with similar, but new, sets of skills.

On a more practical note, the original design team soon move on to other work and projects, leaving a management and budget vacuum that may have form and voice, but little substance. Paradoxically, almost no one can see this. Attempts at development fail after a short time, or drag on interminably, getting nowhere except the regular day-trip to their past glories.

The engineering industry is full to the rafters of examples like this – it seems to be very difficult to continually replicate sparking success. Innovators are best at innovating and are rarely good at development. For those companies and teams that are good at development, they rely (knowingly or unknowingly) on finding a stream of engineering innovation provided by others.

The most complex products, systems or ideas seem to suffer the worst from this design vs development paradox. Whereas the complexity of the original design should, in theory, cement its innovators into first place in their sector of industry, instead it covers them with a cloak of illusion that their advantage will be permanent and that competitors cannot possibly match their ingenuity, coupled with their engineering flair and balance. Time generally proves them wrong.

3.7 Creativity tools

Creativity is important in all facets of engineering design. Many of the developments in creative thinking, however, come from areas outside the engineering field. Figure 3.6 shows the five main creativity tools.

- *Brainstorming* Ideas are put forward by a group of people in a ‘freewheeling’ manner. Judgement of all ideas is deferred absolutely: no criticism is allowed. This helps stimulate originality.
- *Brainwriting* A version of brainstorming in which people contribute their ideas anonymously on slips of paper or worksheets – these are then exchanged and people develop (again anonymously) each other’s ideas in novel ways.

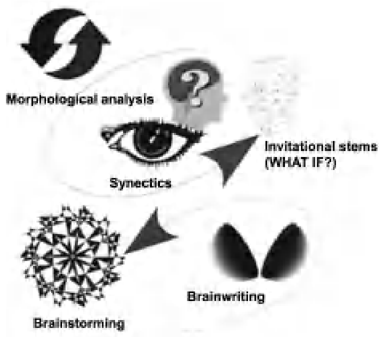


Figure 3.6

- *Synectics* A specialized technique including the joining together of existing, apparently unrelated, ideas to reveal new perspectives or solutions to a design problem.
- *Morphological analysis* This is a formal, structured method of solving design problems using matrix analysis.
- *Invitational stems (wishful thinking)* A loose and open creative process encouraged by asking questions such as 'wouldn't it be nice if' or 'what if material cost wasn't a problem here?'.

3.7.1 Useful references

A key introductory paper to the subject is:

Thompson, G. and **Lordan, M.** 1999, A review of creativity principles applied to engineering design, *Proc. Instn Mech. Engrs*, *Part E*, *J. Process Mechanical Engineering*, **213** (E1), pp. 17–31. This paper includes a list of over 70 detailed reference sources.

A list of publications concerning creative design methodologies can also be found at: http://www.isd.uni.stuttgart.de/∼rudolph/engdesign_publications.html.

3.8 The product design specification (PDS)

Whatever form the design process takes, it ends with a PDS. This sets out broad design parameters for the designed product and sits one step 'above' the detailed engineering specification.

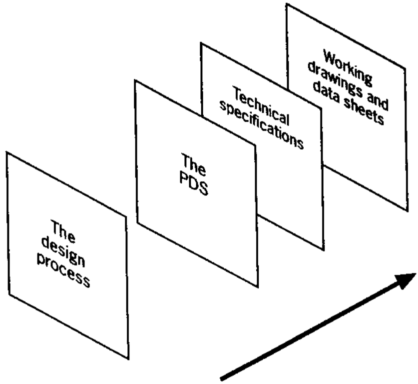


Figure 3.7

The Product Design Specification (PDS) checklist

- Quantity
- Product life-span
- Materials
- Ergonomics
- Standardization
- Aesthetics/finish
- Service life
- Performance
- Product cost
- Production timescale
- Customer preferences
- Manufacture process
- Size
- Disposal
- Market constraints
- Weight
- Maintenance
- Packing and shipping
- Quality
- Reliability
- Patents
- Safety
- Test requirements
- Colour
- Assembly
- Trade marks
- Value analysis
- Competing products
- Environmental factors
- Corrosion
- Noise levels
- Documentation
- Balance and inertia
- Storage

3.9 Presenting technical information

3.9.1 Technical information – what is it?

Technical information is information that has its roots in some sort of technique or method. It can be theoretical, practical, or a subtle mixture of the two and can be thought of as a specific form of language – the language of technology and industry. A further common factor is that technical information is related to the application of a technological skill, either in producing the information itself or using the messages it conveys.

Where is it used?

Your will see technical information used:

- in all fields of pure science;
- in all the applied sciences;
- as the bedrock of all the technical disciplines and subjects that you can think of.

Because of its wide application, the variety of types of technical information is itself wide and complex. Some disciplines (computer technology, for example) have almost a separate technical language of their own, but the majority of technical disciplines thrive on forms of technical information that have fairly general application.

What is it for?

Technical information conveys ideas between people. This is an important point – despite the proliferation of computer-generated data of all types, the prime purpose of technical information is to convey ideas, concepts, and opinions about technical matters between people. These may be rough ideas, elusive and fleeting concepts, or finely honed technical proofs and axioms – all come under the umbrella of technical information.

Does it have any other uses?

Yes. Technical information is a tool of persuasion, and the way it is presented plays a part in convincing people of others' understanding and opinions about technical subjects. All scientific and technological activities hinge around the way that technical ideas are transferred between the participants – it is this flow of technical ideas that gives a technology or a project its direction. This means that you can think of the presentation of technical information (in all its forms, remember) as perhaps *the* most common tool of science and technology.

Presenting technical information – the challenge

The world of technical information is beset with the problem of complexity. The rich technical variety that exists in every technological discipline manifests itself as an ever-increasing amount of complex information that has to be presented in an easily digestible form. The task of presenting technical information is, therefore, about finding *simple ways* to present *complex ideas*. In most cases, algebraic or mathematical expressions become too complicated to be understood by anyone but academics, so it is better to find other ways. Five guidelines are presented below.

Some guidelines

- Use graphical methods of communication wherever possible.
- Supplement algebraic and mathematical information with geometry to make it simpler and/or clearer.
- Use visual *models* to portray ideas.
- Don't be afraid of making approximations where necessary.
- Use sketches, diagrams and drawings.

There is one common factor in these five points – they all involve the use of *models* to present technical information effectively. The task of presenting technical information is therefore about constructing a representation of that information, so that its meaning can be conveyed on a computer screen or printed page.

The need for imagination

Many of the skills of effective technical presentation involve the use of imagination. Although traditional methods are well established there is always room for improvement and adaptation. Trends over the past ten years have favoured the increased use of graphical and pictorial information in preference to tables of mathematical and algebraic data – such modern presentation methods *need* the use of imagination to keep the development and improvement going. Imagination is also needed in the choice of method to be used for the presentation. It is difficult to keep technical presentations looking fresh and interesting if you use the same technique too often; you have to look for alternative ways to convey your information.

Making the choice

For any situation in which you have the task of presenting technical information, you are faced with several general choices:

- Tabulation (i.e. lists of tables of data)
- Graphical methods
- Scientific or symbolic representation
- Technical drawings of some sort
- Pictorial representation, such as sketches and three-dimensional diagrams

The choice between these is best helped along by learning to do a bit of critical thinking. Ask yourself a few questions about the situation, such as:

- Which method will help me to present this technical information in the *clearest* way?
- Is this method really suitable for this type of information, or am I just using it for convenience?
- Does this method have visual power — or does it look mediocre?
- What are the positive and negative aspects of the method I am about to use?

Remember that the purpose of this type of critical thinking is to help you to choose a good presentation technique, not to stifle any imagination you are trying to bring to the process. Viewed from this perspective, the task of presenting technical information begins to resemble a process of technical problem-solving – a logical choice between alternatives, coupled with a bit of imagination and flair to liven up the result.

Presenting technical information: A summary

- *The purpose* of presenting technical information is to convey technical ideas, facts and opinions between people. It is also a tool of persuasion.
- There are always several different ways to present any set of technical information.
- The challenge is to find simple ways to present complex ideas. This leads to five main principles of information presentation:
  - Graphical methods
  - Combining information with diagrams
  - Using 'models'
  - Making approximations
  - Using sketches and diagrams (of various types)

After all of this you have to use a little imagination and flair — and then make a decision about the best presentation method to use.

3.9.2 Categories of information

The way to better understand the general subject of technical information is to think of it as being divided into wide but precise categories. An understanding of the existence of these categories will also help you to think critically about the purpose of different types of technical information, and how to present them in the best possible way. Figure 3.8 shows the situation. Note the three main categories: guidance only, symbolic/schematic, and prescriptive – with all three capable of belonging (at the same time) to categories of information that can be described as being *in*ductive or *de*ductive. Now look at the categories in turn, as shown in Fig. 3.8.

Guidance-only information

Not all technical information is presented in a form that provides an exact description of something (an object, procedure, or idea). Its purpose is merely to give you guidance – to convey a

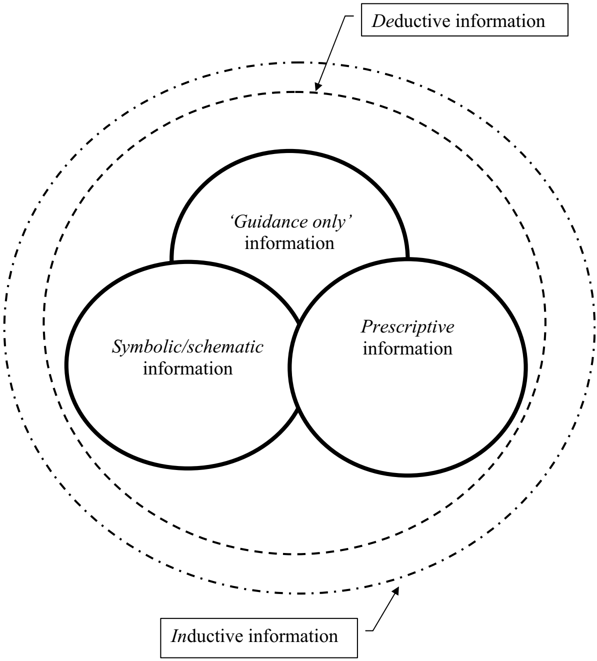


Figure 3.8 Different 'categories' of technical information

general technical idea. To do this, the method of presentation often involves approximations about:

- Fundamental relationships between, for example, technical procedures, designs or physical objects.
- Trends in size or movement.
- The physical shape and layout of objects or components.
- Dimensions.

The best way to understand this is by looking at two examples. Figure 3.9 shows a representation of a simple

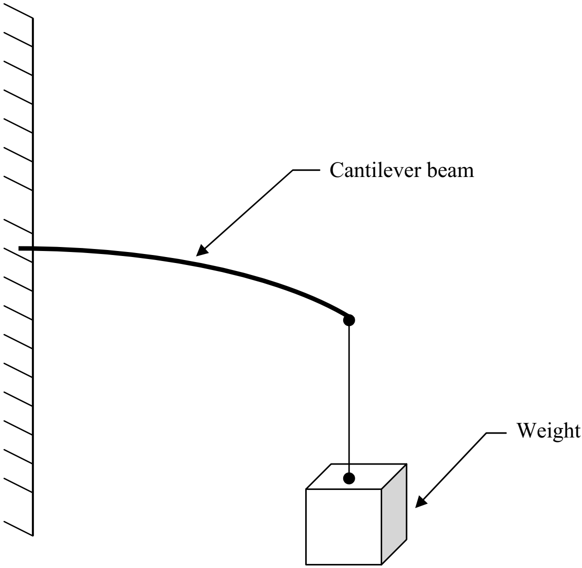


Figure 3.9 An example of 'guidance only' information

cantilever beam supporting a suspended weight. This is a graphical presentation, because it is in the form of a picture. From a quick study of the figure you should be able to infer three main points:

- The diagram is intended to show you that the beam *bends* under the influence of the weight, but not precisely how far it is bending, or the exact shape of its curvature.
- The diagram is showing you a 'general case', which would be applicable to all cantilever beams, because there is no attempt to show the length or cross-section of the beam, its material, or the even the size of the weight on the end.
- The beam and the weight, and the physical way that they relate to each other, are represented by a drawing that has a strong resemblance to the real visual world, i.e. it is similar to

the way the objects look in real life. There are obviously some approximations – the beam itself, for example, is represented by a thin line with no apparent depth or thickness, and there are no proper mechanical details of how the end of the beam locates into the wall, or how the weight is fixed to the free end. None of these, however, would stop you recognizing the physical arrangement of such a loaded beam if you saw one, so the drawing is a close *representation* of the real-life object rather than being merely a symbol.

In summary, the message that this diagram provides – i.e. that cantilever beams bend when a weight is applied – is really of use as 'guidance only'. It is a non-precise but important part of the technical picture – not exactly correct, but good enough. This type of information can be useful in many areas of technology, particularly in engineering design disciplines where technical ideas are developed in a series of steps.

Symbolic/schematic information

Symbolic and schematic types of information are so closely related that they are best thought of as a single category.

Symbols and schematics

What is a symbol?

A symbol is something that represents something else by association, resemblance, or convention.

What is a schematic?

A schematic shows the scheme or arrangement of things, normally by using symbols to artificially reduce complexity.

In practice, many methods of presenting technical information are a merger of the symbolic and schematic approaches. This is valuable in just about all technical disciplines as a way of simplifying a complex system, object, or set of technical relationships down to a level that a reader can understand. In many cases, symbolic/schematic representations are the only way to portray complex technical information in a user-friendly form. Typical examples are:

- Process Instrumentation Diagrams (PIDs) for any type of process plant.
- Hydraulic, pneumatic, electrical and similar circuit diagrams.
- Applications where it is necessary to show the *structure* of something or how it works (such as Fig. 3.10).
- Symbolic illustrations (see Fig. 3.11) which portray technical information and look nice.

One common thread running through schematic representations is that they show directly, or infer, physical interrelationships between parts of things, often in the form of a schematic plan or design. In contrast, pure symbolic representation (as in Fig. 3.11)

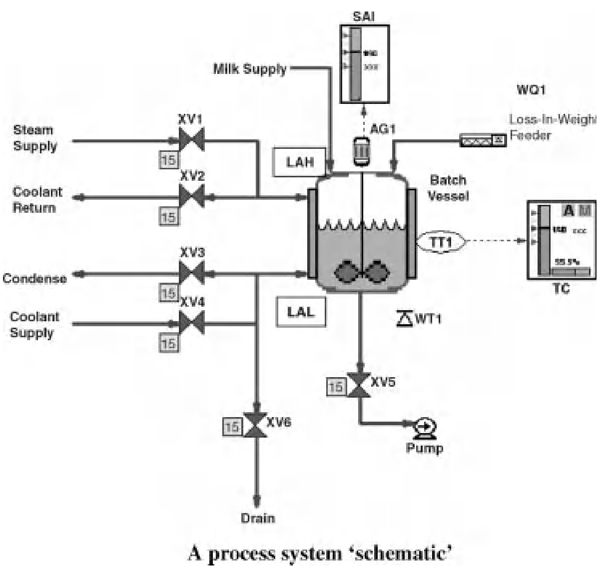


Figure 3.10 An example of schematic information

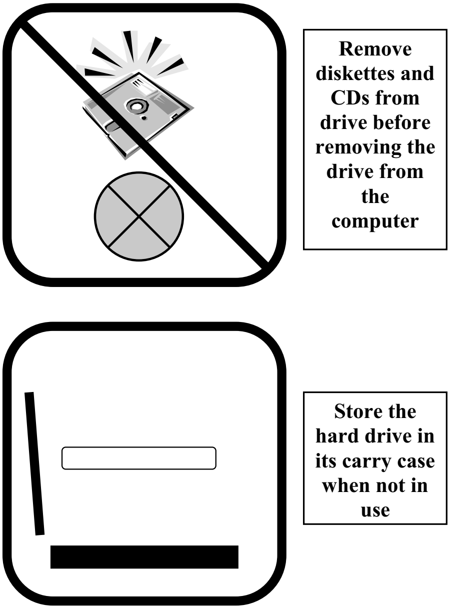


Figure 3.11 An example of symbolic information

can be more 'stand alone', or simply give a small piece of technical advice.

Prescriptive information

'Prescriptive information' is information that sets down firm rules, or provides an exact description of something. Note that the term contains the noun *prescript*, meaning a direction or decree. Not surprisingly, technical information that is prescriptive is generally complex, because it is not always possible to fully describe complex things in a simplified or shortened way. It can also have an air of rigidity about it, rooted in the fact that it is attempting to explain the unique and detailed solution to a difficult technical situation or problem.

The power of prescriptive information lies in its ability to cause people to take action, evaluate a system in a particular way, or assemble a series of engineering components in the correct order. Prescriptive information is often seen (and used) 'nearer' the single solution of technical problems – in contrast to guidance information, which is more of an upstream technique that is used during earlier stages where the technical atmosphere is more diverse and conceptual.

Prescriptive information

You can expect to see prescriptive information:

- in precise mathematical routines and algorithms;
- in manufacturing procedures;
- in instruction manuals; and
- in any situation where technical information contributes to step-by-step problem-solving.

A further feature of prescriptive information is its accuracy. Unless technical information is accurate in number and expression (as in mathematical or algebraic notation) and in form (i.e. shapes or spatial representation) it cannot really be prescriptive, because it would leave too much freedom, thereby hindering the achievement of a unique pattern or solution. This is why prescriptive information is particularly suited to technical and engineering disciplines – it thrives on hard-edged ideas.

Deductive versus inductive information

You can think of deductive and inductive information as features of the technical background against which various presentation techniques are applied, rather than discrete presentation mechanisms in themselves. A particular set of technical information may be predominantly inductive, deductive, or (more likely) a subtle combination of the two, with at least part of the definition coming from an understanding of how that technical information was *derived* rather than its effectiveness in conveying technical ideas. In short, this means that you only need to consider the deductive vs inductive qualities when you come to 'fine-tune' presented information. You don't need it in the earlier stages.

Deductive versus inductive information

Deductive information has a clear link between some previous statement (called the *premise*) and the deduced information (or *conclusion*) that is presented. If the premise is true then it is deduced that the conclusion must also be true. Compare this to the inductive situation where the premise may give support to the conclusion but does not guarantee it. Common examples are:

- Mathematical and algebraic expressions: i.e. $x + x = 2x$. Here x is the premise of sorts, and $2x$ is the conclusion, obtained when x is added to another x.
- Engineering drawings are primarily deductive because they describe (and so rely on) tightly controlled physical relationships between mechanical components that are determined before the drawing is produced.

Inductive information is information that infers a future conclusion based on previous (historical) information or happenings. Examples are:

- Statistical Process Control (SPC) in manufacturing, where the characteristics of components which are not yet manufactured are inferred by previous observation of similar already-completed parts.
- Most empirical laws (e.g. in fluids or mechanics) in which we draw conclusions about a large group of things from observations of one or two specific cases.

You should now be able to see how the differences between inductive and deductive information can be built into the way that technical information is presented. Technical theories, alternatives, and concepts are suited to the use of inductive information because it is never intended that the information is absolutely traceable to a proven premise. Think how this applies to chemistry, materials science, and the gas laws. Newton's laws of motion are also empirical (they have no proof as such) so dynamics and kinematics are disciplines in which technical information is presented in an inductive form. Once these routines are applied for use in engineering disciplines, however, and are metamorphosed into engineering *designs*, the technical information becomes heavily *de*ductive, as it takes its place in the search for precise solutions to engineering problems. Remember that these definitions only become relevant when presentation methods for technical information become heavily refined – they have little relevance to the simpler, (often 'guidance only') forms of presentation.

Graphical methods

The term 'graphical' refers more to the way that information is presented than the nature or purpose of the information itself. The character of some types of technical information makes it particularly suitable to being displayed in graphical form. Graphs are best at showing *relationships*. These may be tight algebraic relationships linked by rigid constants and coefficients, or softer more inferred ones providing information in the form of general guidance and trends. The power of graphical methods lies in their ability to provide answers to several questions at once. A single graph can, if correctly constructed, hold information about:

- linear and non-linear relationships;
- equalities;
- inequalities;
- relationships in time and/or space;
- looser concepts such as regression, correlation and trend.

Because of the complexity that can result, graphical presentations need to be properly ordered if they are to communicate their information clearly.

The character of graphical presentation allows for a wide variety of different types, but brings with it the corresponding disadvantage of an equally wide variety of distortions and misinterpretations. The effective visual impact of graphs means that it is easy to show information in a way that is capable of misinterpretation. You can also make it persuasive or misleading, if that is your intention.

Conventions

Conventions play a pivotal role in the presentation of technical information. They are used in both algebraic and graphical methods to bring uniformity to the way that information is presented (and interpreted) whilst still allowing a degree of flexibility. Don't confuse this with a set of rigid rules, which also bring uniformity, but at the expense of variety and imagination. The conventions themselves are simple – you can think of them as lowest common denominators of the presentation techniques. Some conventions are detailed below.

Scalar methods—Scalar methods use quantities (*scalar* quantities) that have a single 'real number' dimension only — normally magnitude or size. So, any presentation technique that compares information on size only can be loosely referred to as a scalar technique. Figure 3.12 gives some examples. Scalars have the following advantages:

- they are simple;
- quantities can be added, subtracted, and compared using algebraic methods such as addition and subtraction.

Vector methods—Vector methods have more than one dimension; normally size and direction. The appearance of this second quantity is important, as it creates the conditions for illustrating multiple types of information about the subject being presented. Figure 3.13 shows some examples. Vector methods are:

- detailed (or can be);
- useful for showing complex technical situations in many different technical disciplines;
- more difficult to compare with other forms of information — you will not always be comparing 'like with like'.

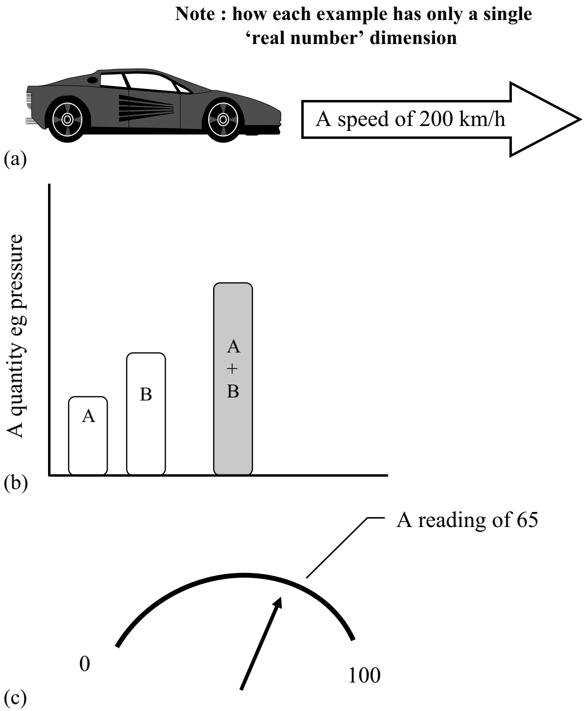


Figure 3.12 Examples of scalar methods

Matrix methods—A matrix is simply a particular type of framework in which information is contained. A common use is as a way to represent a system of mathematical equations containing several unknowns. This forms part of the subject of matrix theory which, together with linear algebra, is used to present information and solve problems in disciplines such as pure mathematics, analysis of structures, thermodynamics and fluid mechanics. Such matrices take the form of an array of 'elements' enclosed in brackets (Fig 3.14(a)).

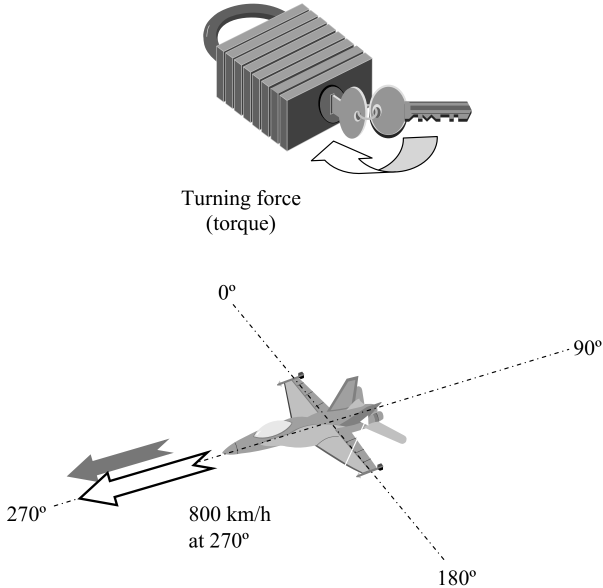


Figure 3.13 Examples of vector methods

$$M_1 = \begin{pmatrix} -2 & 0 & 1 \\ 15 & 3 & -1 \\ 0 & 1 & 2 \end{pmatrix}$$

Figures enclosed in brackets or vertical lines

$$M_2 = \begin{pmatrix} -2 & 0 & 1 \\ -4 & 3 & 8 \\ 0 & 1 & 2 \end{pmatrix}$$

Each matrix *row* represents one equation - the numbers are the coefficients of the variables in the equations

Figure 3.14(a) A set of mathematical *quantitative* matrices

Matrices are also used in their more general sense to display technical information that can be contained in an arrangement of rows and columns. They can exhibit qualitative data about things that have multiple properties, and are particularly useful for use as a selection tool in the design process. Figure 3.14(b) shows a typical example.

This matrix shows qualitative data about design options

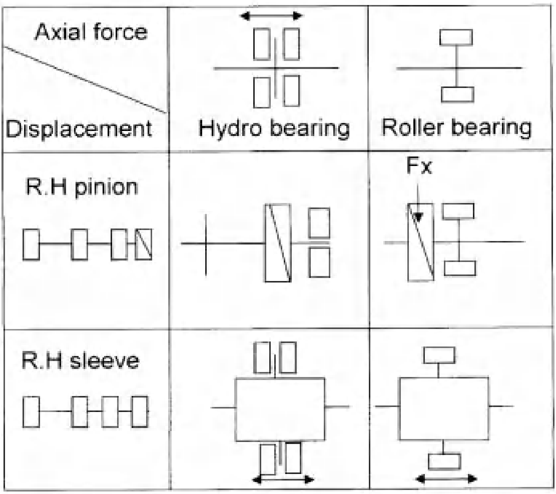


Figure 3.14(b) A *qualitative* use of a matrix

Dimensions—It is convention that graphical and pictorial information can be presented in either one-dimensional (1-D), two-dimensional (2-D), or three-dimensional (3-D) form.

1-D forms, such as simple line graphs, often look as if they are in 2-D format but in reality only convey a single 'dimension field' of information (see Fig. 3.15(a)) – which could if necessary be conveyed by single lines. 1-D information is therefore, by definition, capable of being conveyed by the use of simple lines of negligible thickness (Fig. 3.15(b)).

2-D information conveys information relevant to either two spatial dimensions (x and y axis for example) or to two alternative 'dimension fields' (see Fig. 3.15(c)). As most diagrammatic and pictorial information is presented in 2-D format, it has wide application across the technical and engineering disciplines. 2-D presentations are also useful in that they can masquerade as 3-D views in applications such as wireframe drawings.

3-D presentations are used to portray pictorial views of technical objects. There are several types, each with their own advantages and disadvantages.

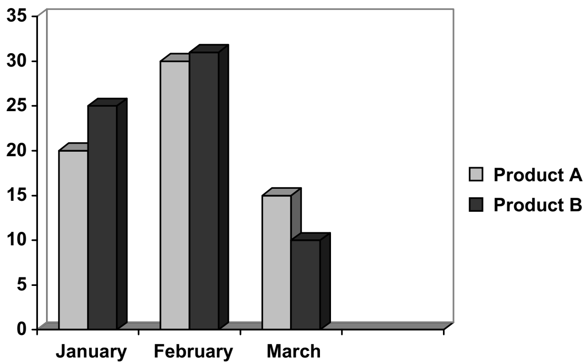


Figure 3.15(a) Sample of a 2-D or 3-D information

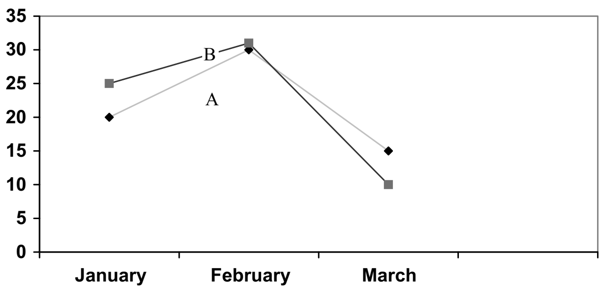


Figure 3.15(b) The actual 1-D message of Figure 3.15(a)

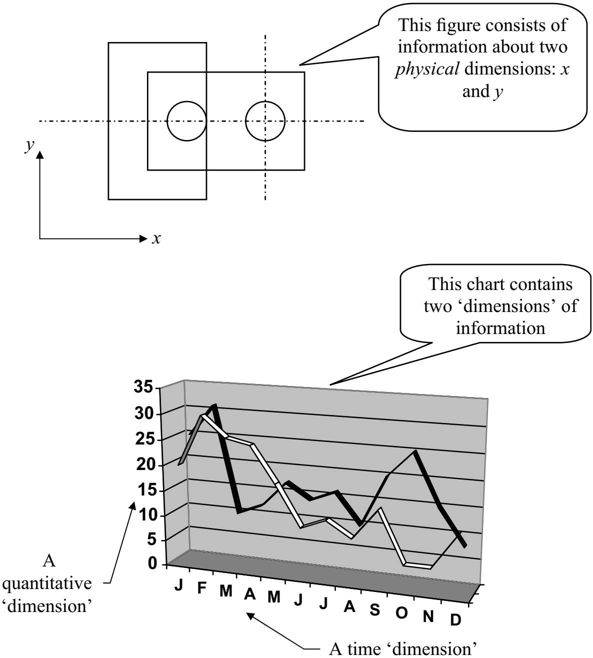


Figure 3.15(c). Two different types of 'two-dimensional' information for Figure 3.15(a)

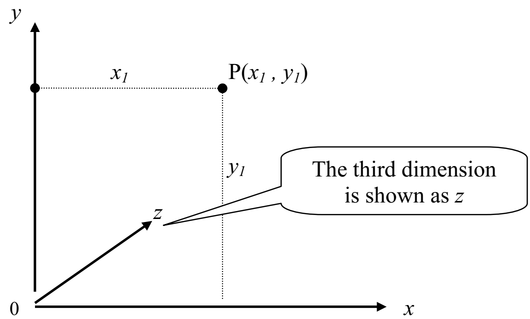
Reminder – Conventions

Conventions act as the unwritten rules of technical presentation. They bring a level of uniformity to the way that information is shown. The main ones are:

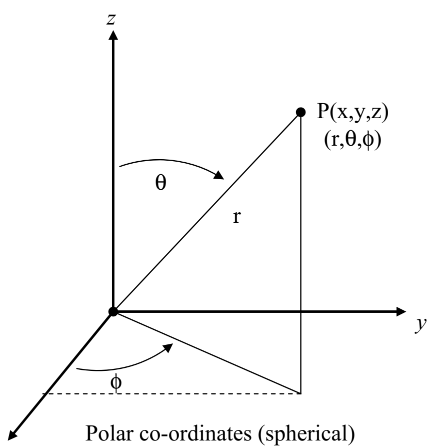
- scalar vs vector presentation;
- matrix conventions;
- 1-D, 2-D and 3-D methods.

Remember that these conventions apply to all forms of technical presentations, not just simple ones in which the conventions may be instantly apparent.

Co-ordinates—Co-ordinates are a method used to locate the position of points, lines and objects in space. They are relevant to most forms of technical presentation that involve accurate graphs or drawings. Figure 3.16 shows the two main co-ordinate systems — note that they can be expressed in either 2-D or 3-D form. The Cartesian system using *x*, *y*, *z* axes and their positive/



Cartesian co-ordinates



Polar co-ordinates (spherical)

Figure 3.16 The main co-ordinate systems negative sign conventions is more commonly used for 3-D application than the 'polar' system, which is easier to depict when limited to use in two dimensions. Readings in either of these two systems of co-ordinates can be easily converted to the other. Note, however, that the fundamental differences in their sign convention means that they are rarely seen being used together.

Presenting technical information – Key point summary

- Technical information has its roots in some sort of technique or method.
- It is used in all technical subjects (see Fig. 3.17)
- Good presentation of technical information involves understanding the traditional methods and then applying some imagination.
- Technical presentation is about *choice*. There are often several different ways to show the same thing.
- The important categories of technical information are:
  - Guidance-only
  - Symbolic/schematic
  - Prescriptive
  - Deductive and inductive
  - Graphical methods
- These categories are often cross-linked and combined.

Don't forget conventions such as scalar, vector and matrix methods, and the two main co-ordinate systems: Cartesian and polar.

3.10 The anatomy of mechanical design

Stripped bare, mechanical design is a bit like economics; driven by one main thing: s*carcity*. Scarcity is the state when something is in short supply. There is not as much to go round as everyone would like, so the desirability goes up. In stark contrast to economics, however, engineering design is

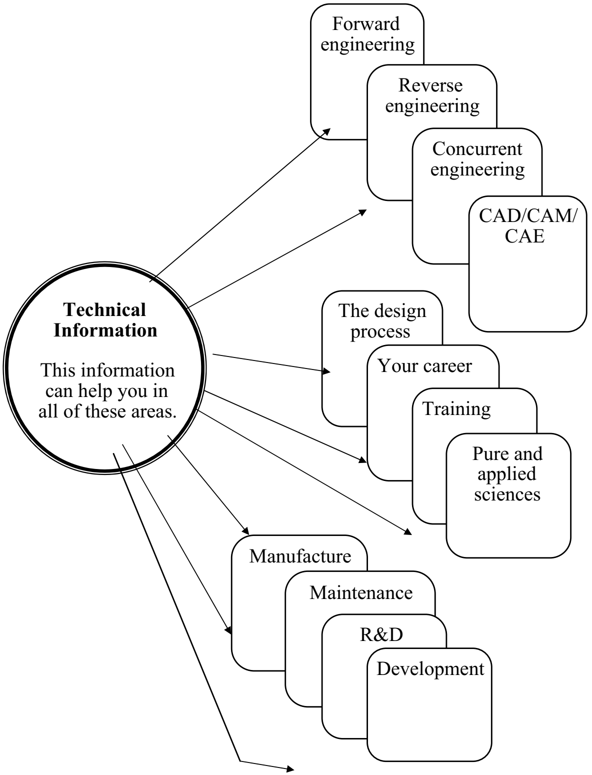


Figure 3.17 Using this information

composed of things you can see, feel and measure, rather than loose concepts and theories surrounded by elusive woolly clouds of this and that.

How does this scarcity show itself? It starts as the driving force that produces the *need* for an engineering product or design. Think of the scarcity of coal leading to the drive to design the steam engine to pump out the mines that produced the coal, and you've got the idea. In a similar way, the scarcity of specialist computer programming skills led to the drive to produce the graphical-user interface with its easy-to-use on-screen icons.

Scarcity really comes into its own, however, when you consider its effect on the *product* (design) side of the equation. The final design of almost any mechanical product is the end result of a series of competitions for things that would make the design 'better', but are in short supply. This is a change from thinking of the design process as a set of linked activities, expressed perhaps in some kind of schematic flowchart or diagram, but it is a fairly accurate reflection of what actually happens.

Figure 3.18 shows the five main things that suffer from the eternal problem of scarcity. Try as they might, there is no way they can escape from it. It is always there, an unseen guiding hand, controlling how each feature can grow and flourish, and how they relate to each other. It's a competition, remember.

The fight for space

In any design, physical space is always at a premium. Small, lights cars are great, but if you need space for multiple occupants they get bigger, and so heavier. Similarly, if you need space for luggage you have to achieve it at the expense of reduced passenger-seating space. The allocation of space to competing design functions (e.g. space for luggage vs space for people) is loosely called *disposition*. Modern design is getting very good at optimizing this. Think of these examples.

- *On-screen keyboards for compact computers*. You need a minimum size of screen to be able to see it, so why not use it to show the keyboard, rather than competing for space with a separate one?
- *Flexible seating in MPV vehicles*. Folding, sliding and/or removable seats allow valuable space to be configured for occupants ***or*** luggage, depending on the need.
- *3-D modelling*. Computer-package modelling of pipework, etc., layouts enables complex piping systems to be shoe-

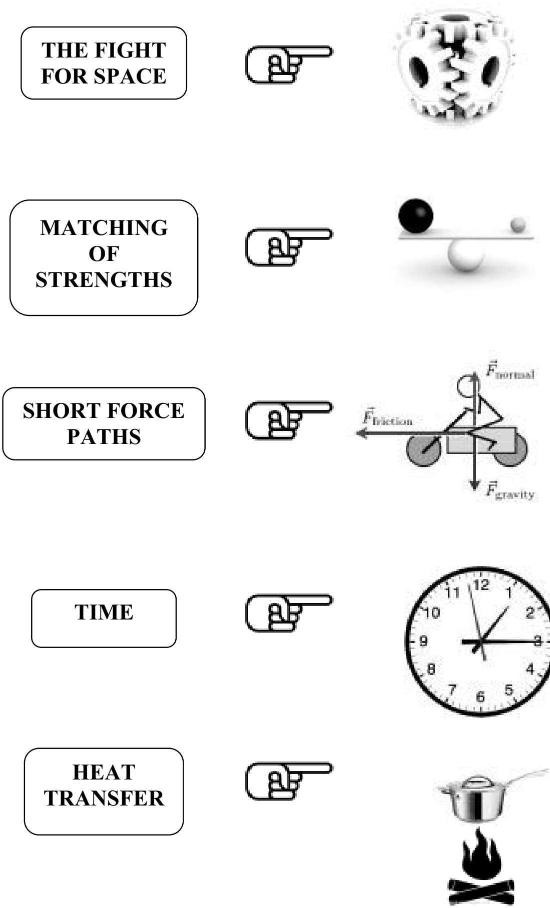


Figure 3.18 Five design factors that suffer from scarcity

horned into the smallest possible space, reducing pipe lengths, weight and therefore cost.

The matching of strengths

Any chain is only as strong as its weakest link. It makes no sense to have oversized components, consuming space and cost, connected to undersized weak ones, which will break before the strong component has even had half a chance to impress its neighbours. For structures, efficient design is about optimizing the scarce resource of the capability to resist load. Each member (strut, tie or beam) would ideally be stressed to the same percentage of the allowable stress it can safely withstand. As load (and, if applicable, time) increases, then eventually all the components would break, neatly and on cue, at exactly the same time.

For mechanisms (containing dynamic elements that move), a similar situation applies, but this time it is not just about force paths, but the transmission of movement, work and power. Think of torsion (a common method of transmitting power, as in an engine or gearbox) as simply a specific case of component loading. The idealized objective is once again to load each member to an identical degree, keeping the sizes of all interconnecting shafts, gears and similar components to the ideal level when, with an excessive increase in load, they would all fail together.

Short force paths

For structures and mechanisms one of the keys to both strength and space issues is that of using *short force paths*. Force (static) and movement (power transmission) both need a path to follow in order that they can appear at a location other than the point at which they were applied. Figure 3.19 shows the idea. Good designs have force paths that are kept short. This keeps bending and torsion to a minimum. Conversely, long force paths encourage bending, resulting in large deflections or torsional distortion. These are particularly bad ideas when acceleration is involved, which will exaggerate the effect of forces.

Examples of short force paths are hidden away in their hundreds in everyday engineering objects. Figure 3.20 shows another example.

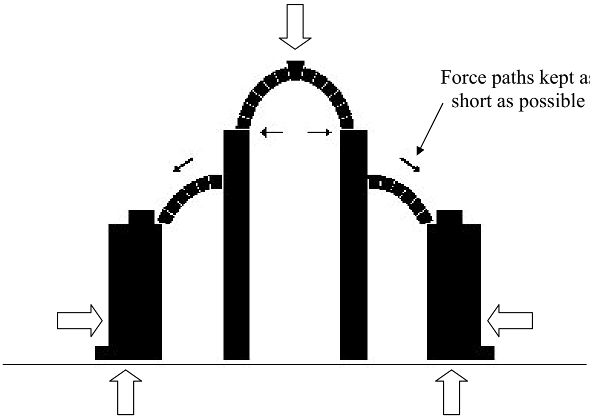


Figure 3.19 Force paths; The flying buttress

Time waits for no one

For mechanical items containing moving parts, as opposed to static structures, time is an important constraint. On balance, it is keeping time to a *minimum* that is the most difficult, i.e. it is relatively easy to get something to happen slowly, but much more difficult to get some movement or action completed quickly.

Physical movement infers a mechanism of some sort. Components such as engines and gearboxes contain hundreds of individual machine elements involved in a variety of rotating, reciprocating, twisting or bending motions. All these movements must happen in the correct place, and at the right time to make the component work as intended.

Conceptually (and practically), the control of time is easy. The time that a component will take to travel from A to B is governed by only two things:

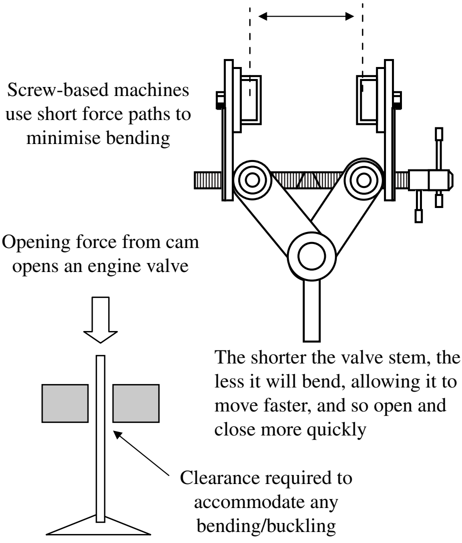


Figure 3.20 Examples of short force paths

- its velocity between A and B; and
- the physical distance from A to B.

If the design need is to reduce the time, this can be achieved by either making the velocity higher, or the distance shorter, or a little of both. Reducing times allows you to make:

- engines faster
- switches more positive
- pumps more efficient
- almost any mechanical component better.

Here are some common examples:

- *Cycle 'Derailleur' gears* (Fig. 3.21). The chain jumps between sprockets with a very quick, positive movement when changing gears. This innovative design goes back to its incarnation in the 1930s but still remains the best way to do the job.

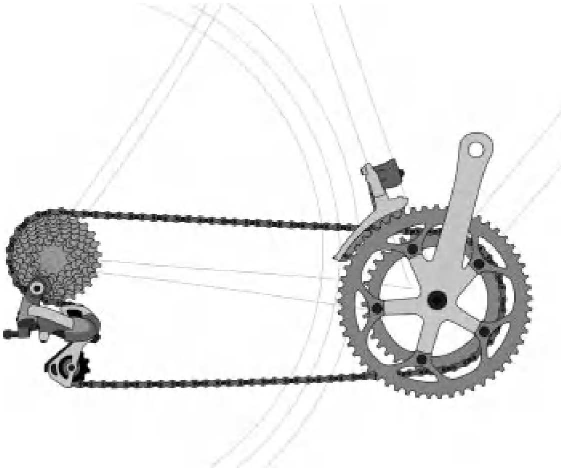


Figure 3.21 Derailleur gear; an example of a 'quick change' mechanism

- *Diesel engine injectors*. Fuel injection into a diesel engine cylinder needs to start, and stop, very quickly. Rapid electronic triggering, with very small physical movement of the injector components, allows the injector to open quickly, and then shut quickly (strong springs give a high velocity). This allows a higher rpm, bringing the potential for increased power.

Good design is therefore about short movements, high speeds and minimal clearances. Any clearance required between two mechanical components (to allow for thermal expansion, misalignment, inaccurate manufacture or whatever) represents 'dead motion', i.e. motion (and hence time) that is wasted. Tight clearances of course require a high accuracy of manufacture.

If the distance between A and B cannot be reduced, the only other solution is to increase the velocity of the component, so that it gets from A to B more quickly. Sadly, constant velocity is a rare concept. Many engineering mechanisms and rotational machines, such as turbines, have constant velocity in some components, until they are subject to vibration when it all goes horribly wrong owing to reciprocating movements. For a component to reciprocate it has to stop and start at either end of a period of movement. This applies whether the reciprocation is planned and predictable (like simple harmonic motion, for example), or random and non-sinusoidal. Stopping and starting brings *acceleration* and its opposite and equally-damaging cousin *deceleration*. On balance it is these that cause components to break rather than velocity. Therefore, in the search for keeping movement time to a minimum, acceleration is a major enemy.

The race from hot to cold

Engines of all types, and many other machines, rely on thermodynamics to make them work. The laws of thermodynamics, all discovered hundreds of years ago, sit quietly in the wings controlling precisely what you can and cannot do. Their advantages allow you to design machines around thermodynamic cycles that work and their limitations tell you precisely what you *can't do*. Try to circumvent these, and you will fail, every time.

There is little more to thermodynamics than the fact that heat will move from hot to cold. A hot body will always lose heat to a nearby cold one, if it can find a route to travel by. Change the speeds of this transfer at various times and places and you have the building blocks of a thermodynamic cycle: adiabatic, isothermal, Carnot or whatever. Once you find a way to get something useful out of the cycle (heat from a boiler cycle, power from an engine cycle, or cooling from a refrigeration cycle) then all you have to do is build the physical parts around it, and away you go (Fig. 3.22 shows an example).

Getting heat from hot to cold is easy because physics will do it for you. Thermal design, therefore, comes down to managing the *transfer* from hot to cold. It is not so much a race as a carefully choreographed procession, with all the bits of heat moving at the correct speed and at the right time. As with the

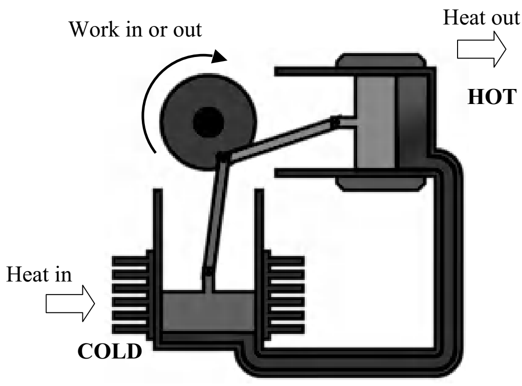


Figure 3.22 Engine cycles: managing the transfer from hot to cold

previous parameters we saw of strength and space, it inevitably ends up as a compromise. The difficulty comes once again in controlling the timescale of the whole affair. Remember the three possible methods of this transfer:

- Conduction
- Convection
- Radiation.

Conduction is fairly predictable. As the conductivity of most materials is well known, the design choice is so difficult. The problem tends to come from combining conductivity with the mechanical properties required. High conductivity materials can be quite weak (copper and aluminium are good examples) so expect the answer to be a compromise.

Radiation is no great mystery either. Properties such as surface emissivity and reflectivity are well defined. Physical distance and space arise again, however, as constraints. On balance, convection is the most difficult to predict, relying on empirical (experimental) results to validate the output of software models. Engine cooling systems, boilers and refrigeration systems are examples of convective systems that developed gradually by iteration and trial and error, rather than appearing in final form almost overnight.

And finally cost

Remember that all of this design activity costs money, and a continuous stream of expenditure can be expected from start to finish.

It is easy to think of cost as a separate category in the anatomy of mechanical design, but of course it is not. It is the direct function of all the others put together. Think of it as a 100% unbreakable correlation – the longer and deeper, and the more iterative the design process, the more that it will all cost. This takes us full circle to the start – the force of scarcity that is the overall driver of the design process. Remember our definition of scarcity:

- *Scarcity is the state when something is in short supply.*

We then have a match where money is used as the universal indication of scarcity. If something is in short supply, the cost will always rise, although the time it takes to do so will vary. Under this set of game rules, the dangers become obvious: designs are driven by the need to reduce cost; products made on a budget may not do their job well or may soon break down; and the marketing and branding departments will then try to make the product look good by presenting and packaging it as a quality item. And there you have it – on the shelf.

Summary

Design is driven by Scarcity

Make sure you use the engineering manifestation of this to work for you because, if you don't . . .

The only better thing about *your* product is that it will cost less.

3.11 Safety in design – principles and practice

Straight thinking about safety in design involves linking together the principles and the practice; both have an engineering basis tempered by common sense.

3.11.1 Safety principles

There are three fundamental principles of design safety, as shown in Fig. 3.23. These are, in *ascending* order of effectiveness: warnings, protection, and avoidance.

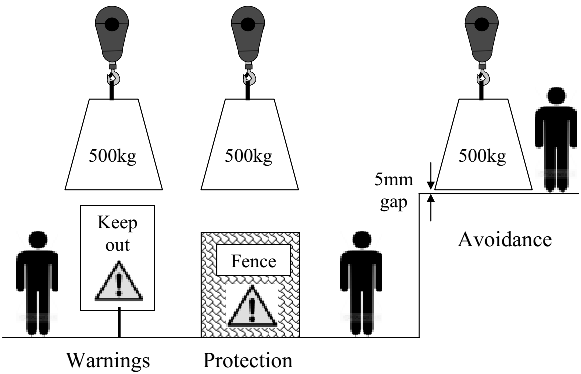


Figure 3.23 Principles of design safety. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

Warnings

Warnings are the least effective method of trying to ensure design safety, but still the most common. Whilst signs and instructions may warn of a danger, they don't make it go away, or make its effect any less. Warnings are passive and don't work particularly well.

Protective features

This is an indirect method of design safety. It comes in many forms but all have the characteristics of relying on *protecting* people from a danger (or failure) or mitigating its effects in some way. The danger itself, however, does not go away. Some typical examples are:

- ***Control and regulation systems* –** These give a basic form of protection by keeping the operation of a process or item of equipment within a set of predetermined safe limits. This minimizes the danger of failure. An example is the combustion control system on a boiler which acts as a safety system because it limits, albeit indirectly, the steam pressure.

- ***Design diversity*** **–** This is a more subtle principle. The idea of using different design principles within the same design gives protection against common-mode faults and failures. It almost guarantees that any fault that does occur unexpectedly will not be replicated throughout the entire design – so it will not 'fail' completely. Computer software systems are a classic example of this approach, but it is also employed in mechanical equipment by using different materials, types of bearings and sealing arrangements, fluid flowpaths, speeds, etc.
- ***Factors of safety*** **–** Factors of safety, design margins, conservatism, prudence – these are all protective instruments, used to reduce the risk of dangers caused by failure. They apply to mechanical, electrical and electronic systems. Sometimes they are carefully calculated using known properties and failure modes, but at other times they are chosen as a *substitute* for detailed design knowledge. In all too many engineering designs, data on material performance or the state of loading of individual components, and a unanimous understanding of how things actually fail, are imperfect. Fatigue life calculations are a good example in which factors of safety are more *palliative* than prescriptive.
- ***General protective devices*** **–** Again, there are different types: safety valves on boilers, overspeed trips on engines; overcurrent devices – fuses and reverse power protection on electrical equipment being typical examples. Larger equipment installations have separate protective systems, often with features such as duplication, diversity and a self-monitoring capability, to keep the level of risk down. A related type of indirect design safety feature is the *lock-out*, which prevents a component or piece of equipment that is in a dangerous state from being put into operation.

Avoidance features

Avoidance is the principle of achieving safety by choosing a design solution that eliminates danger from the outset. It is by far the most direct (and best) method of ensuring design safety – although not always possible. Eliminating potential dangers starts at the embodiment stage of the engineering design process and feeds forward into the engineering specifications for a piece of equipment. There is often a link, of sorts, with some of the protective features described previously. You can think of danger avoidance features as fitting neatly into three separate principles: fail-safe, safe-life, and redundancy.

The fail-safe principle

This is not quite the same as having protective devices. The idea is that a piece of equipment is designed to *allow for* a failure during its service life but the design is such that the failure has no grave effects. The failure is *controlled*. There are a few ways to do this:

- First and foremost, there must be some way of identifying that the failure has happened – it must be signalled.
- The failure must be *restricted*, i.e. for a machine, it must keep operating, albeit in a limited or restricted way, until it can be safely taken out of operation without causing danger.
- The implications of failure of a single component, need to be understood and assessable as to the effect that it will have on the total machine or system design.

All these presuppose that the consequences of failure are properly understood by the designer – a precise understanding of the definitions is less important than the need to develop a clear view of how a component can fail and what the consequences will be. A useful tool to help with this is the technique of *fault tree analysis* (FTA). You may see variations of this, a common one is 'failure modes effect analysis' (FMEA). There are small differences between them, but the principles are the same. To perform an FTA, you list all the possible modes of failure of a design, and display the consequences of each failure in a network or 'tree' diagram. Figure 3.24 shows an example for a bolted steam pipe joint. Note how the tree starts from the smallest, most divisible components and moves 'outwards' to encompass the design of the 'system' (the bolted

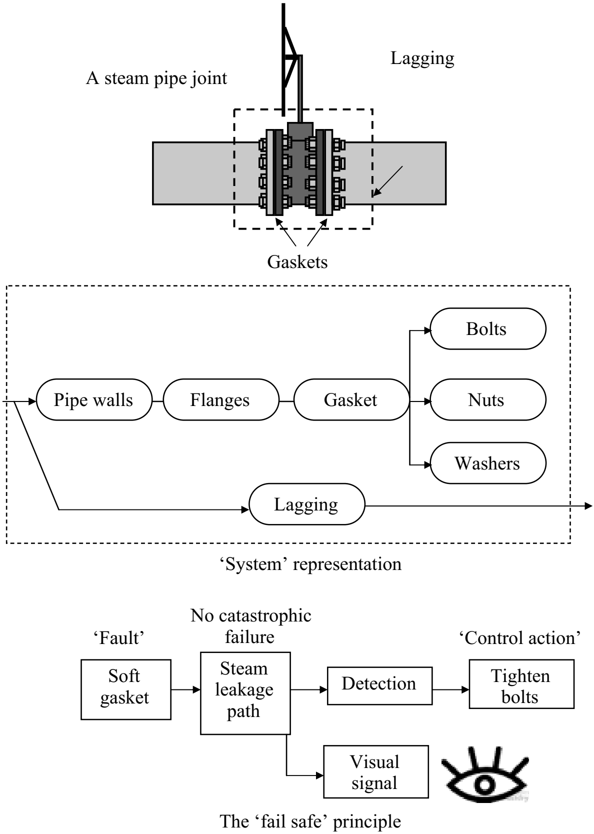


Figure 3.24 A typical component system analysis. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

joint). FTA is of greatest use on complex designs consisting of interlinked and nested systems. Oil and gas installations, nuclear plants, airliners, weapons systems and most electronic products are assessed using FTA techniques.

The safe-life principle

This sounds rather obvious: all design components (mechanical, electrical or electronic remember) need to be designed for an adequate *lifetime* to ensure that they won't fail during their working life. In practice, it is not as easy as it sounds – safety is based exclusively on accurate quantitative and qualitative knowledge (yours) of all the influences at work on a component. It is, frankly, almost impossible to do this from scratch every time you do a design – you have to rely on previous, proven practices. There are four areas to consider:

- Safe *embodiment* design based on proven principles and calculations. This means technical standards and codes of practice —but note that not all of them contain embodiment design details.
- Careful specification of *operating conditions*. Operating conditions for engineering components have to be described fully. Fatigue, creep and corrosive conditions are important for mechanical components as they have a significant effect on material lifetime. For electrical equipment, environmental conditions (heat, dust, dampness, sunlight, etc.) can soon reduce lifetime.
- Safe operating *limits* – –again, it is easy to overlook some of the operating limits of engineering components. Low-cycle fatigue and high-temperature creep cause the most mechanical failures if they are overlooked at the design stage. Stresses due to dynamic and shock loadings are another problem area. These failures often occur well within the estimated lifetime of a component.
- Analysis of *overload conditions*. It is not good enough just to consider normal working stresses, currents or speeds, you need to look for the overload condition.

Many mechanical equipment designs have an accepted way of calculating their projected lifetime. Contact bearings are designed using well-proven lifetime projections expressed as an 'L-number'. High-pressure boilers and steam vessels' technical standards specify calculation methods for creep and fatigue life. Safety-critical items such as structures for nuclear reactors, aircraft, tall buildings and high-integrity rotating plant are also designed in this way. There are, however, numerous items of equipment for which the technical standards do not address lifetime. The common mechanical engineering standards covering, for example, steel castings and forgings place great emphasis on specifying detailed mechanical and chemical properties, but hardly mention fatigue life. To compensate, manufacturers of specialized forged and cast components do in-house tests and develop their own rules and practices for defining (and improving) component lifetime.

The redundancy principle

Redundancy is a common way of improving both the safety and reliability of a design – it is also easily misunderstood. The most common misconception is that incorporating redundancy always increases design safety but there are many cases where this is not true. What do you think of the following statement?

- *An airliner with four engines is safer than one with two engines.*

There appears to be some logic in this. On long-haul Atlantic routes the theory is that a four-engined aircraft can suffer two engine failures and still complete the journey safely using the two remaining engines. This is fine for some types of engine failure, but what if an engine suffers a major blade breakage and the damaged pieces smash through the engine casing into the wing fuel tanks? Here the redundancy has no positive effect, in fact there is a counter-argument that four engines have twice the chance of going wrong than do two. The central message is that redundancy is not a substitute for the proper design use of the fail-safe and safe-life principles. Redundancy *can* increase design safety, but only if the redundant components are themselves designed using fail-safe and safe-life considerations. Some specific examples of design redundancy are shown in Fig. 3.25. Note the different types, and the definitions that go with them. These definitions are not rigid, or unique – their main purpose is to help you to think about and identify the different options that are available.

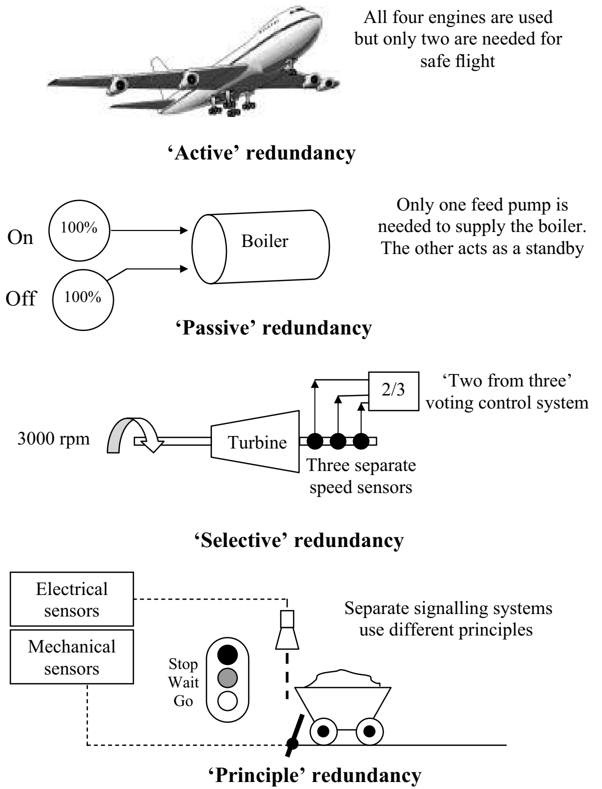


Figure 3.25 Types of design redundancy. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

3.11.2 Embodiment design safety

Embodiment – A re-think

Embodiment design is what happens in the rather large grey area between conceptual design, and detailed engineering design where a system or machine is described by a set of specifications and drawings. Embodiment is therefore about *deciding engineering*

The Danger	Comment
Stored energy	Potential and kinetic energy can be dangerous. Stored pressure energy is a particular hazard if released in an uncontrolled way.
Rotating machinery	Rotating belts, couplings gears, fans — anywhere where there is relative movement between a machine and humans is a potential danger.
'Crushing and trap' gaps	Gaps of more than about 8 mm between moving parts can trap fingers.
Exposed electrics	Exposed electrical equipment is an obvious danger.
Hot parts	Components or fluids above about 50ºC will cause burns.
Falling and slipping places	If there is a place possible to fall or slip, someone will always find it.
Noise	Excessive noise is a recognised industrial hazard

Figure 3.26 Typical design 'dangers'. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

features. Hence, deciding safety features is part of the embodiment process but is not all of it; other engineering considerations (the main one being *function*) have also to be included. The process of identifying general design safety features is easier than choosing between all the available alternatives. This is because, unlike, for example, the mechanical strength of a component design, safety cannot easily be expressed in quantitative terms, so you often have to work without clear-cut acceptance criteria that you can use to compare the safety level of different designs. It is easy to make general statements about design safety, but not so easy to translate these into the language and features of embodiment design. The best place to start is with a list of design *dangers* and then consider them as you think, in turn, about each part of a design. These design dangers are different, in detail, for each individual component or system design, depending upon what it does, but the general principles are common. Figure 3.26 shows a typical list of design dangers. We can use these as part of a series of steps to tease out good safety features during the embodiment process.

Step 1: Split the design into*systems*

Any technical design, simple or complex, can be thought of as consisting of interconnected systems. These systems come

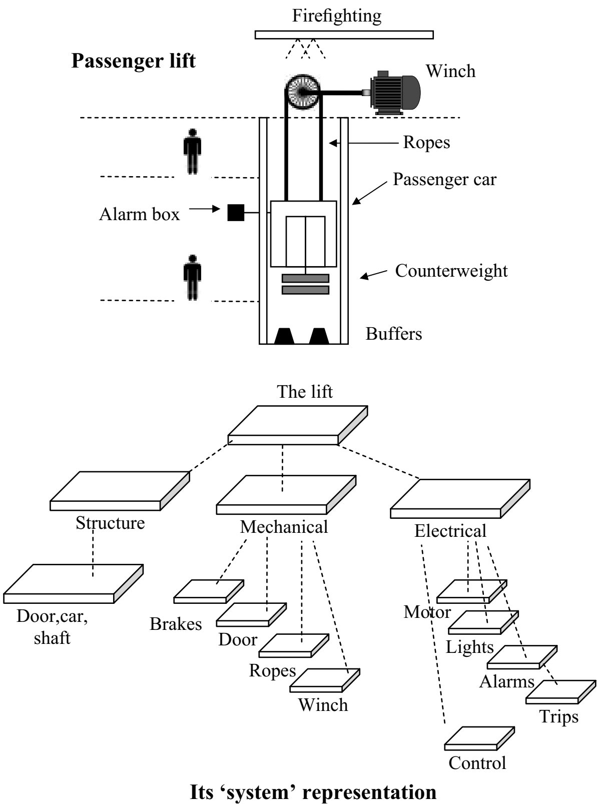


Figure 3.27 Representing a design as 'systems'. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

together to make a design 'work'. The methodology of this should be easier to understand by studying Fig. 3.27 – a simple passenger lift showing the design broken down using this type of systems approach. The lower part of the figure shows the function of the lift split into three primary systems: structure, mechanics and electrics. This primary system allocation is the most important, so note two points:

- Are you comfortable with the way that the lift shaft and car *structure* is shown as a system?
- A 'system' does not have to be a process, or an electrical or control network. Structures and mechanical components can also be thought of as systems.

Each primary system is then subdivided into its constituent subsystems, which gives a better resolution of what each subsystem actually does. In theory, you could go on indefinitely subdividing systems down the levels – a good practical approach. For the purposes of looking at embodiment design, it is best to use no more than three levels, as further subdivisions will overcomplicate the analysis.

Step 2: Consider redundancy

Try to think about redundancy before you get too involved with the details of individual parts of a design. The best technique is to list the various options, showing how they can apply to each system. Figure 3.28 shows a sample for the passenger lift design — note how it incorporates each of the four different types of redundancy shown previously in Fig. 3.25.

Step 3: List the danger features

You have to do this system by system. Any attempt to short-circuit the exercise by trying to 'home in' intuitively on the danger features that you feel are most obvious, or think of first, will not give the best results. Its steps need to be a systematic exercise — this is the whole key to opening up the problem and being able to identify *all* the design safety features, not just the easy ones. Figure 3.29 shows a typical analysis of danger features for one of the systems of the passenger lift. First you have to identify a danger feature, then do something about it. Now is the time to introduce the principles of design safety discussed earlier: avoidance features, protective features and warnings; in this order of preference.

Passenger Lift	A typical redundancy evaluation			
	Active	**Passive**	**Selective**	**Principle**
Shaft structure	High FOS	-	-	-
Car structure	**High FOS**	-	-	-
Winch	High FOS	-	-	-
Brakes	Multiple brake pads	Centrifugal brake	-	Electrical and centrifugal
Ropes	Multiple ropes	-	-	-
Doors	Parallel doors	-	Door closing	-
Motors	Design margins	Standby motor	-	-
Lights	Multiple lights	**Emergency lights**	-	Mains and battery
Alarms	Multiple sensors	Standby electrics	**Fire alarms**	Smoke and fire alarms
Trips	Multiple microswitches	Parallel circuits	Selective circuits	Mains and battery
Control	Multiple circuit	Parallel circuits	Selective positions	Electronic and hard-wired

FOS = Factor ofsafety

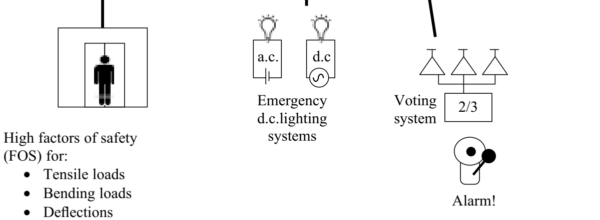


Figure 3.28 A redundancy evaluation. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

Good, objective embodiment design is about eliminating design safety problems at source, before they get *into* the design. It is a proven fact that once a feature becomes an accepted part of a design, and progress is made through the detailed engineering stage, it becomes very difficult to change it, without having to make changes to other (probably desirable) design features also. Natural reaction is to leave the original design features in, hence the only way to cover up the dangerous design feature is by *protection* — a less than ideal method, as we have seen.

Passenger lift door system:Embodiment/safety design features							
Design feature		***Avoidance***		***Protection***			***Warnings***
		Fail-safe	***Safe-Life***	***Control***	***FOS***	***Protection system***	
Stored energy	Door closing force	Soft door seals	Slow closing	Manual opening facility	Low closing force	Proximity interlock for doors	Yes
Rotating parts	External pulleys	Pulleys outside car	NA	NA	NA	Maintenance interlock	No
Crush and trap gaps	Between doors/top & bottom	<5mm gaps	NA	Manual opening	NA	Proximity interlock for doors	Yes
Exposed electrics	Behind car panel only	Low voltage only	Fuses	Controls all automatic	NA	Interlocked electrical doors	Yes
Hot parts		NA	NA	NA	NA	NA	No
Falling/slipping	Slips inside car only	No access to shaft	NA	NA	NA	Non-slip flooring and handrail	No
Noise	Low noise levels only	Remote winch	NA	NA	NA	NA	No

NA: Not applicable

Safe-life criterion comprises: Proven principles/calculations, assessment of operating limits and analysis of overload conditions

Figure 3.29 Embodiment design: danger features. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

The message is simple: danger features must be designed *out* at the embodiment stage, rather than trying to cover them up later. You can infer the basic methodology by a close look at Fig. 3.30. Although there are no rigid rules, you can generally get the best results by looking at the features in the order shown (i.e. working left to right across the table). Note that the figure only shows the analysis for one of the systems – for a full embodiment analysis, the process would be repeated for all the other systems identified previously.

Step 4: Look for embodiment options

It is rare that the first embodiment design ideas will be the best ones. The principle of finding the best solution lies with the activity of 'opening up' the design – revealing its complexity – to find the most appropriate solution from the 'possibles' available. Although the embodiment design activity benefits from a certain level of innovative thinking, it is important not to confuse this with true innovation. True innovation belongs in the conceptual stage that *precedes* the embodiment design steps – embodiment is a more prescriptive, better-defined process than this. Innovative embodiment solutions are fine, as long as they fit within the constraints of using those conceptual design decisions that have already been made. To reinforce this point, here are two examples relating to the passenger lift in Fig. 3.27:

- The conceptual design is for a 'rope operated' lift, not an alternative design operated by hydraulic rams. Hence the embodiment design should accept the use of an electric winch and look for ways to make the electrical system safe. It would be wrong to suggest the use of a hydraulic lifting system instead. That would be interfering with the agreed concept design.
- If, for example, the passenger lift was designed with double sets of doors, the embodiment design stage should accept this fact and look for options to make the double-door arrangement safer, not ways to change the concept to one using only a single set of doors.

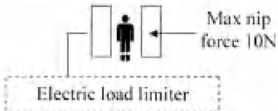
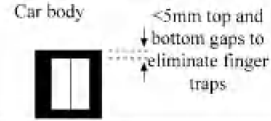
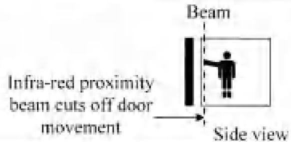
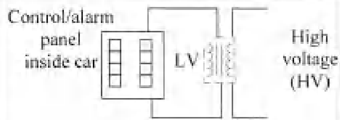
Danger	Embodiment	Good points	Bad points	Alternative
Stored energy. Door closing force		Simple electric limiter	Error signals (continual opening of doors)	Variable closing force
Crush and trap gaps		Safe: no further guards required	Can jam. Accurate assembly needed.	Cover-plates. Alternative guard arrangement
Crush and trap gaps		No moving parts	Unreliable sensors easily damaged	Pressure pads/ physical barrier
Exposed electrics		No HV danger.LV works OK	Transformer needed. More complex wiring	Use HV but include protection devices

Figure 3.30 Embodiment design options. Reprinted from *Case Studies in Engineering Design*, Clifford Matthews, © Elsevier 1998

This is a practical constraint to help to avoid the design process descending into a state of anarchy, not a mechanism to discourage innovation.

Figure 3.30 shows typical embodiment design options for the passenger lift, looking at the safety problem of crush/trap gaps between and around the lift's inner sliding doors. Note how sketches are used rather than detailed written descriptions for two reasons: (1) sketches help *definition*, they can capture and define that fleeting idea in a way that description cannot; and (2) sketches are a better way to *communicate* embodiment design ideas to other people. Other viewpoints are often necessary to help to 'firm up' ideas, but it is always better to use sketches.

- *Embodiment design is about specific features, not general principles – so use sketches.*

Step 5: Deciding

It is no use defining lots of elaborate design options if you can't then decide which to use in the final detailed design. A gamut of terminology surrounds this step; you will see it referred to as 'design evaluation' or 'design synthesis' through to the more elaborate term, 'evaluating concept variants'. They all mean the same: *deciding*. But how? Sadly, there are no hard and fast rules, it would be nice if there were. Several factors impinge upon the decisions, you can analyse and weight design options in order of safety, discuss them, and eliminate the worst ones – but you will still need to apply some intuition and experience. A few broad guidelines should be followed:

- ***Avoid contradictions*** **–** Make sure the technical choices are consistent with each other. There would be little logic, for example, in designing one electrical circuit for low-voltage operation, for safety, if others nearby operated on high voltage. Avoid contradictions by aiming for consistency.
- ***Use technical standards*** **–** These are useful to help you to decide. Design details in published technical standards have invariably been subjected to long discussions between people at the sharp end of manufacture and use of the equipment in

question. You can therefore rely on standards to provide *proven advice*. The main limitation is in the scope of technical standards – not all technical standards cover embodiment design, some being intended more as purchasing and specification guides rather than a design tool. This means that some technical standards are more useful than others.

- ***Technical guidelines*** **–** These are available in many forms: databooks, nomograms and manufacturers' publications. The quality of such information varies widely; databooks can be particularly useful for embodiment design ideas. Manufacturers' catalogues are good at showing different embodiment designs that are available (itself an indication of the success of the design feature) but tend to be optimistic in underestimating any negative aspects of a design option.
- ***Cost*** **–** More specifically, *cost effectiveness*. Frankly, you have to develop an instinct for cost as it is a real constraint in all design projects. Features such as redundancy and diversity are always desirable, but it is not economic to duplicate everything. Your objective should be to keep a focus on cost-effectiveness when deciding embodiment design – but keep it in perspective.

These aspects of deciding embodiment design should be treated as guidelines only. They must be seen as lying within the overall objective of making embodiment design as safe as possible, but also simple. Simplicity is a desirable design characteristic: good, safe, designs are often very simple.

3.12 Design by nature – project toucan

The relationship between nature and intelligent design has always been an awkward one. Many intelligent designs (engineered by humans to fulfil some technical necessity) follow those that can be seen to work well in nature. The spiral 'volute' shape of a pump casing is identical to that of the Nautilus seashell casing and the shape and structure of aircraft wings have a great similarity to those of birds. It's not all a procession after nature, however – nature has never invented the wheel and of the 118 elements in the periodic table, nature is only capable of making 93 of them occur naturally – the rest have to be manufactured artificially.

Overall, however, when searching for good design ideas, it is worth while looking at nature. Natural materials can produce interesting mechanical properties – spiders' webs, for example, have immense tensile strength per unit cross-sectional area, and the bite strength of a crocodile's jaw is in excess of that obtainable from a hydraulic ram, which requires huge tensile and compressive strengths from its various components.

Take the case of the toucan's beak (Fig. 3.31). This is one of the longest in the bird world, comprising more than 30% of the overall length of the bird. Impressively sized and coloured it performs remarkably in day-to-day toucan-like activities such as peeling fruit, fighting off predators and competitors, and impressing other toucans.

Natural design has been hard at work on this design, matching its mechanical properties to its needs, much the same as you would do for an engineering product made of metals. Consider these properties.

***Lightweight* –** Although making up 30% of the length of the body, a toucan's beak is responsible for less than 5% of its overall body weight. Weight is at a premium – birds require hollow bones and an ultra-lightweight skeletal structure if they are to be able to fly.

***Hardness* –** High hardness (resistance to surface indentation) is required for the usual toucan activities of pecking, fighting, peeling fruit, and splitting nuts. Hard surfaces can be made sharp, an advantage for all of these applications.

***Toughness* –** Toughness is the ability to resist brittle fracture under impact. As with metals, materials which are hard often have a tendency to be brittle. By their function, bird beaks are high-impact items, so need to be tough if they are not to break off in use.

***Tensile strength* –** Toucans use their beaks as levers to move stones, prise open gaps in bark and dig the occasional hole. Yield and tensile strength are important but so is stiffness – a high Young's modulus is required to keep deflections to a minimum.

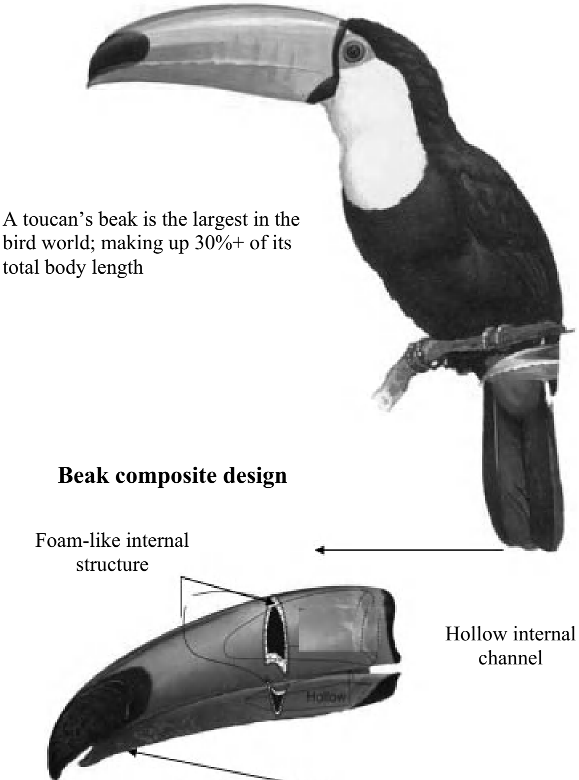


Figure 3.31 The impressive beak of the Toucan

***Compressive strength* –** Rather than pure compressive 'crushing' strength as such, this is more to do with resistance to buckling. The beak must have a stable structure to stop it deforming and bucking (either axially or circumferentially).

***Heat transfer* –** Flying is a high-energy business, generating a lot of heat that has to be transferred away to prevent over-heating. A toucan's beak acts as one of nature's most efficient and adjustable radiators, capable of radiating almost 100% of generated heat when in flight. In many materials, heat transfer capability does not sit easily with strength – good conductors such as copper, aluminium and silver are quite weak materials even when alloyed with trace elements to improve their properties.

The solution: composite design

Almost the only solution to the toucan's list of design requirements lies with composite design. All natural designs are composites, of sorts, but this has to be one of the most striking examples. The internal structure of the beak consists of a closed-cell spaceframe containing pressurized air. This three-dimensional honeycomb construction is very stiff, providing resistance to buckling and torsion (twisting). It also provides resistance to impact – if a small crack were to start as a result of impact, it would soon be arrested by the convoluted path of the closed-cell honeycomb.

In more formal mechanics terms, the closed-cell structure provides an elastic foundation which increases its buckling load under flexure. It is made of fibres of a material called keratin, with mineral trace elements. These increase the strength, giving it a tensile strength of about 50–60 MPa and a high Young's modulus of 2.5–3 GPa.

For hardness, the beak is covered with overlapping keratin scales about 1 micron thick and 50 micron diameter glued together. As well as being hard, it achieves toughness, (resistance to brittle fracture) by allowing the glue to slip under impact. Together with the toughness of the underlying spaceframe, this allows the beak to absorb the worst toucan-induced impacts.

Finally, the hard shell maintains the underlying structure in slight compression, slightly deforming its multidirectional spaceframe struts, hence adding to its stiffness and resistance to torsion and buckling. In return, the foam-like spaceframe supports the shell, fortifying its lower stiffness (Young's modulus about 1–1.5 GPa).

This is a true example of composite design – two or more separate elements, each acting not only to their own strength but also *synergistically* to complement the other. There are many areas of design where composites can provide the combination of properties that a single material cannot. Classic examples are glass-reinforced plastic (GRP), carbon fibre and similar substances.

Thinking about it more widely, all useable metals are effectively composites – you just have to move down to the micro scale to see it. At this level trace elements, acting singly or together, enhance mechanical and chemical properties in fairly predictable ways. Much of this is hidden behind the scenes of course, and it is only relatively recently that the advantage of large 'touch and hold scale' composites have begun to be realized.

And behind it all?

Nature of course, has no intelligent designer – it is all done by natural selection sprinkled with a bit of random chance. If, perchance, there was an intelligent designer, then project toucan must have all gone wrong at the design review stage. Given that the easiest way round a design problem is to design out the need for it, the least effort solution would have been to simply give Mr Toucan a smaller 'off the shelf' beak. No problem with that, given of course, the control of the intelligent designer over the size and squishiness of Mr Toucan's favourite fruit, the aggressiveness of other toucans, and the inherent preferences of lady toucans. Eventually, with intelligent design in full methodical and analytical flow, all intelligently-designed birds would eventually look and perform almost precisely the same. Look at Formula 1 racing cars, and you get the idea.

Section 4

Basic Mechanical Design

4.1 Engineering abbreviations

The following abbreviations are in common use in engineering drawings and specifications.

Table 4.1 Engineering abbreviations in common use

Abbreviation	*Meaning*
A/F	Across flats
ASSY	Assembly
CRS	Centres
L or CL	Centre line
CHAM	Chamfered
CSK	Countersunk
C'BORE	Counterbore
CYL	Cylinder or cylindrical
DIA	Diameter (in a note)
Ø	Diameter (preceding a dimension)
DRG	Drawing
EXT	External
FIG.	Figure
HEX	Hexagon
INT	Internal
LH	Left hand
LG	Long
MATL	Material
MAX	Maximum
MIN	Minimum
NO.	Number
PATT NO.	Pattern number
PCD	Pitch circle diameter
RAD	Radius (in a note)
R	Radius (preceding a dimension)
REQD	Required
RH	Right hand
SCR	Screwed
SH	Sheet
SK	Sketch
SPEC	Specification

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Table 4.1 (Cont.)

Abbreviation	*Meaning*
SQ	Square (in a note)
□	Square (preceding a dimension)
STD	Standard
VOL	Volume
WT	Weight

4.1.1 American terminology

In the USA, slightly different terminology is used, based on the published standard ASME Y14.5 *Dimensioning and Tolerancing*: 2009.

Table 4.2

Abbreviation	*Meaning*
ANSI	American National Standards Institute
ASA	American Standards Association
ASME	American Society of Mechanical Engineers
AVG	Average
CBORE	Counterbore
CDRILL	Counterdrill
CL	Centre line
CSK	Countersink
FIM	Full indicator movement
FIR	Full indicator reading
GD&T	Geometric dimensioning and tolerancing
ISO	International Standards Organization
LMC	Least material condition
MAX	Maximum
MDD	Master dimension definition
MDS	Master dimension surface
MIN	Minimum
mm	Millimetre
MMC	Maximum material condition
PORM	Plus or minus
R	Radius
REF	Reference
REQD	Required
RFS	Regardless of feature size
SEP REQT	Separate requirement
SI	Systèmè International (the metric system)
SR	Spherical radius
SURF	Surface
THRU	Through
TIR	Total indicator reading
TOL	Tolerance

4.1.2 Preferred numbers and preferred sizes

Preferred numbers are derived from geometric series in which each term is a uniform percentage larger than its predecessor. The first five principal series (named the 'R' series) are shown in Table 4.3. Preferred numbers are taken as the basis for ranges of linear sizes of components, often being rounded up or down for convenience. Figure 4.1 shows the development of the R5 and R10 series.

Table 4.3

Series	*Basis*	*Ratio of terms (% increase)*
R5	$\sqrt[5]{10}$	1.58 (58%)
R10	$\sqrt[10]{10}$	1.26 (26%)
R20	$\sqrt[20]{10}$	1.12 (12%)
R40	$\sqrt[40]{10}$	1.06 (6%)
R80	$\sqrt[80]{10}$	1.03 (3%)

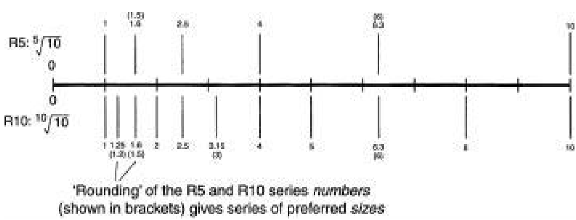


Figure 4.1

USEFUL STANDARD

BS 2045: 1982: Preferred numbers.

4.2 Datums and tolerances – principles

A *datum* is a reference point or surface from which all other dimensions of a component are taken; these other dimensions are said to be *referred to* the datum. In most practical designs, a datum surface is normally used, this generally being one of the surfaces of the machine element itself rather than an 'imaginary' surface. This means that the datum surface normally plays some important part in the operation of the elements – it is usually machined and may be a mating surface or a locating face between elements, or similar. Simple machine mechanisms do not *always* need datums; it depends on what the elements do and how complicated the mechanism assembly is.

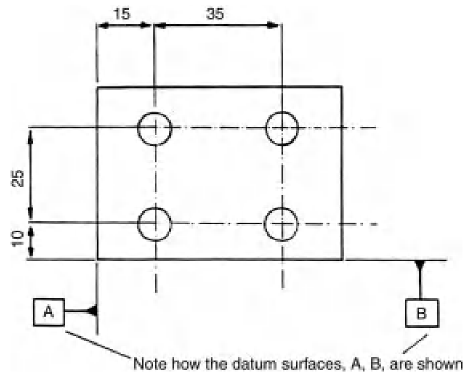


Figure 4.2

A *tolerance* is the allowable variation of a linear or angular dimension about its 'perfect' value. British Standard 8888: 2008 contains accepted methods and symbols.

4.3 Toleranced dimensions

In designing any engineering component it is necessary to decide which dimensions will be toleranced. This is predominantly an

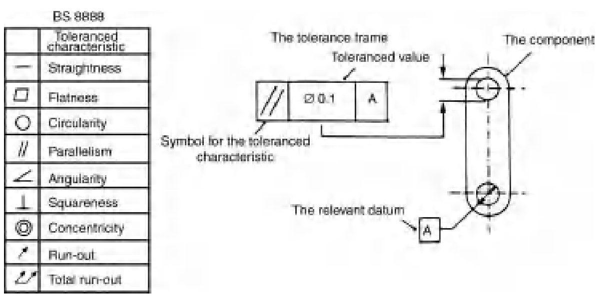


Figure 4.3

exercise in necessity – only those dimensions that *must* be tightly controlled, to preserve the functionality of the component, should be toleranced. Too many toleranced dimensions will increase significantly the manufacturing costs and may result in 'tolerance clash', where a dimension derived from other toleranced dimensions can have several contradictory values.

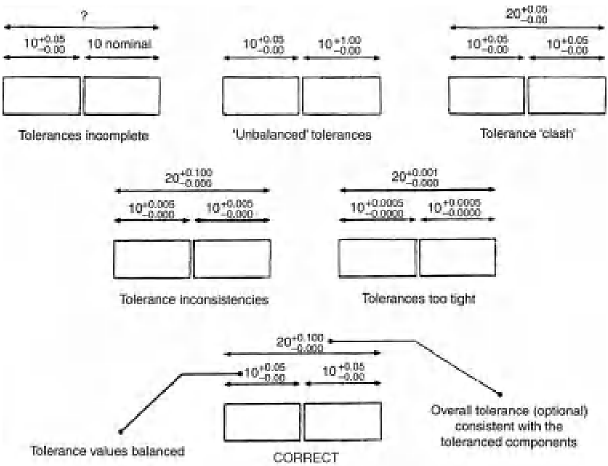


Figure 4.4

4.4 General tolerances

It is a sound principle of engineering practice that in any machine design there will only be a small number of toleranced features. The remainder of the dimensions will not be critical.

There are two ways to deal with this: first, an engineering drawing or sketch can be annotated to specify that a *general tolerance* should apply to features where no specific tolerance is

Table 4.4 Typical tolerances for linear dimensions

Dimension	*Tolerance*
0.6 mm–6.0 mm	± 0.1 mm
6 mm–36 mm	± 0.2 mm
36 mm–120 mm	± 0.3 mm
120 mm–315 mm	± 0.5 mm
315 mm–1000 mm	± 0.8 mm

mentioned. This is often expressed as ± 0.5 mm. Alternatively, the drawing can make reference to a 'general tolerance' standard such as BS EN 22768 which gives typical tolerances for linear dimensions as shown.

4.5 Holes

The tolerancing of holes depends on whether they are made in thin sheet (up to about 3 mm thick) or in thicker plate material. In thin material, only two toleranced dimensions are required:

- *Size* A toleranced diameter of the hole, showing the maximum and minimum allowable dimensions.
- *Position* Position can be located with reference to a datum and/or its spacing from an adjacent hole. Holes are generally spaced by reference to their centres.

For thicker material, three further toleranced dimensions become relevant: straightness, parallelism and squareness.

- *Straightness* A hole or shaft can be *straight* without being perpendicular to the surface of the material.
- *Parallelism* This is particularly relevant to holes and is important when there is a mating hole-to-shaft fit.
- *Squareness* The formal term for this is perpendicularity. Simplistically, it refers to the squareness of the axis of a hole to the datum surface of the material through which the hole is made.

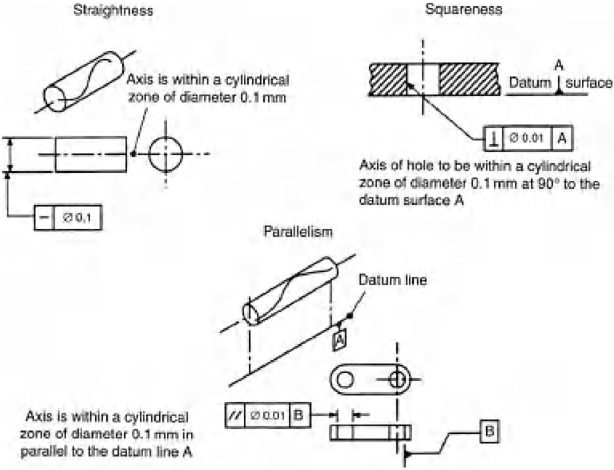


Figure 4.5 Straightness, parallelism, and squareness–BS 8888:2008

4.6 Screw threads

There is a well-established system of tolerancing adopted by British and International Standard Organizations and manufacturing industry. This system uses the two complementary elements of fundamental deviation and tolerance range to define fully the tolerance of a single component. It can be applied easily to components, such as screw threads, which join or mate together.

- *Fundamental deviation* (*FD*) is the distance (or 'deviation') of the nearest 'end' of the tolerance band from the nominal or 'basic' size of a dimension.
- *Tolerance band* (or 'range') is the size of the tolerance band, i.e. the difference between the maximum and minimum acceptable size of a toleranced dimension. The size of the tolerance band, and the location of the FD, governs the system of limits and fits applied to mating parts.

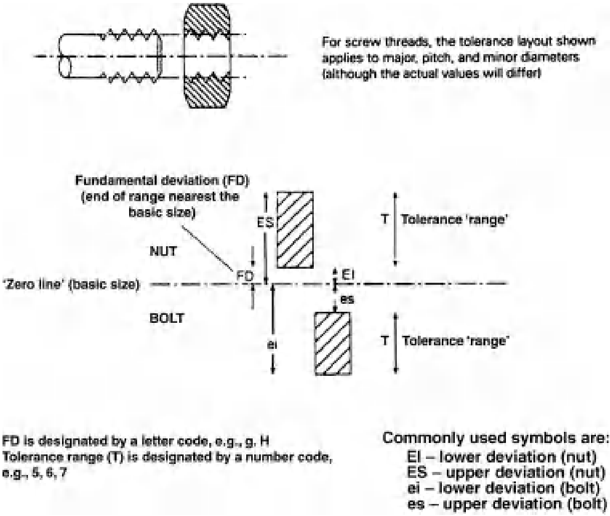


Figure 4.6

Tolerance values have a key influence on the costs of a manufactured item so their choice must be seen in terms of economics as well as engineering practicality. Mass-produced items are competitive and price sensitive, and over-tolerancing can affect the economics of a product range.

4.7 Limits and fits

4.7.1 Principles

In machine element design there is a variety of different ways in which a shaft and hole are required to fit together. Elements such as bearings, location pins, pegs, spindles, and axles are typical examples. The shaft may be required to be a tight fit in the hole, or to be looser, giving a clearance to allow easy removal or rotation. The system designed to establish a series of useful fits between shafts and holes is termed *limits and fits.* This involves a series of tolerance grades so that machine elements can be made with the correct degree of accuracy and be interchangeable with others of the same tolerance grade.

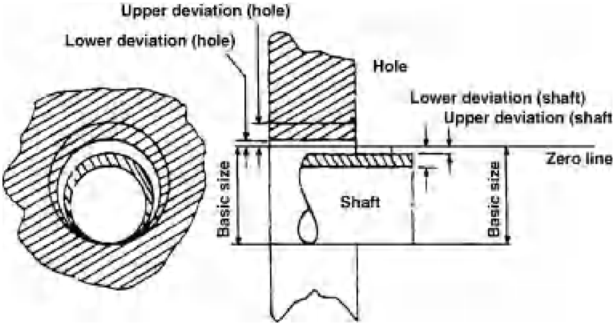


Figure 4.7

The British Standard BS 4500 /BS EN 20286 'ISO limits and fits' contains the recommended tolerances for a wide range of engineering requirements. Each tolerance grade is designated by a combination of letters and numbers, such as IT7, which would be referred to as grade 7.
Figure 4.7 shows the principles of a shaft/hole fit. The 'zero line' indicates the basic or 'nominal' size of the hole and shaft (it is the same for each) and the two shaded areas depict the tolerance zones within which the hole and shaft may vary. The hole is conventionally shown above the zero line. The algebraic difference between the basic size of a shaft or hole and its actual size is known as the *deviation.*

- It is the deviation that determines the nature of the fit between a hole and a shaft.
- If the deviation is small, the tolerance range will be near the basic size, giving a tight fit.
- A large deviation gives a loose fit.

Various grades of deviation are designated by letters, similar to the system of numbers used for the tolerance ranges. Shaft deviations are denoted by small letters and hole deviations by capital letters. Most general engineering uses a 'hole-based' fit in which the larger part of the available tolerance is allocated to the hole (because it is more difficult to make an accurate hole) and then the shaft is made to suit, to achieve the desired fit.

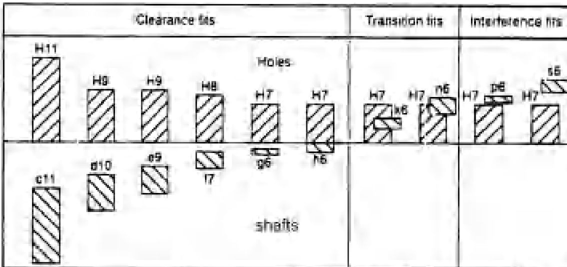
4.7.2 Common combinations

There are seven popular combinations used in general mechanical engineering design:

1. *Easy running fit:* H11–c11, H9–d10, H9–e9. These are used for bearings where a significant clearance is necessary.
2. *Close running fit:* H8–f7, H8–g6. This only allows a small clearance, suitable for sliding spigot fits and infrequently used journal bearings. This fit is not suitable for continuously rotating bearings.
3. *Sliding fit:* H7–h6. Normally used as a locational fit in which close-fitting items slide together. It incorporates a very small clearance and can still be freely assembled and disassembled.
4. *Push fit:* H7–k6. This is a transition fit, mid-way between fits that have a guaranteed clearance and those where there is metal interference. It is used where accurate location is required, e.g. dowel and bearing inner-race fixings.
5. *Drive fit:* H7–n6. This is a tighter grade of transition fit than the H7–k6. It gives a tight assembly fit where the hole and shaft may need to be pressed together.
6. *Light press fit:* H7–p6. This is used where a hole and shaft need permanent, accurate assembly. The parts need pressing together but the fit is not so tight that it will overstress the hole bore.
7. *Press fit:* H7–s6. This is the tightest practical fit for machine elements such as bearing bushes. Larger interference fits are possible but are only suitable for large heavy engineering components.

4.8 Surface finish

Surface finish, more correctly termed ‘surface texture’, is important for all machine elements that are produced by machining processes such as turning, grinding, shaping, or honing. This applies to surfaces which are flat or cylindrical. Surface texture is covered by its own technical standard, BS 1134: 2010 *Assessment of surface texture.* It is measured using the parameter R_a which is



Nominal size in mm	Easy running						Close running				Sliding		Push		Drive		Light press		Press	
	Tols*		Tols		Tols		Tols		Tols		Tols		Tols		Tols		Tols		Tols	
	H11	c11	H9	d10	H9	e9	H8	f7	H7	g6	H7	h6	H7	k6	H7	n6	H7	p6	H7	s6
6–10	+90 0	−80 −170	+36 0	−40 −98	+36 0	−25 −61	+22 0	−12 −28	+15 0	−5 −14	+15 0	−9 0	+15 0	+10 +1	+15 0	+19 +10	+15 0	+24 +15	+15 0	+32 +23
10–18	+110 0	−95 −205	+43 0	−50 −120	+43 0	−32 −75	+27 0	−16 −34	+18 0	−6 −17	+18 0	−11 0	+18 0	+12 +1	+18 0	+23 +12	+18 0	+29 +18	+18 0	+39 +28
18–30	+130 0	−110 −240	+52 0	−65 −149	+52 0	−40 −92	+33 0	−20 −41	+21 0	−7 −20	+21 0	−13 0	+21 0	+15 +2	+21 0	+28 +15	+21 0	+35 +22	+21 0	+48 +35
30–40	+160 0	−120 −280	+62	−80	+62	−50	+39	−25	+25	−9	+25	−16	+25	+18	+25	+33	+25	+42	+25	+59
40–50	+160 0	−130 −290	0	−180	0	−112	0	−50	0	−25	0	0	0	+2	0	+17	0	+26	0	+43

* Tolerance units in 0.001 mm

Data from BS 4500

Figure 4.8 Metric Equivalents

a measurement of the average distance between the median line of the surface profile and its peaks and troughs, measured in micrometres (μm). There is another system from a comparable standard, ISO 1302, which uses a system of N-numbers – it is simply a different way of describing the same thing.

FINE FINISH ← → ROUGH FINISH

R_a (μm) BS 1134	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50
R_a (μ inch) ANSI B46.1	1	2	4	8	16	32	63	125	250	500	1000	2000
N-grade DIN ISO 1302	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12

Ground finishes — Smooth turned — Medium turned

Seal-faces and running surfaces — Rough turned finish

A prescribed surface finish is shown on a drawing as 1.6 ✓ – on a metric drawing this means 1.6 μm R_a

Figure 4.9

4.8.1 Choice of surface finish: 'rules of thumb'

- Rough turned, with visible tool marks: N10 (12.5 μm R_a)
- Smooth machined surface: N8 (3.2 μm R_a)
- Static mating surfaces (or datums): N7 (1.6 μm R_a)
- Bearing surfaces: N6 (0.8 μm R_a)
- Fine 'lapped' surfaces: N1 (0.025 μm R_a)

Finer finishes can be produced but are more suited for precision application such as instruments. It is good practice to specify the surface finish of close-fitting surfaces of machine elements, as well as other BS 8888 parameters such as squareness and parallelism.

Section 5

Motion

5.1 Making sense of equilibrium

The concept of equilibrium lies behind many types of engineering analyses and design.

5.1.1 Definitions

- *Formally* An object is in a state of equilibrium when the forces acting on it are such as to leave it in its state of rest or uniform motion in a straight line.
- *Practically* The most useful interpretation is that an object is in equilibrium when the forces acting on it are producing no tendency for the object to move.

Figure 5.1 shows the difference between equilibrium and non-equilibrium.

5.1.2 How is it used?

The concept of equilibrium is used to analyse engineering structures and components. By isolating a part of a structure (a joint or a member) which is in a state of equilibrium, this enables a 'free body diagram' to be drawn. This aids in the analysis of the stresses (and the resulting strains) in the structure. When co-planar forces acting at a point are in equilibrium, the vector diagram closes.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

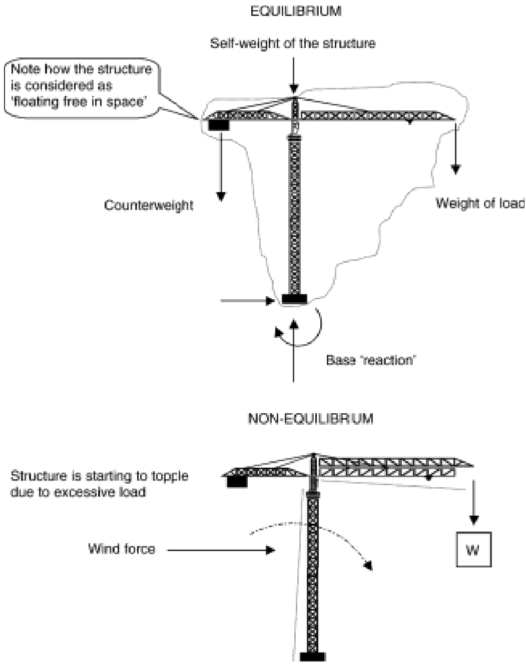


Figure 5.1

5.2 Motion equations

5.2.1 Uniformly accelerated motion

Bodies under uniformally accelerated motion follow the general equations given here.

$$v = u + at$$

$$s = ut + \tfrac{1}{2}at^2 \qquad t = \text{time (s)}$$

$$a = \text{acceleration (m/s}^2\text{)}$$

$$s = \left(\frac{u+v}{2}\right)t \qquad s = \text{distance travelled (m)}$$

$$u = \text{initial velocity (m/s)}$$

$$v^2 = u^2 + 2as \qquad v = \text{final velocity (m/s)}$$

5.2.2 Angular motion

$\omega = \dfrac{2\pi N}{60}$	t = time (s)
$\omega_2 = \omega_1 + \alpha t$	θ = angle moved (rad)
$\theta = \left(\frac{\omega_1 + \omega_2}{2}\right)t$	α = angular acceleration (rad/s^2)
	N = angular speed (rev/min)
$\omega_2^2 = \omega_1^2 + 2\alpha s$	ω_1 = initial angular velocity (rad/s)
	ω_2 = final angular velocity (rad/s)
$\theta = \omega_1 t + \frac{1}{2}\alpha t^2$	

5.2.3 General motion of a particle in a plane

$v = \mathrm{d}s/\mathrm{d}t$	s = distance
$a = \mathrm{d}v/\mathrm{d}t = \mathrm{d}^2 s/\mathrm{d}t^2$	t = time
$v = \int a\mathrm{d}t$	v = velocity
$s = \int v\mathrm{d}t$	a = acceleration

5.3 Newton's laws of motion

First law Everybody will remain at rest or continue in uniform motion in a straight line until acted upon by an external force.

Second law When an external force is applied to a body of constant mass it produces an acceleration which is directly proportional to the force. i.e. Force (F) = mass (m) × acceleration (a)

Third law Every action produces an equal and opposite reaction.

5.3.1 Comparisons: rotational and translational motion

Translation		*Rotation*	
Linear displacement from a datum	x	Angular displacement	θ
Linear velocity	v	Angular velocity	ω
Linear acceleration	$a = \mathrm{d}v/\mathrm{d}t$	Angular acceleration	$\alpha = \mathrm{d}\omega/\mathrm{d}t$
Kinetic energy	$\mathrm{KE} = mv^2/2$	Kinetic energy	$\mathrm{KE} = I\omega^2/2$
Momentum	mv	Momentum	$I\omega$
Newton's second law	$F = m\mathrm{d}_2x/\mathrm{d}t^2$	Newton's second law	$M = \mathrm{d}_2\theta/\mathrm{d}t^2$

5.4 Simple harmonic motion (SHM)

A particle moves with SHM when it has constant angular velocity (ω). The projected displacement, velocity, and acceleration of a point P on the x.y axes are a sinusoidal function of time (t).

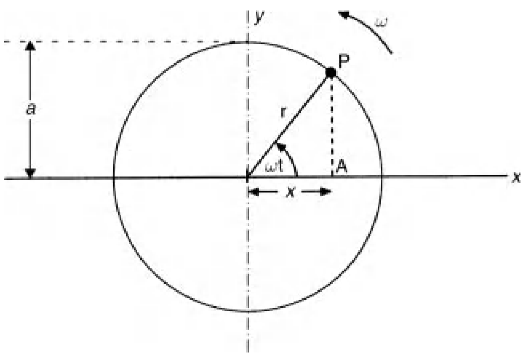


Figure 5.2 Simple harmonic motion

Angular velocity $(\omega) = 2\pi N/60$ where N is in rev/min

Periodic time $(T) = 2\pi/\omega$

Velocity (v) of point A on the x axis is

$v = \mathrm{d}s/\mathrm{d}t = \omega r \sin \omega t$

Acceleration $(a) = \mathrm{d}_2 s/\mathrm{d}t^2 = \mathrm{d}v/\mathrm{d}t = -\omega^2 r \cos \omega t$

5.5 Understanding acceleration

The dangerous thing about acceleration is that it represents a *rate of change* of speed or velocity. When this rate of change is high it puts high stresses on engineering components, causing them to deform and break. In the neat world of physical science, objects in a vacuum experience a constant acceleration (g) due to gravity of 9.81m/s^2 – so if you drop a hammer and a feather they will reach the ground at the same time.

Unfortunately, you won't find many engineering products made of hammers and feathers locked inside vacuum chambers. In practice, the components of engineering machines experience acceleration many times the force of gravity so they have to be designed to resist the forces that result. Remember that these forces can be caused as a result of either linear or angular accelerations and that there is a correspondence between the two as shown on the following page.

Linear acceleration	*Angular acceleration*
$a = \frac{v-u}{t}$ m/s^2	$\alpha = \frac{\omega_2-\omega_1}{t}$ rad/s^2

5.5.1 Design hint

When analysing (or designing) any machine or mechanism think about linear and angular accelerations *first* – they are always important.

5.6 Dynamic balancing

Virtually all rotating machines (pumps, shafts, turbines, gear-sets, generators, etc.) are subject to dynamic balancing during manufacture. The objective is to maintain the operating vibration of the machine within manageable limits.

Dynamic balancing normally involves two measurement/correction planes and involves the calculation of vector quantities. The component is mounted in a balancing rig which rotates it at or near its operating speed, and both senses and records out-of-balance forces and phase angle in two planes. Balance weights are then added (or removed) to bring the imbalance forces to an acceptable level.

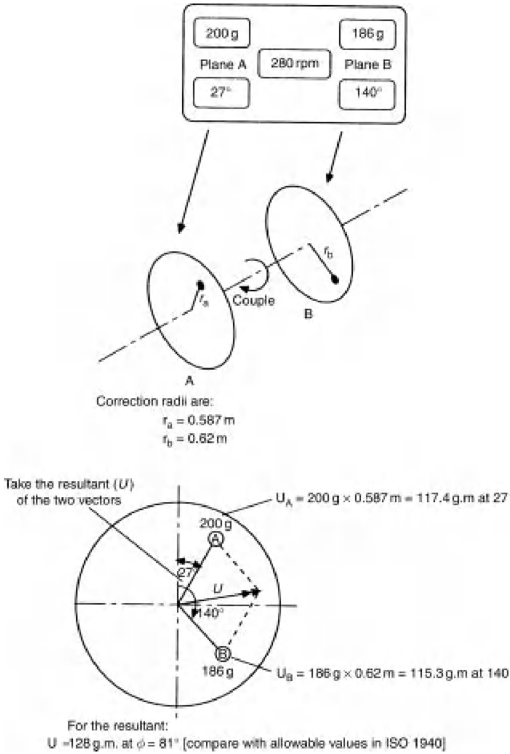


Figure 5.3

5.6.1 Balancing standard: ISO 1940/1: 2003

The standard ISO 1940/1: 2003 (identical to BS 6861: Part 1: 1987): Balance quality requirements of rigid rotors is widely used. It sets acceptable imbalance limits for various types of rotating equipment. It specifies various (G) grades. A similar approach is used by the standard ISO 10816-1.

Finer balance grades are used for precision assemblies such as instruments and gyroscopes. The principles are the same.

5.7 Vibration

Vibration is a subset of the subject of dynamics. It has particular relevance to both structures and machinery in the way that they respond to applied disturbances.

5.7.1 General model

The most common model of vibration is a concentrated spring-mounted mass which is subject to a disturbing force and retarding force.

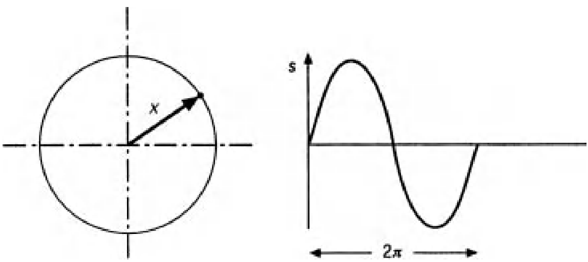


Figure 5.4

The motion is represented graphically as shown by the projection of the rotating vector x. Relevant quantities are

$$\text{frequency (Hz)} = \sqrt{\frac{k}{m}}/2\pi$$

The ideal case represents simple harmonic motion with the waveform being sinusoidal. Hence the motion follows the general pattern:

$$\text{Vibration displacement (amplitude)} = s$$
$$\text{Vibration velocity} = v = \mathrm{d}s/\mathrm{d}t$$
$$\text{Vibration acceleration} = a = \mathrm{d}v/\mathrm{d}t$$

5.8 Machine vibration

There are two types of vibration relevant to rotating machines

- Bearing *housing* vibration. This is assumed to be sinusoidal. It normally uses the velocity (V_{rms}) parameter.
- *Shaft* vibration. This is generally not sinusoidal. It normally uses displacement (s) as the measured parameter.

5.8.1 Bearing housing vibration

Relevant points are:

- It only measures vibration at the 'surface'.
- It excludes torsional vibration.
- V_{rms} is normally measured across the frequency range and then distilled down to a single value.

$$\text{i.e. } V_{rms} = \sqrt{\frac{1}{2}\left(\sum \text{amplitudes} \times \text{angular frequences}\right)}$$

- It is covered in the German standard VDI 2056: Criteria for assessing mechanical vibration of machines and BS 7854: 1995: Mechanical vibration.

5.8.2 Acceptance levels

Technical standards, and manufacturers' practices, differ in their acceptance levels. General 'rule of thumb' acceptance levels are shown in Figures 5.5 and 5.6.

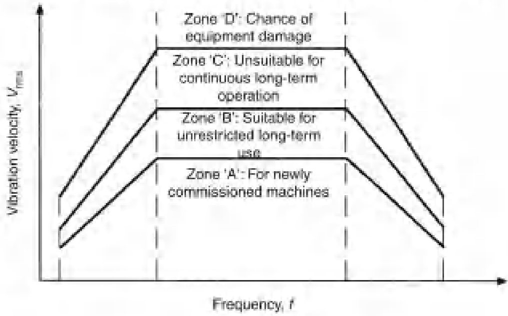
Machine	V_{rms} (mm/s)
Precision components and machines – gas turbines, etc.	1.12
Helical and epicyclic gearboxes	1.8
Spur-gearboxes, turbines	2.8
General service pumps	4.5
Long-shaft pumps	4.5–7.1
Diesel engines	7.1
Reciprocating large machines	7.1–11.2

Figure 5.5

Typical balance grades: from International Standard ISO 1940–1

Balance grade	Types of rotor (general examples)
G 1	Grinding machines, tape-recording equipment
G2.5	Turbines, compressors, electric armatures
G6.3	Pump impellers fans, gears, machine tools
G 16	Cardan shafts, agricultural machinery
G 40	Car wheels, engine crankshafts
G 100	Complete engines for cars and trucks

'Acceptance criteria': from International Standard ISO 10816–1



Typical 'boundary limits': from International Standard ISO 10816–1

<table>
<tr><th>V_{rms}</th><th>Class I</th><th>Class II</th><th>Class III</th><th>Class IV</th></tr>
<tr><td>0.71</td><td>A</td><td rowspan="2">A</td><td rowspan="3">A</td><td rowspan="4">A</td></tr>
<tr><td>1.12</td><td rowspan="2">B</td></tr>
<tr><td>1.8</td><td rowspan="2">B</td></tr>
<tr><td>2.8</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.5</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>7.1</td><td rowspan="3">D</td><td rowspan="2">C</td></tr>
<tr><td>11.2</td><td rowspan="2">D</td><td rowspan="2">C</td></tr>
<tr><td>18</td><td>D</td></tr>
</table>

Class suitability

Class I	Machines < 15kW
Class II	< 300kW
Class III	Large machines with rigid foundations
Class IV	Large machines with 'soft' foundations

(Note how wide these classes are)

Figure 5.6

5.9 Machinery noise

5.9.1 Principles

Noise is most easily thought of as air-borne pressure pulses set up by a vibrating surface source. It is measured by an instrument which detects these pressure changes in the air and then relates this measured sound pressure to an accepted zero level. Because a machine produces a mixture of frequencies (termed *broad-band* noise), there is no single noise measurement that will fully describe a noise emission. In practice, two methods used are:

- The '*overall noise'* level. This is often used as a colloquial term for what is properly described as the *A-weighted sound pressure level.* It incorporates multiple frequencies, and weights them according to a formula which results in the best approximation of the loudness of the noise. This is displayed as a single instrument reading expressed as decibels dB(A).
- *Frequency band* sound pressure level. This involves measuring the sound pressure level in a number of frequency bands. These are arranged in either octave or one-third octave bands in terms of their mid-band frequency. The range of frequencies of interest in measuring machinery noise is from about 30 Hz to 10 000 Hz. Note that frequency band sound pressure levels are also expressed in decibels (dB).

The decibel scale itself is a logarithmic scale – a sound pressure level in dB being defined as:

$$\text{dB} = 10\log_{10}(p_1/p_0)^2$$

where

p_1 = measured sound pressure
p_0 = a reference zero pressure level

Noise tests on rotating machines are carried out by defining a 'reference surface' and then positioning microphones at locations 1 m from it.

5.9.2 Typical levels

Approximate 'rule of thumb' noise levels are given in Table 5.1.

A normal 'specification' level is 90–95 dB (A) at 1 m from operating equipment. Noisier equipment needs an acoustic

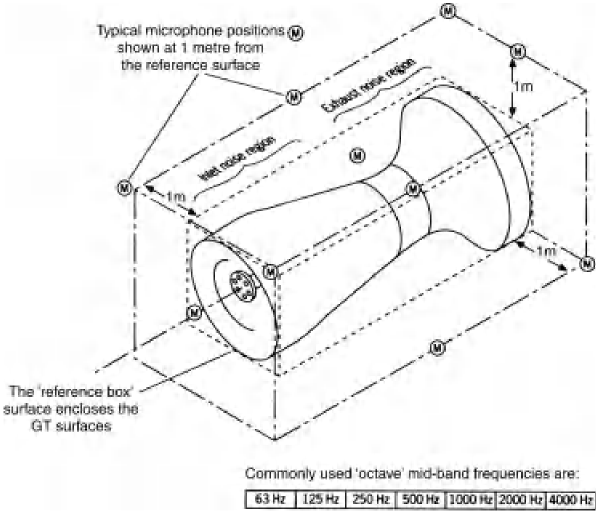


Figure 5.7

Table 5.1

Machine/environment	*dB(*A*)*
A whisper	20
Office noise	50
Noisy factory	90
Large diesel engine	97
Turbocompressor/gas turbine	98

enclosure. Humans can continue to hear increasing sound levels up to about 120 dB. Above this causes serious discomfort and long-term damage.

Section 6

Deformable Body Mechanics

6.1 Quick reference – mechanical notation

Principal symbols are used to represent mechanical engineering terms. Symbols may have several different meanings – the commonly used ones are shown below.

Table 6.1

Symbol	*Meaning*
a	Acceleration
	Crack length
	Strain hardening constant
	Bore radius of cylinder
A	Cross-sectional area
	Creep constant
A_1	Eutectoid temperature
b	Rim radius of a cylinder
B	A general constant
c	Maximum distance from neutral axis
C	A general constant
CE	Carbon equivalent
CVN	Charpy V-notch energy
d	Diameter
	Depth
e	Misalignment radial
E	Young's modulus
f	Force
	Frequency
f_{cr}	Critical whirling speed
F	Force
F_{cr}	Buckling load (Euler)
g	Acceleration due to gravity
G	Shear modulus
G_c	Toughness (critical strain energy release rate)
G_{1c}	Toughness (plane)
h	Height
	Depth
HAZ	Heat affected zone
HB	Brinel hardness
HRC	Rockwell C hardness

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Table 6.1 (Cont.)

Symbol	*Meaning*
HV	Vickers hardness
I	Second moment of area
Ix	Second moment of area (parallel axis theory)
J	Polar moment of area
k	Spring constant
k_e	Equivalent shear stress (Von Mises)
K	Bulk modulus
K_c	Fracture toughness
K_I	Stress intensity factor
K_{1c}	Plane strain fracture toughness
ΔK	K range in a fatigue cycle
l	Length
m	Mass
	Exponent in crack growth or strain hardening expression
M	Bending moment
	Couple
n	Nominal strain
N	Number of fatigue cycles
N_f	Number of fatigue cycles to failure
p	Pressure
p_{cr}	Critical pressure (external-pressure buckling)
P	Load
Q	Creep activation energy
r	Radius
r_y	Radius of plastic crack-zone tip
R	Reaction force
	Radius
s	Nominal stress
SCF	Stress concentration factor
t	Thickness
	Time
t_f	Time to failure
T	Tension
	Torque
u	Displacement
v	Velocity
V	Volume
	Shear force
w	Uniformly distributed load
W	Weight
	Width of a cracked component
x	Co-ordinate direction
y	Co-ordinate direction
Y	Crack geometry factor
z	Distance from neutral axis
	Co-ordinate direction

6.2 Engineering structures – so where are all the pin joints?

Much of engineering mechanics is based on the assumption that parts of structures are connected by pin joints. Similarly, members are continually assumed to be 'simply supported' and structural members pretend to be infinitely long, compared with their section thickness. The question is: do such members really exist?

They are certainly not immediately apparent – look at a bridge or steel tower and you will struggle to find a single joint containing a pin. The structural members will be channels, I-beams, or box sections surrounded by a clutter of plates, gussets, and flanges, not simple beams of nice prismatic section. So where is the relevance of all those clean theories of statics and vector mechanics?

Fortunately, the answer exists already, hidden in 200 years of engineering experience. Calculations based on simple bending theory, for example, have been validated against actual maximum stresses and deflections experienced in real structures and proved sufficiently accurate (say $\pm$ 10%) to represent reality. Once a factor of safety is introduced (see Section 7.5), then the simplified calculations are as accurate as they need to be. They are, to all intents and purposes, *correct*.

Simply supported assumptions work the same way. The complicated-looking supports of a bridge deck do act like simple supports when you consider the length of the beamlike members they are supporting. Equally, the members themselves dissipate stresses induced by constraint from the 'real' supports within a short distance from the support, so they *act like* long thin members, even though they may not be.

The design of engineering structures is built around findings like this. They have been proven quantitatively, by using strain-gauges and measuring deflections, and by advanced techniques such as FE analysis and photo-elastic models. Complete structures, aeroplanes, ships, and buildings have been investigated to demonstrate the validity of taught theories of statics and mechanics. The results is that all these types of structures in the world are designed using equations which are unerringly similar – proof enough of the validity of the theories behind them. Try to improve theoretical techniques, by all means, but don't ignore what has been found already, including those assumptions about pin joints and simply supported beams.

6.3 Simple stress and strain

$$\text{Stress, } \sigma = \frac{\text{load}}{\text{area}} = \frac{\text{P}}{\text{A}} (\text{units are N/m}^2)$$

$$\text{Strain}, \varepsilon = \frac{\text{change in length}}{\text{original length}} = \left(\frac{\delta l}{l} \text{ a ratio, therefore no units}\right)$$

$$\text{Hooke's Law}: \frac{\text{stress}}{\text{strain}} = \text{constant}$$

$$= \text{Young's modulus}, E\,(\text{units are } N/\text{m}^2)$$

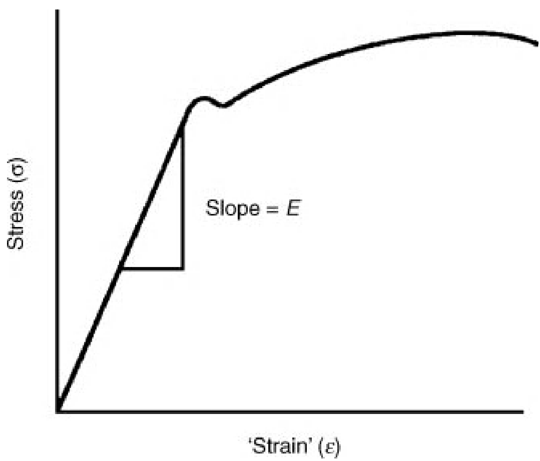


Figure 6.1

$$\text{Poisson's ratio}, \nu = \frac{\text{lateral strain}}{\text{longitudinal strain}}$$

$$= \frac{\delta d/d}{\delta l/l} (\text{a ratio, therefore no units})$$

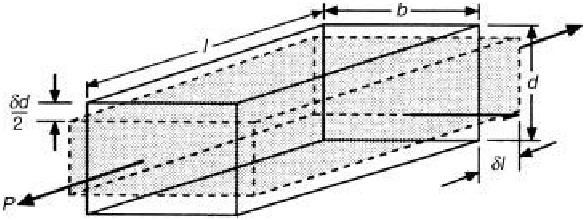


Figure 6.2

$$\text{Shear stress}, \tau = \frac{\text{shear load}}{\text{area}} = \frac{Q}{A} (\text{units are } N/\text{m}^2)$$

$$\text{Shear strain}, \gamma = \text{angle of deformation under shear stress}$$

$$\begin{aligned}\text{Modulus of rigidity}, G &= \frac{\text{shear stress}}{\text{shear strain}} = \frac{\tau}{y} \\ &= \text{Constant}, G \quad (\text{units are N}/m^2)\end{aligned}$$

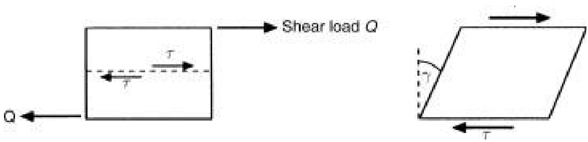


Figure 6.3

$$\text{Thermal stress}, \sigma_t \cong E\varepsilon = E\alpha t$$

where

α = linear coefficient
t = temperature change

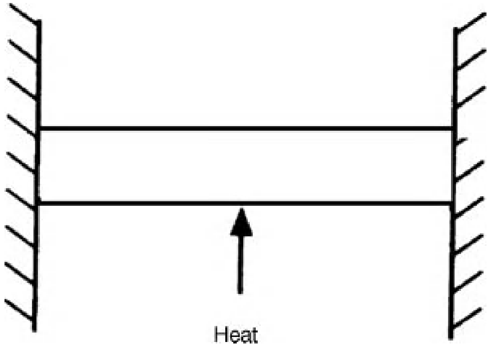


Figure 6.4

6.4 Simple elastic bending

Simple theory of elastic bending is:

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

M = applied bending moment
I = second moment about the neutral axis
R = radius of curvature of neutral axis
E = Young's modulus
σ = stress due to bending at distance y from neutral axis

The second moment of area is defined, for any section, as

$$I = \int y^2 \mathrm{d}A$$

I for common sections is calculated as follows in Fig. 6.5.

Section modulus Z is defined as

$$Z = \frac{l}{y}$$

Strain energy due to bending U is defined as

$$U = \int_0^l \frac{M^2 \mathrm{d}s}{2El}$$

For uniform beams subject to constant bending moment this reduces to

$$U = \frac{M^2 l}{2El}$$

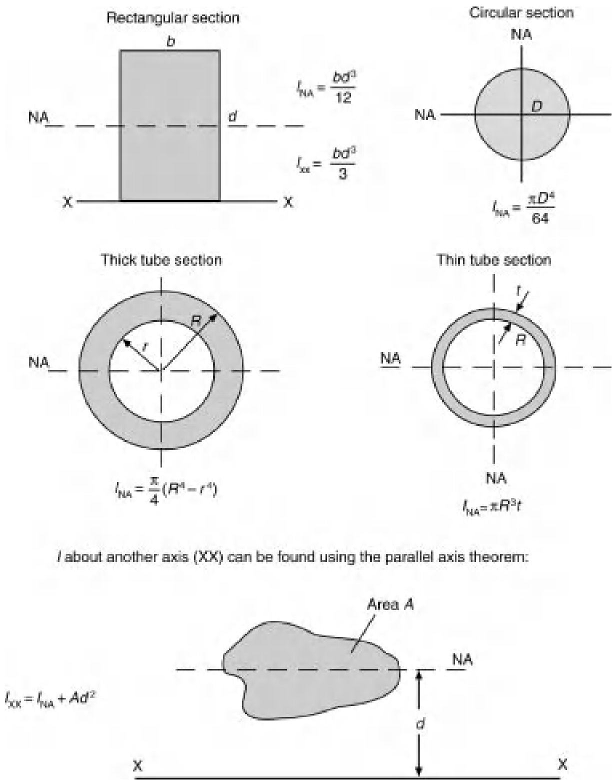


Figure 6.5

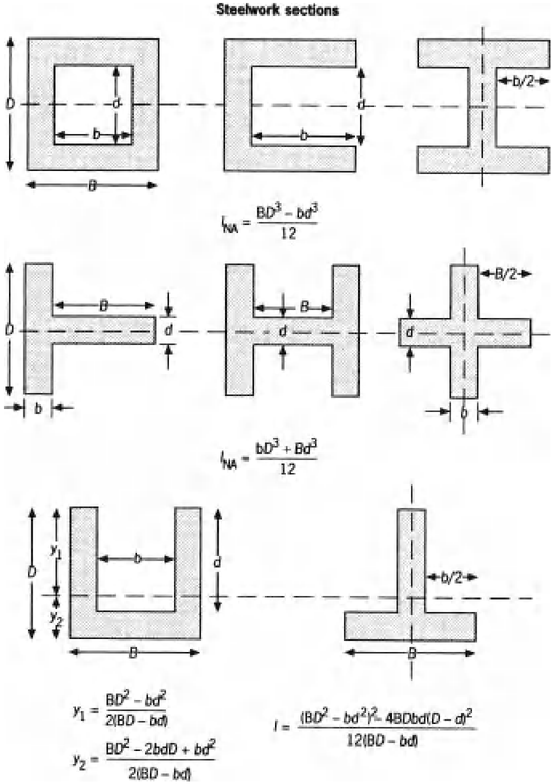


Figure 6.5 (cont.)

6.5 Slope and deflection of beams

Many engineering components can be modelled as simple beams.

The relationships between load W, shear force SF, bending moment M, slope, and deflection are

$$\text{Deflection} = \delta(\text{or } y)$$
$$\text{Slope} = \frac{dy}{dx}$$

$$M = EI\frac{d^2y}{dx^2}$$

$$F = EI\frac{d^3y}{dx^3}$$

$$W = EI\frac{d^4y}{dx^4}$$

Values for common beam configurations are shown in Fig 6.6.

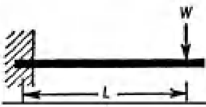
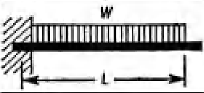
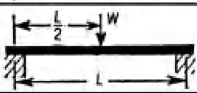
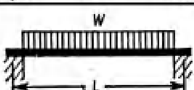
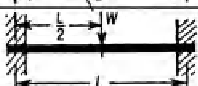
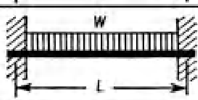
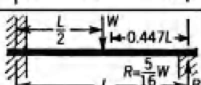
Conditions of support and loading	Bending moment (maximum)	Shearing force maximum)	Safe load W	Deflection (maximum)
	WL	W	$\frac{M}{L}$	$\frac{WL^3}{3EI}$
	$\frac{WL^2}{2}$	W	$\frac{2M}{L}$	$\frac{WL^3}{8EI}$
	$\frac{WL}{4}$	$\frac{W}{2}$	$\frac{4M}{L}$	$\frac{WL^3}{48EI}$
	$\frac{WL^2}{8}$	$\frac{W}{2}$	$\frac{8M}{L}$	$\frac{5WL^3}{384EI}$
	$\frac{WL}{8}$	$\frac{W}{2}$	$\frac{8M}{L}$	$\frac{WL^3}{192EI}$
	$\frac{WL^2}{12}$	$\frac{W}{2}$	$\frac{12M}{L}$	$\frac{WL^3}{384EI}$
	$\frac{3WL}{16}$	$\frac{11W}{16}$	$\frac{16M}{3L}$	$\frac{WL^3}{107EI}$
	$\frac{WL}{8}$	$\frac{5W}{8}$	$\frac{8M}{L}$	$\frac{WL^3}{187EI}$

Figure 6.6

6.6 Torsion

For solid or hollow shafts of uniform cross-section, the torsion formula is

$$\frac{T}{J} = \frac{\tau}{R} = \frac{G\theta}{l}$$

T = torque applied (N m)
J = polar second moment of area (m^4)
τ = shear stress (N/m^2)
R = radius (m)
G = modulus of rigidity (N/m^2)
θ = angle of twist (rad)

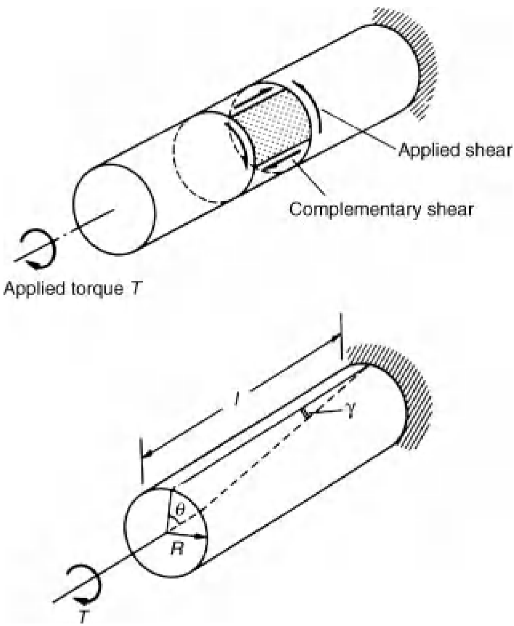
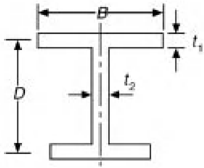
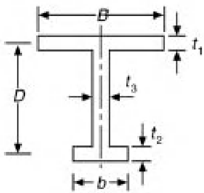


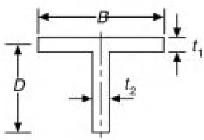
Figure 6.7



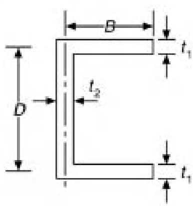
$$J = \frac{1}{3}(2Bt_1^3 + Dt_2^3)$$



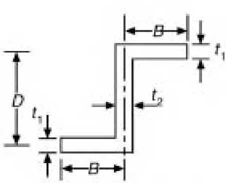
$$J = \frac{1}{3}(Bt_1^3 + bt_2^3 + Dt_3^3)$$



$$J = \frac{1}{3}(Bt_1^3 + Dt_2^3)$$



$$J = \frac{1}{3}(2Bt_1^3 + Dt_2^3)$$



$$J = \frac{1}{3}(2Bt_1^3 + Dt_2^3)$$

The polar second motion of area (J) m^4 is a measure of the stiffness of a member in pure twisting

Figure 6.8 Torsion Formulae

For solid shafts

$$J = \frac{\pi D^4}{32}$$

For hollow shafts

$$J = \frac{\pi(D^4 - d^4)}{32}$$

For thin-walled hollow shafts

$$J \cong \pi D^3 t$$

where

r = mean radius of shaft wall
t = wall thickness

Strain energy in torsion

$$U = \frac{T^2 l}{2GJ} = \frac{GJ\,\theta^2}{2l}$$

Shaft under combined bending moment, M, and torque, T, from bending

$$\sigma = \frac{MD}{2l}$$

from torsion

$$\tau = \frac{TD}{2J}$$

This results in an 'equivalent' bending moment (M_e) of

$$M_e = \frac{1}{2}(\sqrt{M^2 + T^2})$$

A similar approach can be used to give an equivalent torque T_e

$$T_e = \sqrt{M^2 + T^2}$$

6.7 Thin cylinders

Most pressure vessels have a diameter:wall thickness ratio of >20 and can be modelled using thin cylinder assumptions. The basic equations form the basis of all pressure vessel codes and standards.

Basic equations are

$$\text{Circumferential(hoop)stress}, \sigma_H = \frac{pd}{2t}$$

$$\text{Hoop strain}, \varepsilon_H = \frac{1}{E}(\sigma_H - v\sigma_L)$$

$$\text{Longitudinal(axial)stress}, \sigma_L = \frac{pd}{4t}$$

$$\text{Longitudinal strain}, \varepsilon_L = \frac{1}{E}(\sigma_L - v\sigma_H)$$

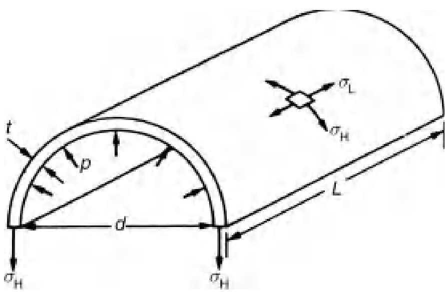


Figure 6.9

6.8 Cylindrical vessels with hemispherical ends

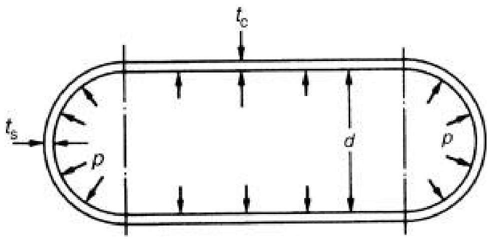


Figure 6.10

For the cylinder

$$\sigma_{HC} = \frac{pd}{2t_c} \text{ and } \sigma_{LC} = \frac{pd}{2t_c}$$

Hoop strain

$$\varepsilon_{HC} = \frac{1}{E}(\sigma_{HC} - \nu\sigma_{LC})$$

For the hemispherical ends

$$\sigma_{HS} = \frac{pd}{4t_s} \text{ and } \varepsilon_{HS} = \frac{pd}{4t_s E}(1 - \nu)$$

The differences in strain produce *discontinuity stress* at a vessel head/shell joint.

6.9 Thick cylinders

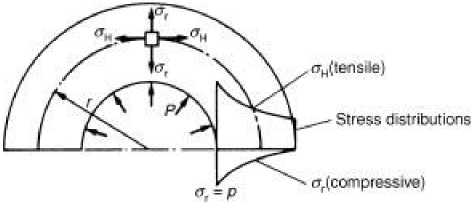


Figure 6.11

Components such as hydraulic rams and boiler headers are designed using thick cylinder assumptions. Hoop and radial stresses vary through the walls, giving rise to the Lamé equations.

$$\sigma = A + \frac{B}{r^2} \text{ and } \sigma_r = A - \frac{B}{r^2}$$

where A and B are 'Lamé' constants

$$\varepsilon_H = \frac{\sigma_H}{E} - \frac{\nu\sigma_r}{E} - \frac{\nu\sigma_L}{E}$$

$$\varepsilon_L = \frac{\sigma_L}{E} - \frac{\nu\sigma_r}{E} - \frac{\nu\sigma_H}{E}$$

Lamé constant (A) is given by

$$A = \frac{P_1 R_1^2 - P_2 R_2^2}{R_2^2 - R_1^2}$$

$P_1 =$ internal pressure
$P_2 =$ external pressure
$R_1 =$ internal radius
$R_2 =$ external radius

6.10 Buckling of struts

Long and slender members in compression are termed struts. They fail by buckling before reaching their true compressive yield strength. Buckling loads W_b depend on the loading case.

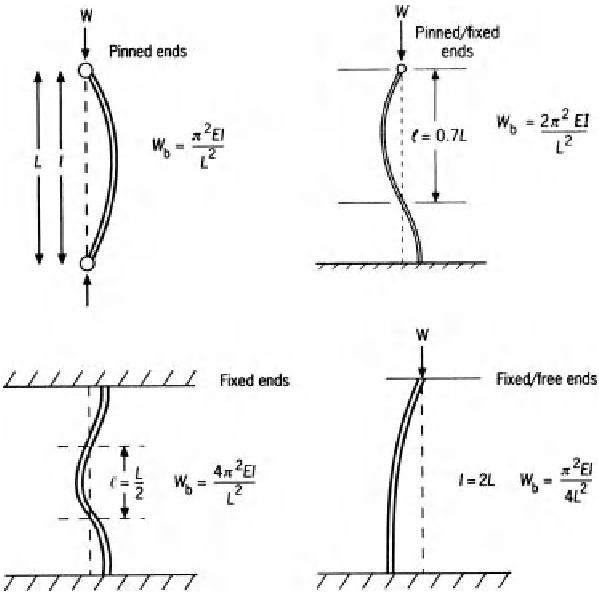


Figure 6.12

The *equivalent length*, l, of the strut is the length of a single 'bow' in the deflected condition.

6.11 Flat circular plates

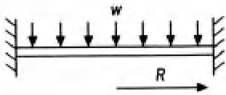
Many parts of engineering assemblies can be analysed by approximating them to flat circular plates or annular rings. The general equation governing slopes and deflections is

$$\frac{\mathrm{d}}{\mathrm{d}r}\left[\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}y}{\mathrm{d}r}\right)\right]=\frac{W}{D}$$

where

$$D=\frac{Et^3}{12(1-\nu^2)}$$

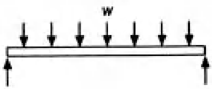
$\hat{y}$ = maximum deflection
$\frac{\mathrm{d}y}{\mathrm{d}r}$ = slope
W = applied load
t = thickness
D = flexural stiffness
E = Young's modulus
$\hat{\sigma}_r$ = maximum radial stress
$\hat{\sigma}_z$ = maximum tangential stress



$$\hat{y} = \frac{3wR^4}{16Et^3}(1-\nu^2)$$

$$\hat{\sigma}_r = \frac{3wR^2}{4t^2}$$

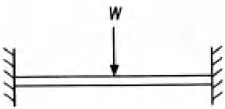
$$\hat{\sigma}_t = \frac{3wR^2}{8t^2}(1+\nu)$$



$$\hat{y} = \frac{3wR^4}{16Et^3}\quad(5+\nu)(1-\nu)$$

$$\hat{\sigma}_r = \frac{3wR^2}{8t^2}(3+\mu)$$

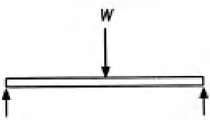
$$\hat{\sigma}_t = \frac{3wR^2}{8t^2}(3+\nu)$$



$$\hat{y} = \frac{3WR^2}{4\pi Et^3}(1-\nu^2)$$

$$\hat{\sigma}_r = \frac{3W}{2\pi t^2}$$

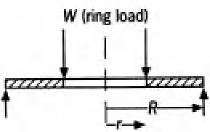
$$\hat{\sigma}_t = \frac{3\nu W}{2\pi t^2}$$



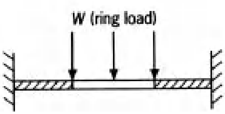
$$\hat{y} = \frac{3WR^2}{4\pi Et^3}(3+\nu)(1-\nu) \quad (1-\nu^2)$$

$$\hat{\sigma}_r = \frac{3W}{2\pi t^2}(1+\nu)\ln\frac{R}{r} \qquad \text{at radius } r$$

$$\hat{\sigma}_t = \frac{3W}{2\pi t^2}\left[(1+\nu)\ln\frac{R}{r} + (1-\nu)\right] \qquad \text{at radius } r$$



$$\hat{\sigma} = \frac{3W(1+\nu)}{\pi t^2}\left[\frac{R^2}{(R^2-r^2)}\ln\frac{R}{r}\right]$$

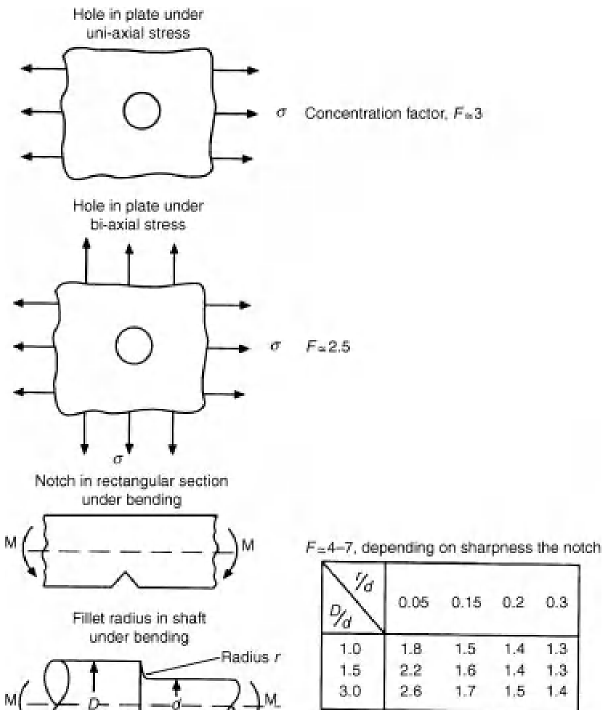


$$\hat{\sigma} = \frac{3W}{2\pi t^2}\left(\frac{R^2-r^2}{R^2}\right)$$

Figure 6.13

6.12 Stress concentration factors

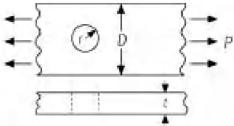
The effective stress in a component can be raised well above its expected levels owing to the existence of geometrical features causing stress concentrations under dynamic elastic conditions. Typical factors are as shown in 6.14.



D/d \ r/d	0.05	0.15	0.2	0.3
1.0	1.8	1.5	1.4	1.3
1.5	2.2	1.6	1.4	1.3
3.0	2.6	1.7	1.5	1.4

Approximate value of stress concentration factor, F

Figure 6.14

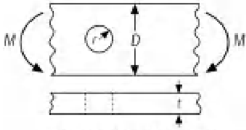


Hole in plate under uni-axial stress

$$\hat{\sigma} \simeq F\left[\frac{P}{t(D-2r)}\right]$$

$$F \simeq 3 - 3.13\left(\frac{2r}{D}\right) + 3.66\left(\frac{2r}{D}\right)^2 - 1.53\left(\frac{2r}{D}\right)^3$$

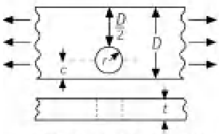
The maximum stress is at the edge of the hole



Hole in plate under in-plane bending

$$\hat{\sigma} \text{ at edge of the hole} \simeq 2\left[\frac{12Mr}{t[D^3 - (2r)^3]}\right]$$

$$\hat{\sigma} \text{ at edge of the plate} \simeq \frac{6MD}{t[D^3 - (2r)^3]}$$

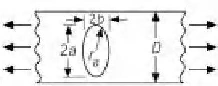


Off-centre hole in plate under uni-axial stress

$$\hat{\sigma} = F\sigma_{nominal}$$

$$\sigma_{nominal} \simeq \frac{P\sqrt{1-(r/c)^2}\,[1-(c/D)]}{Dt[1-(r/c)]\,[1-(c/D)]\,\left[2-\sqrt{1-(r/c)^2}\right]}$$

$$F \simeq 3 - 3.13\,(r/c) + 3.66\,(r/c)^2 - 1.53\,(r/c)^3$$



Elliptical hole in plate under uni-axial stress

$$\hat{\sigma} = F\sigma_{nominal}$$

$$\sigma_{nominal} = \frac{P}{t(D-2a)}$$

$$F \simeq F_1 + F_2\left(\frac{2a}{D}\right) + F_3\left(\frac{2a}{D}\right)^2 + F_4\left(\frac{2a}{D}\right)^3$$

for $0.5 \le \frac{a}{b} \le 10$

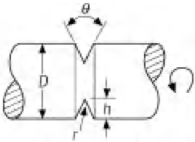
$$F_1 \simeq 1 + \sqrt{\frac{a}{b}} + \frac{2a}{b}$$

$$F_2 \simeq -0.351 - 0.021\sqrt{\frac{a}{b}} - \frac{2.483a}{b}$$

$$F_3 \simeq -3.621 - 5.183\sqrt{\frac{a}{b}} + \frac{4.494a}{b}$$

$$F_4 \simeq -2.27 + 5.2\sqrt{\frac{a}{b}} - \frac{4a}{b}$$

Figure 6.15 Approximate stress concentration factors (Elastic Stresses)



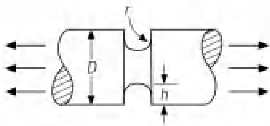
V-notch in circular shaft under torsion

F_v = stress concentration factor for V-notch

$$F_v \simeq F_u - \left[0.02 + 0.14\left(\frac{\theta}{135}\right)^2\right](F_u - 1)\,F_u$$

where F_u = stress concentration factor for U-notch in torsion

for $\frac{r}{D-2h} \le 0.01$ and $\theta \le 135°$



U-notch in circular shaft under axial tension

F_u = stress concentration for U-notch

$$F_u = F_1 + F_2\left(\frac{2h}{d}\right) + F_3\left(\frac{2h}{d}\right)^2 + F_4\left(\frac{2h}{d}\right)^3$$

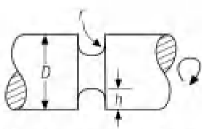
for $0.25 \le \frac{h}{r} \le 2$

$$F_1 = 0.46 + 3.35\sqrt{\frac{h}{r}} - \frac{0.77h}{r}$$

$$F_2 = 3.13 - 16\sqrt{\frac{h}{r}} + \frac{7.4h}{r}$$

$$F_3 = -6.9 + 29.3\sqrt{\frac{h}{r}} + \frac{16.1h}{r}$$

$$F_4 = 4.3 - 16.7\sqrt{\frac{h}{r}} + \frac{9.5h}{r}$$



U-notch in circular shaft under torsion

F_u = stress concentration for U-notch

$$F_u = F_1 + F_2\left(\frac{2h}{D}\right) + F_3\left(\frac{2h}{D}\right)^2 + F_4\left(\frac{2h}{D}\right)^3$$

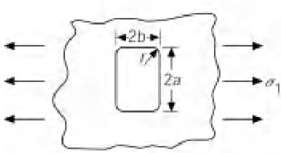
for $0.25 \le \frac{h}{r} \le 2$

$$F_1 = 1.24 + 0.26\sqrt{\frac{h}{r}} + 0.5\frac{h}{r}$$

$$F_2 = -3 + 3.3\sqrt{\frac{h}{r}} + \frac{3.63h}{r}$$

$$F_3 = 7.2 - 11.3\sqrt{\frac{h}{r}} + \frac{8.3h}{r}$$

$$F_4 = -4.4 + 7.75\sqrt{\frac{h}{r}} - \frac{5.17h}{r}$$



Rectangular hole with round corners in "infinite" plate under uniaxial stress

$$\hat{\sigma} = F\sigma_1$$

$$F \simeq F_1 + F_2\left(\frac{b}{a}\right) + F_3\left(\frac{b}{a}\right)^2 + F_4\left(\frac{b}{a}\right)^3$$

for $0.2 \le \frac{r}{b} \le 1$ and $0.3 \le \frac{b}{a} \le 1$

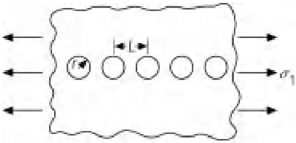
$$F_1 \simeq 14.8 - 15.8\sqrt{\frac{r}{b}} + \frac{8.15r}{b}$$

$$F_2 = -11.2 - 9.7\sqrt{\frac{r}{b}} + \frac{9.6r}{b}$$

$$F_3 = 0.2 + 38.6\sqrt{\frac{r}{b}} - \frac{27.4r}{b}$$

$$F_4 = 3.2 - 23\sqrt{\frac{r}{b}} + \frac{15.5r}{b}$$

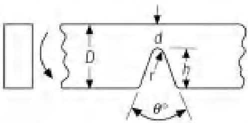
Figure 6.15 (Cont.)



Row of circular holes in "infinite" plate under uniaxial stress

$$\hat{\sigma} = F\sigma_1$$

$$F = 3 - \frac{2r}{L} - 2.1\left(\frac{2r}{L}\right)^2 + 1.9\left(\frac{2r}{L}\right)^3$$

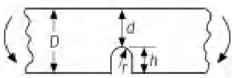


V-notch in rectangular section under bending

F_V = Stress concentration factor for V-notch

$$F_V = 1.11\ F_u - \left[0.03 + 0.11\left(\frac{\theta^\circ}{150}\right)^4\right] F_u^2$$

where F_u = Stress concentration factor for U-notch



U-notch in rectangular section under bending

F_u = Stress concentration factor for u-notch

$$F_u = F_1 + F_2\left(\frac{h}{d}\right) + F_3\left(\frac{h}{d}\right)^2 + F_4\left(\frac{h}{d}\right)^3$$

for $0.5 \le \frac{h}{r} \le 4$

$$F_1 \simeq 0.72 + 2.4\sqrt{\frac{h}{r}} - \frac{0.13h}{r}$$

$$F_2 \simeq 1.98 - 11.5\sqrt{\frac{h}{r}} + \frac{2.2h}{r}$$

$$F_3 \simeq -4.4 + 18.75\sqrt{\frac{h}{r}} + \frac{4.6h}{r}$$

$$F_4 \simeq 2.7 - 9.7\sqrt{\frac{h}{r}} + \frac{2.5h}{r}$$

Figure 6.15 (Cont.)

Section 7

Material Failure

7.1 How materials fail

There is no single, universally accepted explanation covering the way that materials (particularly metals) fail. Figure 7.1 shows the generally accepted phases of failure. Elastic behaviour, up to yield point, is followed by increasing amounts of irreversible plastic flow. The fracture of the material starts from the point in time at which a crack initiation occurs and continues during the propagation phase until the material breaks.

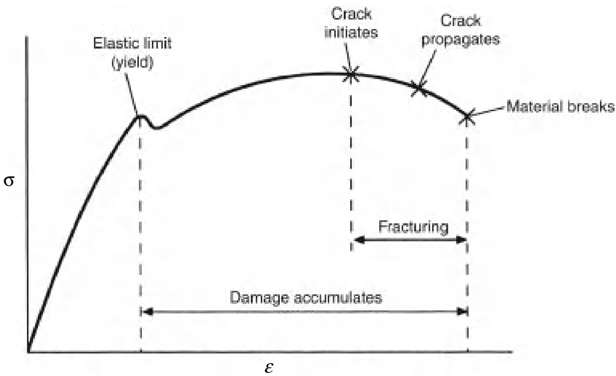


Figure 7.1

There are several approaches to both the characteristics of the original material and the way that the material behaves at a crack tip (see Fig. 7.2). Two of the more common ones are:

- the linear elastic fracture mechanics (LEFM) approach with its related concept of fracture toughness (K_{1c}) parameter (a material property);
- fully plastic behaviour at the crack tip, i.e. 'plastic collapse' approach.

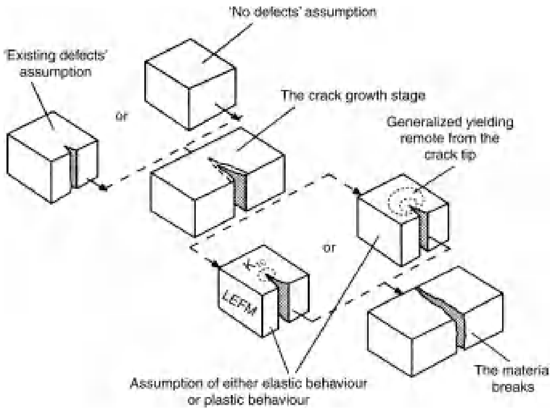


Figure 7.2

7.2 LEFM method

This is based on the 'fast fracture' equation:

$$K_{1c} = K_1 \equiv y\sigma\sqrt{\pi a}$$

K_{1c} = plane strain fracture toughness
K_1 = stress intensity factor
a = crack length
y = dimensionless factor based on geometry

Typical y values used are shown in Figure 7.3.

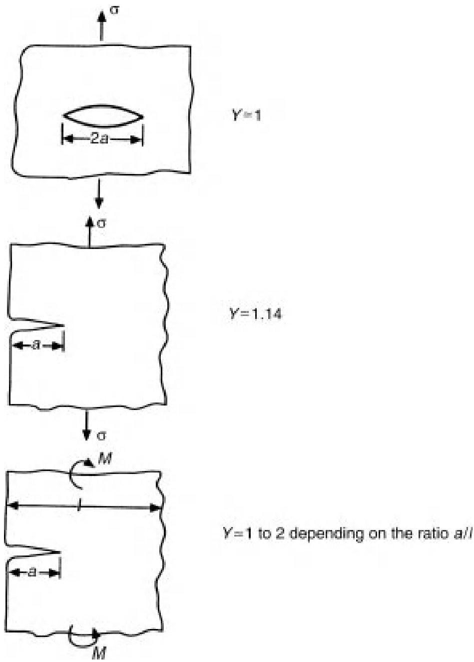


Figure 7.3

7.3 Multi-axis stress states

When stress is not uniaxial (as in many real components), yielding is governed by a combination of various stress components acting together. There are several different 'approaches' as to how this happens.

7.3.1 Von Mises criterion (or 'distortion energy' theory)

This states that yielding will begin to take place when

$$\left(\frac{1}{\sqrt{2}}\right)\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{\frac{1}{2}} = \pm\sigma_y$$

where σ_1, σ_2, σ_3 are the principal stresses at a point in a component.

It is a useful theory for ductile metals. It is more conservative than the Von Mises approach.

7.3.2 Tresca criterion (or maximum shear stress theory)

$$\frac{(\sigma_1-\sigma_2)}{2} \text{ or } \frac{(\sigma_2-\sigma_3)}{2} \text{ or } \frac{(\sigma_3-\sigma_1)}{2} \text{ or } = \pm\frac{\sigma_y}{2}$$

This is also a useful theory for ductile materials.

7.3.3 Maximum principal stress theory

This is a simpler theory which is a useful approximation for brittle metals.

The material fails when

$$\sigma_1 \text{ or } \sigma_2 \text{ or } \sigma_3 = \pm\sigma_y$$

7.4 Fatigue

Ductile materials can fail at stresses significantly less than their rated yield strength if they are subject to fatigue loadings. Fatigue data are displayed graphically on a *S–N* curve. Some materials exhibit a 'fatigue limit', representing the stress at which the material can be subjected to (in theory) an infinite number of cycles without exhibiting any fatigue effects. This

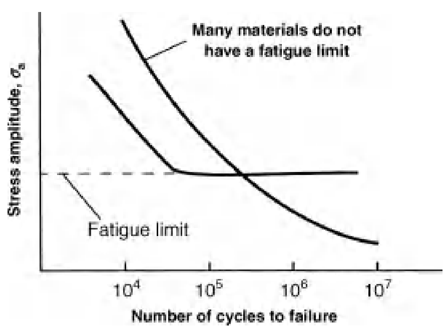


Figure 7.4

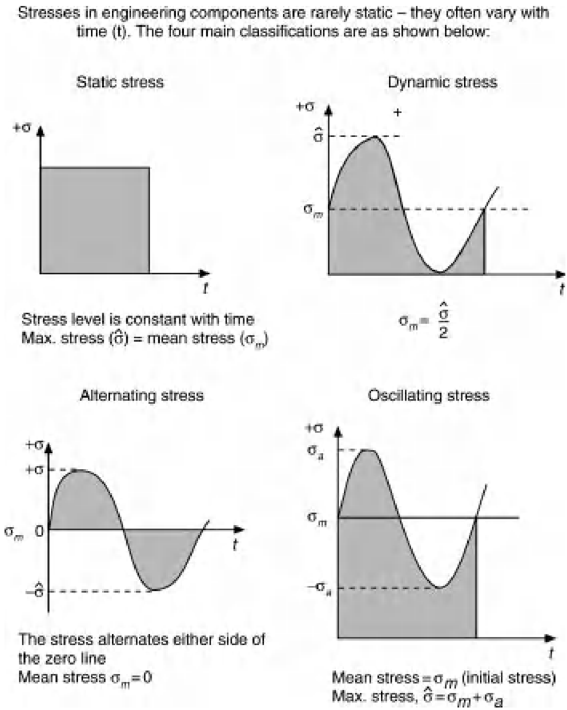


Figure 7.5 Types of Stress Loading

fatigue limit is influenced by the size and surface finish of the specimen, as well as the material's properties.

Characteristics of fatigue failures are:

- visible crack-arrest and 'beach mark' lines on the fracture face;
- striations (visible under magnification) - these are the result of deformation during individual stress cycles;

- an initiation point such as a crack, defect, or inclusion, normally on the surface of the material.

Table 7.1 Typical fatigue limits

Material	*UTS* (B_m)*(MN/m²)*	*Fatigue limit (MN/m²)*
Low-carbon steel	450	≅200
Cr Mo steel	950	≅480
Cast iron	300	≅110
S.G. cast iron	380	≅170
Titanium	550	≅320
Aluminium	100	≅ 40
Brass	320	≅100
Copper	260	≅ 75

7.4.1 Typical fatigue limits

7.4.2 Fatigue strength – rules of thumb

The fatigue strength of a material varies significantly with the size and shape of section and the type of fatigue stresses to which it is subjected. Some 'rules of thumb' values are shown in

Table 7.2

	Bendin			*Tension*		*Torsion*		
	$\sigma_{w(b)}$	$\sigma_{a(b)}$	$\sigma_{y(b)}$	σ_w	σ_a	$\tau_{w(t)}$	$\tau_{a(t)}$	$\tau_{y(t)}$
Steel (structural)	$0.5R_m$	$0.75R_m$	$1.5R_e$	$0.45R_m$	$0.59R_m$	$0.35R_m$	$0.38R_m$	$0.7R_m$
Steel (hardened and tempered)	$0.45R_m$	$0.77R_m$	$1.4R_e$	$0.4R_m$	$0.69R_m$	$0.3R_m$	$0.5R_m$	$0.7R_m$
Cast Iron	$0.38R_m$	$0.68R_m$	–	$0.25R_m$	$0.4R_m$	$0.35R_m$	$0.56R_m$	–

$\sigma_{w(b)}$ Fatigue strength under alternating stress (bending)
$\sigma_{a(b)}$ Fatigue strength under fluctuating stress (bending)
$\sigma_{y(b)}$ Yield point (bending)
σ_W Fatigue strength under alternating stress (tension)
σ_a Fatigue strength under fluctuating stress (tension)
R_e Yield point (tension)
$\tau_{w(t)}$ Fatigue strength under alternating stress (torsion)
$\tau_{a(t)}$ Fatigue strength under fluctuating stress (torsion)
$\tau_{y(t)}$ Yield point (torsion)

Table 7.2. Note how they relate to R_e and R_m values in pure tension.

7.5 Factors of safety

Factors of safety (FOSs) play a part in all aspects of engineering design. For statutory items such as pressure vessels and cranes FOSs are specified in the design codes. In other equipment it is left to established practice and designers' preference. The overall FOS in a design can be thought of as being made up of three parts:

1. the R_e/R_m ratio;
2. the nature of the working load condition; i.e. static, fluctuating, uniform, etc.;
3. unpredictable variations such as accidental overload.

Table 7.3 Typical overall FOSs

Equipment	*FOS*
Pressure vessels	5–6
Heavy duty shafting	10–12
Structural steelwork (buildings)	4–6
Structural steelwork (bridges)	5–7
Engine components	6–8
Turbine components (static)	6–8
Turbine components (rotating)	2–3
Aircraft components	1.5–2.5
Wire ropes	8–9
Lifting equipment (hooks etc.)	8–9

Design factors of safety are mentioned in many published technical standards but there is no dedicated standard on the subject.

7.6 United states practice

Table 7.4

	Yield strength	*Ultimate tensile strength*	*Modulus*
SI/European	R_e (MN/m^2)	$\mathbf{R}_m$ (MN/m^2)	E (GN/m^2)
USCS	F_{ty} (ksi)	F_{tu} (ksi)	E_t(psi 10^6)

Conversions are 1 ksi = 1000 psi = 6.89 MPa = 6.89 MN/m^2 = 6.89 N/mm^2

Technical standards in the USA often follow the United States Customary System (USCS) of units or its derivatives. Material strength definitions and equivalent units are as shown in Table 7.4.

7.7 Ultimate jigsaw – what everything is made of

Rocks, trees, water, fish, sheep and goats must have been the first conclusion. Common comparisons probably helped to decide that sheep's wool and goat's wool looked much the same, and that air was a useful thing to have around, making it impossible to dive for fish or shells for very long. Gradually, people wondered whether all the things of the world were there to see and hold or whether there might be others. It must have been difficult to know where to start – a large jigsaw with an unknown shower of pieces, and no picture on the box (and no box).

Bits of the jigsaw started to develop with the identification of the common elements by experiment or by chance. Gold, silver, phosphorus and tin grew to a list of about 33 in the year 1800. These weren't exactly the corners of the jigsaw (who said it had corners?) but, importantly, some of them did fit crudely together.

- Elements with similar physical and chemical properties showed similar atomic weights.
- Some elements seemed to have a similar willingness to bond with others – a property that was called *valency*.

Under the hypothesis that there must be an order (of some sort), others were gradually discovered. It's likely that most new findings were elements similar to those discovered already rather than completely blind shots in the dark.

The problem of completely false theorems

There has never been a scientific development that didn't have to fight its way through a soup of completely false theorems. Much time and effort was spent on the search for a mystical, atmospheric substance known as 'the ether' – a medium believed to exist to enable the propagation of light. Similar mediums were thought to exist in relation to fire and water. All were fake, and still are.

The emerging picture

Once under way, the picture on the jigsaw box emerged fairly quickly, in scientific terms. It started off being circular but was found to be better represented by a rectangle, as elements were found which fitted naturally as edge-pieces (because there was nothing similar that seemed lighter, or heavier, or with less enthusiasm to bond with anything else).

As with a jigsaw, leaving temporary gaps is a part of the exercise. Once a gap has been surrounded by linked pieces, it is then clear that something is missing, so you can begin to look for it. Once it is finished, the picture is complete – the ordered tabular display of all the chemical elements that there are, and ever will be:

The Periodic Table.

Seen as a collection of interlinking squares or boxes, the glue between them is pretty firm. Elements in the same row exhibit similar properties to their immediate neighbours in the same row, with decreasing similarity to those further away. It also works vertically, with the same continuity of similarity, although the properties that link them (chemical, physical, weight, valency or whatever) are different. As with any crowd, there are large and small family groups, inseparable partners, and the odd unlikely liaison. There won’t be anyone else joining the party however, and no one is allowed to leave.

Figure 7.6 shows the Periodic Table. In essence the order is based on recurring (or ‘periodic’) chemical properties. The listing of the elements is based on the atomic number. The horizontal rows are known as *periods* and relate to the way that electrons fill the ‘quantum shell’ around each atom. Elements in the same column have similar chemical and physical properties. Of the current total of 118 elements, only 94 occur naturally –

Figure 7.6 Ultimate jigsaw: The periodic table

the others are synthetic and need to be artificially produced. The left-hand edge column contains the common alkali metals and the right-hand edge the very light noble gases.

Within the table, several *blocks* exist, delineated in a rather complex manner by the atomic shell in which the last electron resides. The main blocks are:

- The s-block (alkali and alkali earth metals)
- The p-block (includes the so-called semi-metals)
- The d-block (transition metals)
- The f-block (offset below the rest of the table, it contains actinides and lanthanides, many of which are synthetics)

There is no real split as to those elements more common to the engineering world. Even the simplest manufactured engineering materials are usually a mixture of many of them, in addition to the iron (Fe) and carbon (C) that you would expect.

Section 8

Thermodynamics and Cycles

8.1 Quick reference: symbols – thermodynamics

Table 8.1

Symbol	*Quantity*
A	Area
As	Surface area
C	Specific heat
$\boldsymbol{c_p}$	Specific heat (constant pressure)
c_v	Specific heat (constant volume)
D	Diameter
E	Thermal 'internal' energy
E	Thermal internal energy per unit mass
F	Force
	Heat exchanger correction factor
	Black body radiation factor
	View factor
Fo	Fourier number
G	Irradiation
Gr	Grashot number
Gz	Graetz number
H	Convection heat transfer coefficient
	Planck's constant
h_{fg}	Latent heat of vaporization
h_m	Convection mass transfer coefficient
h_{rad}	Radiation heat transfer coefficient
J	Radiosity
K	Thermal conductivity
	Boltzman's constant
M (m)	Mass
Nu	Nusselt number
P	Pitch of a tube-bank
Pe	Peclet number (Re, Pm)
Pr	Prandtl number
P	Pressure
Q	Heat transfer
Q	Rate of heat transfer
Q	Rate of energy generation per unit volume

Table 8.1 (Cont.)

Symbol	*Quantity*
R	Universal gas constant
Re	Reynolds number
$\mathrm{R_f}$	Fouling factor
R	Radius of cylinder or sphere
r, φ, z	Cylindrical co-ordinates
Symbol	*Quantity*
r, θ, φ	Spherical co-ordinates
St	Stanton number
T	Temperature
T	Time
U	Overall heat transfer coefficient
V	Volume
V	Specific volume
x, y, z	Rectangular co-ordinates
A	Thermal diffusivity
B	Volumetric thermal expansion coefficient
Δ	Hydrodynamic boundary layer thickness
δ_t	Thermal boundary layer thickness
E	Emissivity
ε_f	Fin effectiveness
η_f	Fin efficiency
Θ	Temperature difference
K	Absorption coefficient
Λ	Wavelength
M	Dynamic viscosity
N	Kinematic viscosity
P	Density
P	Reflectivity
Σ	Stefan-Boltzman constant
T	Shear stress
	Transmissivity
Φ	Stream function

8.2 Basic thermodynamic laws

The basic laws of thermodynamics govern the design and operation of engineering machines. The most important principles are those concerned with the conversion of heat energy from available sources such as fuels into useful work.

8.2.1 The first law

The first law of thermodynamics is merely a specific way to express the principle of conservation of energy. It says, effectively, that heat and work are two mutually convertible forms of energy. So:

$$\text{heat in} = \text{work out}$$

or, in symbols

$$\Sigma \mathrm{d}Q = \Sigma \mathrm{d}W (\text{over a complete cycle})$$

This leads to the non-flow energy equation

$$\mathrm{d}Q = \mathrm{d}u + \mathrm{d}W$$

where u = internal energy.

8.2.2 The second law

This can be expressed several ways:

- heat flows from hot to cold, not cold to hot;
- in a thermodynamic cycle, gross heat supplied must exceed the net work done – so some heat has to be *rejected* if the cycle is to work;

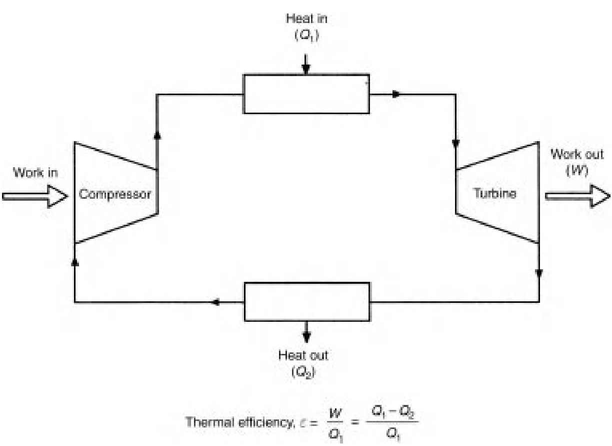


Figure 8.1

- a working cycle must have a heat supply and a heat sink;
- the thermal efficiency of a heat engine must always be less than 100 percent.

The two laws point towards the general representation of a heat engine as shown.

8.3 Entropy

- The existence of entropy follows from the second law.
- Entropy (s) is a property represented by a reversible adiabatic process.
- In the figure, each p–v line has a single value of entropy (s).

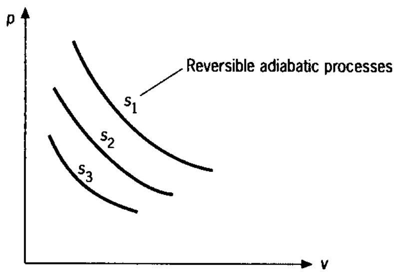


Figure 8.2

Symbolically, the situation for all working substances is represented by

$$ds = \frac{dQ}{T}$$

where s is entropy.

8.4 Enthalpy

Enthalpy (h) is a property of a fluid itself.
Enthalpy, $h = u + pv$ (units kJ/kg)

It appears in the steady flow energy equation (SFEE). The SFEE is

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W$$

8.5 Other definitions

Other useful thermodynamic definitions are:

- A perfect gas follows:

$$\frac{pv}{T} = \text{constant} = R\ (\text{kJ/kgK})$$

- γ ratio $= c_p/c_v$ (ratio of specific heats) $\cong 1.4$
- A constant volume process follows:

$$Q = mc_v(T_2 - T_1)$$

- A constant pressure process follows:

$$Q = h_2 - h_1 = mc_p(T_2 - T_1)$$

- A polytropic process follows:

$$pv^N = c \text{ and work done } = \frac{p_1 v_1 - p_2 v_2}{N - 1}$$

8.6 Cycles

Heat engines operate on various adaptations of ideal thermodynamic cycles. These cycles may be expressed on a p–v diagram or T–s diagram, depending on the application.

Reciprocating machines such as diesel engines and simple air compressors are traditionally shown on a p–v diagram. Refrigeration and steam cycles are better explained by the use of the T–s diagram.

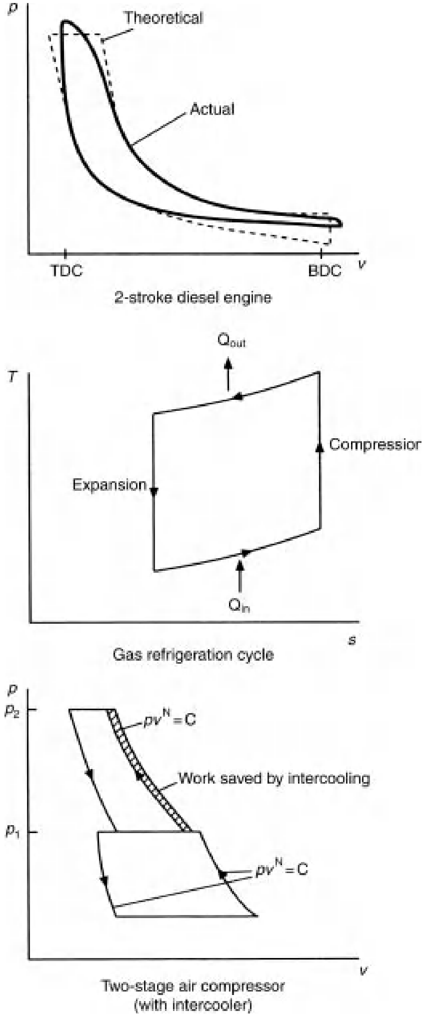

p
Theoretical
Actual
TDC
BDC
v
2-stroke diesel engine
Q_out
T
Compressior
Expansion
Q_in
s
Gas refrigeration cycle
p
p2
pv^N = C
Work saved by intercooling
p1
pv^N = C
v
Two-stage air compressor
(with intercooler)

Figure 8.3

8.7 The steam cycle

All steam turbine systems for power generation or process use are based on adaptations of the Rankine cycle. Features such as superheating, reheating, and regenerative feed heating are used to increase the overall cycle efficiency.

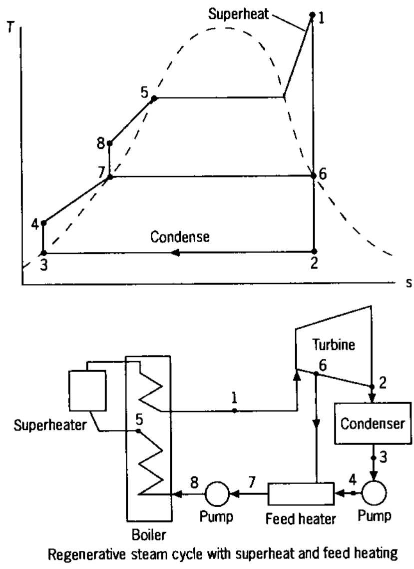


Figure 8.4 Regenerative steam cycle with superheat and feed heating

8.8 Properties of steam

Three possible conditions of steam are:

- wet (or 'saturated');
- containing a dryness fraction (x);
- superheated ('fully dry').

Standard notations h_f, h_{fg} and h_g are used.

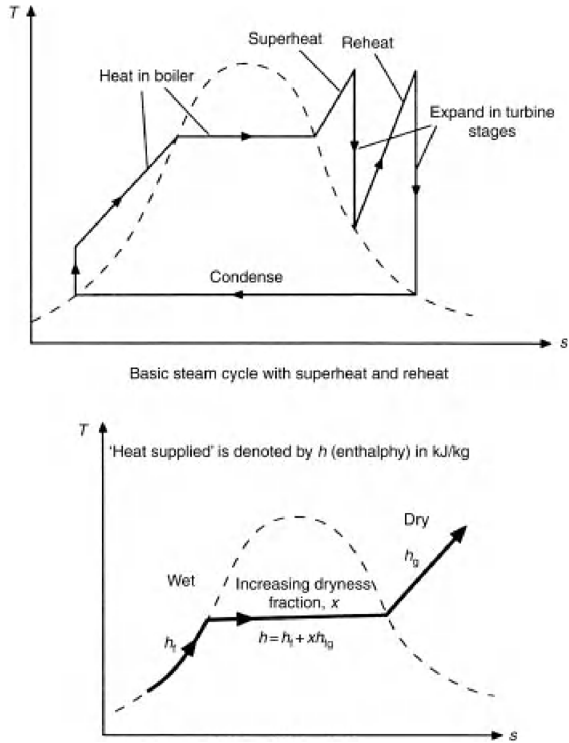


Figure 8.5

Published 'steam' tables list the properties of steam for various conditions. Two types of table are most commonly used; saturated state properties and superheat properties.

8.8.1 Saturated state properties

These list the properties corresponding to a range of temperatures (in °C) or pressures (in bar) and are formally termed; 'properties of saturated water and steam'.

	Pressure p (bar)	*Sat. temp.* t_s *(°C)*	*Specific volume* v_g *(m³ kg)*	*Specific enthalpy (kJ/kg)*			*Specific entropy (kJ/kgK)*		
				h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
Example for 100°C	1.01325	100	1.673	419.1	2256.7	2675.8	1.307	6.048	7.355

Note that:

– The maximum pressure listed is 221.2 bar – known as the *critical pressure.*
– Pressure and temperature are dependent on each other.

Figure 8.6

The format is shown in Fig. 8.6 (below):

8.8.2 Superheat properties

These list the properties in the superheat region. The two reference properties are temperature and pressure: all other properties can be derived.

The format is shown in Figure 8.7.

Note that:

- In the superheat region, pressure and temperature are independent of each other – it is only the t_s that is a function of pressure.

8.9 Reference information

The accepted reference data source in this field is:

Rogers and **Mayhew,** 1994, *Thermodynamic and Transport Properties of Fluids – SI units* (Basil Blackwell). This is a full set of tables, including data on steam, water, air, ammonia, and other relevant fluids.

8.10 The gas turbine (GT) cycle

The most basic 'open cycle' gas turbine consists of a compressor and turbine on a single shaft. The compression and expansion processes are approximately adiabatic. Figure 8.8 shows the basic (simplified) cycle diagram.

			Temperature, t (°C)		
			250		600
p = 30 bar	Specific volume v_g = 0.0666 m^3/kg	v	0.0812		0.1324
Sat. temp. t_s = 233.8°C	Specific internal energy u_g = 2603 kJ/kg	u	2751	Listed for temp. intervals of 50°C	3285
	Specific enthalpy h_g = 2803 kJ/kg	h	2995		3682
	Specific entropy S_g = 6.186 kJ/kg	s	6.541		7.505

Figure 8.7

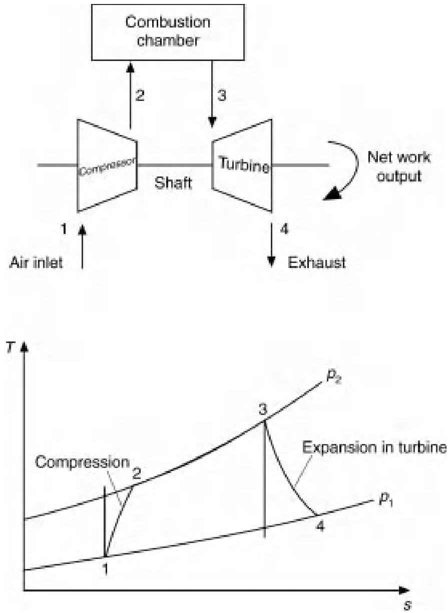

Combustion chamber
2
3
Compressor
Shaft
Turbine
Net work output
1
Air inlet
4
Exhaust
T
p_2
3
Expansion in turbine
Compression
2
p_1
4
1
s

Figure 8.8

Section 9

Basic Fluid Mechanics and Aerodynamics

9.1 Basic properties

9.1.1 Basic relationships

Fluids are divided into (a) liquids, which are virtually incompressible and (b) gases, which are compressible. A fluid consists of a collection of molecules in constant motion. A liquid adopts the shape of the vessel containing it, while a gas expands to fill any container in which it is placed. Some basic fluid relationships are given in Table 9.1.

Table 9.1 Basic fluid relationships

Density (ρ)	Mass per unit volume. Units kg/m^3 (lb/in^3)
Specific gravity (s)	Ratio of density to that of water i.e. $s = \rho/\rho_{water}$
Specific volume (v)	Reciprocal of density i.e. $s = 1/\rho$. Units m^3/kg (in^3/lb)
Dynamic viscosity (μ)	A force per unit area or shear stress of a fluid. Units Ns/m^2 (lbf.s/ft^2)
Kinematic viscosity (ν)	A ratio of dynamic viscosity to density i.e. $\nu = \mu/\rho$. Units m^2/s (ft^2/s)

9.1.2 Perfect gas

A perfect, or 'ideal', gas is one which follows Boyles/Charles law $pv = RT$ where

p = pressure of the gas
v = specific volume
T = absolute temperature
R = the universal gas constant

Although no actual gases follow this law totally, the behaviour of most gases at temperatures well above their liquification temperature will approximate to it and so they can be *considered* as a perfect gas.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

9.1.3 Changes of state

When a perfect gas changes state its behaviour approximates to

$$pv^n = \text{Constant}$$

where n is known as the polytropic exponent.

Figure 9.1 shows the four main changes of state relevant to aeronautics; isothermal, adiabatic, polytropic, and isobaric.

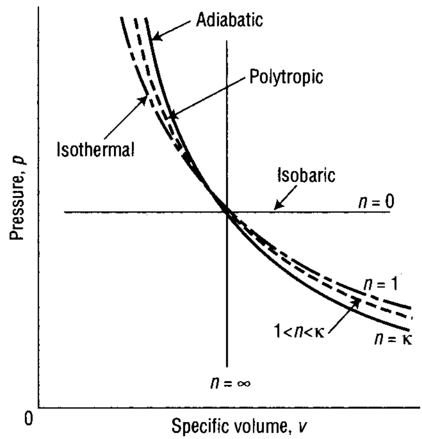


Figure 9.1

9.1.4 Compressibility

The extent to which a fluid can be compressed in volume is expressed using the compressibility coefficient β.

$$\beta = \frac{\Delta v / v}{\Delta p} = \frac{1}{K}$$

where

Δv = change in volume
v = initial volume
Δp = change in pressure
K = bulk modulus

Also

$$K = \rho \frac{\Delta p}{\Delta \rho} = \rho \frac{\mathrm{d}p}{\mathrm{d}\rho}$$

and

$$a = \sqrt{\frac{\mathrm{d}p}{\mathrm{d}\rho}} = \sqrt{\frac{K}{\rho}}$$

where

a = the velocity of propagation of a pressure wave in the fluid.

9.1.5 Fluid statics

Fluid statics is the study of fluids that are at rest (i.e. not flowing) relative to the vessel containing them. Pressure has four important characteristics:

- pressure applied to a fluid in a closed vessel (such as a hydraulic ram) is transmitted to all parts of the closed vessel at the same value (Pascal's law);
- magnitude of pressure force acting at any point in a static fluid is the same, irrespective of direction;
- pressure force always acts perpendicular to the boundary containing it;
- the pressure 'inside' a liquid increases in proportion to its depth.

Other important static pressure statements are:

- absolute pressure = gauge pressure + atmospheric pressure;
- pressure (p) at depth (h) in a liquid is given by $p=\rho g h$;
- a general equation for a fluid at rest is

$$p\mathrm{d}A - \left(p + \frac{\mathrm{d}p}{\mathrm{d}z} \cdot \mathrm{d}z\right)\mathrm{d}A - \rho g \,\mathrm{d}A \,\mathrm{d}z = 0$$

This relates to an infinitesimal vertical cylinder of fluid.

9.2 Flow equations

Flow of a fluid may be one dimensional (1-D), two dimensional (2-D), or three dimensional (3D), depending on the way in which the flow is constrained.

9.2.1 One-dimensional flow

One-dimensional flow has a single-direction coordinate x and a velocity in the direction of v. Flow in a pipe or tube is generally considered one-dimensional. The equations for 1-D flow are derived by considering flow along a straight-stream tube (see Fig. 9.2). Table 9.2 shows the principles, and their resulting equations.

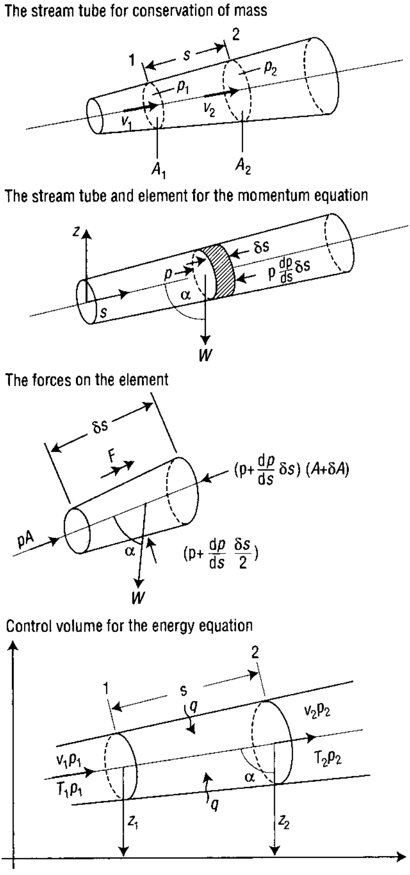


Figure 9.2

Table 9.2 Fluid principles

Law	*Basis*	*Resulting equations*
Conservation of mass	Matter (in a stream tube or anywhere else) cannot be created or destroyed.	$\rho vA = \text{constant}$
Conservation of momentum	The rate of change of momentum in a given direction = algebraic sum of the forces acting in that direction (Newton's second law of motion).	$\int \sqrt{\frac{dp}{\rho}} + 1/2\, v^2 + gz = \text{constant}$ This is Bernoulli's equation.
Conservation of energy	Energy, heat, and work are convertible into each other and are in balance in a steadily operating system.	$c_p T + \frac{v^2}{2} = \text{constant}$ for an adiabatic (no heat transferred) flow system.
Equation of state	Perfect gas state: $p/\rho T = R$ and the first law of thermodynamics	$p = k\rho^{\gamma}$ k = constant γ = ratio of specific heat c_p/c_v

9.2.2 *Two-dimensional flow*

Two-dimensional flow (as in the space between two parallel flat plates) is that in which all velocities are parallel to a given plane. Either rectangular (x, y) or polar (r, θ) coordinates may be used to describe the characteristics of 2-D flow. Figure 9.3 and Table 9.3 show the fundamental equations.

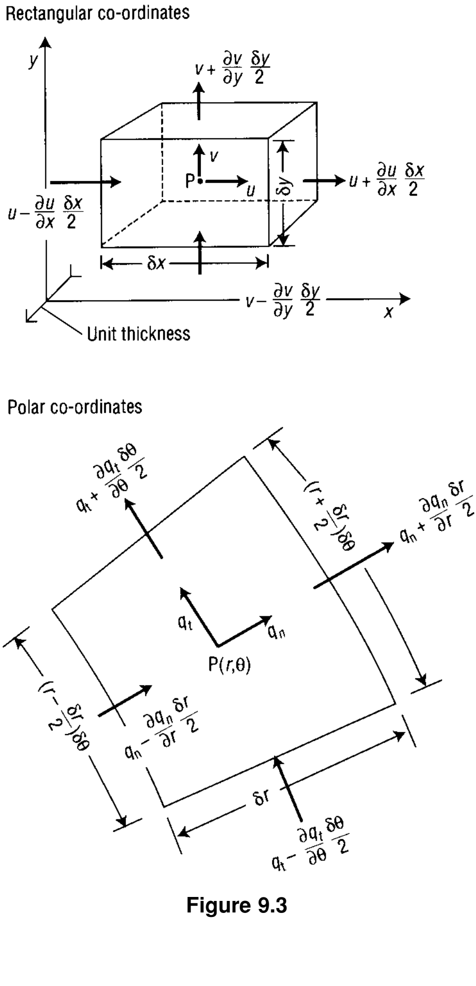

Rectangular co-ordinates
y
x
$v + \frac{\partial v}{\partial y}\frac{\delta y}{2}$
v
P
u
δy
$u + \frac{\partial u}{\partial x}\frac{\delta x}{2}$
$u - \frac{\partial u}{\partial x}\frac{\delta x}{2}$
δx
$v - \frac{\partial v}{\partial y}\frac{\delta y}{2}$
Unit thickness
Polar co-ordinates
$q_t + \frac{\partial q_t}{\partial \theta}\frac{\delta \theta}{2}$
$(r + \frac{\delta r}{2})\delta\theta$
$q_n + \frac{\partial q_n}{\partial r}\frac{\delta r}{2}$
q_t
q_n
P(r,θ)
$(r - \frac{\delta r}{2})\delta\theta$
$q_n - \frac{\partial q_n}{\partial r}\frac{\delta r}{2}$
δr
$q_t - \frac{\partial q_t}{\partial \theta}\frac{\delta \theta}{2}$

Figure 9.3

Table 9.3 Two-dimensional flow: fundamental equations

Basis	*The equation*	*Explanation*
Laplace's equation	$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=0=\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}$ or $\nabla^2\phi=\nabla^2\psi=0$ where $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$	A flow described by a unique velocity potential is irrational.
Equation of motion in 2-D	$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho}\left(Y-\frac{\partial p}{\partial x}\right)$ $\frac{\partial v}{\partial t}+u\frac{\partial y}{\partial x}+v\frac{\partial v}{\partial t}=\frac{1}{\rho}\left(Y-\frac{\partial p}{\partial y}\right)$	The principle of force = mass × acceleration (Newton's law of motion) applies to fluids and fluid particles.
Equation of continuity in 2-D (incompressible flow)	$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$ or in polar $\frac{q_n}{r}+\frac{\partial q_n}{\partial r}+\frac{1}{r}\frac{\partial q_t}{\partial\theta}=0$	If fluid velocity increases in the x direction, it must decrease in the y direction (see Fig. 9.3)
Equation of vorticity	$\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}=\varsigma$ or, in polar $\varsigma=\frac{q_t}{r}+\frac{\partial q_t}{\partial r}-\frac{1}{r}\frac{\partial q_n}{\partial\theta}$	A rotating or spinning element of fluid can be investigated by assuming it is a solid. (See Fig. 9.4)
Stream function ψ (incompressible flow)	Velocity at a point is given by $u=\frac{\partial\psi}{\partial y}$ $v=-\frac{\partial\psi}{\partial x}$	ψ is the stream function. Lines of constant ψ give the flow pattern of a fluid stream (See Fig. 9.5)
Velocity potential φ (irrotational 2-D flow)	Velocity at a point is given by $u=\frac{\partial\phi}{\partial x}$ $v=-\frac{\partial\phi}{\partial y}$	φ is defined as $\phi=\int_{op} q\cos\beta\,\mathrm{d}s$ (See Fig. 9.6)

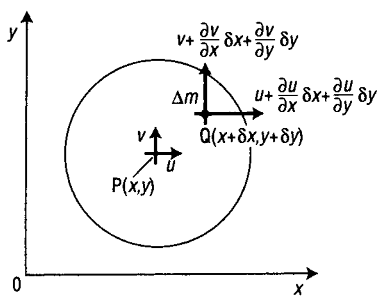


Figure 9.4

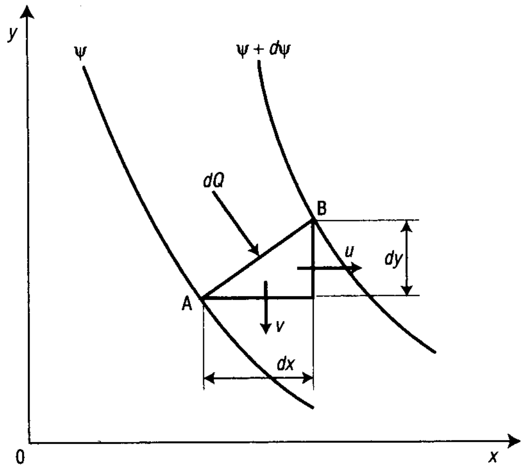


Figure 9.5

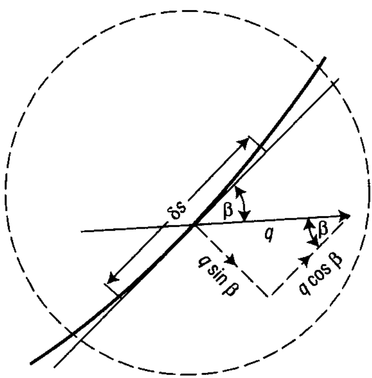


Figure 9.6

9.2.3 The navier–stokes equations

The Navier–Stokes equations are written as

$$\left.\begin{aligned}\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)&=\rho X-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)\\ \rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)&=\rho Y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)\end{aligned}\right\}$$

Inertia term; Body Force Term; Pressure term; Viscous term

9.2.4 Sources and sinks

A '*source*' is an arrangement in which a volume of fluid (+ q) flows out evenly from an origin toward the periphery of an (imaginary) circle around it. If q is negative, such a point is termed a *sink* (see Fig. 9.7). If a source and sink of equal strength have their extremities infinitesimally close to each other, while increasing the strength, this is termed a '*doublet*'.

9.3 Flow regimes

9.3.1 General descriptions

Flow regimes can generally be described as follows (see Fig. 9.8):

- *Steady flow* Flow parameters at any point do not vary with time (even though they may differ between points).
- *Unsteady flow* Flow parameters at any point vary with time.
- *Laminar flow* Flow that is generally considered smooth, i.e. not broken up by eddies.
- *Turbulent flow* Non-smooth flow in which any small disturbance is magnified, causing eddies and turbulence.
- *Transition flow* The condition lying between laminar and turbulent flow regimes.

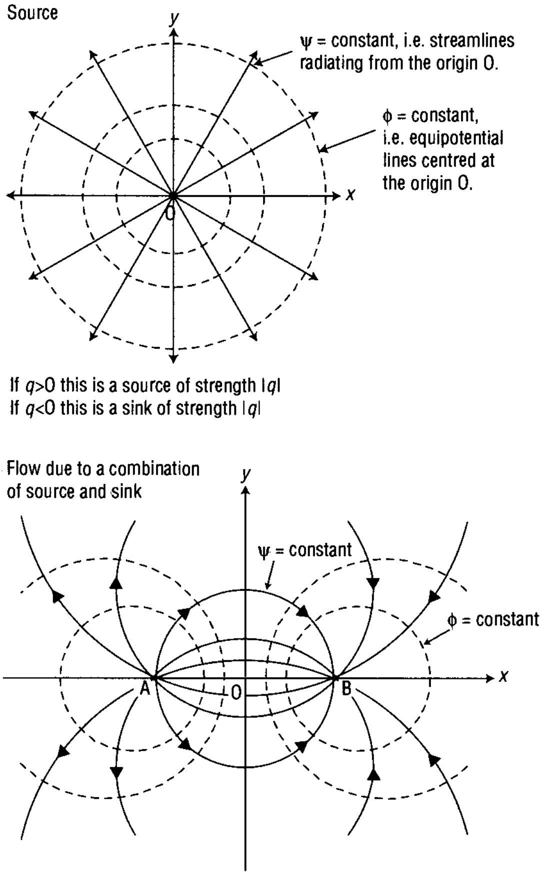

Source
y
ψ = constant, i.e. streamlines radiating from the origin O.
ϕ = constant, i.e. equipotential lines centred at the origin O.
x
O
If q>0 this is a source of strength |q|
If q<0 this is a sink of strength |q|
Flow due to a combination of source and sink
y
ψ = constant
ϕ = constant
x
A
O
B

Figure 9.7

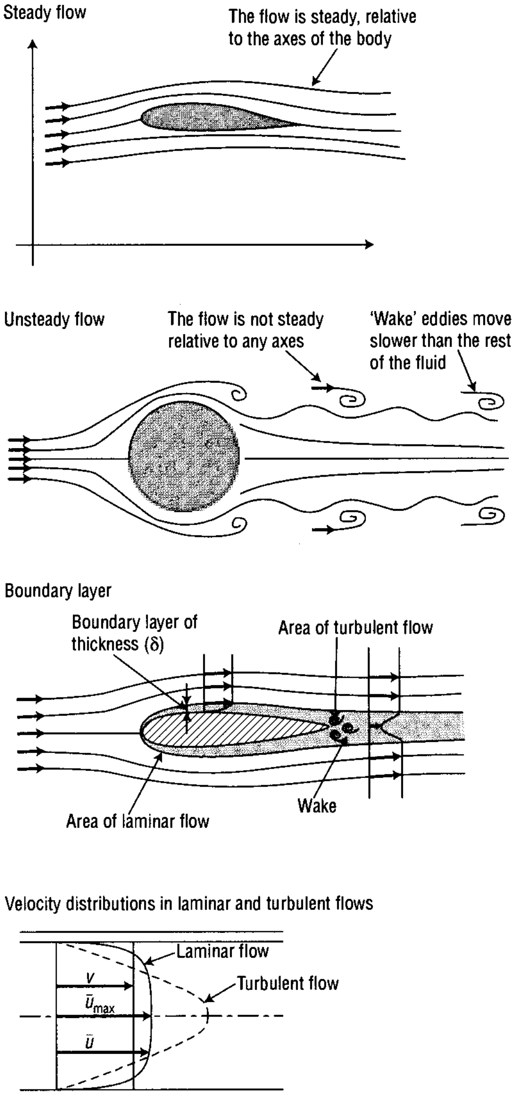

Steady flow
The flow is steady, relative to the axes of the body
Unsteady flow
The flow is not steady relative to any axes
'Wake' eddies move slower than the rest of the fluid
Boundary layer
Boundary layer of thickness (δ)
Area of turbulent flow
Area of laminar flow
Wake
Velocity distributions in laminar and turbulent flows
Laminar flow
Turbulent flow
V
Ū max
Ū

Figure 9.8

9.3.2 Reynolds number

Reynolds number is a dimensionless quantity that determines the nature of flow of fluid over a surface.

$$\text{Renolds number (Re)} = \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{\rho VD}{\mu} = \frac{VD}{\nu}$$

where

ρ = density
μ = dynamic viscosity
ν = kinematic viscosity
V = velocity
D = effective diameter

- Low Reynolds numbers (below about 2000) result in laminar flow.
- High Reynolds numbers (above about 2300) result in turbulent flow.
- Values of Re for $2000 < Re < 2300$ are generally considered to result in transition flow. Exact flow regimes are difficult to predict in this region.

9.4 Boundary layers

9.4.1 Definitions

- *The boundary layer* is the region near a surface or wall where the movement of the fluid flow is governed by frictional resistance.
- *The main flow* is the region outside the boundary layer which is not influenced by frictional resistance and can be assumed to be 'ideal' fluid flow.
- *Boundary layer thickness*: it is convention to assume that the edge of the boundary layer lies at a point in the flow which has a velocity equal to 99 per cent of the local mainstream velocity.

9.4.2 Some boundary layer equations

Figure 9.9 shows boundary layer velocity profiles for dimensional and non-dimensional cases. The non-dimensional case is used to allow comparison between boundary layer profiles of different thickness.

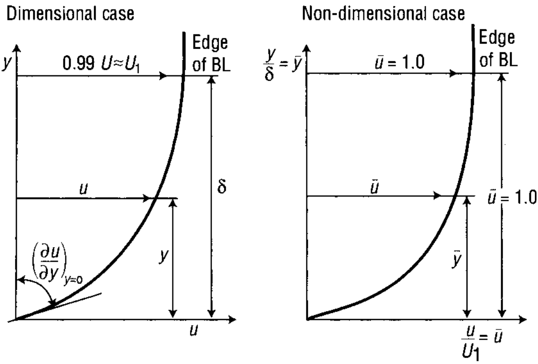


Figure 9.9

u = velocity parallel to the surface
y = perpendicular distance from the surface
δ = boundary layer thickness
U_1 = mainstrean velocity
$\bar{u}$ = velocity parameters u/U_1

Boundary layer equations of turbulent flow:

$$\rho\left(\bar{u}\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{u}}{\partial y}\right)=-\frac{\partial \bar{p}}{\partial x}+\frac{\partial \tau}{\partial y}$$

$$\tau=\mu\frac{\partial \bar{u}}{\partial y}-\overline{\rho u' v'}$$

$$\frac{\partial \bar{p}}{\partial x}=0$$

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}=0$$

9.5 Isentropic flow

For flow in a smooth pipe with no abrupt changes of section:

continuity equation	$\frac{d\rho}{\rho}+\frac{du}{u}+\frac{dA}{A}=0$
equation of momentum conservation	$-dp\,A=(A\rho u)du$
isentropic relationship	$p=c\rho^k$
sonic velocity	$a^2=\frac{dp}{d\rho}$

These lead to an equation being derived on the basis of mass continuity i.e.

$$\frac{d\rho}{\rho}=-M^2\frac{du}{u}$$

or

$$M^2=-\frac{d\rho}{\rho}\Big/\frac{du}{u}$$

Table 9.4 shows equations relating to convergent and convergent–divergent nozzle flow.

Table 9.4 Isentropic flows

Pipe flows		$\frac{-dp}{\rho}\Big/\frac{du}{u}=M^2$
Convergent nozzle flows	Flow velocity	$u=\sqrt{2\left(\frac{k}{k-1}\right)\left(\frac{p_0}{\rho_0}\right)\left[1-\frac{\rho^{\frac{k-1}{k}}}{p_0}\right]}$
	Flow rate	$m=\rho uA$
Convergent–divergent nozzle flow	Area ratio	$\frac{A}{A^*}=\frac{\left(\frac{2}{k+1}\right)^{\frac{1}{(k-1)}}\left(\frac{p_0}{p}\right)^{1/k}}{\sqrt{\frac{k+1}{k-1}\left[1-\frac{p_0^{\frac{(1-k)}{k}}}{p}\right]}}$

9.6 Compressible one-dimensional flow

Basic equations for 1-D compressible flow are given below.

Euler's equation of motion in the steady state along a streamline

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}s}+\frac{\mathrm{d}}{\mathrm{d}s}\left(\frac{1}{2}u^2\right)=0$$

or

$$\int\frac{\mathrm{d}p}{\rho}+\frac{1}{2}u^2=\text{constant}$$

so

$$\frac{k}{k-1}RT+\frac{1}{2}u^2=\text{constant}$$

$$\frac{p_o}{p}=\left(\frac{T_o}{T}\right)^{k/(k-1)}=\left(1+\frac{k-1}{2}M^2\right)^{k/(k-1)}$$

where T_o = total temperature

9.7 Normal shock waves

9.7.1 One-dimensional flow

A shock wave is a pressure front that travels at speed through a gas. Shock waves cause an increase in pressure, temperature, density and entropy and a decrease in normal velocity.

Equations of state and equations of conservation applied to a unit area of shock wave give (see Fig. 9.10).

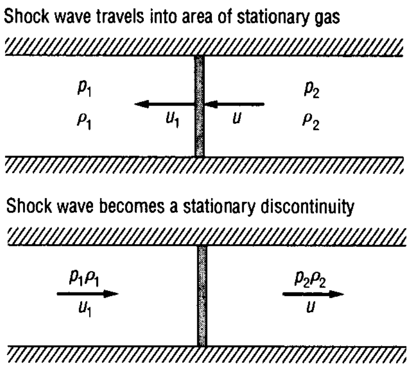


Figure 9.10

State	$p_1/\rho_1 T_1 - 1 = p_2/\rho_2 T_2$
Mass flow	$\dot{m} = \rho_1 u_1 = \rho_2 u_2$
Momentum	$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$
Energy	$c_p T_1 + \frac{u_1^2}{2} = c_p T_2 + \frac{u_2^2}{2} = c_p T_0$

Pressure and density relationships across the shock are given by the Rankine–Hugoniot equations

$$\frac{p_2}{p_1} = \frac{\frac{\gamma+1}{\gamma-1}\frac{\rho_2}{\rho_1} - 1}{\frac{\gamma+1}{\gamma-1} - \frac{\rho_2}{\rho_1}}$$

$$\frac{p_2}{p_1} = \frac{\frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1} + 1}{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}}$$

Static pressure ratio across the shock is given by

$$\frac{p_2}{p_1} = \frac{2\gamma M_2^2 - (\gamma-1)}{\gamma+1}$$

Temperature ratio across the shock is given by

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \Big/ \frac{\rho_2}{\rho_1}$$

$$\frac{T_2}{T_1} = \left(\frac{2\gamma M_1^2 - (\gamma-1)}{\gamma+1}\right)\left(\frac{2 + (\gamma-1)M_1^2}{(\gamma+1)M_1^2}\right)$$

Velocity ratio across the shock is given by

From continuity

$$u_2/u_1 = \rho_1/\rho_2$$

so

$$\frac{u_2}{u_1} = \frac{2 + (\gamma-1)M_1^2}{(\gamma+1)M_1^2}$$

In axisymmetric flow the variables are independent of θ so the continuity equation can be expressed as

$$\frac{1}{R^2}\frac{\partial(R^2 q_R)}{\partial R}+\frac{1}{R\sin\varphi}\frac{\partial(\sin\varphi\, q_\varphi)}{\partial\varphi}=0$$

Similarly in terms of stream function ψ

$$q_R = \frac{1}{R^2\sin\varphi}\frac{\partial\psi}{\partial\varphi}$$

$$q_\varphi = -\frac{1}{R\sin\varphi}\frac{\partial\psi}{\partial R}$$

9.7.2 The pitot tube equation

An important criterion is the Rayleigh supersonic pitot tube equation (see Fig. 9.11).

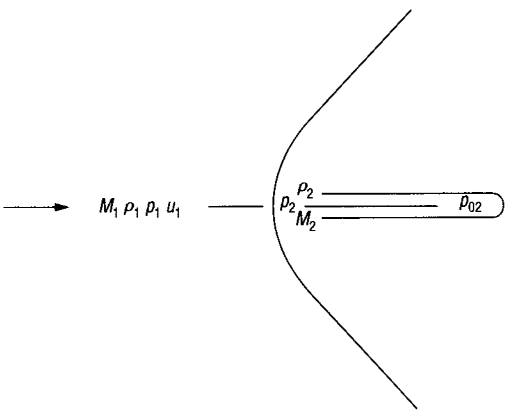


Figure 9.11

$$\text{Pressure ratio } \frac{p_{02}}{p_1}=\frac{\left[\frac{\gamma+1}{2}M_1^2\right]^{\gamma/(\gamma-1)}}{\left[\frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}\right]^{1/(\gamma-1)}}$$

9.8 Axisymmetric flows

Axisymmetric potential flows occur when bodies such as cones and spheres are aligned into a fluid flow. Figure 9.12 shows the layout of spherical coordinates used to analyse these types of flow.

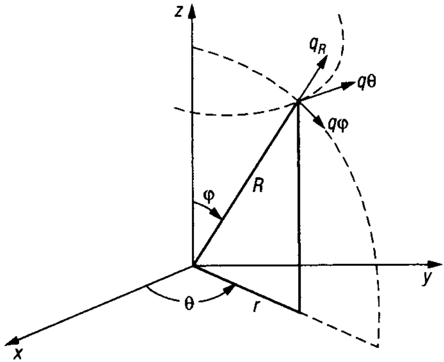


Figure 9.12

Relationships between the velocity components and potential are given by

$$q_R = \frac{\partial \phi}{\partial R} \quad q_\theta = \frac{1}{R \sin \varphi} \frac{\partial \phi}{\partial \theta} \quad q_\varphi = \frac{1}{R} \frac{\partial \phi}{\partial \varphi}$$

9.9 Drag coefficients

Figures 9.13(a) and (b) show drag types and ‘rule of thumb’ coefficient values.

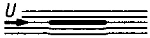
Shape	*Pressure drag* D_P *(%)*	*Friction drag* D_f *(%)*
	0	100
	≈ 10	≈ 90
	≈ 90	≈ 10
	100	0

Figure 9.13(a)

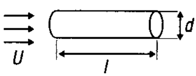
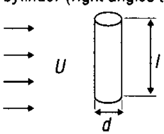
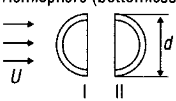
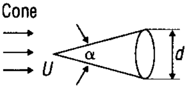
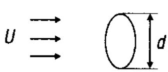
Shape	*Dimensional ratio*	*Datum area, A*	*Approximate drag coefficient,* C_D
Cylinder (flow direction)	$l/d = 1$		0.91
	2		0.85
	4	$\frac{\pi}{4}d^2$	0.87
	7		0.99
Cylinder (right angles to flow)	$l/d = 1$		0.63
	2		0.68
	5		0.74
	10	dl	0.82
	40		0.98
	∞		1.20
Hemisphere (bottomless)	I	$\frac{\pi}{4}d^2$	0.34
	II		1.33
Cone	$a = 60°$	$\frac{\pi}{4}d^2$	0.51
	$a = 30°$		0.34
		$\frac{\pi}{4}d^2$	1.2

Figure 9.13(b)

9.10 General airfoil theory

When an airfoil is located in an airstream, the flow divides at the leading edge – the stagnation point. The camber of the airfoil section means that the air passing over the top surface has further to travel to reach the trailing edge than that travelling along the lower surface. In accordance with Bernoulli's equation the higher velocity along the upper airfoil surface results in a lower pressure, producing a lift force. The net result of the velocity differences produces an effect equivalent to that of a parallel air stream and a rotational velocity ('vortex'), see Figures 9.14 and 9.15.

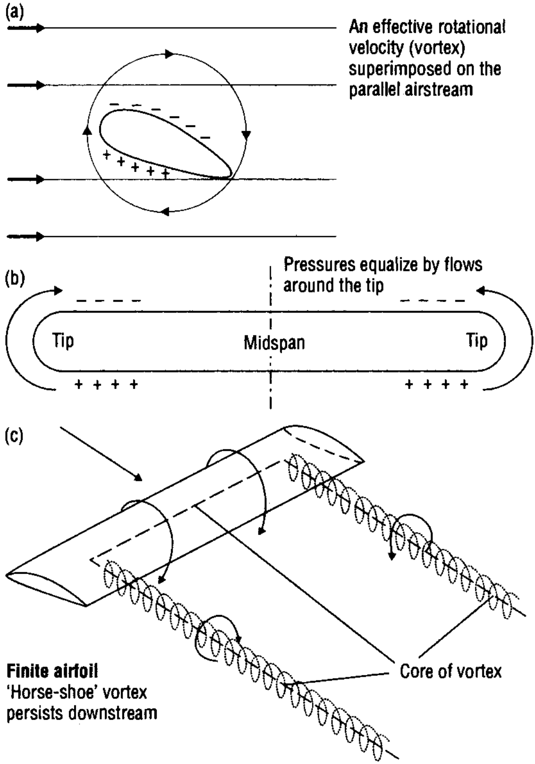


Figure 9.14

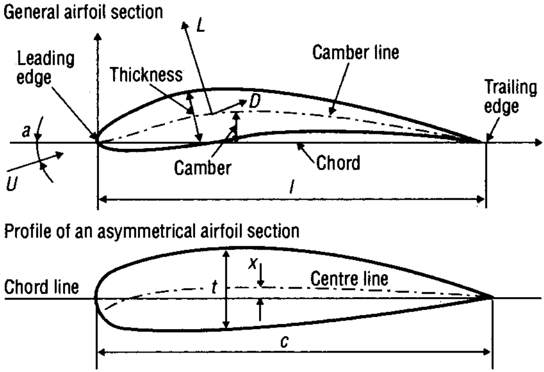


Figure 9.15

For the case of a theoretical finite airfoil section, the pressure on the upper and lower surface, tries to equalize by flowing around the tips. This rotation persists downstream of the wing resulting in a long 'U'-shaped vortex (see Fig. 9.14). The generation of these vortices needs the input of a continuous supply of energy, the net result being to increase the drag of the wing, by the addition of so-called '*induced*' *drag*.

9.11 Airfoil coefficients

Lift, drag, and moment (L, D, M) acting on an aircraft wing are expressed by the equations:

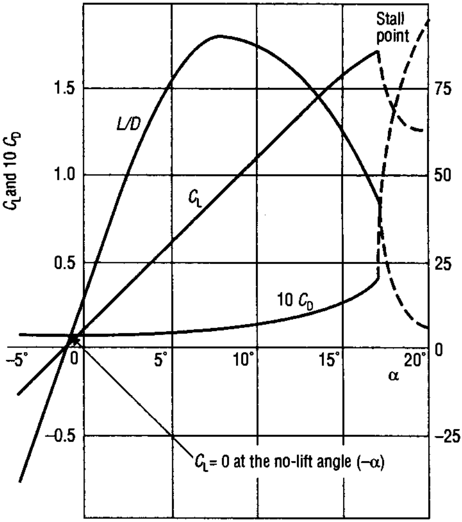
$$\text{Lift } (L) \text{ per unit width} = C_L l^2 \frac{\rho U^2}{2}$$

$$\text{Drag } (D) \text{ per unit width} = C_D l^2 \frac{\rho U^2}{2}$$

$$\text{Moment } (M) \text{ about leading edge (LE) or } 1/4 \text{ chord} = C_M l^2 \frac{\rho U^2}{2} \text{ per unit width.}$$

The lift, drag, and moment coefficients are C_L, C_D, and C_M respectively. Figure 9.16 shows typical values plotted against the angle of attack, or incidence α. The value of C_D is small so a value of 10 C_D is often used for the characteristic curve. C_L rises towards

Characteristics for an asymmetrical 'infinite-span 2D airfoil'



Characteristic curves of a practical wing

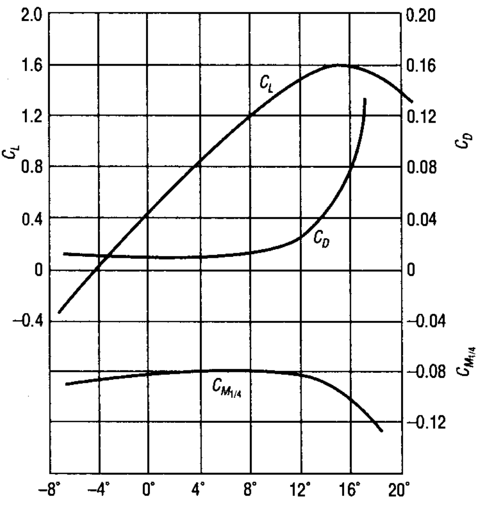


Figure 9.16

stall point and then falls off dramatically, as the wing enters the stalled condition. C_D rises gradually, increasing dramatically after the stall point. Other general relationships are outlined below.

- As a rule of thumb, a Reynolds number of $Re \cong 10^6$ is considered a general flight condition.
- Maximum C_L increases steadily for Reynolds numbers between 10^5 and 10^7.
- *CD* decreases rapidly up to Reynolds numbers of approximately 10^6, beyond which the rate of change reduces.
- Thickness and camber both affect the maximum C_L that can be achieved. As a general rule, C_L increases with thickness and then reduces again as the airfoil becomes even thicker. C_L generally increases as camber increases. The minimum C_D achievable increases fairly steadily with section thickness.

9.12 Pressure distributions

The pressure distribution across an airfoil section varies with the angle of attack α. Figure 9.17 shows the effect as α increases, and the notation used. The pressure coefficient C_p reduces towards the trailing edge.

9.13 Aerodynamic centre

The aerodynamic centre (AC) is defined as the point in the section about which the pitching moment coefficient (C_M) is constant i.e. does not vary with lift coefficient (C_L). Its theoretical positions are indicated in Table 9.5.

Using common approximations, the following equations can be derived

$$\frac{x_{AC}}{c} = \frac{9}{c} - \frac{\mathrm{d}}{\mathrm{d}C_L}(C_{Ma})$$

where

Table 9.5 Position of aerodynamic centre

Condition	*Theoretical position of the AC*
$\alpha < 10$ degrees	At approx $^1/_4$ chord somewhere near the chord line
Section with high aspect ratio	At 50% chord
Flat or curved plate: inviscid, incompressible flow	At approx $^1/_4$ chord

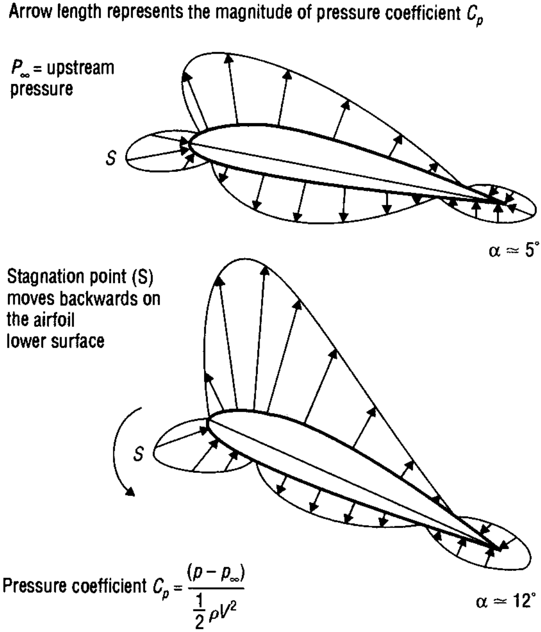


Figure 9.17

C_{Ma} = pitching moment coefficient at distance a back from LE.
x_{AC} = position of AC back from LE.
c = chord length.

9.14 Centre of pressure

The centre of pressure (CP) is defined as the point in the section about which there is no pitching moment, i.e. the aerodynamic forces on the entire section can be represented by a lift and drag force acting at this point. The CP does not have to lie within the airfoil profile and can change location, depending on the magnitude of the lift coefficient C_L. The CP is conventionally shown at distance k_{CP} back from the section leading edge (see Fig. 9.18).

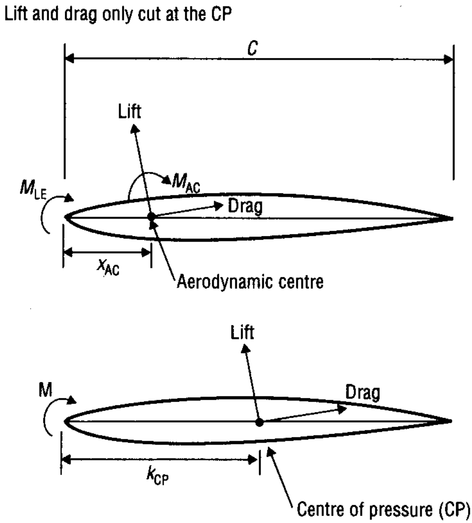


Figure 9.18

Using the principle of moments the following expression can be derived for k_{CP}

$$k_{CP} = \frac{x_{AC}}{c} - \frac{C_{M_{AC}}}{C_L \cos\alpha + C_D \sin\alpha}$$

Assuming that $\cos\alpha \cong 1$ and $C_D \sin\alpha \cong 0$ gives

$$k_{CP} \cong \frac{x_{AC}}{c} - \frac{C_{M_{AC}}}{C_L}$$

9.15 Supersonic conditions

As an aircraft is accelerated to approach supersonic, speed the equations of motion that describe the flow change in character. In order to predict the behaviour of airfoil sections in upper subsonic and supersonic regions, compressible flow equations are required.

9.15.1 Basic definitions

M = Mach number
M_∞ = free stream Mach number

M_c = critical Mach number, i.e. the value of M_∞ that results in flow of $M = 1$ at some location on the airfoil surface.

Figure 9.19 shows approximate forms of the pressure distribution on a two-dimensional airfoil around the critical region. Owing to the complex non-linear form of the equations of motion that describe high-speed flow, two popular simplifications are used: the *small perturbation* approximation and the so-called *exact* approximation.

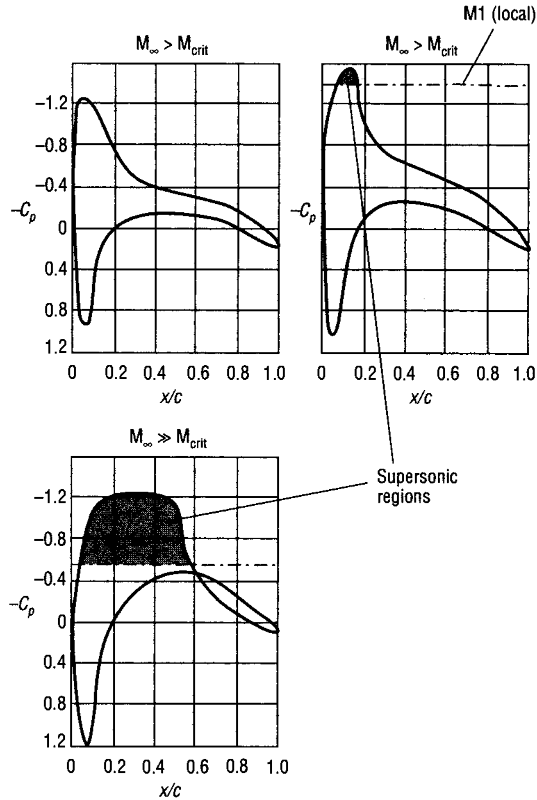


Figure 9.19

9.15.2 Supersonic effects on drag

In the supersonic region, induced drag (due to lift) increases in relation to the parameter $\sqrt{M^2-1}$ and is a function of the plan form geometry of the wing.

9.15.3 Supersonic effects on aerodynamic centre (AC)

Figure 9.20 shows the location of wing AC for several values of tip chord/root chord ratio (λ). These are empirically based results that can be used as a 'rule of thumb'.

9.16 Wing loading: semi-ellipse assumption

The simplest general loading condition assumption for symmetric flight is that of the semi-ellipse. The equivalent equations for lift, downwash, and induced drag become:

For lift

$$L = \rho \frac{VK_0 \pi s}{2}$$

replacing L by $C_L \, {}^1\!/_2 \rho V^2 S$ gives

$$K_0 = \frac{C_L VS}{\pi s}$$

For downwash velocity (w)

$$w = \frac{K_0}{4S} \text{ i.e. it is constant along the span.}$$

For induced drag (vortex)

$$C_{D_V} = \frac{C_L^2}{\pi AR}$$

where aspect ratio

$$(AR) = \frac{\text{span}^2}{\text{area}} = \frac{4s^2}{S}$$

Hence, C_{Dv} falls (theoretically) to zero as aspect ratio increases. At zero lift in symmetric flight, $C_{Dv} = 0$.

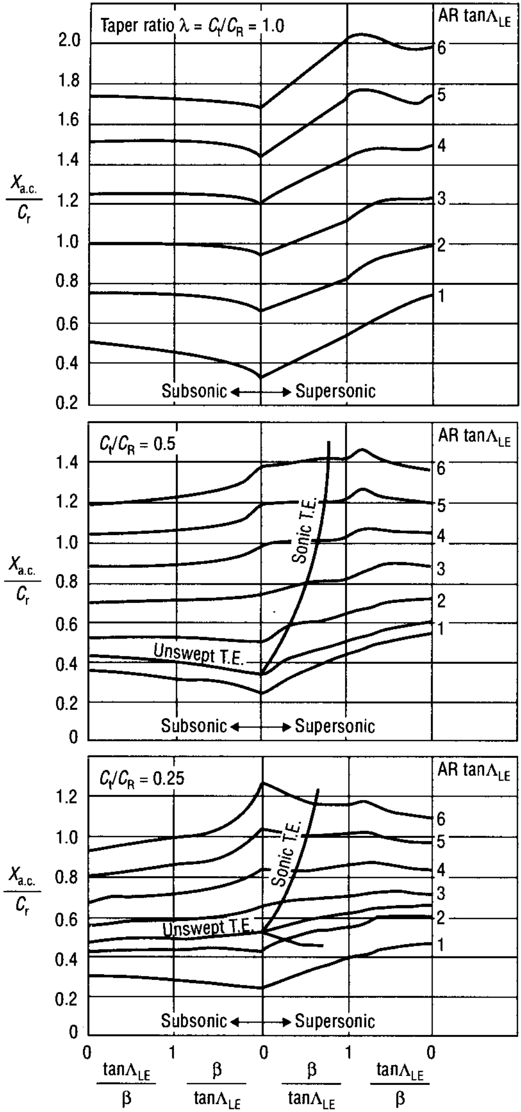

Taper ratio λ = Ct/CR = 1.0
AR tanΛLE
6
5
4
3
2
1
Xa.c./Cr
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Subsonic ← → Supersonic
Ct/CR = 0.5
AR tanΛLE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Sonic T.E.
Unswept T.E.
Subsonic ← → Supersonic
Ct/CR = 0.25
AR tanΛLE
1.2
1.0
0.8
0.6
0.4
0.2
0
Sonic T.E.
Unswept T.E.
Subsonic ← → Supersonic
0
1
0
1
0
tanΛLE/β
β/tanΛLE
β/tanΛLE
tanΛLE/β

Figure 9.20

Section 10

Fluid Equipment

10.1 Turbines

Both steam and gas turbines are in common use for power generation and propulsion. Power ranges are:

Steam turbines	*Gas turbines*
Coal/oil generation: Up to 1000 MW	Power generation: Up to 230 MW
Nuclear generation: Up to 600 MW	Aircraft: Up to about 30 MW
Combined cycle application: Up to 30 MW	Warships: Up to about 35 MW
	Portable power units: Up to about 5 MW

Both types are designed by specialist technology licensors and are often built under licence by other companies.

Table 10.1 Gas turbine propulsion terminology

Gas turbine (GT)	Engine comprising a compressor and turbine. It produces jet thrust and/or shaft 'horsepower' output via a power turbine stage.
Turbojet	A GT which produces only jet thrust (i.e. no power turbine stage). Used for jet aircraft.
Turboprop	A GT that produces shaft output and some jet thrust. Used for propeller-driven aircraft.
Afterburner	A burner which adds fuel to the later stages of a GT to give increased thrust. Used for military aircraft.
Pulse-jet	A turbojet engine with an intermittent 'pulsed' thrust output.
Ramjet	An advanced type of aircraft GT which compresses the air using the forward motion (dynamic head) of the engine.
Rocket motor	A 'jet' engine that carries its own fuel and oxygen supply. Produces pure thrust when there is no available oxygen (e.g. space travel).

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Useful Standards

Steam turbines

1. API 611: 2008: General purpose steam turbines for refinery services (American Petroleum Institute).
2. API 612: 2003: Special purpose steam turbines for refinery services (American Petroleum Institute).
3. ANSI/ASME Performance Test Code No 6: 2004 (American Society of Mechanical Engineers).
4. BS EN 60953: 1996: Rules for steam turbine acceptance tests.
5. BS EN 60045-1: 1993: Guide to steam turbine procurement.
6. BS EN 45510-5-1: 2008: Steam turbines.

Gas turbines

1. BS 3863: 1992 (identical to ISO 3977: 1991): Guide for gas turbine procurement.
2. BS 3135: 1989 (identical to ISO 2314): Specification for gas turbine acceptance test.
3. ANSI/ASME Performance Test Code 22: 2005 (The American Society of Mechanical Engineers).
4. API 616: 1998: Gas turbines for refinery service, (American Petroleum Institute).
5. BS ISO 11042: 1996: Gas turbines – exhaust gas emissions.
6. BS ISO 11086: 1996: Gas turbines – vocabulary.
7. BS EN 45510-5-2: 2001: Gas turbines.

10.2 Refrigeration systems

The most common industrial refrigeration plant operates using a vapour compression refrigeration cycle consisting of the standard components of compressor, evaporator, expansion valve, and condenser connected in series.

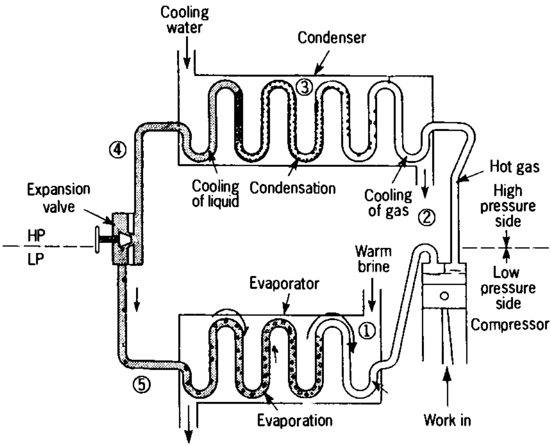


Figure 10.1

The process can be shown on $T-s$ or $P-\upsilon$ cycle charts.

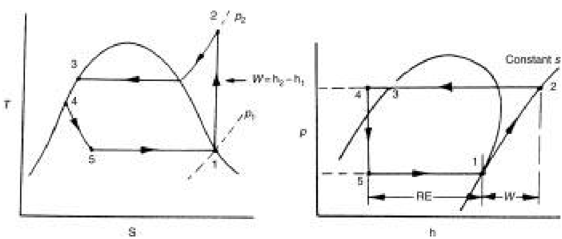


Figure 10.2

Performance characteristics are:

- Refrigerating effect $= \text{RE} = h_1 - h_5$
- Coefficient of performance $(\text{COP}) = \dfrac{\text{RE}}{W} = \dfrac{\text{RE}}{h_2 - h_1}$

Common refrigerants such as R12 and R22 still use halogenated hydrocarbons. These are being replaced with other types because of environmental considerations.

Useful Standards

1. BS 3122: Part 1: 1990: Refrigerant compressors – methods of test for performance (similar to ISO 917).
   Part 2: 1990: Methods for presentation of performance data (similar to ISO 9309).
2. BS EN 378-1: 2008: Specification for refrigeration systems and heat pumps. Safety and environmental requirements.
3. BS 4434: 1995: Specification for safety and environmental aspects in the design, construction and installation of refrigeration appliances and systems.

10.3 Diesel engines

10.3.1 Categories

Diesel engines are broadly divided into three categories based on speed.

Table 10.2

Designation	*Application*	*(Brake) Power rating (MW)*	*Rpm*	*Piston speed (m/s)*
Slow speed (2 or 4 stroke)	Power generation, ship propulsion	Up to 45	<150	<9
Medium speed (4 stroke)	Power generation, ship propulsion	Up to 15	200–800	<12
High speed (4 stroke vee)	Locomotives, portable power generation	Up to 5	>800	12–17

10.3.2 Performance

Performance criteria are covered by manufacturers' guarantees. The important ones, with typical values are:

Maximum continuous rating (MCR): 100 percent
Specific fuel consumption: 220 g/kW h (brake)
Lubricating oil consumption: 1.5 g/kW h (brake)
NO_x limit: 1400 mg/Nm^3

Note that many of these vary with the speed and load of the engine.

USEFUL STANDARDS

The main ones covering diesel engine design, testing and performance are:

1. ISO 3046: Reciprocating internal combustion engines: performance.
   This is identical to BS 5514. It contains the following parts (separate documents):
   ISO 3046/1: Standard reference conditions
   ISO 3046/2: Test methods
   ISO 3046/3: Test measurements
   ISO 3046/4: Speed governing
   ISO 3046/5: Torsional vibrations
   ISO 3046/6: Overspeed protection
   ISO 3046/7: Codes for engine power

10.4 Heat exchangers

Heat exchangers can be classified broadly into parallel and counterflow types. Similar equations govern the heat flow. The driving force is the parameter known as log mean temperature difference (LMTD).

For the parallel flow configuration

$$LMTD(\theta_{\mathrm{m}}) = \frac{\theta_1 - \theta_2}{\ln \theta_1/\theta_2}$$

where:

U = overall heat transfer coefficient (W/m^{2}K)
A = tube surface area (m^2)
θ = temperature difference (°C)
Heat transferred, $q = UA\theta$ (Watts)

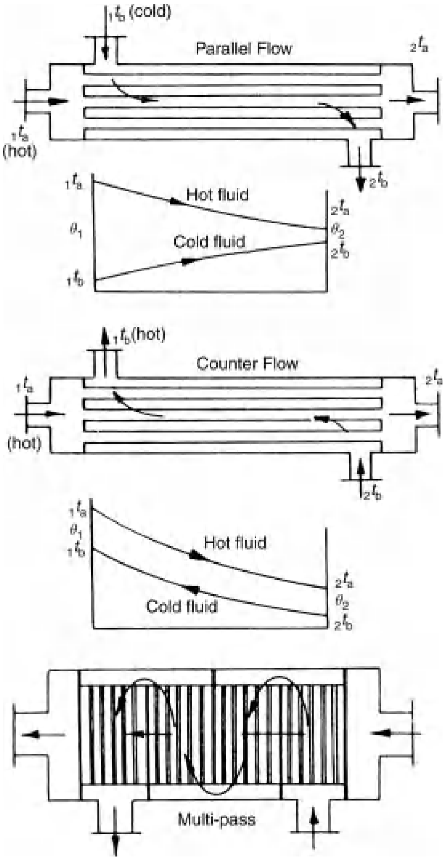


Figure 10.3

For counterflow the same formulae are used.

For more complex configurations, such as cross flow and multi-pass exchangers, LMTD is normally determined from empirically derived tables.

Useful Standards

1. TEMA: 2007: Standards for design and construction of heat exchangers (Tubular Exchangers Manufacturers Association).
2. BS 853 Part 2: 1996: Tubular heat exchangers and storage vessels for buildings and industrial services.
3. BS 2871 Part 3: 1971: Tubes for heat exchangers.
4. BS EN 3274: 1998: Specification for tubular heat exchangers for general purposes.
5. BS 3606: 1992: Specification for steel tubes for heat exchangers.
6. BS EN 247: 1997: Heat exchangers – terminology.

10.5 Centrifugal pumps

Pumps are divided into a wide variety of types. The most commonly used are those of the dynamic displacement type. These are mainly centrifugal (radial) but also include mixed flow and axial types. The performance of a pump is mainly to do with its ability to move quantities of fluid. The main parameters are:

- Volume flowrate, q_ν (m^3/s).
- Mass throughput, q_m (kg/s).
- Head, H (m). This represents the useable mechanical work transmitted to the fluid and is measured in metres. Together, q and H define the *duty point* of a pump – a key part of its acceptance guarantee.
- Pump efficiency, η (%) is a measure of the efficiency with which the pump transfers useful work to the fluid.

$$\eta = \frac{\text{pump power output}}{\text{pump power input}} = \frac{q_m g H}{\text{pump power input}}$$

For most centrifugal pumps the q/H characteristics are as shown.

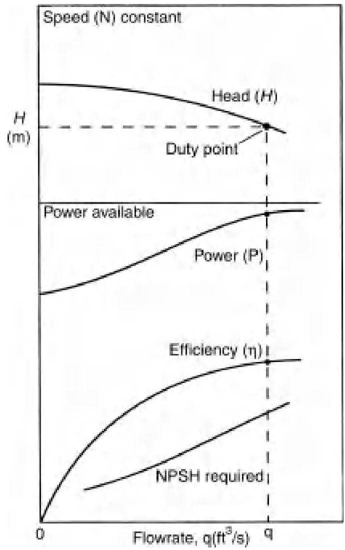


Figure 10.4

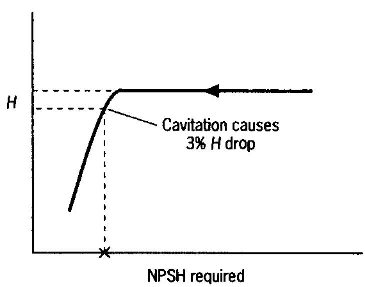


Figure 10.5

A further performance requirement of a centrifugal pump is its net positive suction head (NPSH), a measure of suction performance at various volume throughputs.

The hydrodynamic performance of centrifugal pumps is covered by the equation:

$$\text{Total head, } H = Z_2 - Z_1 + \frac{p_2 - p_1}{\rho g} + \frac{v_2^2 - v_1^2}{2g}$$

where

Z = distance to a reference plane
ρ = density
g = acceleration due to gravity

$$\text{NPSH} = H_1 + \frac{P_{\text{atmos}}}{\rho g} - \frac{\text{vapour pressure}}{\rho g}$$

where

$$H_1 = \frac{p_1}{\rho g} + Z_1 \frac{v_1^2}{2g}$$

10.6 Impeller types

The impeller shape used in a pump is related to the pump's efficiency and a dimensionless 'specific speed' (sometimes referred to as 'type number') parameter which is a function of rotational speed, q_v and H. Figure 10.6 shows approximate design ranges.

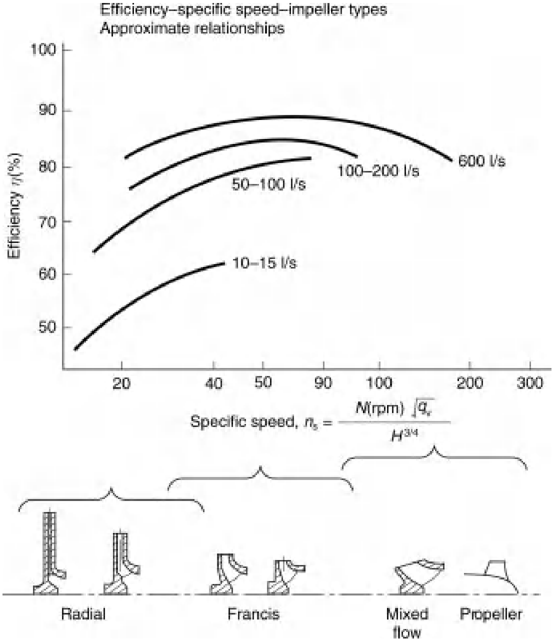


Figure 10.6

Useful Standards

1. ISO 2548: 1973: (is identical to BS 5316) Part 1: 1976: Specification for acceptance tests for centrifugal mixed flow and axial pumps – Class C tests.
2. ISO 3555: 1977: (is identical to BS 5316) Part 2: 1977: Class B tests.
3. ISO 5198: 1999: Precision class tests.
4. DIN 1944: Acceptance test for centrifugal pumps (VDI rules or centrifugal pumps) (Verein Deutscher Ingenieure).
5. API 610: 10th Edition, 2011: Centrifugal pumps for general refinery service (American Petroleum Institute).
6. BS 5257: 1975: Specification for horizontal end-suction centrifugal pumps (up to 16 Barg).
7. ISO 5199: 2002: Technical specifications for centrifugal pumps – Class 2.

Section 11

Pressure Vessels

11.1 Vessel codes and standards

Pressure vessels can be divided broadly into 'simple' vessels and those which have more complex features. The general arrangement of a simple vessel is as shown – note it has no complicated supports or sections and that the ends are dished, not flat.

The main code for simple pressure vessels is:
BS EN 286-1: 1991: Simple unfired pressure vessels *designed to contain air or nitrogen.*

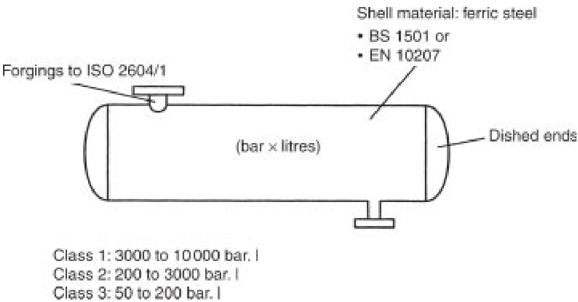


Figure 11.1

All aspects of designing and manufacturing the vessel are included under the following sections:

Section 4:	Classification and certification procedures
Section 5:	Materials
Section 6:	Design
Section 7:	Fabrication
Section 8–9:	Welding
Section 10:	Testing

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Section 11: Documentation
Section 12: Marking

There are three vessel categories, based on capacity in bar × litres. More complex pressure vessels follow accepted codes such as:

BS PD 5500: 2010: Specification for unfired fusion welded pressure vessels.
ASME VIII: 2010: Pressure Vessel Code.

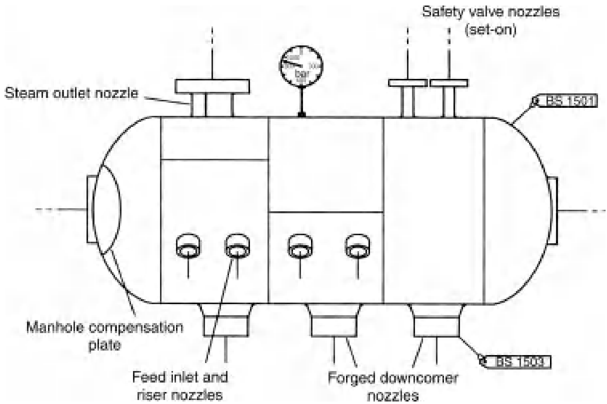

Figure 11.2

These also divide vessels into different categories depending on their application and manufacture.

The codes provide comprehensive information about the design and manufacture of the vessels. BS PD 5500 sections are:

BS PD 5500 Section 1: General
BS PD 5500 Section 2: Materials
BS PD 5500 Section 3: Design
BS PD 5500 Section 4: Manufacture and workmanship
BS PD 5500 Section 5: Inspection and testing

There are also several other BSI documents that give BS PD 5500-related background information.

BS 7910: 2006

The full title of this standard is BS 7910: 2006: *Guide for assessing the acceptability of flaw in metallic structures*. It evolved from the British Standard published document PD 6493 first published in 1980 and was issued as a more comprehensive version of BS PD 6493, covering both high and low-temperature failure modes resulting from flaws in welds and some types of corrosion.

EN 13445:2002 Unfired Pressure Vessels

This is the European harmonized standard for unfired pressure vessels. Vessels manufactured to this standard receive an automatic 'presumption of conformity' with the PED. It consists of several parts:

- Part 1: General
- Part 2: Materials
- Part 3: Design
- Part 4: Fabrication
- Part 5: Inspection and testing
- Part 6: Requirements for the design and fabrication of pressure vessels and pressure parts constructed from spheroidal graphite cast iron

This standard is one of a developing set of similar standards that address piping, boilers, and other items of pressure equipment.

ASME VIII

The ASME Boiler and Pressure Vessel Code, Section VIII is an accepted code used in the USA and many other parts of the world. It provides a thorough and basic reference for the design of pressure vessels and heat exchangers covering: design, material selection, fabrication, inspection, and testing.

Being a comprehensive code, ASME VIII is complicated and can be difficult to follow, until you become familiar with its structure and principles. ASME VIII is divided into two divisions.

- *Division 1* (VIII-1) covers normal vessels.
- *Division 2* (VIII-2) covers alternative rules for pressure vessels and is used for various types of special applications,

including nuclear. VIII-2 was recently formally withdrawn, but is still used by many manufacturers.

Both divisions are structured into a large number of paragraphs designated by reference letters, e.g. UG-22.

ASME VIII is written against a well-defined theoretical background that is similar, but not identical, to that used for other pressure vessel codes. This theoretical background is reflected in the design rules that apply to all the components of pressure vessels and the way in which size, shape, and material choices are made.

11.2 Pressure vessel design features

Although straightforward in concept, pressure vessels can exhibit a variety of design features. Different methods of design and assessment are used – all of which are covered in detail in the design codes. Common weld, nozzle, and flange types are as shown.

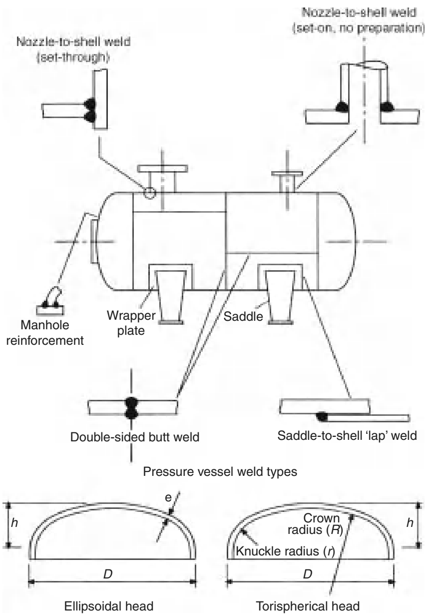

Figure 11.3

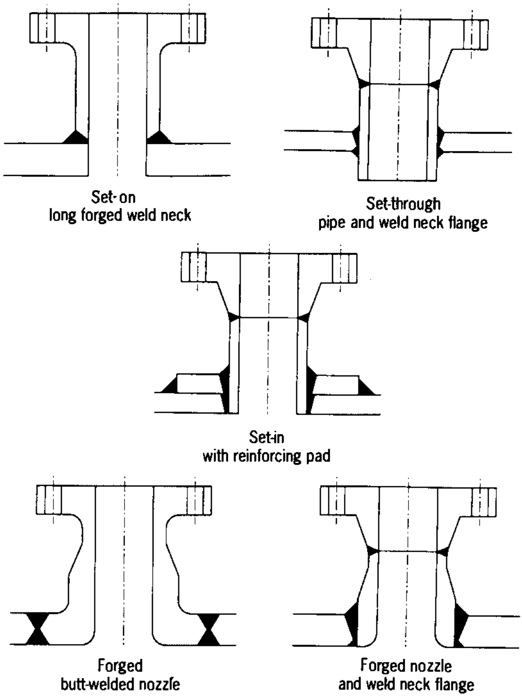

Figure 11.3 (Cont.)

11.3 Cylindrical pressure vessel design stresses

Design stress formulae in cylindrical pressure vessels are well defined in codes and standards. ASME VIII-1 gives rules for the design of cylindrical shells of uniform thickness subject to internal pressure, external pressure, and axial loads. The governing equations for longitudinal and circumferential stresses are broadly as shown below.

Cylindrical Shells: Basic Equations ASME VIII-1
Thin cylindrical shells under internal pressure:
For circumferential stress:

$$t = PR/(SE - 0.6P)$$

when $t < 0.5R$ or $P < 0.385\,SE$

For longitudinal stress

$$t = PR/(2SE + 0.4P)$$

when $t < 0.5R$ or $P < 1.25\,SE$

where

P = internal pressure
R = internal radius
S = allowable stress in the material
E = joint efficiency factor
t = thickness of shell material

Note how these equations are expressed in terms of the *inside* radius of the cylinder shell.

Thick cylindrical shells under internal pressure
For circumferential stress

$$t = R(z^{1/2} - 1)$$

where $Z = (SE + P)/(SE - P)$
For longitudinal stress

$$t = R(Y^{1/2} - 1) \text{ for } t > 0.5R \text{ or } P > 1.25\,SE$$

where $Y = (P/SE) + 1$

For vessels in ASME VIII Div 2, different equations have to be used.

11.4 Stress categories

The three stress categories recognized by ASME VIII-2 are listed below.

Primary stress

The best examples are longitudinal and circumferential stresses in a cylindrical vessel under internal pressure. Primary stress does not cause load redistribution and can itself be subdivided into:

- bending stress;
- general membrane stress (e.g. from internal pressure);
- local membrane stress (such as caused by local nozzle loads, etc.).

Secondary stress

This is essentially caused by some component of a pressure vessel being *restrained*, either by other components, or by being fixed to something external to the vessel. In contrast to primary stresses, which can cause failure if they rise too high, secondary stresses are self-limiting, i.e. they can be redistributed by local yielding, without the vessel having 'failed'. Thermal stresses are classed as having secondary stress characteristics.

Peak stress

This is highly localized stress that, although does not necessarily cause detectable yielding, may result in fatigue. Typical examples are notches and crack-like features.

11.5 Analysis of stress combinations

ASME VIII-2 covers various simplified methodologies for calculating acceptable stresses when a component is subjected to a *combination* of stresses. The basic idea is outlined below.

- Three normal stresses σ_{r}, σ_{l}, σ_{h} are calculated
- Three tangential stresses τ_{rl}, τ_{rh}, τ_{lh} are calculated.
- The three principal stresses σ_1, σ_2, σ_3 are calculated using

$$\sigma_{\substack{max \\ min}} = \frac{(\sigma_{1i} + \sigma_j)}{2} \pm \left[\frac{(\sigma_{1i} + \sigma_j)^2}{2} + {\tau_{ij}}^2 \right]^{\frac{1}{2}}$$

- The maximum stress intensity (S) as defined in VIII-2 is then assumed to be the largest value obtained from

$$S_{12} = \sigma_1 - \sigma_2$$
$$S_{13} = \sigma_1 - \sigma_3$$
$$S_{23} = \sigma_1 - \sigma_3$$

11.6 Vessel certification

Pressure vessels contain large amounts of stored energy and hence are considered as potentially dangerous pieces of equipment. Prior to the inception of the Pressure Equipment Directive, most vessels were subject to independent 'certification' involving design review, witnessing of testing etc by an independent 'third-party' authority.

11.7 Flanges

Vessel flanges are classified by type and *rating*. The main British and US standards differ slightly in their classification but the essential principles are the same.

11.7.1 Flange types

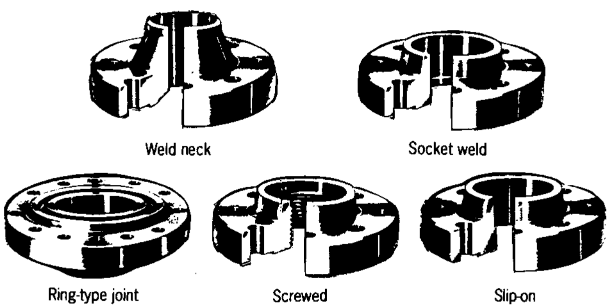

Figure 11.4

11.7.2 Flange ratings

Flanges are rated by pressure (in psi) and temperature e.g. ASME B16.5 classes:

150	psi
300	psi
600	psi
900	psi
1500	psi
2500	psi

Detailed size and design information is given in the ASME B16.5 standard

11.7.3 Flange facings

The type of facing is important when designing a flange. Pressure vessel and piping standards place constraints on the designs that are considered acceptable for various applications.

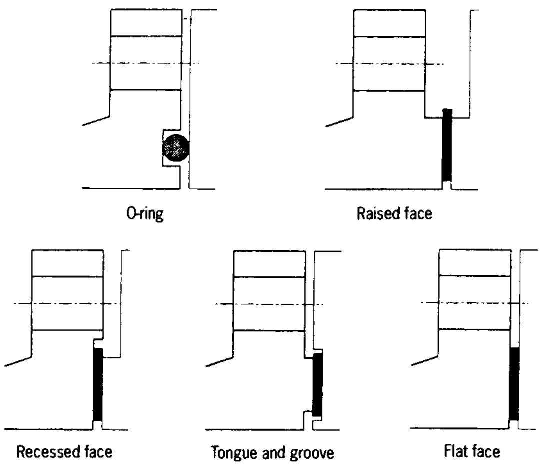

Figure 11.5

Section 12

Materials

12.1 Observing crystals: order and disorder

The common idea of a crystal is something that is geometrically regular in shape, transparent, and has lustre. While this is sometimes true it is not a good general description of a crystalline material.

All metals are crystalline. The basic reason for this is that the molecules are all attracted to each other by 'binding forces'. These forces are non-directional, giving the tendency to pull the molecules into a regular shape. Every molecule is free to choose where it goes, so it roams around until it finds a location that will make the structure neat and ordered and in which it has the least potential energy. Conceptually, the structure of a metal wants to be arranged like a neat stack of bricks, rather than a random pile. The neat stack is called a crystal.

All solids have some tendency to be crystalline but some manage it and some don't. Metals form highly regular and packed arrangements of molecules which can take forms such as body-centred cubic (bcc), face-centred cubic (fcc) and close-packed hexagonal (cph). Paradoxically, although such crystal structures are an attempt at achieving natural *order*, some metals like to crystallize around an impurity or irregularity of some sort – which you could argue is a search for *disorder*. The existence of dislocations and weakness in materials is proof that a crystal structure, ordered though it is, also contains some disorder at the same time. The science of metallurgy is about trying to improve order (because it makes materials stronger) while also finding, and understanding, the inevitable disorder.

Material properties are of great importance in all aspects of mechanical engineering. It is essential to check the up-to-date version of the relevant European Standards or equivalent when

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choosing or assessing a material. The most common steels in general engineering use are divided into the generic categories of carbon, low-alloy, alloy, and stainless.

12.2 Carbon steels

The effects of varying the carbon content of plain steels are broadly as shown.

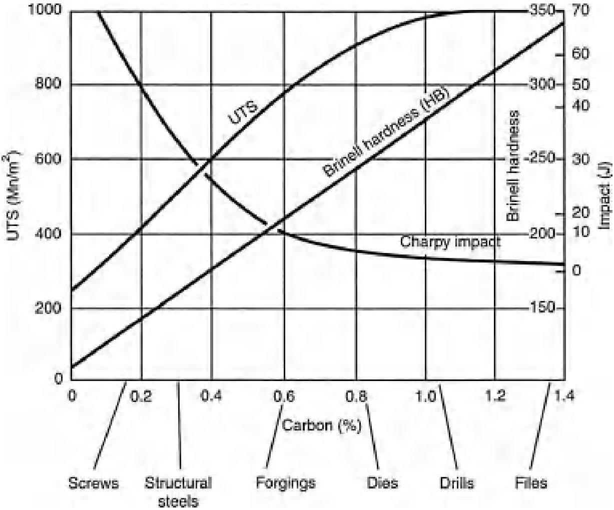


Figure 12.1

Typical properties are shown in Table 12.1.

Table 12.1

Type	*%C*	*%Mn*	*Yield, R_e (MN/m^2)*	*UTS, Rm (MN/m^2)*
Low C steel	0.1	0.35	220	320
General structural steel	0.2	1.4	350	515
Steel castings	0.3	–	270	490
Constructional steel for machine parts	0.4	0.75	480	680

Useful Standards

1. BS EN 970: Part 1: 1997: General inspection and testing procedures and specific requirements for carbon, carbon manganese, alloy and stainless steels.
2. BS 4360 (A withdrawn standard).
3. BS EN 10027-2: 1992: Designation systems for steel – steel numbers.
4. BS EN 10025: 2004: Hot rolled products of non alloy structural steels.
5. DIN 17100: 1981: General purpose structural steels.

12.3 Low-alloy steels

Low-alloy steels have small amounts of Ni, Cr, Mn, Mo added to improve properties. Typical properties are shown in Table 12.2.

Table 12.2

Type	*%C*	*Others (%)*	R_e *(MN/m²)*	R_m *(MN/m²)*
Engine crankshafts: Ni/Mn steel	0.4	0.85Mn 1.00Ni	480	680
Ni/Cr Steel	0.3	0.5Mn 2.8Ni 1.0Cr	800	910
Gears: Ni/Cr/Mo steel	0.4	0.5Mn 1.5Ni 1.1Cr 0.3Mo	950	1050

Useful Standards

1. BS EN 970 (See 'Carbon steels').
2. BS EN 10083-1: 2006: Technical delivery conditions for special steels.

12.4 Alloy steels

Alloy steels have a larger percentage of alloying elements (and a wider range) to provide strength and hardness properties for special applications. Typical properties are shown in Table 12.3.

Table 12.3

Type	*%C*	*Others (%)*	R_e *(MN/m²)*	R_m *(MN/m²)*
Chisels, dies C/Cr steel	0.6	0.6Mn 0.6Cr	700	870
Heavy-duty Dies	2.0	0.3Mn 12.0Cr	680	920
Extrusion dies	0.32	1.0Si 5.0Cr 1.4Mo 0.3V 1.4W	820	1020
High-speed steel Lathe tools	0.7	4.2Cr 18.0W 1.2V	950	1110
Milling cutters and drills	0.8	4.3Cr 6.5W 1.9V		
5.0Mo	970	1200		

Useful Standards

1. BS 4659: 1989: Specification for tool and die steels.
2. DIN 17201: 2005: Case hardening steels.

12.5 Cast iron (CI)

Cast irons are iron/carbon alloys that possess more than about 2%C. They are classified into specific types as shown in Figure 12.2.

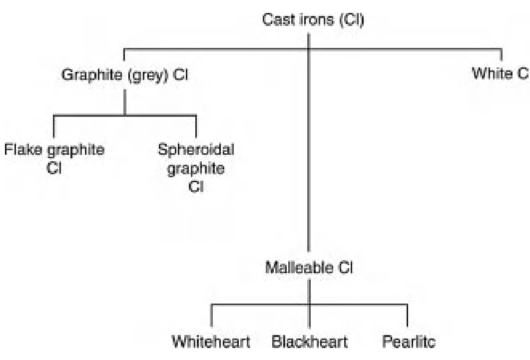


Figure 12.2

General properties and uses are varied as shown in Table 12.4.

Table 12.4

Type	*R_m (MN/m²)*	*Elongation (%)*	*HB*
Grey CI (engine cylinders)	170–370	0.5–0.8	150–250
Nodular ferritic SG CI (piping)	350–480	6–16	115–215
Nodular pearlitic SG CI (crankshafts)	600–800	2–3	210–300
Pearlitic malleable (camshafts and gears)	450–550	3–8	140–240
'Whiteheart' CI (wheel hubs)	250–400	4–10	120–180
'Blackheart' CI (general hardware)	290–340	6–12	125–150

12.5.1 Grey CI

These types have a structure of ferrite, pearlite, and graphite, giving a grey appearance on a fractured surface. The graphite can exist as either flakes or spheres. Nodular (SG) CI is obtained by adding magnesium, which encourages the graphite to form into spheres or 'nodules'.

12.5.2 White CI

This has a structure of cementite and pearlite making it hard, brittle, and difficult to machine. Its main use is for wear-resisting components. Fracture surfaces have a light- coloured appearance.

12.5.3 Malleable CI

These are heat-treated forms of white CI to improve their ductility while maintaining the benefits of high tensile strength. There are three types:

- *Whiteheart* This is heated with an iron compound to produce a ferrite outer layer and a ferrite/pearlite core.
- *Blackheart* Soaked at high temperature to cause the cementite to break down, then slowly cooled to give ferrite and graphite.
- *Pearlite* Similar to blackheart, but faster cooling to produce a pearlite structure with higher UTS.

USEFUL STANDARDS

1. BS EN 1561: 1997: Founding – Grey cast iron.
2. BS EN 1563: 1997: Founding – Spheroidal graphite cast iron.
3. BS EN 1562: 1997: Founding – Malleable cast irons.
4. DIN 1691: 1985: Lamellar graphite cast iron.
5. DIN 1693: 1997: Nodular graphite cast iron.

12.6 Stainless steels

Stainless steel is a generic term used to describe a family of steel alloys containing more than about 11 percent chromium. The family consists of four main classes, subdivided into about 100 grades and variants. The main classes are austenitic and duplex – the other two; ferritic and martensitic classes tend to have more specialized application and so are not so commonly found in general use. The basic characteristics of each class are:

- *Austenitic* The most commonly used basic grades of stainless steel are usually austenitic. They have 17–25% Cr, combined with 8–20% Ni, Mn, and other trace alloying elements which encourage the formation of austenite. They have low carbon content, which makes them weldable. They have the highest general corrosion resistance of the family of stainless steels.
- *Ferritic* Ferritic stainless steels have high chromium content (>17% Cr) coupled with medium carbon, which gives them good corrosion resistance properties rather than high strength. They normally have some Mo and Si, which encourage the ferrite to form. They are generally non-hardenable.
- *Martensitic* This is a high-carbon (up to 2% C), low-chromium (12% Cr) variant. The high carbon content can make it difficult to weld.
- *Duplex* Duplex stainless steels have a structure containing both austenitic and ferritic phases. They can have a tensile strength of up to twice that of straight austenitic stainless steels and are alloyed with various trace elements to aid corrosion resistance. In general, they are as weldable as austenitic grades but have a maximum temperature limit, because of the characteristic of their microstructure.

Table 12.5 Stainless steels – basic data

Stainless steels are commonly referred to by their AISI equivalent classification (where applicable)

AISI	*Other classifications*	*Type*[*2]	*Yield R_e (MPa)*	*UTS R_m (MPa)*	*E(%) 50 mm*	*HRB*	*%C*	*%Cr*	*% others*[*1]	*Properties*
302	ASTM A296 (cast), Wk 1.4300, 18/8, SIS 2331	Austenitic	276	621	55	85	0.15	17–19	8–10 Ni	A general purpose stainless steel
304	ASTM A296, Wk 1.4301, 18/8/LC, SIS 2333, 304S18	Austenitic	290	580	55	80	0.08	18–20	8–12 Ni	An economy grade. Not resistant to seawater
304L	ASTM A351, Wk 1.4306 18/8/ELC, SIS 2352, 304S14	Austenitic	269	552	55	79	0.03	18–20	8–12 Ni	Low C to avoid intercrystalline corrosion after welding
316	ASTM A296, Wk 1.4436 18/8/Mo, SIS 2243, 316S18	Austenitic	290	580	50	79	0.08	16–18	10–14 Ni	Addition of Mo increases corrosion resistance. Better than 304 in seawater.
316L	ASTM A351, Wk 1.4435, 18/8/Mo/ELC, 316S14, SIS 2353	Austenitic	291	559	50	79	0.03	16–18	10–14 Ni	Low C weldable variant of 316
321	ASTM A240, Wk 1.4541, 18/8/Ti, SIS 2337, 321S18	Austenitic	241	621	45	80	0.08	17–19	9–12 Ni	Variation of 304 with Ti added to improve temperature resistance.

Table 12.5 (Cont.)

Stainless steels are commonly referred to by their AISI equivalent classification (where applicable)

AISI	*Other classifications*	*Type*[*2]	*Yield* R_e *(MPa)*	*UTS* R_m *(MPa)*	*E(%) 50 mm*	*HRB*	*%C*	*%Cr*	*% others*[*1]	*Properties*
405	ASTM A240/A276/ A351, UNS 40500	Ferritic	276	483	30	81	0.08	11.5–14.5	1 Mn	A general-purpose ferritic stainless steel
430	ASTM A176/A240/ A276, UNS 43000, Wk 1.4016	Ferritic	310	517	30	83	0.12	14–18	1 Mn	Non-hardening grade with good acid-resistance
403	UNS S40300, ASTM A176/A276	Martensitic	276	517	35	82	0.15	11.5–13	0.5 Si	Turbine grade of stainless steel
410	UNS S40300, ASTM A176/A240, Wk 1.4006	Martensitic	276	517	35	82	0.15	11.5–13.5	4.5–6.5 Ni	Used for machine parts, pump shafts etc.
–	255 (Ferralium)	Duplex	650	793	25	280 HV	0.04	24–27	4.5–6.5 Ni	Better resistance to SCC than 316.
–	Avesta SAF 2507[*3], UNS S32750	'Super' Duplex 40% ferrite	≃680	≃800	≃25	300 HV	0.02	25	7Ni, 4Mo, 0.3N	High strength. Max 300°C due to embrittlement

[*1]Main constituents only shown.
[*2]All austenitic grades are non-magnetic, ferritic and martensitic grades are magnetic.
[*3]Avesta trade mark.

12.7 Non-ferrous alloys

The term non-ferrous alloys is used for those alloy materials which do not have iron as the base element. The main ones used for mechanical engineering applications, with their tensile strength ranges are:

Nickel alloys	400–1200 MN/m^2
Zinc alloys	200–360 MN/m^2
Copper alloys	200–1100 MN/m^2
Aluminium alloys	100–500 MN/m^2
Magnesium alloys	150–340 MN/m^2
Titanium alloys	400–1500 MN/m^2

12.8 Nickel alloys

Nickel is frequently alloyed with copper or chromium and iron to produce material with high temperature and corrosion resistance. Typical types and properties are shown in Table 12.6.

Table 12.6

Alloy type	*Designation*	*Constituents (%)*	*UTS (MN/m^2)*
Ni–Cu	UNS N04400 ('Monel')	66Ni, 31Cu, 1Fe, 1Mn	415
Ni–Fe	'Ni lo 36'	36Ni, 64Fe	490
Ni–Cr	'Inconel 600'	76Ni, 15Cr, 8Fe	600
Ni–Cr	'Inconel 625'	61Ni, 21Cr, 2Fe, 9Mo, 3Nb	800
Ni–Cr	'Hastelloy C276'	57Ni, 15Cr, 6Fe, 1Co, 16Mo, 4W	750
Ni–Cr (age hardenable)	'Nimonic 80A'	76Ni 20Cr	800–1200
Ni–Cr (age hardenable)	'Inco Waspalloy'	58Ni, 19Cr, 13Co, 4Mo, 3Ti, 1Al	800–1000

Useful Standards

1. BS 3072: 1996: Specification for nickel and nickel alloys – sheet and plate.
2. BS 3073: 1996: Specification for nickel and nickel alloys – strip.
3. BS 3074: 1996: Specification for nickel and nickel alloys – seamless tube.

4. ASTM B574: 2005: Specification for low carbon nickel–chromium and other alloys.

12.9 Zinc alloys

The main use for zinc alloys is for die casting. The alloys are widely known by 'letter' designations. Typical types and properties are shown in Table 12.7.

Table 12.7

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Alloy 'A' (for die casting)	4Al, 0.05Mg, 0.03Cu	285	83
Alloy 'B' (for die casting)	4Al, 0.05Mg, 1Cu	330	92
Alloy 'ZA12' (for cold die casting)	11Al, 0.02Mg, 1Cu	400	100

Useful Standards

1. BS 1004: 1985: Specification for zinc alloys for die casting and zinc alloy die castings. Similar to ISO 301.
2. EN ISO 3815: 2005: Zinc and zinc alloys – optical emission spectrometric analysis.

12.10 Copper alloys

- Copper–zinc alloys are *brasses*
- Copper–tin alloys are *tin bronzes*
- Copper–aluminium alloys are *aluminium bronzes*
- Copper–nickel alloys are *cupronickels*

Perhaps the most common range are the brasses, which are made in several different forms.

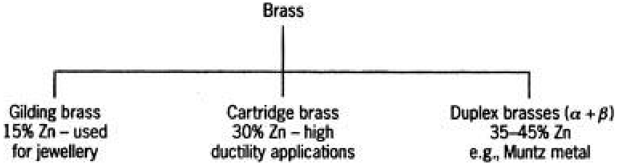


Figure 12.3

Typical types and properties of copper alloys are shown in Table 12.8.

Table 12.8

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Cartridge brass (shells)	30Zn	650	185
Tin bronze	5Sn, 0.03P	700	200
Gunmetal (marine components)	10Sn, 2Zn	300	80
Aluminium bronze (valves)	5Al	650	190
Cupronickel (heat exchanger tubes)	10Ni, 1Fe	320	155
Nickel silver (springs, cutlery)	21Zn, 15Ni	600	180

Useful Standards

There is a wide range of British Standards covering copper alloy products:

1. BS EN 1172: 1997: Copper and copper alloys – sheet and strip for building purposes.
2. BS EN 1652: 1998: Copper and copper alloys for general purposes.
3. BS 1400: 1985: Specification for copper alloy ingots, and copper alloy and high conductivity copper castings.
4. DIN 1705: 1985: Copper–tin and copper–zinc casting alloys.

12.11 Aluminium alloys

Pure aluminium is too weak to be used for anything other than corrosion-resistant linings. The pressure of relatively small percentages of impurities, however, increases significantly the strength and hardness. The mechanical properties also depend on the amount of working of the material. The basic grouping of aluminium alloys is:

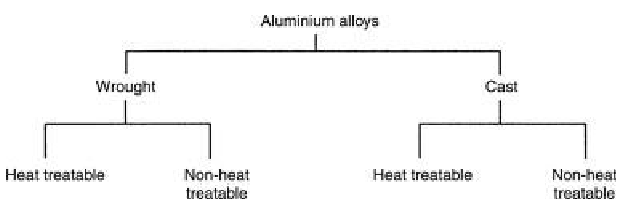


Figure 12.4

Typical alloy types and properties are shown in Table 12.9.

Table 12.9

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Duralumin (wrought, heat treatable) – aircraft components	4Cu, 0.8Mg, 0.5Si, 0.7Mn	190	45
Wrought, non-heat treated	1.25Mn	180	50
Cast, non-heat treated	12Si	185	60
Cast, heat treated	4Cu, 2Ni, 1.5Mg	275	110

Useful Standards

1. BS 1471 to 1475, e.g. BS 1471: 1972: Specification for wrought aluminium and aluminium alloys for general engineering purposes – drawn tube.
2. BS 1490: 1988: Specification for aluminium, and aluminium alloy ingots and castings for general engineering purposes. Similar to ISO 3522/ISO 7722.
3. DIN 1725: 1998: Aluminium casting alloys.

12.12 Titanium alloys

Titanium can be alloyed with aluminium, copper, manganese, molybdenum, tin, vanadium, or zirconium, producing materials which are light, strong and have high corrosion resistance. They

Table 12.10

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Ti–Cu	2.5Cu	750	360
Ti–Al	5Al, 2Sn	880	360
Ti–Sn	11Sn, 4Mo, 2Al, 0.2Si	1300	380

are all expensive. Typical alloy types and properties are shown in Table 12.10.

Useful Standards

1. BS EN 2858-1: 1994: Titanium and titanium alloys – forging stock and forgings – technical specifications. General requirements.
2. BS EN 2808: 2007: Anodizing of titanium and titanium alloys.

12.13 Engineering plastics

Engineering plastics are widely used in engineering components and are broadly divided into three families: thermoplastics, thermosets, and composites.

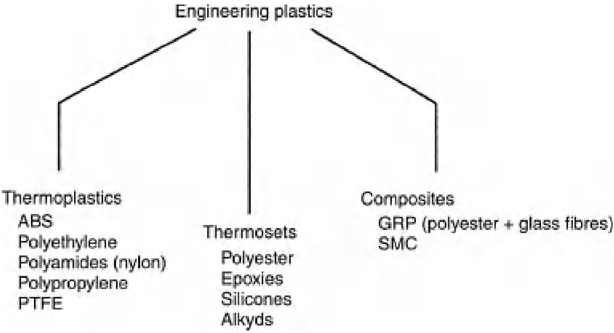


Figure 12.5

Thermoplastic polymers can be resoftened by heating whereas thermosets cannot. Most practical applications of plastic (e.g. car body components) need to use composites to achieve the necessary strength and durability. Typical properties are shown in Table 12.11.

Table 12.11

Alloy type	*UTS (MN/m^2)*	*Modulus E (GN/m^2)*
PVC	50	3.5
PTFE	14	0.3
Nylon	60	2
Polyethylene	20	0.6
GRP	Up to 180	Up to 20
Epoxies	80	8

Useful Standards

1. BS 1755: Part 1: 1982: *Glossary of terms used in the plastics industry*. This is a withdrawn standard – see ISO 472: 1979.
2. BS 3496: 1989: Specification of E glass fibre chopped strand mat for reinforcement of polyester and other liquid laminating systems.
3. BS 2872 (various parts): Methods of testing plastics.
4. BS 3502 (various parts): Symbols for plastics and rubber materials.

5. BS 4618 (various parts): Recommendations for the presentation of plastics design data.

12.14 Material traceability and documentation

Material traceability is a key aspect of the manufacture of mechanical engineering equipment. Fabricated components such as pressure vessels and cranes are subject to statutory requirements which include the need for proper material traceability.

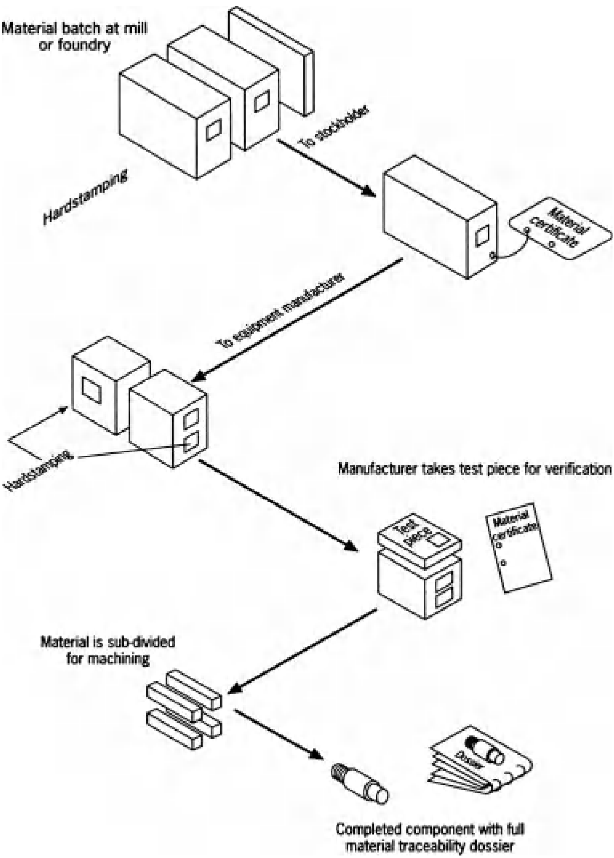


Figure 12.6

12.15 Corrosion

12.15.1 Types of corrosion

There are three basic types of corrosion:

- chemical corrosion;
- galvanic corrosion;
- electrolytic corrosion.

To complicate matters there are a variety of sub-types, some hybrids, and a few which do not fit neatly into any single category at all.

12.15.2 Chemical corrosion

This is caused by attack by chemical compounds in a material's environment. It is sometimes referred to as 'dry' corrosion or oxidation.

Examples are:

- oxidation (scaling) of iron at high temperatures;
- oxidation of nickel in sulphurous gas.

12.15.3 Galvanic corrosion

This is caused by two or more dissimilar metals in contact in the presence of a conducting electrolyte. One material becomes anodic to the other and corrodes (Fig. 12.7). Examples are:

- stainless steel trim causes anodic corrosion on carbon steel vehicle bodywork;
- defective coating of tin on carbon steel increases the corrosion rate of steel.

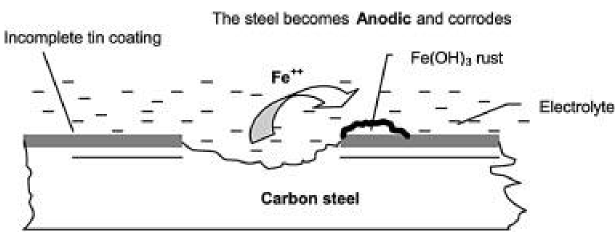


Figure 12.7

The tendency of a metal to become anodic or cathodic is governed by its position in the electrochemical series (Fig. 12.8). This is, strictly, only accurate for pure metals rather than metallic compounds and alloys.

Galvanic corrosion occurs when dissimilar metals are in contact with a conducting electrolyte. The electrochemical series shows the relative potentials of pure metals.

Gold	(Au)	**+ Volts**
Platinum	(Pt)	↑
Silver	(Ag)	Noble metals **(Cathodic)**
Copper	(Cu)	
Hydrogen	(H)	**Reference potential 0 Volts**
Lead	(Pb)	
Tin	(Sn)	
Nickel	(Ni)	
Cadmium	(Cd)	
Iron	(Fe)	
Chromium	(Cr)	Base metals **(Anodic)**
Zinc	(Zn)	
Aluminium	(Al)	
Magnesium	(Mg)	↓
Lithium	(Li)	**– Volts**

Remember. Metals higher in the table become cathodic and are protected by the (anodic) metals below them in the table.

Figure 12.8 The electrochemical series

A more general guide to galvanic corrosion attack of common engineering materials is given in Figure 12.9.

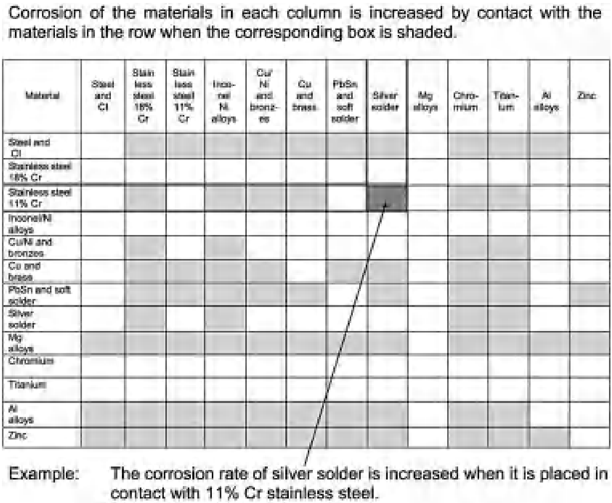


Figure 12.9 Galvanic corrosion attack – guidelines

12.15.4 Electrolytic corrosion

This is sometimes referred to as 'wet' corrosion. It is similar to galvanic corrosion in that it involves a potential difference and an electrolyte but it does not have to have dissimilar materials. The galvanic action often happens on a microscopic scale. Examples are:

- pitting of castings due to galvanic action between different parts of the crystals (which have different composition);
- corrosion of castings due to grain boundary corrosion (Fig. 12.10).

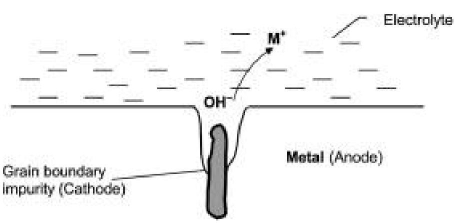


Figure 12.10

12.15.5 Crevice corrosion

This occurs between close-fitting surfaces, crevice faces, or anywhere a metal is restricted from forming a protective oxide layer (Fig. 12.11). Corrosion normally propagates in the form of pitting. Examples are:

- corrosion in crevices in seal welds;
- corrosion in lap-joints used in fabricated components and vessels.

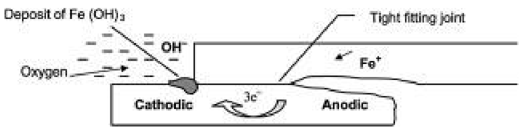


Figure 12.11

12.15.6 Stress corrosion

This is caused by a combination of corrosive environment and tensile loading. Cracks in a material's brittle surface layer propagate into the material, resulting in multiple bifurcated (branching) cracks. Examples are:

- failure in stainless steel pipes and bellows in a chloraterich environment;
- corrosion of austenitic stainless steel pressure vessels.

12.15.7 Corrosion fatigue

This is a hybrid category in which the effect of a corrosion mechanism is increased by the existence of a fatigue condition. Seawater, fresh water, and even air can reduce the fatigue life of a material.

12.15.8 Intergranular corrosion

This is a form of local anodic attack at the grain boundaries of crystals due to microscopic difference in the metal structure and composition. Examples are:

- 'weld decay' in unstabilized 18/8 austenitic stainless steels;
- 'dezincification' of brass in seawater: the selective removal of zinc from the alloy leaving behind a spongy mass of copper.

12.15.9 Erosion–corrosion

Almost any corrosion mechanism is made worse if the material is subject to simultaneous corrosion and abrasion. Abrasion removes the protective passive film that forms on the surface of many metals, thereby exposing the underlying metal. An example is:

- the walls of pipes containing fast-flowing fluids and suspended solids.

Section 13

Machine Elements

Machine elements is the term given to the set of basic mechanical components that are used as building blocks to make up a mechanical product or system. There are many hundreds of these – the most common ones are shown, subdivided into their common groupings, in Fig. 13.1. The established reference source for the design of machine elements is:

Shigley, J. E. and **Mischke, C. R.** *Standard Handbook of Machine Design*, 1986 (McGraw-Hill).

13.1 Screw fasteners

The ISO metric thread is the most commonly used. They are covered by different standards, depending on their size, material, and application.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Locating	*Drives and mechanisms*	*Energy transmission*	*Rotary bearings*	*Dynamic sealing*
Threaded fasteners	**Shafts**	**Gear trains**	**Rolling**	**Rotating shaft seals**
Nuts and bolts	Parallel	Spur	Ball	Face
Set screws	Taper	Helical	Roller (parallel)	Interstilial
Studs	Concentric	Bevel	Roller (tapered)	Axial radial
Grub screws		Worm and wheel	Needle	Bush
Expanding bolts	**Mechanisms**	Epicyclic	Self-aligning	Labyrinth
	Crank and sliding			Lip ring
Keys	Ratchet and pawl	**Belt drives**	**Sliding**	Split ring
Flat	Genera	Flat	Axial	
Taper	Scotch-yoke	Vee	Radial	**Reciprocating shaft seals**
Woodruff	Carden joint	Wedge	Bush	Piston rings
Profiled		Synchronous	Hydrodynamics	Packing rings
	Cams		Hydrostatic	
Pins	Constant velocity	**Chain drives**	Self-lubricating	
Split	Uniform accelleration	Roller	Sideways	
Taper	Simple harmonic	Conveyor		
	motion (shm)	Leaf		
Spines				
	Clutches	**Pulleys**		
Retaining rings	Dog	Simple		
	Cone	Differential		
Clamps	Disc			
	Spring	**Springs**		
Clips	Magnetic	Tension		
Circlips	Fluid coupling	Compression		
Spring				
	Brakes			
Shoulders and grooves	Disc			
	Drum			
	Couplings			
	Rigid			
	Flexible			
	Spring			
	Membrane			
	Cordon			
	Claw			

Figure 13.1

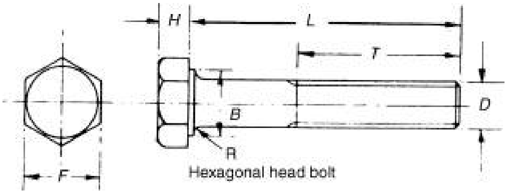


Figure 13.2

Useful Standards

1. BS 4190: 2001: Specification for ISO metric black hexagon bolts, screws and nuts. (The term `black' implies loose tolerances for non-precision applications, dia. 5–68 mm.) Similar to ISO 272.
2. BS 3692: 2001: Specification for ISO metric precision hexagon bolts, screws and nuts. (Covers dia. 1.6–68 mm.)
3. BS 3643: ISO metric screw threads.
   Part 1: 1998: Principles and basic data. [Gives data for dia. 1.0–300 mm (see also ISO 68/ISO 261/ISO 965).]
   Part 2: 1998: Specification for selected limits of size. (Gives size data for ISO coarse threads dia. 1.0–68 mm and ISO fine threads dia. 1.0–33 mm.)
4. DIN 13 Part 1: ISO metric screw threads.

Typical BS 3692 sizes (all in mm) are shown in Table 13.1.

Table 13.1

Size	*Pitch*	*Width A/F (F)*		*Head height (H)*		*Nut thickness (m)*	
		Max.	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*
M5	0.8	8.00	7.85	3.650	3.350	4.00	3.7
M8	1.25	13.00	12.73	5.650	5.350	6.50	6.14
M10	1.5	17.00	16.73	7.180	6.820	8.00	7.64
M12	1.75	19.00	18.67	8.180	7.820	10.00	9.64
M20	2.5	30.00	29.67	13.215	12.785	16.00	15.57

13.1.1 Nuts and washers

Useful standards are shown below.

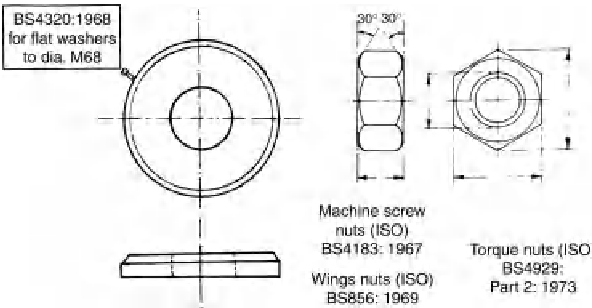


Figure 13.3

13.2 Bearings

13.2.1 Types

Bearings are basically subdivided into three types: sliding bearings (plane motion), sliding bearings (rotary motion) and rolling element bearings (see Fig. 13.4). There are three lubrication regimes for sliding bearings:

- *Boundary lubrication* There is actual physical contact between the surfaces.
- *Mixed-film lubrication* The surfaces are partially separated for intermittent periods.
- *Full-film 'hydrodynamic' lubrication* The two surfaces 'ride' on a wedge of lubricant.

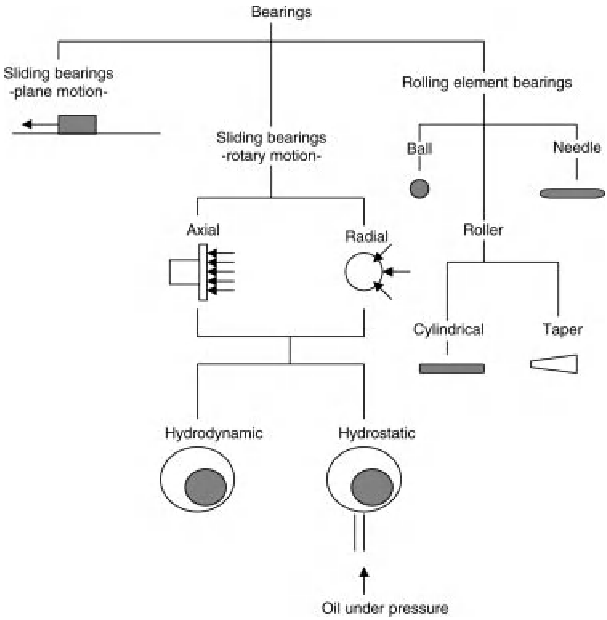


Figure 13.4

13.3 Ball and roller bearings

Some of the most common designs of ball and roller bearings are as shown. The amount of misalignment that can be tolerated is a critical factor in design selection. Roller bearings have higher basic load ratings than equivalent sized ball-types.

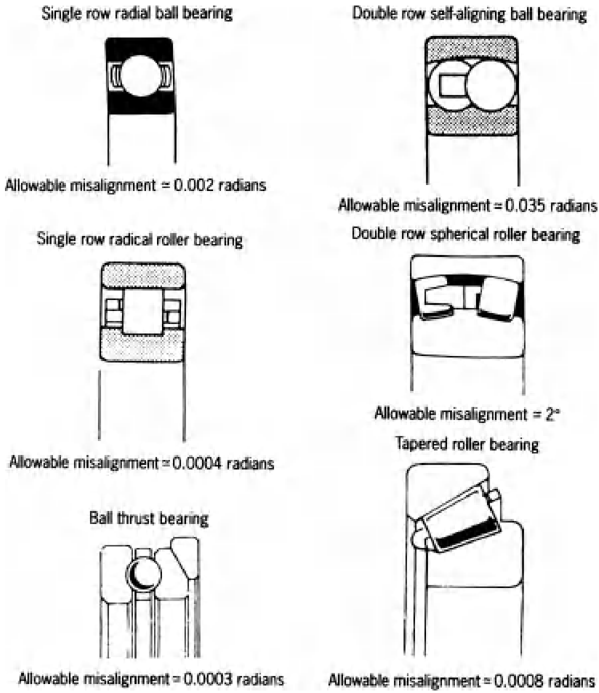


Figure 13.5

13.4 Bearing lifetime

Bearing lifetime ratings are used in purchasers' specifications and manufacturers' catalogues and datasheets. The rating life (L_{10}) is that corresponding to a 10% probability of failure and is given by:

$$
\begin{aligned}
L_{10}\text{ radial ball bearings} &= (Cr/Pr)^{3} &&\times 10^{6}\text{ revolutions}\\
L_{10}\text{ radial roller bearings} &= (Cr/Pr)^{10/3} &&\times 10^{6}\text{ revolutions}\\
L_{10}\text{ thrust ball bearings} &= (Ca/Pa)^{3} &&\times 10^{6}\text{ revolutions}\\
L_{10}\text{ thrust roller bearings} &= (Ca/Pa)^{10/3} &&\times 10^{6}\text{ revolutions}
\end{aligned}
$$

Cr and Ca are the static radial and axial load ratings that the bearing can theoretically endure for 10^6 revolutions. Pr and Pa are corresponding dynamic equivalent radial and axial loads.

So, as a general case:

$$\text{Roller bearings: } L_{10} \text{ lifetime} = [16667(C/P)^{10/3}]/n$$

$$\text{Ball bearings: } L_{10} \text{ lifetime} = [16667(C/P)^{3}]/n$$

where

$$\left.\begin{aligned} C &= \text{Cr or Ca} \\ P &= \text{Pr or Pa} \end{aligned}\right\} \text{as appropriate}$$

n = speed in rev/min

13.5 Coefficient of friction

The coefficient of friction between bearing surfaces is an important design criterion for machine elements which have rotating, meshing, or mating parts. The coefficient value (μ) varies depending on whether the surfaces are static or already sliding, and whether they are dry or lubricated. Table 13.2 shows some typical values.

Table 13.2 Typical friction coefficients

	Static		*Sliding*	
Material	*Dry*	*Lubricated*	*Dry*	*Lubricated*
Steel/steel	0.75	0.15	0.57	0.10
Steel/cast iron	0.72	0.20	0.25	0.14
Steel/phosphor bronze	–	–	0.34	0.18
Steel/bearing 'white metal'	0.45	0.18	0.35	0.15
Steel/tungsten carbide	0.5	0.09	–	–
Steel/aluminium	0.6	–	0.49	–
Steel/Teflon	0.04	–	–	0.04
Steel/plastic	–	–	0.35	0.06
Steel/brass	0.5	–	0.44	–
Steel/copper	0.53	–	0.36	0.2
Steel/fluted rubber	–	–	–	0.05
Cast iron/cast iron	1.10	–	0.15	0.08
Cast iron/brass	–	–	0.30	–
Cast iron/copper	1.05	–	0.30	–
Cast iron/hardwood	–	–	0.5	0.08
Cast iron/zinc	0.85	–	0.2	–
Hardwood/hardwood	0.6	–	0.5	0.17
Tungsten carbide/tungsten carbide	0.2	0.12	–	–
Tungsten carbide/steel	0.5	0.09	–	–
Tungsten carbide/copper	0.35	–	–	–

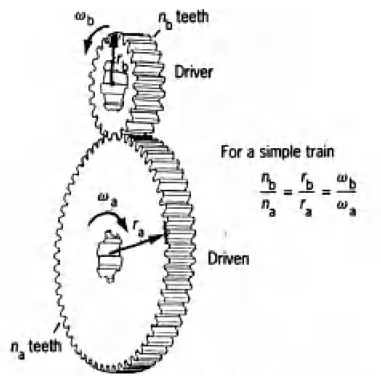
Note: The static friction coefficient between like materials is high, and can result in surface damage or seizure.

13.6 Gear trains

Gear trains are used to transmit motion between shafts. Gear ratios and speeds are calculated using the principle of relative velocities. The most commonly used arrangements are simple or compound trains of spur or helical gears, epicyclic, and worm and wheel.

13.6.1 Simple trains

Simple trains have all their teeth on their 'outside' diameter.



Spur gears – simple train

If an idler gear of radius r_i and n_i teeth is placed in the train, it changes the direction of rotation of the driver or driven gear but does not affect the relative speeds.

Figure 13.6

13.6.2 Compound trains

Speeds are calculated as follows.

Hence the number of teeth on the idler gear does affect the relative speeds of the driver and driven gear.

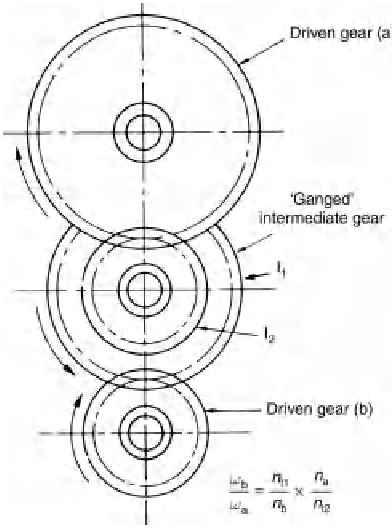


Figure 13.7

13.6.3 Worm and wheel

The worm and wheel is used to transfer drive through 90°, usually incorporating a high gear ratio and output torque. The wheel is a helical gear.

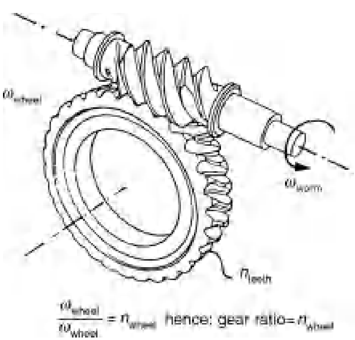


Figure 13.8

13.6.4 Double helical gears

These are used in most high-speed gearboxes. The double helices produce opposing axial forces which cancel each other out.

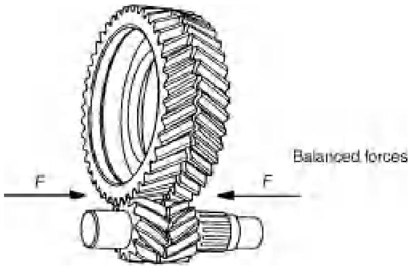


Figure 13.9

13.6.5 Epicyclic gear

An epicyclic gear consists of a sun gear on a central shaft, and several planet gears which revolve around it. A second coaxial shaft carries a ring gear whose internal teeth mesh with the planet gears. Various gear ratios can be obtained depending upon which member is held stationary (by friction brakes). An advantage of epicyclic gears is that their input and output shafts are concentric, hence saving space.

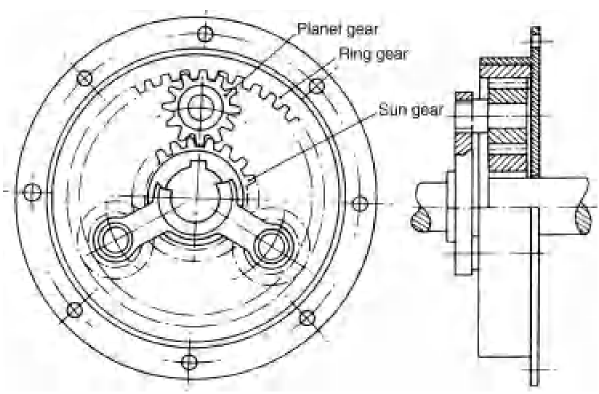


Figure 13.10

13.6.6 Gear nomenclature

Gear standards refer to a large number of critical dimensions of the gear teeth. These are controlled by tight manufacturing tolerances. (See Fig. 13.11.)

USEFUL STANDARDS

1. ISO 1328: 1975: Parallel involute gears – ISO system of accuracy. This is a related standard to BS 436.
2. BS 436: Part 1: 1987: Basic rack form, pitches and accuracy.
3. BS 1807: 1988 (withdrawn): Specification for main propulsion gears and similar drives.
4. The AGMA (American Gear Manufacturers' Association) range of standards.
5. API 613: 2005: Special purpose gear units for refinery service.
6. BS 978 (various parts): Specification for fine pitch gears.
7. BS 4582: Part 1: 1990: Involute, spur and helical gears.
8. DIN 3990: 2002: Calculation of load capacity of cylindrical gears.

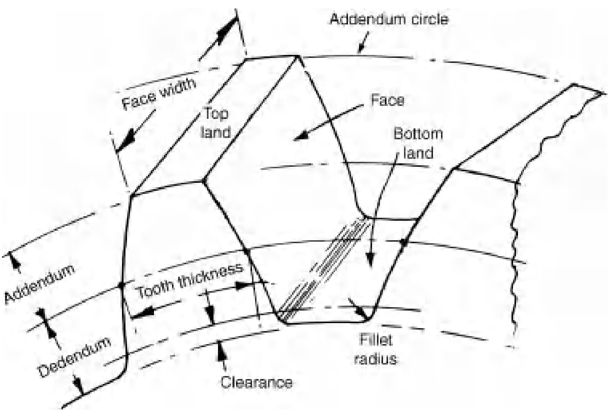


Figure 13.11

13.7 Seals

Seals are used to seal either between two working fluids or to prevent leakage of a working fluid to the atmosphere past a rotating shaft. They are of several types.

13.7.1 Bellows seal

This uses a flexible bellows to provide pressure and absorb misalignment.

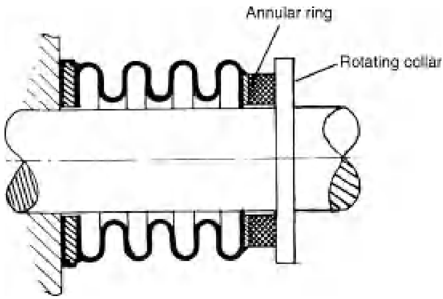


Figure 13.12

13.7.2 Labyrinth gland

This consists of a series of restrictions formed by projections on the shaft and/or casing. The pressure of the steam or gas is broken down by expansion at each restriction. There is no physical contact between the fixed and moving parts.

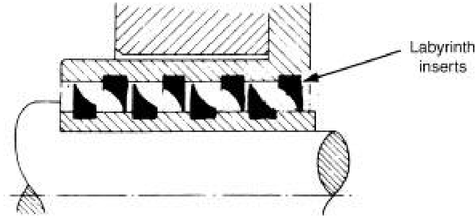


Figure 13.13

13.7.3 Mechanical seals

The key parts of a mechanical seal are a rotating ‘floating’ seal ring and a stationary seat or collar. Both are made of wear-resistant material and the floating ring is kept under an axial force from a spring (and fluid pressure) to force it into contact with its mating surface.

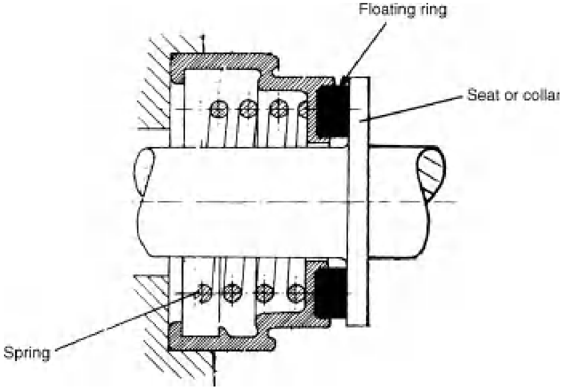


Figure 13.14

Mechanical seals are used to seal either between two working fluids or to prevent leakage of a working fluid to the atmosphere past a rotating shaft. They can work with a variety of fluids at pressures of up to 500 bar and sliding speeds of more than 20 m/sec. The core parts of the seal are the rotating 'floating' seal ring and the stationary seat (see Fig. 13.15).

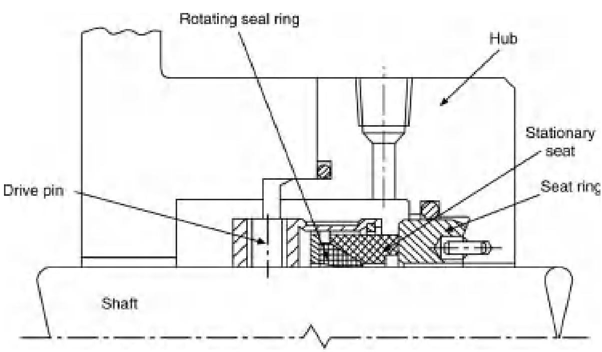


Figure 13.15

Web sites
www.flexibox.com
www.garlock-inc.com

13.8 Shaft couplings

Shaft couplings are used to transfer drive between two (normally co-axial) shafts. They allow either rigid or slightly flexible coupling, depending on the application.

13.8.1 Bolted couplings

The flanges are rigidly connected by bolts, allowing no mis-alignment. Positive location is achieved using a spigot on the flange face.

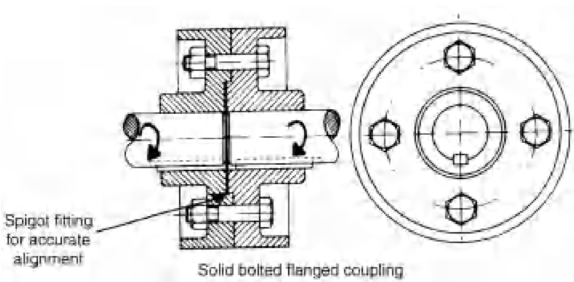


Figure 13.16

13.8.2 Bushed-pin couplings

Similar to the normal bolted coupling but incorporating rubber bushes in one set of flange holes. This allows a limited amount of angular misalignment.

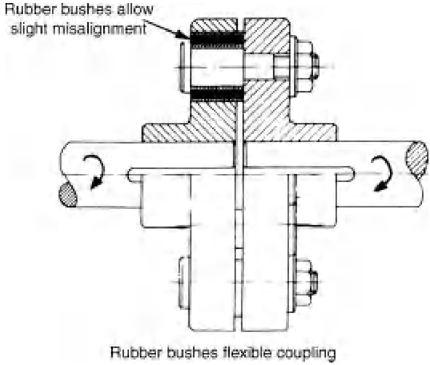


Figure 13.17

13.8.3 Disc-type flexible coupling

A rubber disc is bonded between thin steel discs held between the flanges.

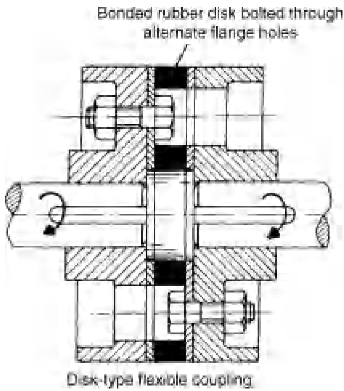


Figure 13.18

13.8.4 Diaphragm-type flexible couplings

These are used specifically for high-speed drives such as gas turbine gearboxes, turbocompressors, and pumps. Two stacks of flexible steel diaphragms fit between the coupling and its mating input/output flanges. These couplings are installed with a static prestretch – the resultant axial force varies with rotating speed and operating temperature.

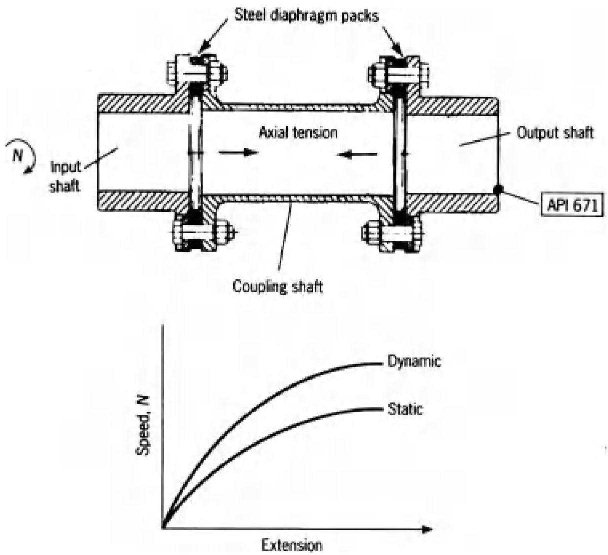


Figure 13.19

13.9 Cam mechanisms

A cam and follower combination are designed to produce a specific form of output motion. The motion is generally represented on a displacement/time (or lift/angle) curve. The follower may have knife-edge, roller, or flat profile.

13.9.1 Constant velocity cam

This produces a constant follower speed and is only suitable for simple applications.

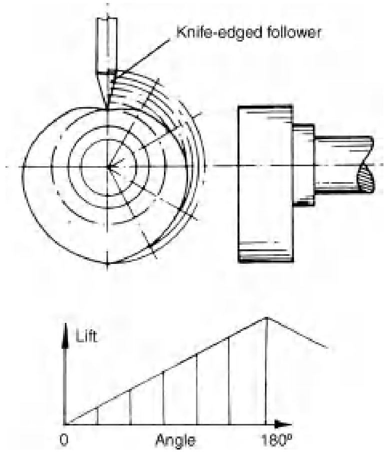


Figure 13.20

13.9.2 Uniform acceleration cam

The displacement curve is second-order function giving a uniformly increasing/decreasing gradient (velocity) and constant d^2x/dt^2 (acceleration).

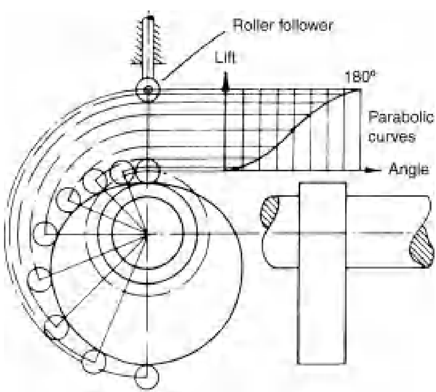


Figure 13.21

13.9.3 Simple harmonic motion cam

A simple eccentric circle cam with a flat follower produces simple harmonic motion (SHM).

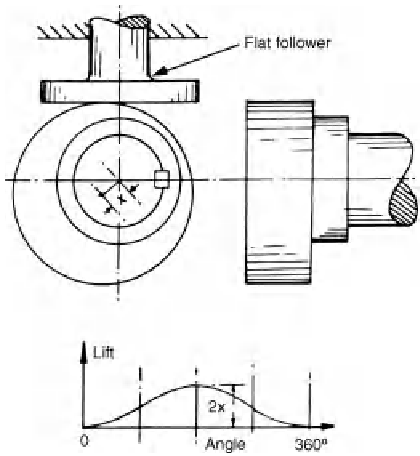


Figure 13.22

The motion follows the general SHM equations:

$$d^2x/dt^2 = -\omega^2 x$$

where

x = displacement
ω = angular velocity
T = periodic time
$dx/dt = -\omega a \sin \omega t$
$T = 2\pi/\omega$

13.10 Clutches

Clutches are used to enable connection and disconnection of driver and driven shafts.

13.10.1 Dog clutch

One half of the assembly slides on a splined shaft. It is moved by a lever mechanism into mesh with the fixed half on the other shaft.

The clutch can only be engaged when both shafts are stationary. Used for crude and slow-moving machines such as crushers.

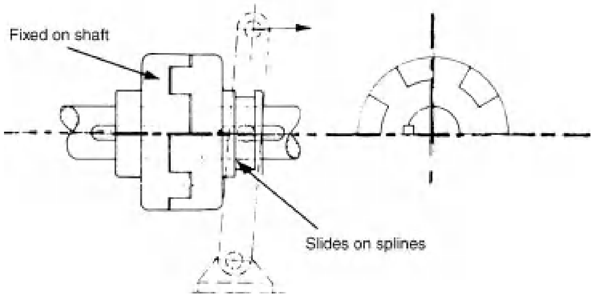


Figure 13.23

13.10.2 Cone clutch

The mating surfaces are conical and normally lined with friction material. The clutch can be engaged or disengaged when the shafts are in motion. Used for simple pump drives and heavy-duty materials handling equipment.

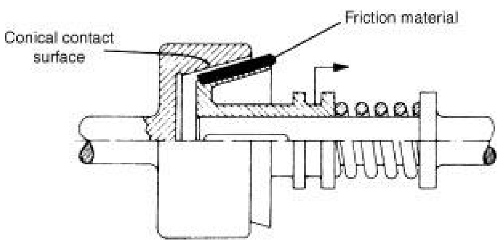


Figure 13.24

13.10.3 Multi-plate disc clutch

Multiple friction-lined discs are interleaved with steel pressure plates. A lever or hydraulic mechanism compresses the plate stack together. Universal use in cars and other motor vehicles with manual transmission.

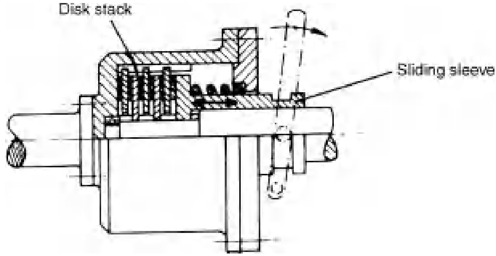


Figure 13.25

13.10.4 Fluid couplings

Radial-vaned impellers run in a fluid-filled chamber. The fluid friction transfers the drive between the two impellers. Used in automatic transmission motor vehicles and for larger equipment such as radial fans and compressors.

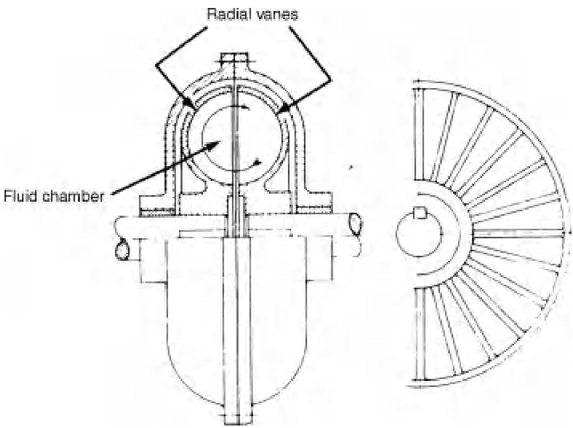


Figure 13.26

13.10.5 Clutch friction

The key design criterion of any type of friction clutch is the axial force required in order to prevent slipping. A general formula is used, based on the assumption of uniform pressure over the contact area.

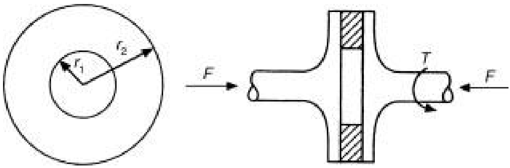


Figure 13.27

$$\text{Force } F = \frac{3T\left(r_2^2 - r_1^1\right)}{2\mu\left(r_2^3 - r_1^3\right)}$$

T = torque
μ = coefficient of friction

USEFUL STANDARDS

BS 3092:1988: Specification for main friction clutches for internal combustion engines.

13.11 Pulley mechanisms

Pulley mechanisms can generally be divided into either *simple* or *differential* types.

13.11.1 Simple pulleys

Velocity ratio, VR = the number of rope cross-sections supporting the load.

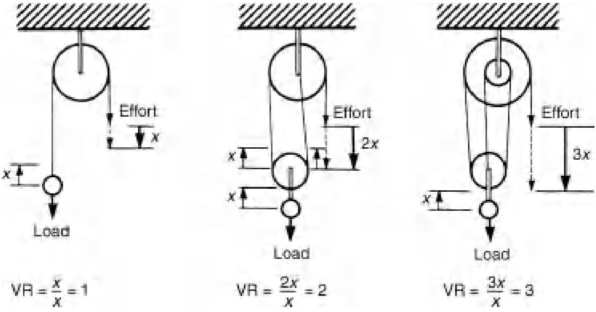


Figure 13.28

13.11.2 Differential pulleys

These are used to lift very heavy loads and consist of twin pulleys 'ganged' together on a single shaft.

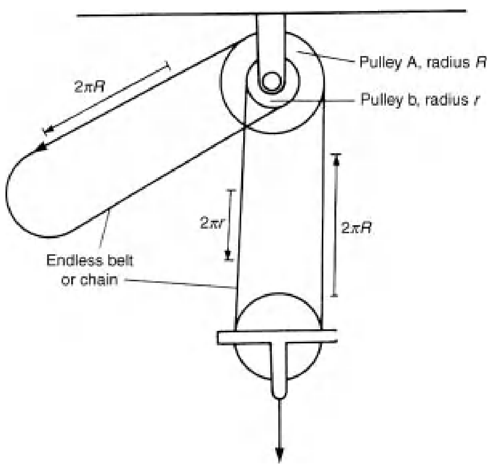


Figure 13.29

$$\text{VR} = \frac{2\pi R}{\pi(R-r)} = \frac{2R}{R-r}$$

13.12 Drive types

The three most common types of belt drive are flat, vee, and ribbed. Flat belts are weak and break easily. Vee belts can be used in multiples. An alternative for heavy-duty drive is the 'ribbed' type incorporating multiple v-shaped ribs in a wide cross-section.

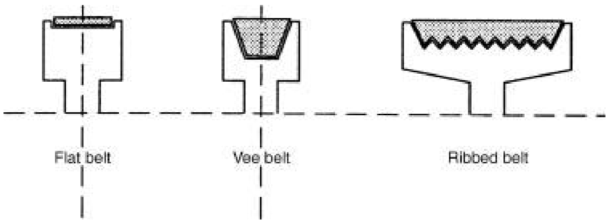


Figure 13.30

Section 14

Quality Assurance and Quality Control

14.1 Quality assurance: ISO 9001: 2008

14.1.1 Development

Quality standards have been around for many years. Their modern-day development started with the US Military and NATO. First published in 1979, the British standard BS 5750 has been revised and adapted by the International Organization for Standardization (ISO) and by CEN (the national standards organization of the European countries) as an effective model for quality assurance. With recent harmonization of standards under the EN classification it has obtained (almost) universal status as *the* standard of quality assurance.

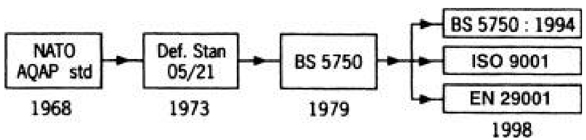


Figure 14.1

14.1.2 What is ISO 9001:2008?

The ISO 9000 documents were designed with the principle of ‘universal acceptance’ in mind – and to be capable of being developed in a flexible way to suit the needs of many different businesses and industries. The series was developed in the form of a number of sections, termed ‘models’ – intended to fit in broadly with the way that industry is structured. Inevitably, this has resulted in a high level of *generalization*. The current

Engineers’ Data Book, Fourth Edition. Clifford Matthews.

standard ISO 9001:2008 was developed from the previous 2000 version.

The current standard shares several features with its predecessors. First, it is still all about *documentation*. This means that everything written in the standard refers to a specific document – the scope of documentation is very wide. This does not mean that it does not have an effect on the product or service produced by a company – merely that these are not controlled directly by what is mentioned in the standard. Second, ISO 9001:2008 is about the effectiveness of a quality *management* system – unlike its predecessors it attempts to have an improving effect on the design, usefulness, and fitness for purpose of the product produced. It is, however, still a quality *management* standard, not a product conformity standard. It is still, therefore, not impossible for a manufacturer with a fully compliant ISO 9001 system installed and working, to make a product which is not suited to its market.

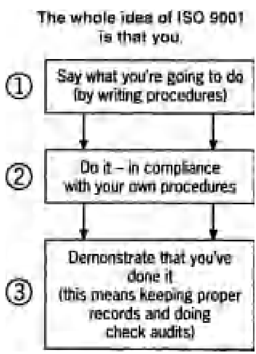


Figure 14.2

14.2 Quality system certification

Most businesses that install an ISO 9001: 2008 system do so with the objective of having it checked and validated by an outside body. This is called *certification*. Certification bodies are themselves *accredited* by a national body which ensures that their management and organizational capabilities are suitable for the task. Some certification bodies choose not to become accredited – this is perfectly legal in the UK, as long as they do not make misleading claims as to the status of the certificates they award. Some other countries have a more rigid system in which the certification body is a quasi-government institution and is the only organization able to award ISO 9001:2000 compliance certificates.

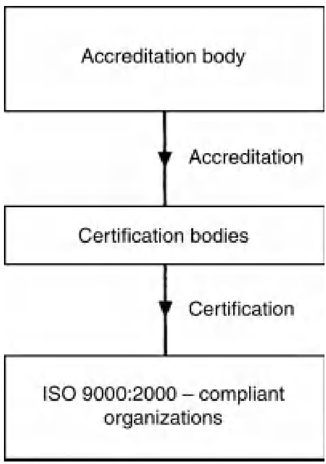


Figure 14.3

14.3 The ISO 9001 standard

Figure 14.4 shows the main outline contents of a company QA manual that mirrors the requirements of ISO 9001. Figure 14.5 shows the way that activities within an organization can be visualized as 'processes' (an important tenet of ISO 9001 since its year 2000 edition).

SECTION	*Management responsibility*
1.1	Quality Policy
1.2	Quality Objective
1.3	Scope of Service
1.4	Company Organization
1.5	Resources and Personnel
1.6	Management Review
1.7	Management Commitment
1.8	Customer Focus
2.0	**Quality Management System**
2.1	General Requirements
2.2	Documentation Requirements
2.3	Document and Data Control
2.4	Interaction between Processes
2.5	Quality Planning
3.0	**Resource Management**
3.1	Human Resources
3.2	Infrastructure
3.3	Work Environment
4.0	**Product Realization**
4.1	Planning of Product
4.2	Customer Related Processes
4.3	Design Control
4.4	Purchasing
4.5	Production and Service Provision
4.6	Inspection, Measuring, and Test Equipment
5.0	**Monitoring and Measurement**
5.1	Customer Satisfaction
5.2	Internal Audit and Monitoring of Processes
5.3	Monitoring and Measurement of Courses
5.4	Course Records, Examination Certificates
5.5	Inspection Status
5.6	Control of Non-conforming Service
5.7	Analysis of Course Data and Presentation
5.8	System Improvements
5.9	Corrective Action
5.10	Preventive Action

Figure 14.4 The structure of a typical ISO 9001 company quality manual

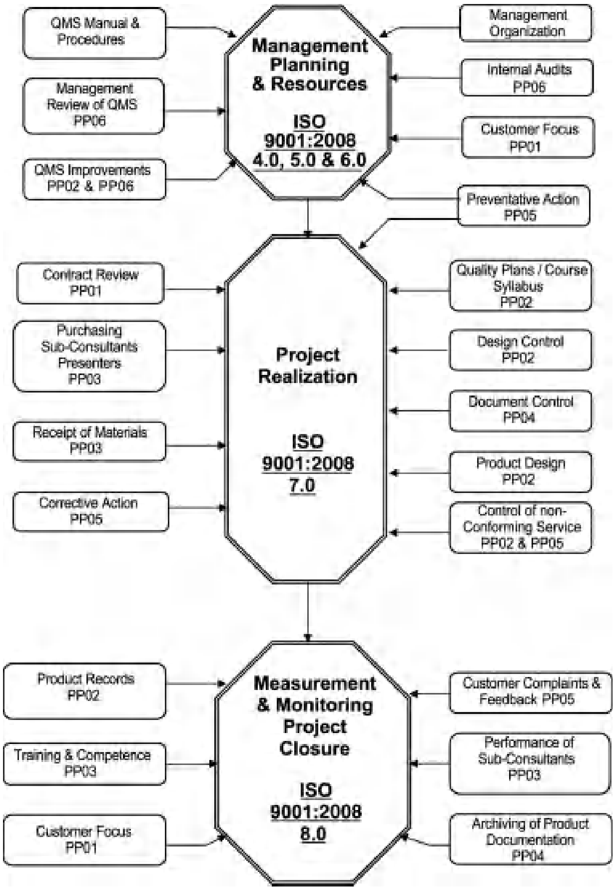


Figure 14.5

14.4 Taguchi methods

Taguchi is a specific type of SPC. It moves away from the estimation or counting of defective components to a wider view that encompasses *reducing* the variability of production, and hence the cost of defective items. The key points of the Taguchi idea are:

- Choose a manufacturing system or process that *reduces variability* in the end product.
- Design tolerances are chosen from the standpoint of costs – asking what is an acceptable price to pay for a certain set of tolerances.
- Push the quality assessment back to the *design stage* – again, the objective is to reduce the possible variability of the product.

Taguchi's basic principles are not, in themselves, new. Many of the principles coincide with the requirements for good, practical engineering design. The accepted reference sources are:

1. **Taguchi, G.** *Experimental Designs*, 3rd edition, 1976 (Marmza Publishing Company, Tokyo).
2. **Bendall, A.** *et al. Taguchi Methods – Applications in World Industry*, 1989 (IFS Publications, Bedford, UK).

14.5 Statistical process control (SPC)

SPC is a particular type of quality control used for mass production components such as nuts and bolts, engine and vehicle components, etc. It relies on the principle that the pattern of variation in dimension, surface finish, and other manufacturing 'parameters' can be studied and controlled by using *statistics*.

14.6 Normal distribution

The key idea is that by inspecting a sample of components it is possible to infer the compliance (or non-compliance) with specification of the whole batch. The core assumption is that of the *normal distribution*.

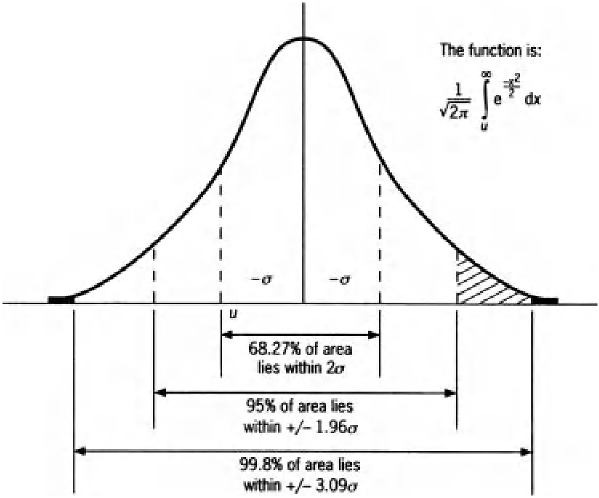


Figure 14.6

The quantities used are:

Standard deviation, $\sigma = \sqrt{variance}$

$$\sigma = \sqrt{\frac{f_1(x_1 - \bar{x})^2 + f_2(x_2 - \bar{x})^2 + \cdots}{N}}$$

$N =$ number of items
$f =$ frequency of items in each group
x_1, x_2, etc. $=$ mid size of the groups
$\bar{x} =$ arithmetic mean

From the normal distribution, a 'rule of thumb' is:

1 in 1000 items lie outside $\pm 3\sigma$
1 in 40 items lie outside $\pm 2\sigma$

14.6.1 Sample size

Symbols and formulae used for sample and 'population' parameters are shown in Table 14.1

Table 14.1

	Population	*Sample*
Average value	X	X
Standard deviation	σ	S
Number of items	N	n

Mean value $\bar{X} = \bar{x}$
Standard deviation of $\bar{x} = \sigma/\sqrt{2\pi}$
Standard error (deviation) of $s = \sigma/\sqrt{2\pi}$

14.7 The binomial and poisson distributions

This is sometimes used to estimate the number (p) of defective pieces or dimensions. An easier method is to use a Poisson distribution which is based on the exponential functions e^x and e^{-x}.

$$e^{-x}.e^x = e^{-x} + xe^{-x} + \frac{x^2 e^{-x}}{2!} + \frac{x^3 e^{-x}}{3!} + \cdots$$

This provides a close approximation to a binomial series and gives a probability of there being less than a certain number of defective components in a batch.

USEFUL STANDARDS

1. BS 600: 1993: The application of statistical methods to industrial standardization and quality control.
2. BS 7782: 1994: *Control charts, general guide and introduction*. This is an equivalent standard to ISO 7870: 1993.
3. BS 6000: 1994: *Guide to the selection of an acceptance sampling system*. This is an equivalent standard to ISO/TR 8550: 1994.
4. BS ISO 3534-2: 1993: *Statistical quality control*. This is an equivalent standard to ISO 3534-2: 1993.

14.8 Reliability

It is not straightforward to measure, or even define, the reliability of an engineering component. It is even more difficult at the design stage, before a component or assembly has even been manufactured.

- In essence reliability is about *how*, *why*, and *when* things fail.

14.8.1 The theoretical approach

There is a well-developed theoretical approach based on probabilities. Various methods such as:

- Fault tree analysis (FTA)
- Failure mode analysis (FMA)
- Mean time to failure (MTTF)
- Mean time between failures (MTBF)
- Monte Carlo analysis (based on random events)

14.8.2 MTTF and MTBF

Mean time to failure (MTTF) is defined as the mean operating time *between* successive failures without considering repair time. Mean time between failures (MTBF) includes the time needed to repair the failure. If a component or system is not repaired then MTTF and MTBF are equal (see Fig. 14.7).

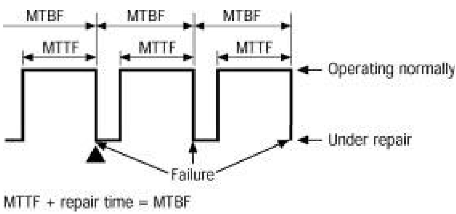


Figure 14.7

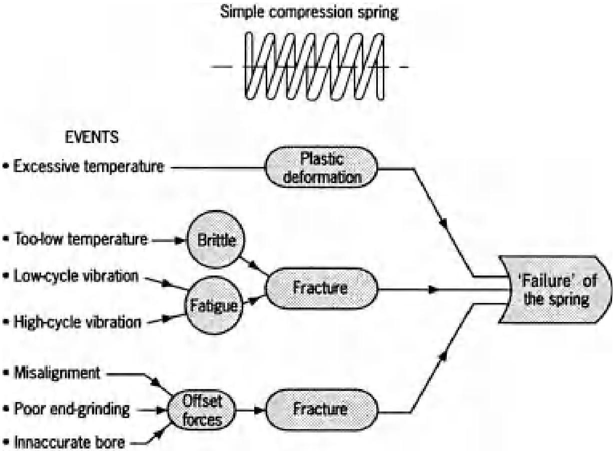


Figure 14.8 The principle of failure mode effects analysis (FMEA)

14.8.3 The practical approach

The 'bathtub curve' is surprisingly well proven at predicting when failures can be expected to occur. The chances of failure are quite high in the early operational life of a product item; this is due to inherent defects or fundamental design errors in the product, or incorrect assembly of the multiple component parts. A progressive wear regime then takes over for the 'middle 75 percent' of the product's life – the probability of failure here is low. As lifetime progresses, the rate of deterioration increases, causing progressively higher chances of failure.

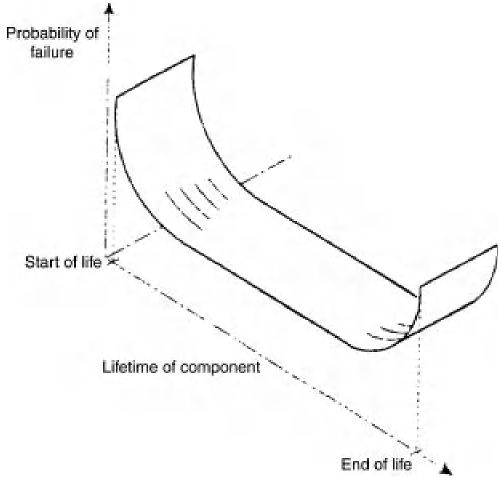


Figure 14.9 Component reliability–the 'bathtub curve'

The best way to improve the reliability of a mechanical engineering component is to eliminate problems at the design stage, before they occur.

14.9 Improving design reliability: main principles

- *Reduce static loadings* It is often the most highly stressed components that fail first.
- *Reduce dynamic loadings* Dynamic stress and shock loadings can be high.
- *Reduce cyclic conditions* Fatigue is the largest single cause of failure of engineering components.

- *Reduce operating temperature* Operation at near ambient temperatures improves reliability.
- *Remove stress raisers* They cause stress concentrations.
- *Reduce friction* Or keep it under control.
- *Isolate corrosive and erosive effects* Keep them away from susceptible materials.

14.10 'Design for reliability' – a new approach

Design for reliability (DFR) is an evolving method of stating and evaluating design issues in a way which helps achieve maximum reliability in a design. The features of this 'new approach' are:

- It is a quantitative but *visual* method – hence not too difficult to understand.
- No separate distinction is made between the functional performance of a design and its reliability – both are considered equally important.
- It does not rely on pre-existing failure rate data which can be inaccurate.

14.10.1 The technique

Design parameters are chosen with the objective of maximizing all of the safety margins that will be built in to a product or system. All the possible modes of failure are investigated and then expressed as a set of design constraints (see Fig. 14.10).

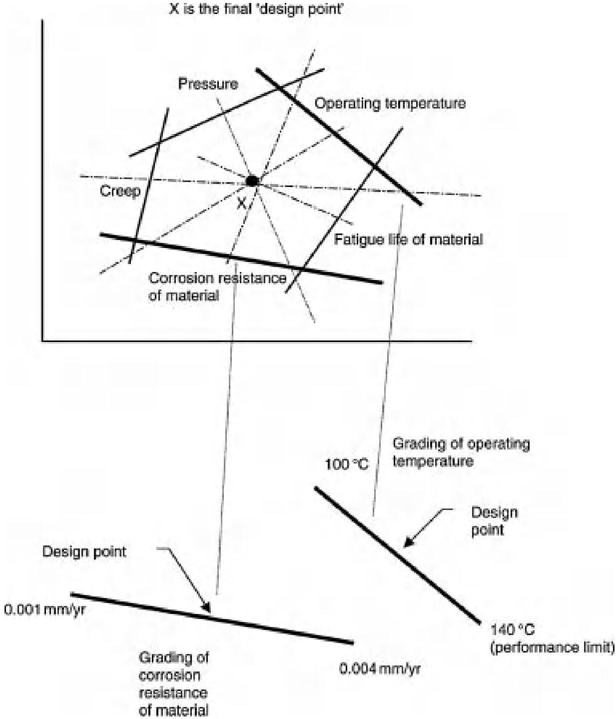


Figure 14.10

The idea is that a design which has the highest safety margin with respect to all the constraints will be the most reliable (point X in the figure).

Constraints are inevitably defined in a variety of units so a grading technique is required which yields a non-dimensional performance measure of each individual constraint. Figure 14.9 shows an example.

14.10.2 Useful references

Thompson, G., Liu, J. S., and **Holloway, L.,** 1999, An approach to design for reliability, *Proc. Instn Mech. Engrs Part E, J. Process Mechanical Engineering*, **213** (E1), 61–67.

USEFUL STANDARDS

The standard reference in this area is BS 5760: *Reliability of systems, equipment and components*. Several parts are particularly useful:

1. BS 5760:
   Part 0: 1993: Introductory guide to reliability.
   Part 2: 1994: Guide to the assessment of reliability.
   Part 3: 1993: Guide to reliability practices: examples.
   Part 5: 1991: Guide to FMEA and FMECA.
   Part 6: 1991: *Guide to fault tree analysis*. Equivalent to IEC 1025: 1996.

Other useful standards are:

2. BS 4778: Part 3: 1991: Availability, reliability and maintainability terms.
3. BS ISO 2382-14: 1978: Reliability, maintainability and availability.

Section 15

Project Engineering

15.1 Project planning

The most common tool to help plan and manage a project is the Programme Evaluation and Review Technique (PERT). In its simplest form it is also known as Critical Path Analysis (CPA) or network analysis. It is used for projects and programmes of all sizes and marketed as software packages under various trade names. The technique consists of five sequential steps.

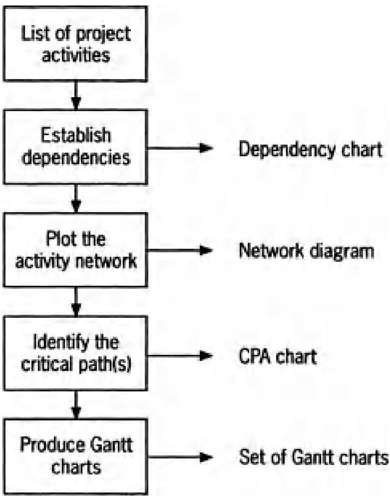


Figure 15.1

15.1.1 Listing the activities

All individual activities are input into the package. There may be thousands of these on a large construction programme.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

15.1.2 Tabulating dependencies

The dependency table is the main step in organizing the logic of the listed activities. It shows the previous activities on which each individual activity is dependent.

No.	Activity: e.g.	Preceding activity
1	Conceptual design	–
2	Embodiment design	1
3	Detailed design	2
4	Research materials	–

Figure 15.2

15.1.3 Creating a network

A network is created showing a graphical 'picture' of the dependency table. The size of the boxes and length of interconnecting lines have no programme significance. The lines are purely there to link dependencies, rather than to portray timescale.

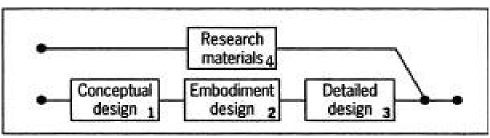


Figure 15.3 Network diagram

15.2 Critical path analysis (CPA)

The CPA introduces the concept of timescale into the network. It shows not only the order in which each project activity is done but also the duration of each activity. CPA diagrams are traditionally shown as a network of linked circles, each containing the three pieces of information shown. The critical path is shown as a thick arrowed line and is the path through the network that has *zero float*. Float is defined as the amount of

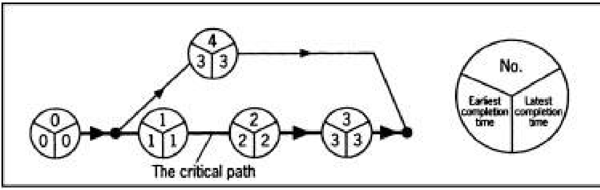


Figure 15.4 CPA chart

time an activity can shift, without affecting the pattern or completion date of the project.

15.3 Planning with Gantt charts

Gantt charts are produced from the CPA package and are used as the standard project management documents. Their advantages are:

- they provide an easy-to-interpret picture of the project;
- they show critical activities;
- they can be used to monitor progress by marking off activities as they are completed.

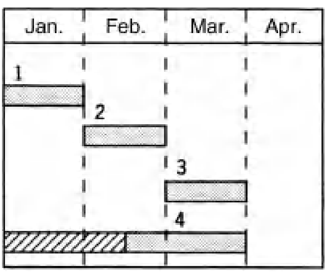


Figure 15.5 Gantt chart

A large construction or manufacturing project will have a hierarchy of Gantt charts to provide a general overview and more detailed analysis of the important parts of the project.

USEFUL STANDARDS

CPA terminology and techniques are given in:

1. BS 4335: 1993: Glossary of terms used in project network techniques.
2. BS 6046: Use of network techniques in project management. (This is a withdrawn standard.)
3. BS 6079: 1996: Guide to project management.
4. BS ISO 10006: 1997: Guidelines to quality in project management.

15.4 Rapid prototyping

The later stages of the design process for many engineering products involve making a prototype. A prototype is a nonworking (or sometimes working) full-size version of the product under design. Despite the accuracy and speed of CAD/CAM packages, there are still advantages to be gained by having a model in physical form, rather than on a computer screen. Costs, shapes, colours, etc. can be more easily assessed from a physical model.

The technology of *rapid prototyping* produces prototypes in a fraction of the time, and cost, of traditional techniques using wood, card, or clay models. Quickly available, solid prototypes enable design ideas to be tested and analysed quickly – hence increasing the speed and efficiency of the design process.

15.4.1 Prototyping techniques

These are state-of-the-art technologies which are developing quickly. Most use similar principles of building up a solid model by stacking together elements or sheets. The main ones are:

- *Stereolithography* This involves laser-solidification of a thin polymer film which is floating on a bath of fluid. Each layer is solidified sequentially, the shapes being defined by the output from a CAM package.
- *Laser sintering* Here a CAM-package driven laser is used to sinter the required shape out of a thin sheet of powder.
- *Laminated manufacture* This is a slightly cruder version of the same principle. Laminated sheets of foam are stuck together in an automated process using glue or heat.

15.5 Value analysis

Value analysis (or value engineering) is a generic name relating to quantifying and reducing the cost of an engineering product or project. Value analysis is about asking questions at the design stage, before committing to the costs of manufacture. All aspects of product design, manufacture, and operation are open to value analysis. Several areas tend to predominate: shape, materials of construction, surface finish, and tolerances.

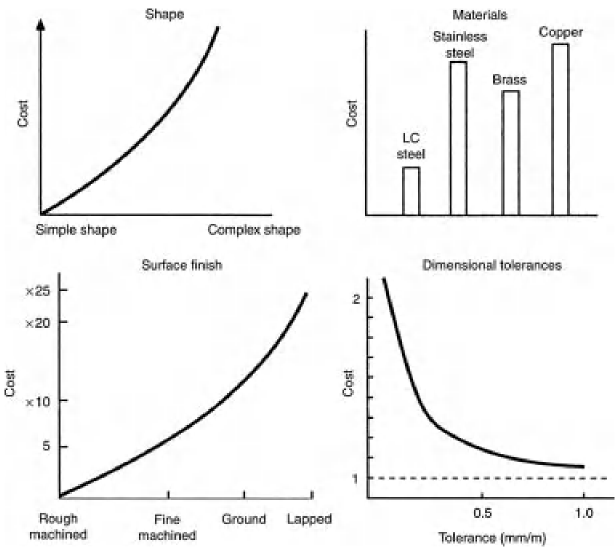


Figure 15.6

Techniques tend to be manufacturer-specific. One useful published document is:

PD 6470: 1981: *The management of design for economic production. Standardization philosophy aimed at improving the performance of the electrical and mechanical manufacturing sectors.*

Section 16

Welding

16.1 Welding processes

16.1.1 Manual metal arc (MMA)

This is the most commonly used technique. There is a wide choice of electrodes, metal and fluxes, allowing application to different welding conditions. The gas shield is evolved from the flux, preventing oxidation of the molten metal pool.

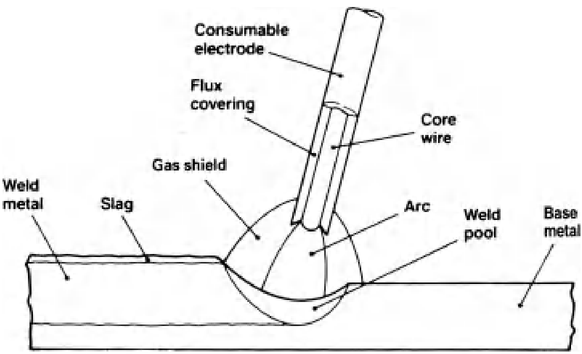


Figure 16.1

16.1.2 Metal inert gas (MIG)

Electrode metal is fused directly into the molten pool. The electrode is therefore consumed rapidly, being fed from a motorized reel down the centre of the welding torch.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

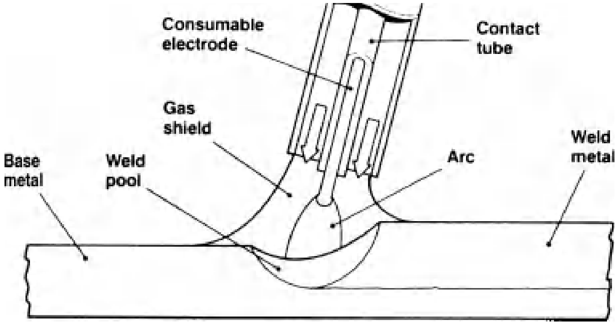


Figure 16.2

16.1.3 Tungsten inert gas (TIG)

This uses a similar inert gas shield to MIG but the tungsten electrode is not consumed. Filler metal is provided from a separate rod fed automatically into the molten pool.

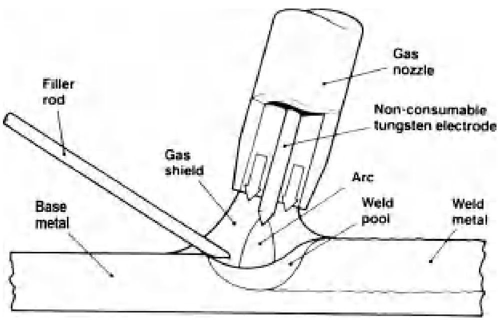


Figure 16.3

16.1.4 Submerged arc welding (SAW)

Instead of using shielding gas, the arc and weld zone are completely submerged under a blanket of granulated flux. A continuous wire electrode is fed into the weld. This is a common process for welding structural carbon or carbon – manganese steelwork. It is usually automatic with the welding head being mounted on a traversing machine. Long continuous welds are possible with this technique.

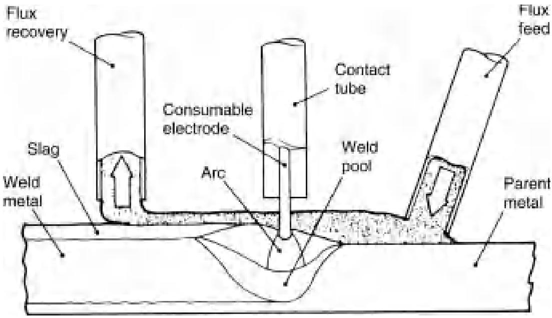


Figure 16.4

16.1.5 Flux-cored arc welding (FCAW)

Similar to the MIG process, but uses a continuous hollow electrode filled with flux, which produces the shielding gas. The advantage of the technique is that it can be used for outdoor welding, as the gas shield is less susceptible to draughts.

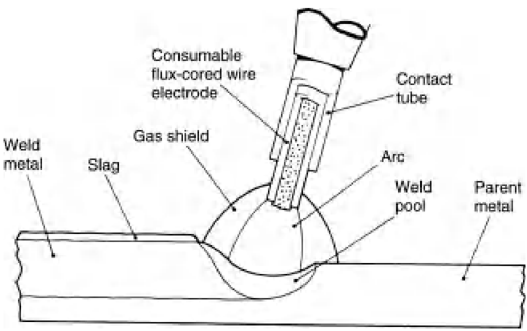


Figure 16.5

16.1.6 Electrogas welding (EGW)

This is a mechanized electrical process using an electric arc generated between a solid electrode and the workpiece. It has similarities to the MIG process.

16.1.7 Plasma welding (PW)

Plasma welding is similar to the TIG process. A needle-like plasma arc is formed through an orifice and fuses the parent metal. Shielding gas is used. Plasma welding is most suited to high-quality and precision welding applications.

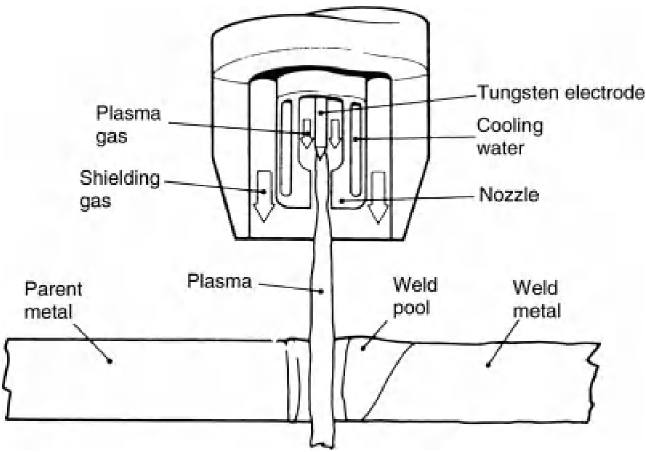


Figure 16.6

16.2 Weld types and orientation

The main *types* are butt and fillet welds – with other specific ones being developed from these.

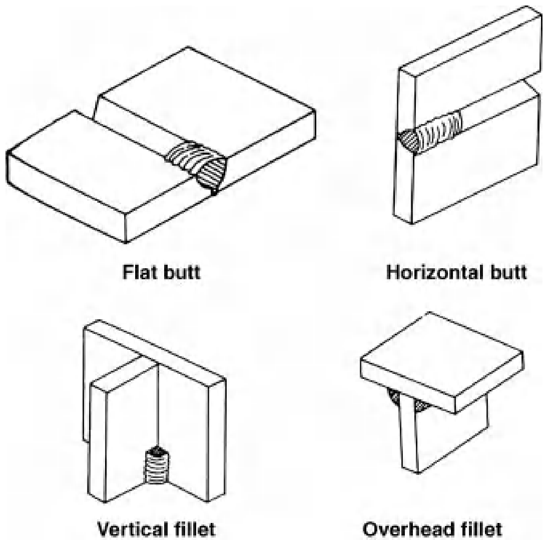


Figure 16.7

Orientation of the weld (i.e. the position in which it was welded) is also an important factor. Weld positions are classified formally in technical standards such as ASME IX, Part QW 461.

16.2.1 Weld terminology

Fillet and butt welds features have specific terminology that is used in technical standards such as BS 499: 2009.

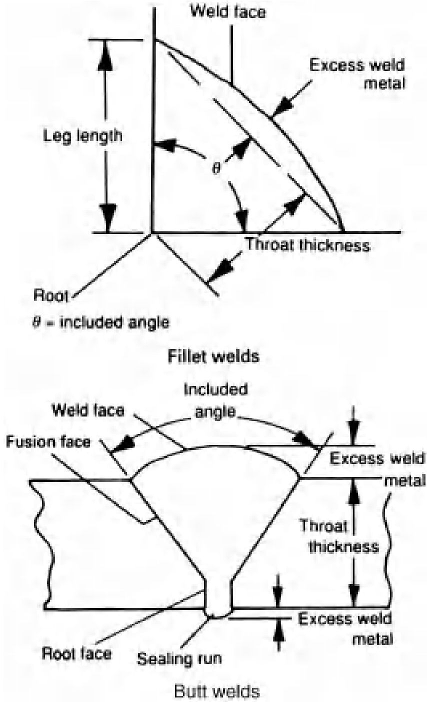

Weld face
Excess weld metal
Leg length
θ
Throat thickness
Root
θ = included angle
Fillet welds
Included angle
Weld face
Fusion face
Excess weld metal
Throat thickness
Excess weld metal
Root face
Sealing run
Butt welds

Figure 16.8

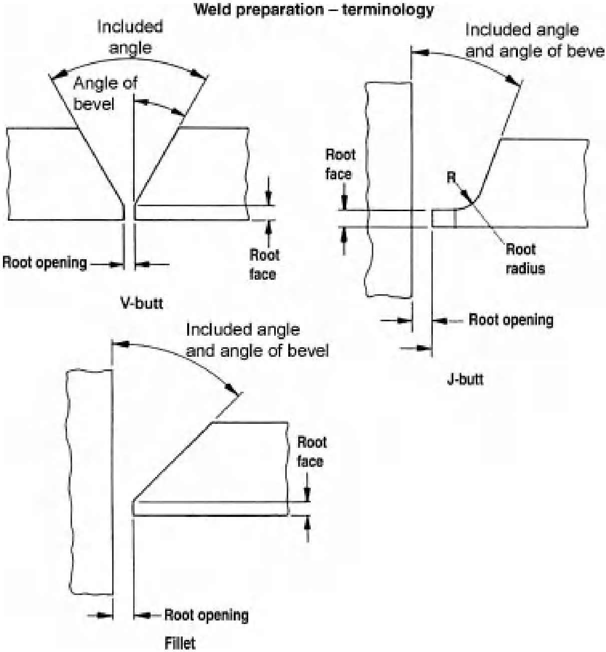


Figure 16.8 (Cont.)

16.3 Welding symbols

Standards such as BS 499, ISO 2553, and AWS A2.4: 2007 contain libraries of symbols to be used on fabrication drawings to denote features of weld preparations and the characteristics of the welds themselves.

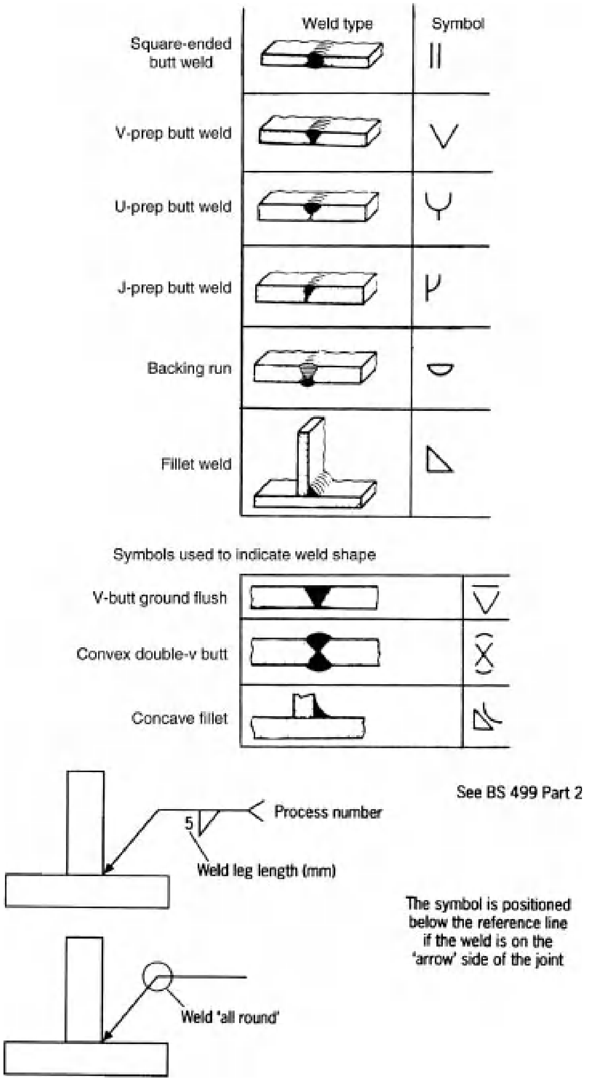

Weld type
Symbol
Square-ended butt weld
V-prep butt weld
U-prep butt weld
J-prep butt weld
Backing run
Fillet weld
Symbols used to indicate weld shape
V-butt ground flush
Convex double-v butt
Concave fillet
See BS 499 Part 2
5
Process number
Weld leg length (mm)
The symbol is positioned below the reference line if the weld is on the 'arrow' side of the joint
Weld 'all round'

Figure 16.9

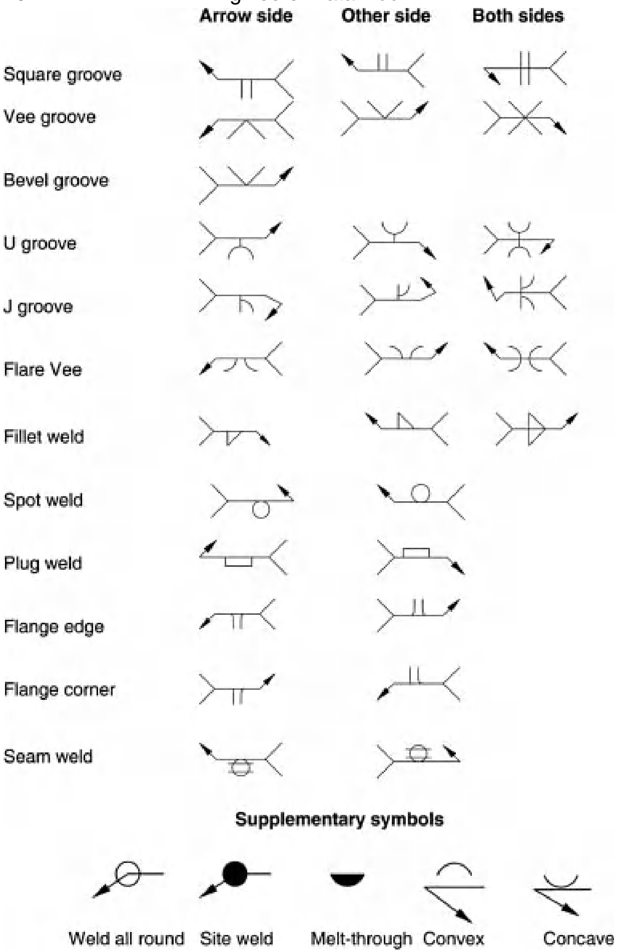

Arrow side
Other side
Both sides
Square groove
Vee groove
Bevel groove
U groove
J groove
Flare Vee
Fillet weld
Spot weld
Plug weld
Flange edge
Flange corner
Seam weld
Supplementary symbols
Weld all round
Site weld
Melt-through
Convex
Concave

Figure 16.10

16.4 Welding defects

All welding processes, particularly the manual ones, can suffer from defects. The causes of these are reasonably predictable.

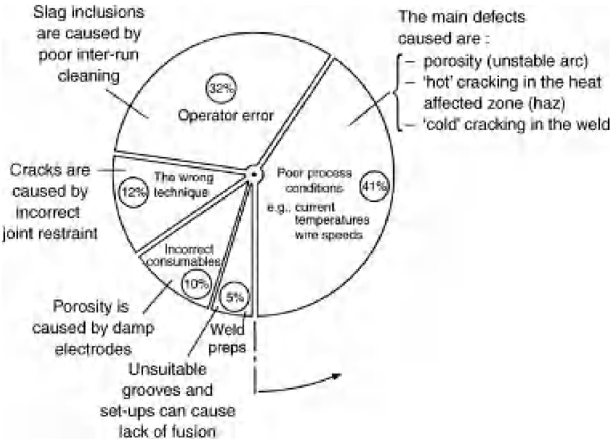


Figure 16.11

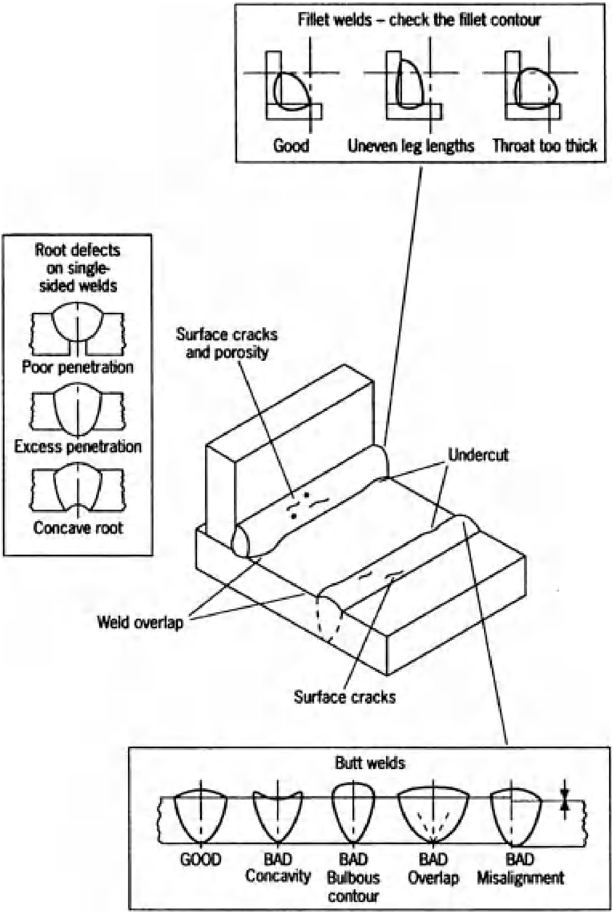


Figure 16.11 (Cont.)

Many weld defects can be detected by close visual inspection backed up by surface non-destructive testing (NDT).

16.5 Welding documentation

Welding is associated with a well-defined set of documentation designed to specify the correct weld method to be used, confirm that this method has been tested, and ensure that the welder performing the process has proven ability. The documents are shown below.

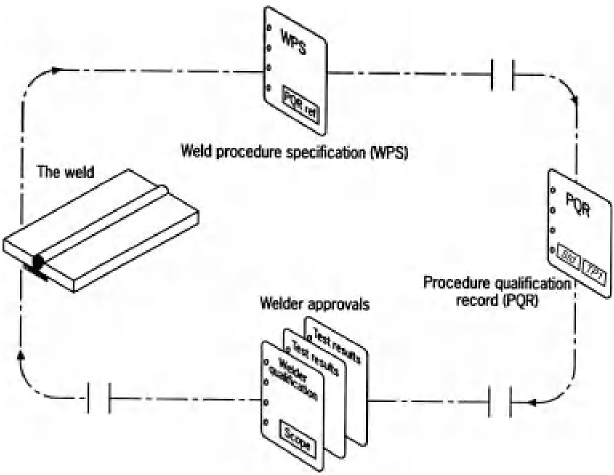


Figure 16.12

16.5.1 Weld procedure specification (WPS)

The WPS describes the weld technique and includes details of:

- parent material;
- filler material;
- weld preparation;
- welding variables; current, orientation, etc.;
- pre- and post-weld heat treatment; and
- the relevant procedure qualification record (PQR).

16.5.2 Procedure qualification record (PQR)

This is sometimes called a weld procedure qualification (WPQ) and is the 'type-test' record of a particular type of weld. The weld is subjected to non-destructive and destructive tests to test its quality.

16.5.3 Welder qualifications

'Coded' welders are tested to a range of specific WPSs to ensure their technique is good enough.

USEFUL STANDARDS

1. BS2633: 1987: Specification for Class I arc welding of ferritic steel pipework for carrying fluids.
2. BS 2971: 1991: Specification for Class II arc welding of carbon steel pipework for carrying fluids.
3. BS 4570: 1985: Specification for fusion welding of steel castings.
4. BS EN 288: Parts 1–8: 1995: Specification and approval of welding procedures for metallic materials.
5. BS EN 287-1: 2004: Approval testing of welders for fusion welding.
6. BS EN 26520: 1992: Classification of imperfections in metallic fusion welds, with explanations. This is an identical standard to ISO 6520.
7. BS EN 25817: 1992: Arc welded joints in steel – guidance on quality levels for imperfections.
8. BS EN 970: 1997: Non-destructive examination of fusion welds.
9. PD 6493: 1991: Guidance on methods for assessing the acceptability of flaws in fusion welded structures.
10. ISO 9692: 2003: Metal arc welding.
11. EN 1011: 2009: Recommendations for welding of metallic materials.
12. ISO EN 3834: 2005: Quality requirements for welding.

Section 17

Non-Destructive Testing (NDT)

NDT techniques are in common use to check the integrity of engineering materials and components. The main applications are plate, forgings, castings, and welds.

17.1 Non-destructive testing acronyms

Non-destructive testing procedures, reports, and general literature are full of acronyms. The most common ones are listed below.

AE	Acoustic emission
AFD	Automated flaw detection
A-scan	Amplitude scan
ASNT	American Society for Non-destructive Testing
ASTM	American Society for Testing and Materials
B-scan	Brightness scan
BVID	Barely visible impact damage
CDI	Crack detection index
CRT	Cathode ray tube
C-scan	Contrast scan
CSI	Compton scatter imaging
CTM	Coating thickness measurement
CW	Continuous wave/compression wave
DAC	Distance amplitude correction
dB	Decibel
DGS	Distance, gain, size (diagram)
DPEC	Deep penetration eddy currents
EC	Eddy current
ECII	Eddy current impedance imaging
EPS	Equivalent penetrameter sensitivity
ET (ECT)	Eddy current testing
FFD	Focus-to-film distance

FSH	Full scale height
HAZ	Heat affected zone
HDR	High-definition radiography
HVT	Half value thickness
IF	Industrial fiberscope
IQI	Image quality indicator
IV	Industrial video-imagescope
LD	Linear detectors
LFECA	Low-frequency eddy current array
LPI	Liquid penetrant inspection
LW	Longitudinal wave
MFL	Magnetic flux leakage
MPI	Magnetic particle inspection
MPT	Magnetic particle testing
MR	Microradiography
MRI	Magnetic resonance imaging
MT	Magnetic testing
NDA	Non-destructive assessment
NDE	Non-destructive examination
NDI	Non-destructive inspection
NDT	Non-destructive testing
NMR	Nuclear magnetic resonance
PA	Peak amplitude
PCN	Personal certificate in non-destructive testing
PDRAM	Pulsed digital reflection acoustic microscopy
POD	Probability of detection
P-scan	Projection scan
PT	Penetrant testing
PVT	Pulse video thermography
QNDE	Quantitative non-destructive evaluation
RFET	Remote field eddy current testing
ROI	Region of interest
ROV	Remotely operated vehicle
RT	Radiographic testing
RT	Real time
RTUIS	Real time ultrasonic imaging system
RVI	Remote visual inspection

RVT	Remote visual testing
SAM	Scanning acoustic microscopy
SDT	Static deflection techniques
SEM	Scanning electron microscopy
SFD	Source-to-film distance
SH	Horizontally polarized shear waves
SI	Sensitivity indicator
SIT	Simulated infrared thermography
SMNR	Signal-to-material noise ratio
SNR	Signal-to-noise ratio
SPATE	Stress pattern analysis by thermal emission
TDR	Time-domain reflectometry
TOFD	Time-of-flight diffraction
TSE	Total spectral energy
TW	Transverse wave
US	Ultrasonic
UT	Ultrasonic testing
VAP	Variable angle (ultrasonic) probe
VT	Visual testing
WFMPI	Wet fluorescent magnetic particle inspection
WIR	Work and inspection robot
WT	Wall thickness

17.1.1 References

A useful reference on the subject is *The NDT Yearbook* (ISSN 0952-2395), published annually by The British Institute of Non-destructive Testing (Tel: 01604 893811, Fax: 01604 893861).

17.2 Visual examination

Close visual examination can reveal surface cracks and defects of about 0.1 mm and above. This is larger than the 'critical crack size' for most ferrous materials.

17.3 Dye penetrant (DP) testing

This is an enhanced visual technique using three aerosols, a cleaner (clear), penetrant (red), and developer (white). Surface defects appear as a thin red line.

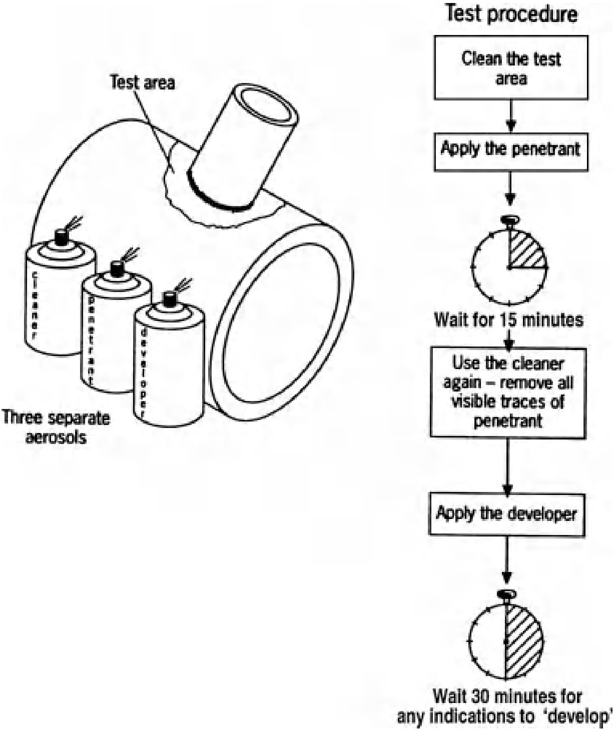


Figure 17.1

17.4 Magnetic particle (MP) testing

This works by passing a magnetic flux through the material while spraying the surface with magnetic ink. An air gap in a surface defect forms a discontinuity in the field which attracts the ink, making the crack visible. Defects are classified into:

- 'Crack-like' flaws
- Linear flaws ($1 > 3w$)
- Rounded flaws ($1 < 3w$)

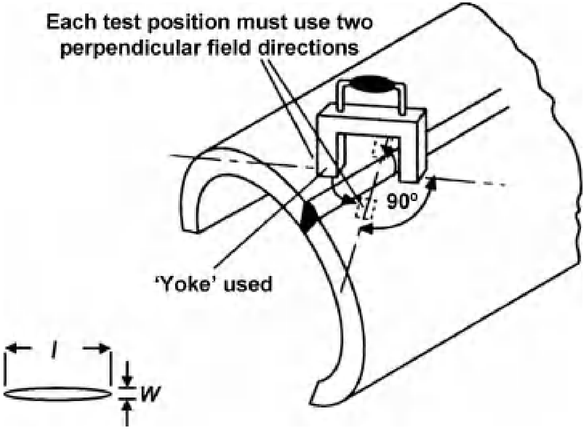


Figure 17.2

17.5 Ultrasonic testing (UT)

Different practices are used for plate, forgings, castings, and welds. The basic technique is the 'A-scope pulse-echo' method.

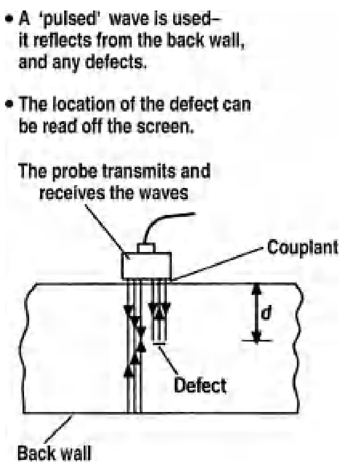


Figure 17.3

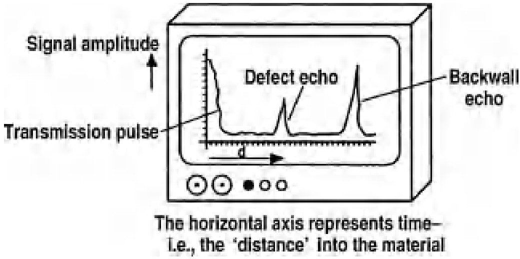


Figure 17.3 (Cont.)

17.5.1 UT of plate

Technical standards contain various 'grades' of acceptance criteria. Plate is tested to verify its compliance with a particular grade specified for the edges and body of the material. Typical criteria are given in Tables 17.1 and 17.2.

Table 17.1 Material 'edge-grades'

Acceptance 'grade'	*Single imperfection, max. length (area)*	*Multiple imperfections, max. no. per 1 m length*	*Above min. length*
E1	50 mm (1000 mm^2)	5	30 mm
E2	30 mm (500 mm^2)	4	20 mm
E3	20 mm (l00 mm^2)	3	10 mm

Table 17.2 Material 'body'-grades

Acceptance 'grade'	*Single imperfection max. area (approximate)*	*Multiple imperfections, max. no. per 1 m length*	*Above min. size (area)*
B1	10 000 mm^2	5	10 mm × 20 mm (2 500 mm^2)
B2	5 000 mm^2	5	75 mm × 15 mm (1 250 mm^2)
B3	2 500 mm^2	5	60 mm × 12 mm (750 mm^2)
B4	1 000 mm^2	10	35 mm × 8 mm (300 mm^2)

Useful Standard

BS 5996: 1993: Specification for acceptance levels for internal imperfections in steel plate, based on ultrasonic testing (equivalent to EN 160).

17.5.2 UT of castings

Casting discontinuities can be either planar or volumetric. Separate gradings are used for these when discovered by UT technique. The areas of a casting are divided into critical and non-critical areas, and by thickness 'zones', Figure 17.4. Typical grading criteria are as shown in Tables 17.3 and 17.4.

17.5.3 UT of welds

Weld UT has to be a well-controlled procedure because the defects are small and difficult to classify. Ultrasonic scans may be necessary from several different directions, depending on the weld type and orientation.

The general technique is:

- Surface scan using normal (0°) probe.
- Transverse scan (across the weld) to detect *longitudinal* defects.
- Longitudinal scan (along the weld direction) to detect *transverse* defects.

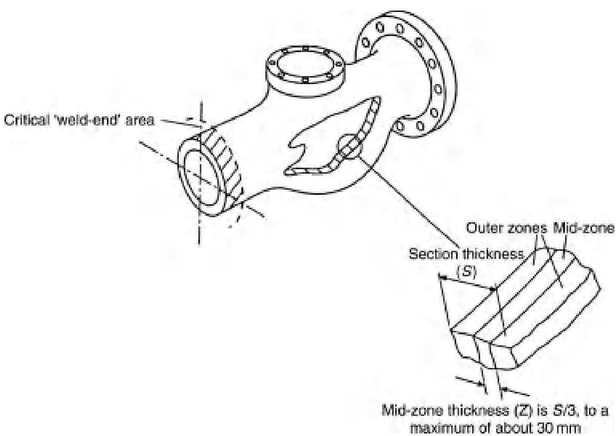


Figure 17.4

Table 17.3

Planar discontinuities	*Grade*			
	1	*2*	*3*	*4*
Max. 'through-wall' discontinuity size	0 mm	5 mm	8 mm	11 mm
Max. area of a discontinuity	0 mm	75 mm^2	200 mm^2	360 mm^2
Max. total area* of discontinuities	0 mm	150 mm^2	400 mm^2	700 mm^2

Table 17.4

Non-Planar discontinuities	*Grade*			
	1	*2*	*3*	*4*
Outer zone Max. size	0.2Z	0.2Z	0.2Z	0.2Z
Out zone Max. total area*	250 mm^2	1000 mm^2	2000 mm^2	4000 mm^2
Mid zone Max. size	0.1S	0.1S	0.15S	0.15S
Mid zone Max. total area*	12 500 mm^2	20 000 mm^2	31 000 mm^2	50 000 mm^2

*All discontinuity levels are per unit (10 000 mm^2) area

17.5.4 UT corrosion mapping

Corrosion mapping is an ultrasonic testing technique developed specifically for in-service inspection of engineering components. Its main use is in the petrochemical and offshore industries, where corrosion of pipework and vessels is a serious problem. Although the technique is straightforward in concept it requires a special equipment set-up, making it suitable for pre-planned rather than impromptu inspections.

How does it work?

Corrosion mapping uses a standard (normally 2 MHz) 0 degree ultrasonic probe, producing compression waves. This is the same type used for standard wall thickness measurement or lamination checks. The probe measures the thickness of the material being scanned using a simple back wall echo displayed on an A-scan screen. The main factors are listed below (see also Fig. 17.6):

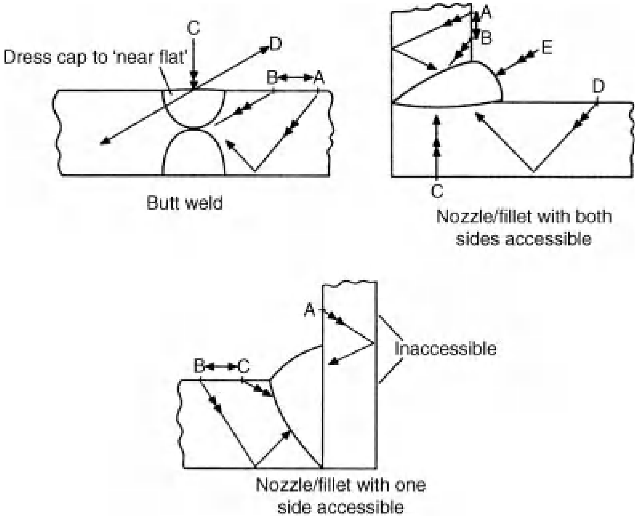


Figure 17.5

- *Scanning* The probe is scanned over 100 per cent of the surface, thereby building up a complete picture of the wall thickness.
- *Display* The display shows a colour representation of the wall thickness. The thickness readings that trigger each colour are pre-set to match the acceptance criteria for the specific job. For a 20 mm material wall thickness a typical display format would be:
  - <10 mm remaining wall thickness: Red
  - 10–15 mm remaining wall thickness: Yellow
  - 15–20 mm remaining wall thickness: Green
  - Reading not yet recorded: Black
- *Resolution* The resolution of the scan, in pixel size, can be chosen to suit the material, and the type of corrosion expected. A typical resolution set to detect pipe internal wall corrosion, including flow-accelerated corrosion and isolated oxygen pitting, would be 2 mm × 2 mm. Where corrosion is expected to be more widespread the pixels could be bigger, resulting in a quicker scan.

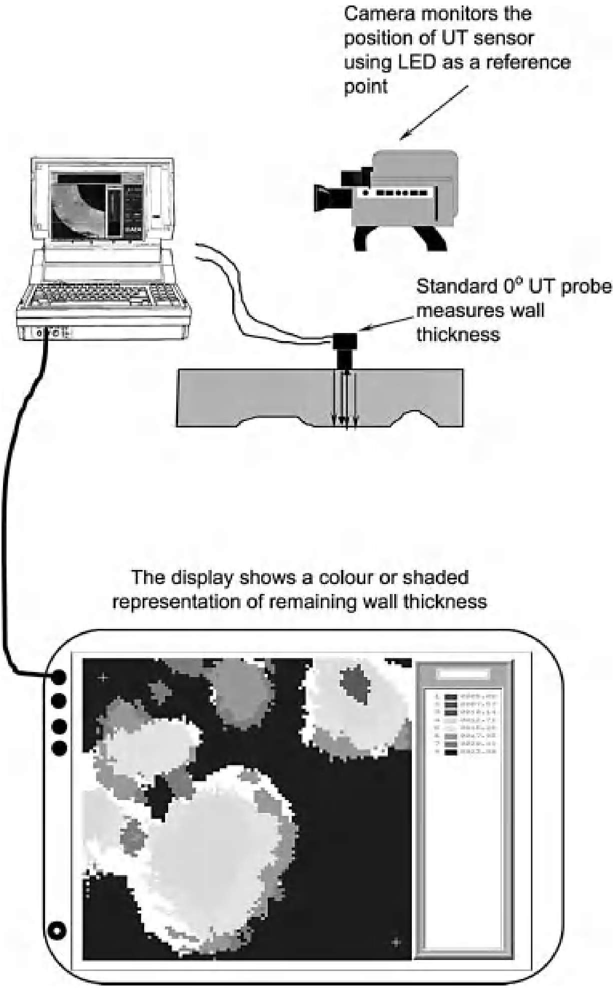

Camera monitors the position of UT sensor using LED as a reference point
Standard 0° UT probe measures wall thickness
The display shows a colour or shaded representation of remaining wall thickness

Figure 17.6

- *Location reference* The scanned area is mapped out using a set of *x:y* co-ordinates, referenced to a fixed origin point defined on the component – a light emitting diode (LED) is normally used for this. Scan location is then plotted via a fixture-mounted video camera respective to the LED 'origin'. To help with location, grid-lines or datum points may be marked on the surface of the component itself.

What are the advantages of corrosion mapping?
The main advantage of corrosion mapping is that it guarantees 100 per cent scan coverage of the area under examination. This gives a much-improved effectiveness over a standard 'random' UT wall thickness scan where it cannot be demonstrated whether a specific area has been fully examined or not. Tests with a corrosion mapping system will quickly show that, without the aid of a display confirming the unscanned areas (grey or black on the screen), even a competent technician doing a thorough technique will only cover about 60–70 per cent of the scan area. This percentage reduces when the scan is complicated by poor surface finish or irregular geometry. Another practical advantage is that corrosion mapping produces a permanent record of corrosion measurement. This allows comparisons to be made between subsequent in-service inspections to check the rate at which corrosion is progressing.

17.5.5 Remote UT thickness monitoring strips

This is a technique used for in-situ testing of buried pipelines. There are several similar methods marketed under proprietary tradenames. Figure 17.7 shows the principles. A number (10+) of simple 0 degree UT mini-probes (fixed frequency) are built into a flexible plastic strip, each one linked by a flat copper conductor strip to wire connectors at the end of the strip. The strip is wrapped around the pipeline, under any wrapping or lagging, and is connected by hard-wiring or radio link to a remote monitoring computer. The probes are triggered on a periodic basis, giving a crude measurement of the wall thickness at multiple radial points. The strips are fitted at

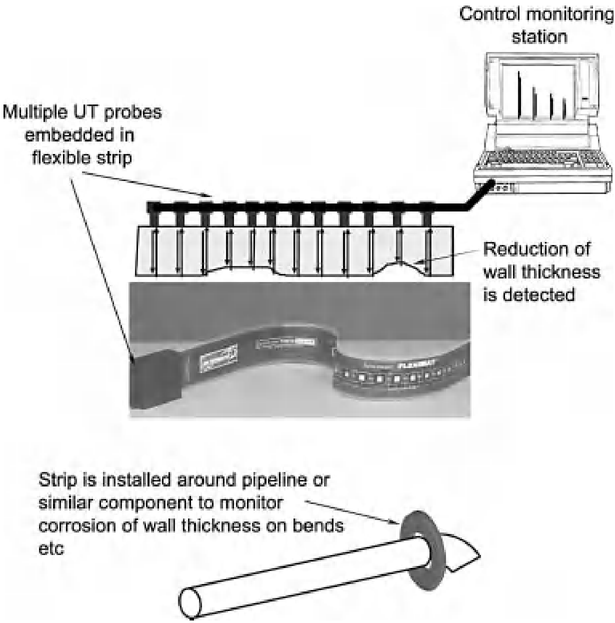


Figure 17.7

key wall thinning points such as changes of section, flow restrictions, and bends. This technique is particularly useful for buried or long-distance desert/mountain terrain pipelines where access is difficult. Two limitations of this method are given below.

- Only a 'first estimate' of wall thickness is given: the probes are not as sensitive as full-scale UT testing.
- Where low thicknesses are identified, the pipeline still has to be excavated for more detailed checks: spurious results are not unknown.

17.5.6 Time of flight diffraction (TOFD)

Time of flight diffraction (TOFD) is an advanced UT technique that has claimed advantages in the detection and sizing of defects. It has been in use for more than twenty years but has not yet achieved widespread recognition as a practical replacement for standard UT technique.

The TOFD principle

TOFD works on the principle of ultrasonic beam *diffraction* rather than *reflection*, as in standard UT techniques. Simplistically the amount of diffraction achieved is less dependent on ideal orientation of a defect than is reflection, with the result that TOFD is more sensitive than conventional UT techniques. Figures 17.8 to 17.10 show the principle: the ultrasonic wave

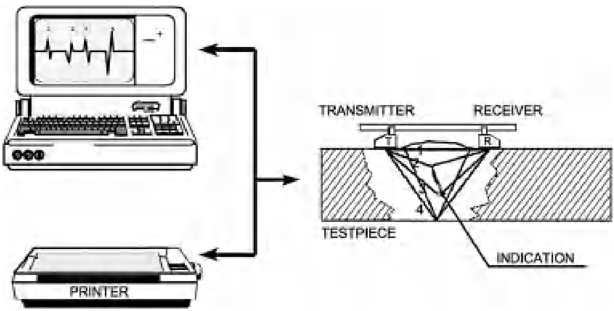


Figure 17.8

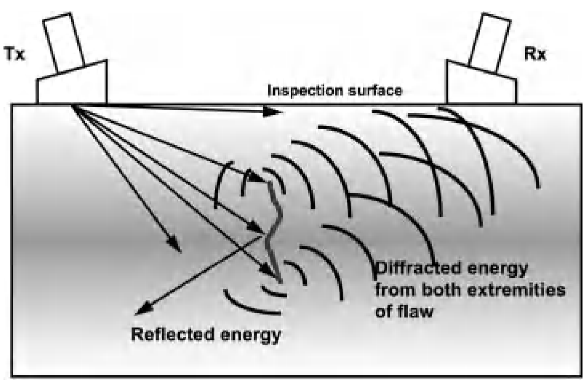


Figure 17.9

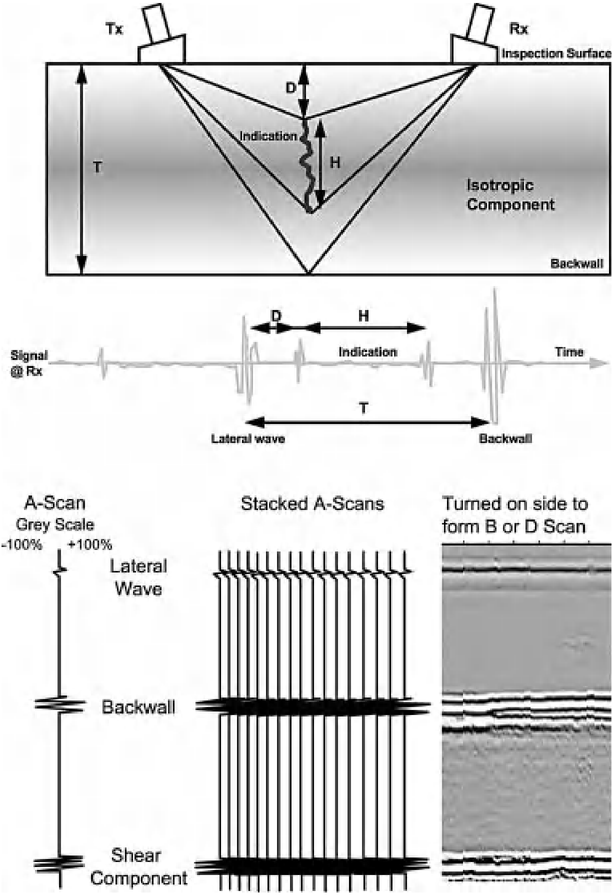


Figure 17.10

diffraction from the tip of a defect is almost independent of the orientation of the defect relative to the beam path. The intensity of the diffraction is increased if the defect is sharp edged. This is a useful characteristic as sharp-tipped defects pose a greater risk to integrity than blunt-tipped ones of the same length.

Unlike conventional UT compression and shear wave techniques, TOFD uses separate probes for emitting the ultrasonic beam input and receiving the diffracted 'output'. Beam angles are also restricted, which means that the two probes must be separated by a minimum spacing distance. This is achieved by mounting the probes on a custom-made frame – the whole assembly being pushed along the weld. This constitutes the full scan, replacing the traditional longitudinal and transverse shear-wave scans used in conventional UT. Maximum scanning speed is about 150 mm per second, so, once set up, the technique allows quick scanning of long, regular geometry weld joints. Figure 17.10 shows a typical arrangement, and the way that various common defects appear on the display.

17.6 Radiographic testing (RT)

Radiography is widely used for NDT of components and welds in many engineering applications.

- X-rays are effective on steel up to a thickness of approximately 150 mm.
- Gamma (γ) rays can also be used for thickness of 50–150 mm but definition is not as good as with X-rays.

17.6.1 Techniques

For tubular components a single- or double-wall technique may be used. Note the way the technique is specified.

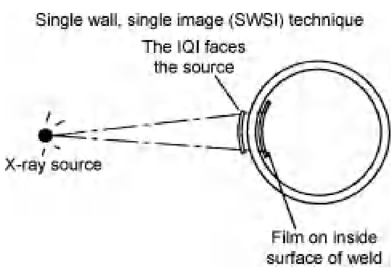
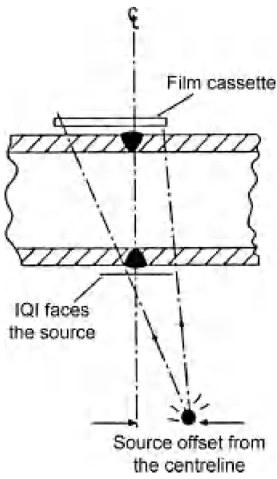


Figure 17.11

Specification	*Explanation*
Single wall	Only one weld 'thickness' shows on the film
Technique no. 1	A reference to BS 2910 which lists techniques nos 1–16
Class A	X-ray and single wall techniques give the best (class A) results
Fine film	BS 2910 mentions the use of fine or medium film grades
X-220kV	The X-ray voltage depends on the weld thickness



Specification	*Explanation*
Double-wall/image	Two weld 'thicknesses' show
Technique no. 13	A reference to BS 2910 which lists techniques nos 1–16
Class B	Double-wall techniques are inferior to single-wall methods
Fine film	BS 2910 mentions the use of fine or medium grades
Density 3.5–4.5	The 'degree of blackness' of the image

17.6.2 Penetrameters

Penetrameters, or image quality indicators (IQIs) check the sensitivity of a radiographic technique – to ensure that any defects present will be visible. The two main types are the 'wire' type and 'hole' type.

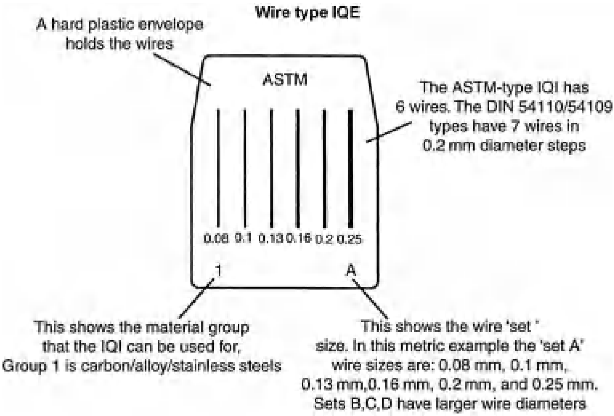
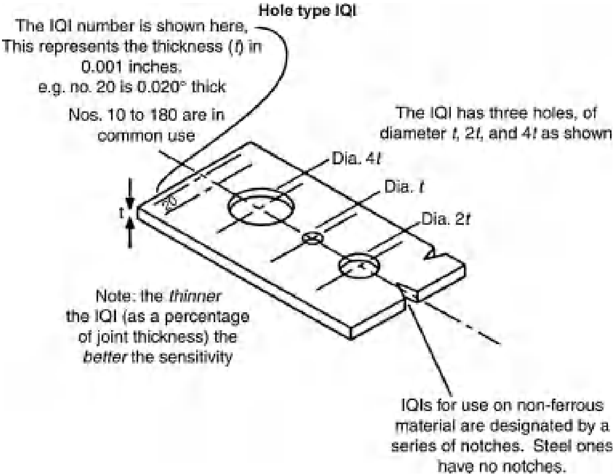


Figure 17.12

- The objective is to look for the smallest wire visible
- Sensitivity = diameter of smallest wire visible/maximum penetrated thickness of weld
- If the above IQI is used on 10 mm material and the 0.16 mm wire is visible, then sensitivity = 0.16/10 = 1.6%
- Check the standard for the maximum allowable sensitivity for the technique/application being used



IQI designation	*Sensitivity*	*Visible hole**
1–2t	1	2t
2–1t	1.4	1t
2–2t	2.0	2t
2–4t	2.8	4t
4–2t	4.0	2t

*The hole that must be visible in order to ensure the sensitivity level shown

Useful NDT Standards

1. EN 287-1: 1992: Approval testing of welders – fusion welding – Part 1: Steels.
2. EN 473: 2000: Non-destructive testing – Qualification and certification of NDT personnel – General principles.
3. EN 571-1: 1997: Non-destructive testing – Penetrant testing – Part 1: General principles.
4. prEN 764-6: 2002: Pressure equipment – Part 6: Operating instructions.

5. EN 583-4: 1999: Non-destructive testing – Ultrasonic examination – Part 4: Examination for discontinuities perpendicular to the surface.
6. EN 970: 1997: Non-destructive examination of fusion welds – Visual examination.
7. EN 1289: 1998: Non-destructive examination of welds – Penetrant testing of welds – Acceptance levels.
8. EN 1290: 1998: Non-destructive examination of welds – Magnetic particle examination of welds.
9. EN 1291: 1998: Non-destructive examination of welds – Magnetic particle testing of welds – Acceptance levels.
10. EN 1418: 1997: Welding personnel – Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials.
11. EN 1435: 1997: Non-destructive examination of welds – Radiographic examination of welded joints.
12. EN 1712: 1997: Non-destructive examination of welds – Ultrasonic examination of welded joints – Acceptance levels.
13. EN 1713: 1998: Non-destructive examination of welds – Ultrasonic examination – Characterization of indications in welds.
14. EN 1714: 1997: Non-destructive examination of welds – Ultrasonic examination of welded joints.
15. EN 1779: 1999: Non-destructive testing – Leak testing – Criteria for method and technique selection.
16. EN 12062: 1997: Non-destructive examination of welds – General rules for metallic materials.
17. EN 12517: 1998: Non-destructive examination of welds – Radiographic examination of welded joints – Acceptance levels.
18. EN 13445-2: 2002: Unfired pressure vessels – Part 2: Materials.
19. EN 13445-3: 2002: Unfired pressure vessels – Part 3: Design.
20. EN 13445-4: 2002: Unfired pressure vessels – Part 4: Fabrication.

Section 18

Surface Protection

18.1 Painting

There are numerous types of paint and application techniques. Correct preparation, choice of paint system, and application are necessary if the coating is to have the necessary protective effect.

18.1.1 Preparation

Commonly used surface preparation grades are taken from Swedish standard SIS O5 5900.

Table 18.1

Designation	*Preparation grade*
Sa 3	Blast cleaning to pure metal. No surface staining remaining
Sa $2^1/_2$	Thorough blast cleaning but some surface staining may remain
Sa 2	Blast cleaning to remove most of the millscale and rust
Sa 1	Light blast cleaning to remove the worst millscale and rust

18.1.2 Paint types

These are divided broadly into air-drying, two-pack, and primers.

- Air-drying types: alkyd resins, esters, and chlorinated rubbers.
- Two pack types: epoxy, polyurethanes.
- Primers: zinc phosphate or zinc chromate.

18.1.3 Typical paint system

Most paint systems for outdoor use have a minimum of three coats with a final dry film thickness (dft) of 150–200 μm.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

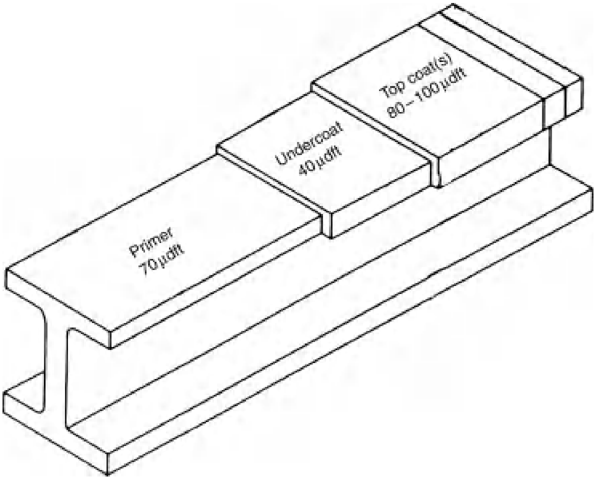


Figure 18.1

USEFUL STANDARDS

1. BS 7079: Preparation of steel substrates before application of paints and related products. This document is in 16 separate parts.
2. SIS 05 5900: Pictorial standards for blast-cleaned steel (and for other methods of cleaning). (Standardiseringskommissionen, I Sverige, Stockholm).
3. BS 5493: 1977: Code of practice for protective coating of iron and steel structures against corrosion.
4. BS 381: 1988: Specification for colours for identification, coding and special purposes.
5. BS 3900: Methods for tests for paints. There are more than 100 parts to this standard.
6. ASTM D1186: 1993: Test methods for non-destructive measurement of dry film thickness of non-magnetic coatings applied to a ferrous base.

18.2 Galvanizing

Galvanizing is the generic term for the coating of iron and steel components with zinc. It can be used instead of painting to protect the base material from corrosion. The coating is usually applied by weight, in accordance with a standard such as BS 729. Guidelines are shown in Table 18.2.

Table 18.2

Parent material	*Min. galvanized coating weight (g/m^2)*
Steel 1–2 mm thick	335
Steel 2–5 mm thick	460
Steel >5 mm thick	610
Castings	610

An approximate conversion from coating weight to coating thickness is:

$$1\ \text{g/m}^2 \cong 0.14\ \mu\text{m}$$

Coating uniformity is tested by a 'Preece test' which involves exposing a coated specimen to a salt solution.

18.3 Chrome plating

Chrome plating provides a fine finish for hydraulic components and provides protection against some environmental conditions. The process is well covered by technical standards such as BS 1224. A typical specification for a plated component is:

Fe/Cu 20 Ni (p) Cr (mc)

- Fe denotes iron or steel parent material.
- Cu 20 denotes a minimum 20 µm of copper plated on to the steel.
- Ni 25 (p) denotes a minimum of 25 µm nickel plated on to the copper:
  (p) means 'semi-bright';
  (b) means 'fully bright'.
- Cr (mc) denotes the condition of the top chromium layer.

The classes are:
Cr (r): a ‘regular finish’ – minimum thickness 0.3 μm;
Cr (f): ‘free’ from cracks – minimum thickness 0.8 μm;
Cr (mc): ‘micro-cracked’ – minimum thickness 0.8 μm;
Cr (mp): ‘microporous’ – minimum thickness 0.3 μm.

Useful Standards

1. BS 729: 1994: Specification for hot dip galvanized coatings on iron and steel articles. Similar to ISO 1459/ISO 1460/ISO 1461.
2. BS 1224: 1970: Specification for electroplated coatings of nickel and chromium. Similar to ISO 1456/ISO 1458.

18.4 Rubber linings

Rubber lining is commonly used to protect materials in seawater and chemical process systems against corrosive and erosive attack. It is applied in sheets up to about 6 mm thick. There are two main types:

- *Natural rubbers* for low temperatures in oil-free water or slurry applications.
- *Synthetic rubbers* (nitryl, butyl, neoprene) - for temperatures up to 120 °C or when oil is present.

18.4.1 Properties

Both natural and synthetic rubbers can be divided into hard and soft types. Two hardness scales are in use; IRHD (international rubber hardness degrees) and the ‘Shore’ scale.

- *Hard* rubber (sometimes called ebonite) is 80–100 degrees IRHD or 60–80 ‘Shore D’ scale (see BS 903: Part A57).
- *Soft* rubber is 40–80 degrees IRHD or 40–80 ‘Shore A’.

18.4.2 Design features

Rubber-lined components need to have specific design features to help the lining adhere properly (see Fig. 18.2 and BS 6374: Part 5).

18.4.3 Application

The basic application procedure is:

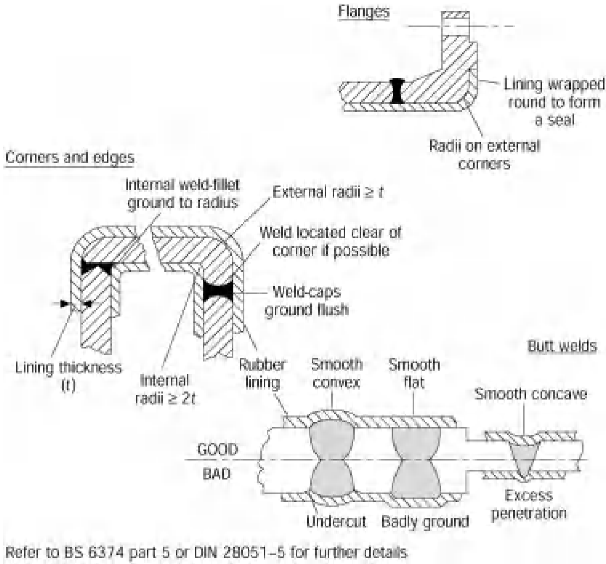


Figure 18.2 Rubber lined components – design features

1. Shotblast the metal surface to SIS 05 5900 grade Sa $2^1/_2$;
2. Apply adhesive to the surface;
3. Lay the sheets of rubber manually in scarf-jointed overlapping courses;
4. Vulcanize the rubber by heating to approximately 120 °C using steam or hot water.

18.4.4 Testing

Common tests on the applied rubber lining are:

- *Spark testing* (≅ 20 kV) to check the continuity of the lining.
- *Rapping test* using a special hammer to test the adhesion of the lining to the metal.
- *Hardness test* using a hand-held gauge to measure the Shore or IRHD hardness. This shows whether vulcanization is complete.

USEFUL STANDARDS

1. BS 6374: Parts 1–5: Lining of equipment with polymeric materials for the process industries.
2. DIN 28 051: 1990: Chemical apparatus – designs of metal components to be protected by organic coatings or linings.
3. BS 903 (various parts): *Physical testing of rubber*.
4. DIN 53 505: Rubber hardness testing.

Section 19

Metallurgical Terms

Terminology used in metallurgy is complex. Some of the more common (and sometimes misunderstood) terms are given below:

age hardening Hardening by aging, usually after rapid cooling or cold working.

ageing A change of properties that occurs at ambient or moderately elevated temperatures after hot working, heat treating, quenching, or cold working.

alloy A substance having metallic properties and composed of two or more chemical elements of which at least one is a metal.

alloy steel Steel containing significant quantities of alloying elements (other than carbon and small amounts of manganese, silicon, sulfur, and phosphorus) added to produce changes in mechanical or physical properties. Those containing less than about 5 percent total metallic alloying elements are termed low-alloy steels.

annealing Heating metal to a suitable temperature followed by cooling to produce discrete changes in microstructure and properties.

austenite A solid solution of one or more alloying elements in the fcc structure of iron.

bainite A eutectoid transformation product of ferrite and dispersed carbide.

beach marks Crack arrest 'lines' seen on fatigue fracture surfaces.

billet A solid piece of steel that has been hot worked by forging, rolling, or extrusion.

brittle fracture Fracture preceded by little or no plastic deformation.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

brittleness The tendency of a material to fracture without first undergoing significant plastic deformation.

barbide A compound of carbon with metallic elements (e.g. tungschromium).

carbon equivalent (CE) A 'weldability' value that takes into account the effects of carbon and other alloying elements on a particular characteristic of steel. A formula commonly used is:

$$CE = C + (Mn/6) + [(Cr + Mo + V)/5] + [(Ni + Cu)/15]$$

carbon steel A steel containing only small quantities of elements other than carbon.

cast iron Iron containing more than about 2 percent carbon.

cast steel Steel castings, containing less than 2 percent carbon.

cementite A carbide, with composition Fe_3C.

cleavage Fracture of a crystal by crack propagation.

constitutional diagram A graph showing the temperature and composition limits of various phases in a metallic alloy.

crack initiator Physical feature which encourages a crack to start.

creep Time-dependent strain occurring under stress.

critical cooling rate The maximum rate at which austenite needs to be cooled to ensure that a particular type of structure is formed.

crystalline The general structure of many metals.

crystalline fracture A fracture of a metal showing a grainy appearance.

decarburization Loss of carbon from the surface of a ferrous alloy caused by heating.

deformation General term for strain or elongation of a metal's lattice structure.

duplex Containing two phases (e.g. ferrite and pearlite).

deoxidation Removal of oxygen from molten metals by use of chemical additives.

diffusion Movement of molecules through a solid solution.

dislocation A linear defect in the structure of a crystal.

ductility The capacity of a material to deform plastically without fracturing.

elastic limit The maximum stress to which a material may be subjected without any permanent strain occurring.

equilibrium diagram A graph of the temperature, pressure, and composition limits of the various phases in an alloy 'system'.

etching Subjecting the surface of a metal to an acid to reveal the microstructure.

fatigue A cycle or fluctuating stress conditions leading to fracture.

ferrite A solid solution of alloying elements in bcc iron.

fibrous fracture. A fracture whose surface is characterized by a dull or silky appearance.

grain An individual crystal in a metal or alloy.

grain growth Increase in the size of the grains in metal caused by heating at high temperature.

graphitization Formation of graphite in iron or steel.

hardenability The property that determines the depth and distribution of hardness induced by quenching.

hardness (indentation) Resistance of a metal to plastic deformation by indentation (measured by Brinel, Vickers, or Rockwell test).

inclusion A metallic or non-metallic material in the matrix structure of a metal.

initiation point The point at which a crack starts.

killed steel Steel deoxidized with silicon or aluminium, to reduce the oxygen content.

K_{1C} A fracture toughness parameter.

lamellar tear A system of cracks or discontinuities, normally in a weld.

lattice A pattern (physical arrangement) of a metal's molecular structure.

macrograph A low-magnification picture of the prepared surface of a specimen.

macrostructure The structure of a metal as revealed by examination of the etched surface at a magnification of about $\times$ 15.

martensite A supersaturated solution of carbon in ferrite.

microstructure The structure of a prepared surface of a metal as revealed by a microscope at a magnification of about × 15.

micro-cracks Small ‘brittle’ cracks, normally perpendicular to the main tensile axis.

necking Local reduction of the cross-sectional area of metal by stretching.

normalizing Heating a ferrous alloy and then cooling in still air.

notch brittleness A measure of the susceptibility of a material to brittle fracture at locations of stress concentration (notches, grooves, etc.).

notch sensitivity A measure of the reduction in strength of a metal caused by the presence of stress concentrations.

nitriding Surface hardening process using nitrogenous material.

pearlite A product of ferrite and cementite with a lamellar structure.

phase A portion of a material ‘system’ that is homogenous.

plastic deformation Deformation that remains after release of the stress that caused it

polymorphism The property whereby certain substances may exist in more than one crystalline form.

precipitation hardening Hardening by managing the structure of a material, to prevent the movement of dislocations.

quench hardening Hardening by heating and then quenching quickly, causing austenite to be transformed into martensite.

recovery Softening of cold-worked metals when heated.

segregation Non-uniform distribution of alloying elements, impurities, or phases in a material.

slip Plastic deformation by shear of one part of a crystal relative to another.

slip plane Plane of dislocation movement.

soaking Keeping metal at a predetermined temperature during heat treatment.

solid solution A solid crystalline phase containing two or more chemical species.

solution heat treatment Heat treatment in which an alloy is heated so that its constituents enter into solid solution and then cooled rapidly enough to 'freeze' the constituents in solution.

spheroidizing Heating and cooling to produce a spheroid or globular form of carbide in steel.

strain ageing Ageing induced by cold working.

strain hardening An increase in hardness and strength caused by plastic deformation at temperatures below the recrystallization range.

stress-corrosion cracking Failure by cracking under the combined action of corrosion and stress.

sulfur print A macrographic method of examining the distribution of sulfur compounds in a material (normally forgings).

tempering Supplementary heat treatment to reduce excessive hardness.

temper brittleness An increase in the ductile–brittle transition temperature in steels.

toughness Capacity of a metal to absorb energy and deform plastically before fracturing.

transformation temperature The temperature at which a change in phase occurs.

transition temperature The temperature at which a metal starts to exhibit brittle behaviour.

weldability Suitability of a metal for welding.

work hardening Hardening of a material due to straining or 'cold working'.