5TH edition

an elementary guide to Reliability

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Contents

Introduction

An Elementary Guide to Reliability explains in simple, largely non-technical language what is meant by reliability and the various factors that make an equipment or machine reliable. It deals with basic considerations which apply equally to electrical, electronic or mechanical designs.

The Guide has been written to provide an introduction to reliability for those without any previous knowledge of it. However, even those who are already familiar with some aspects of reliability should find the book of interest, since it covers all basic facets of reliability.

Those who need to obtain some knowledge of reliability in the course of their studies, of their training or of their work, can use this Guide to acquire the basic concepts, on which more detailed and more technical knowledge can subsequently be based. In particular the Guide will serve as a textbook for teachers and students concerned with the following courses:

- *City and Guilds of London Institute*
  Course 2750 Industrial Measurement and Control Technicians Certificate, Part III Section 07 – Maintenance and fault diagnostics of a complete control system.
  Course 7430 Certificate in Quality Assurance, Part II Section 07 – Evaluating and predicting reliability.
  Course 8030 (This course is primarily designed for overseas students) Electrical Engineering Technicians Certificate, Part II Section 7 – Reliability.
- *Business and Technology Education Council*
  College devised course units at BTEC National and Higher National levels that include the basic concepts of reliability or of quality assurance in the syllabus.
- *Institute of Quality Assurance (UK)*
  Reliability syllabus in the C subject of the qualifying examination.

Those, whether technical or not, who are interested in learning something about reliability in an age when it is assuming more and more importance, will find the background they need in these pages. In order to give readers an opportunity to put their newly acquired knowledge into practice, we have included a number of 'self-assessment' questions at various points within the text. The answers to these questions appear at the end of the book.

Many books on reliability deal mainly with particular aspects in specialized language, which is usually beyond the grasp even of the technical person without previous knowledge of the subject. *An Elementary Guide to Reliability* is intended to fill this gap.

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1 The importance of reliability

Electrical, electronic and mechanical equipment is used in a number of fields – in industry for the control of processes, in computers, in medical electronics, atomic energy, communications, navigation at sea and in the air, and in many other fields. It is essential that this equipment should operate reliably under all the conditions in which it is used. In the air navigation, military and atomic energy fields, for instance, failure could result in a dangerous situation. Very complicated systems, involving large numbers of separate units, such as avionic and aerospace electronic systems, are coming into use more and more. These systems are extremely complex and use a large number of component parts. As each individual part is liable to failure, the overall reliability will decrease unless the reliability of each component part can be improved.

Suppose, for example, it is known that one component out of half a million would break down every hour. Then an item of equipment using 100 000 of these components would break down at an average interval of 5 hours.

Self-assessment Question 1.1

Tests reveal that, on average, an item of equipment using 1000 similar components fails after a period of 100 hours. If the number of components were to be reduced by half, what would be the new average time before a failure occurs?

The requirement for reliability is different for each application. In the transatlantic cable service, for instance, the underwater amplifiers must operate for 20 years or so without failure, because the cost of raising the cable to repair a failure would be about £500 000 (since it would be necessary to send a cable ship to the location, find the failure under several miles of ocean, supply and install a new amplifier, lower the cable to the bottom again and return to port). Added to this is the loss of revenue while the cable is out of action, which might bring the total to £1 000 000, or more.

In Britain the Air Registration Board will only license aircraft to use a blind landing system if the fault rate for the total system is less than one in ten million.

In the case of military aircraft on a combat mission, or a missile flight, it is vital for the equipment to operate for the period of flight, or the mission and perhaps a battle might be lost. It has been estimated that unreliability costs the RAF alone up to £100 million each year in spares and servicing costs. In the case of an equipment controlling a chemical plant or some complex industrial process, the cost of 'shutdown' may be considerable in spoiled production and loss of output.

It is essential to 'build-in' reliability by sound design and construction and to carry out enough tests to make sure that this has been done.

The 'availability' or time an equipment is functioning correctly while in use depends both on reliability and on maintainability. Reliability is defined in detail in the next chapter, but may be said to be a measure of an equipment's ability to perform its functions consistently under given conditions. Maintainability is a measure of the speed with which loss of performance is detected, diagnosed and made good, and this is discussed in Chapter 8.

Reliability is of course a most important factor in the safety of an equipment, but it is by no means the only factor. A system or equipment can 'perform its required function' (see definition on page 5) and yet be unsafe. There are well-documented major disasters caused not by mechanical or electronic breakdown but by human failure. Such human failures can be due to failures of operators, of maintenance staff, or of management.

Breakdowns and disasters can arise from failure of management to establish proper operating procedures and regulations. Management's share of the responsibility for 'failure' has been estimated to be above 50%. They can also arise from operators' failure, accidental or deliberate, to observe laid-down operating procedures and regulations. The results of accidental failure can be allowed for to some extent by anticipating, during the equipment design stage, what accidental operating mistakes might be made and introducing safeguards. However, it is impossible to anticipate deliberate failure to follow operating procedures, and it is essential to impress on operators and on maintenance staff, during their training, how vital it is that they never depart from laid-down procedures and regulations however safe it may appear to do so.

Self-assessment Question 1.2

A small manufacturing company produces a range of switches for use in mains operated domestic appliances. The Production Manager has asked you to give a brief presentation to new employees on the 'Importance of Reliability'. Identify THREE key factors that should form part of your presentation and write brief notes (using not more than a single A4 page) that will help you when you deliver your talk.

Figures 1.1, 1.2 and 1.3 illustrate in a lighthearted way the importance of reliability and some of its aspects.

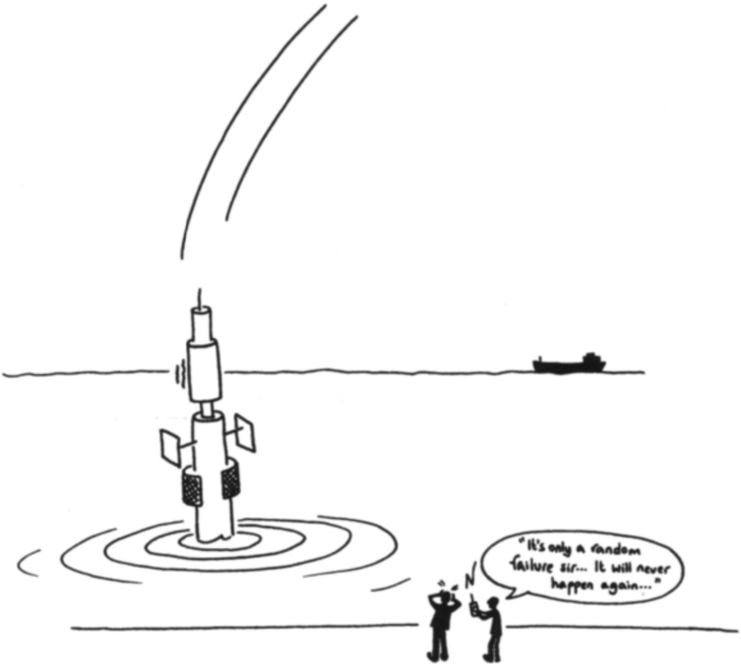

"It's only a random failure sir... It will never happen again...."

Figure 1.1 'It's only a random failure, Sir.'

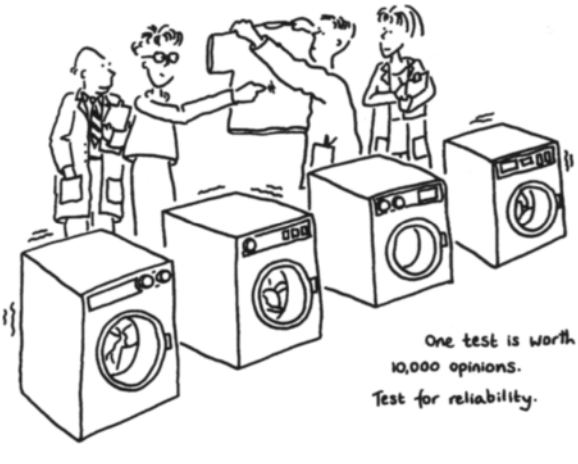


Figure 1.2 One test is worth 10 000 opinions.

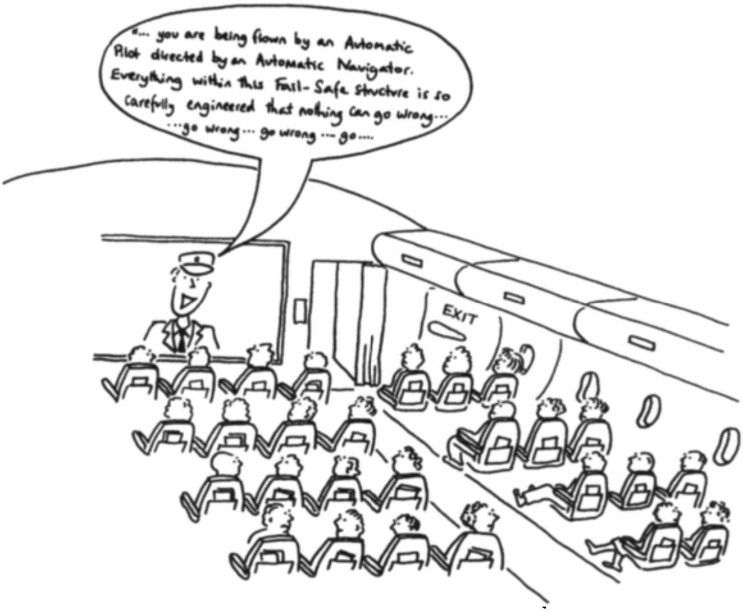

"... you are being flown by an Automatic Pilot directed by an Automatic Navigator. Everything within this Fail-Safe Structure is so carefully engineered that nothing can go wrong... ...go wrong... go wrong ... go....
EXIT

Figure 1.3 You are being flown by an automatic pilot.

2 Definitions of reliability

Because of the many differing operational requirements and varying environments, 'reliability' means different things to different people. The generally accepted definition of reliability[1] is

> Reliability – the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time.

It will be noted that by definition reliability is a probability of success and this aspect is dealt with in more detail in Chapter 4.

General definitions are given below while fuller definitions are given in Chapter 12.

A 'failure' is any inability of a part or equipment to carry out its specified function.

An 'item' may be any part, subsystem, system or equipment which can be individually considered and separately tested.

An item can fail in many ways and these failures are classified as follows:

(a) Causes of failure:
   (i) *Misuse failure* Failures attributable to the application of stresses beyond the stated capabilities of the item.
   (ii) *Inherent weakness failure* or *latent defect* Failures attributable to weakness inherent in the item itself when subjected to stresses within the stated capabilities of that item.

(b) Times of failure:
   (i) *Sudden failure* Failures that could not be anticipated by prior examination.
   (ii) *Gradual failure* Failures that could be anticipated by prior examination.

(c) Degrees of failure:
   (i) *Partial failure* Failures resulting from deviations in characteristic(s)

[1] BSI (British Standards Institution) and IEC (International) definitions.

beyond specified limits not such as to cause complete lack of the required function.

(ii) *Complete failure* Failures resulting from deviations in characteristic(s) beyond specified limits such as to cause complete lack of the required function. The limits referred to in this category are special limits for this purpose.

(d) Combinations of failures:

(i) *Catastrophic* Failures which are both sudden and complete.

(ii) *Degradation* Failures which are both gradual and partial.

Self-assessment Question 2.1

Consider each of the following scenarios and classify the failure using the table shown below:

(a) A set of motor car brake pads wear out and need replacement at a 9000 mile service.

(b) A light bulb fitted in a domestic table lamp fails when switched 'on' after 18 months of intermittent use.

(c) A 3 A supply fuse fitted to a dual-heat 0.5/1 kW 220 V electric fan heater blows when the heater is set to its 'max heat' setting.

(d) The amber lamp fails in one of four cross-roads traffic lights.

	Cause		*Time*		*Degree*		*Combination*	
	Misuse	*Inherent weakness*	*Sudden*	*Gradual*	*Partial*	*Complete*	*Catastrophic*	*Degradation*
(a)								
(b)								
(c)								
(d)								

An important criterion that the user or the maintenance engineer must know is how often the item breaks down and this is defined in two ways.

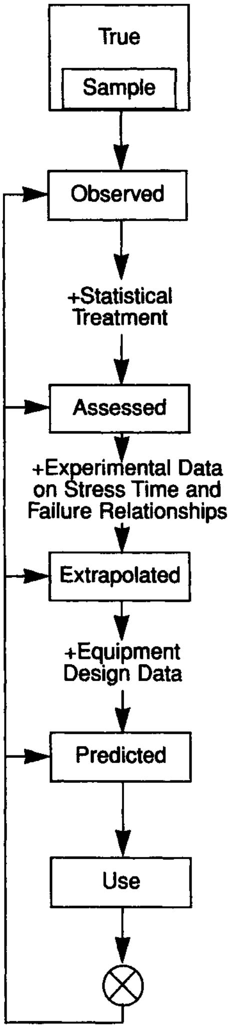
1 Mean time between failures – MTBF
This applies to repairable items, and means that if an item fails, say, five times over a period of use totalling 1000 hours, the mean (or average) time between failures would be 1000 divided by 5 or 200 hours.

2 Mean time to failure – MTTF
This applies to non-repairable items, and means the average time an item may be expected to function before failure. It is found by stressing a large number

of the items in a specified way (e.g. by applying certain electrical, mechanical, heat or humidity conditions), and after a certain period dividing the length of the period by the number of failures during the period.

General relationship between terms

The diagram below gives the general relationship between variants of reliability characteristics – for example, the possible variants of failure rate, mean time between failures, mean time to failure and mean life.



The value determinable only when the whole population has failed or has been subjected to stated stress conditions for a stated time.

The value relating to a sample subjected to stated stress conditions for a stated time.

Note. The sample may be equal to the whole population; in this case the observed value is equal to the true value.

A limiting value relating to a population of the confidence interval with a stated probability level based on observed data. This value may be the upper or lower limit of the confidence interval, as the case may be.

The value relating to different time and/or stress conditions.

The value relating to an item based for example on the failure rates of its parts.

The item may now be used or tested and its reliability characteristic values, subject to suitable variations for conditions applying to the use or tests, compared with those variants referred to above.

Equipment failure pattern during life

When a new purchase is made, whether it is a motor car, radio set, washing machine or an aeroplane or tank, early failures may occur. These may be caused by manufacturing faults, design faults or misuse. The early failure rate may, therefore, be relatively high, but falls as the weak parts are replaced. There is then a period during which the failure rate is lower and fairly constant, and finally the failure rate rises again as parts start to wear out. This is illustrated in Figure 2.1, where the high rate of initial failures can be seen. Although the steady rate is often shown as a straight line, in practice it will be wavy and in good (reliable) equipments it may be a long time before the wear-out period is reached. The part of main interest is the constant failure rate period. The three parts are defined by the BSI as follows:

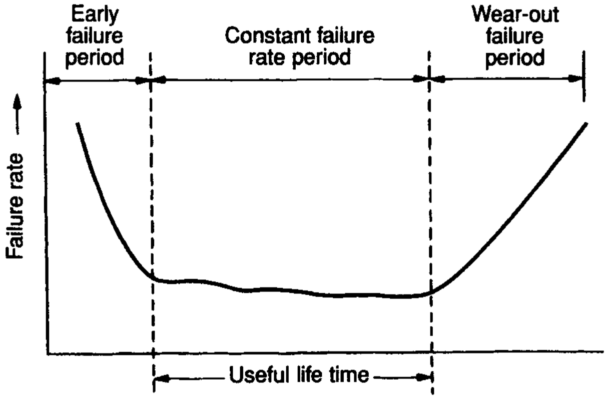


Figure 2.1 Bath tub curve.

Early failure period That early period, beginning at some stated time and during which the failure rate of some items is decreasing rapidly.

Constant failure rate period That period during which failure occurs in some items at an approximately uniform rate.

Wear-out failure period That period during which the failure rate of some items is rapidly increasing due to deterioration processes. In practice there is more interest concerning reliability during the 'early life' and 'wear out' periods than during the 'constant' failure period. There are several reasons for this:

(a) For most integrated circuits the failure rate during the 'constant' failure period is so low as to be almost trivial compared with other problems or concerns.

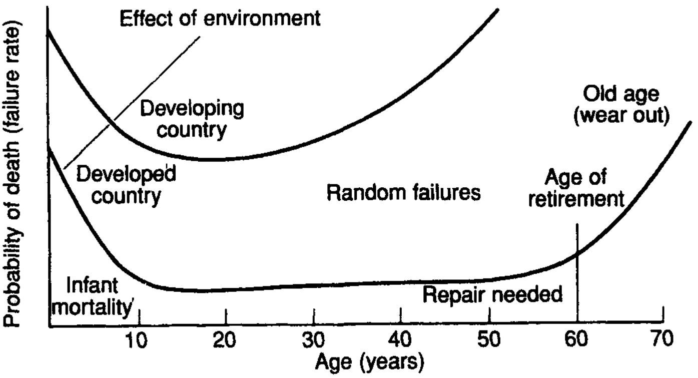


Figure 2.2 Human life characteristics.

(b) Customers who have a large installed base of equipment (e.g. telephone exchanges) need to be confident that there is not going to be a catastrophic failure rate due to 'wear-out' in a period significantly less than their planned period of equipment obsolescence. While their equipment designs and operating procedures can accommodate the comparatively low failure rates normally experienced during 'early life' and the even lower failure rates associated with the 'constant' failure period, they may not be able to handle the flood of failures that could possibly arise in the case of a serious 'wear-out'.

(c) 'Early life' period for many electronic components extends well beyond any factory 'burn-in' and therefore failures in this period will include failure while in the hands of the end customer. Since such failures will occur during the early stages of end customer ownership they will often be viewed far more negatively than equivalent failures in later life. (We might tolerate the windscreen wiper failure on our car after a period of a year but most of us would be far less tolerant if the failure occurred while we were demonstrating the new car to our friends during the first week of our ownership of it.) For many electronic equipments the usage can be so low that 'early life' period could be well in excess of a year and in some situations could extend beyond the full working life of the equipment. (The windscreen wiper of a car may operate for typically no more than 1000 hours during the full life of the car.)

Figure 2.2 compares the practical aspects of human life with the kind of curve illustrated in Figure 2.1. It also illustrates the effect of environment on reliability (or life) which is discussed in Chapter 5.

Self-assessment Question 2.2

A batch of 100 'long-life' projector lamps are tested over a period of 11 000 hours. The results are shown in the table below:

Time (hours)	*Number of operational lamps*
0	100
1 000	85
2 000	77
3 000	71
4 000	65
5 000	60
6 000	55
7 000	51
8 000	47
9 000	43
10 000	38
11 000	32

(a) Calculate the failure rate in each 1000 period (using the relationship: failure rate =

$$\frac{\text{number of failures during the 1000 hour period}}{\text{number of operational components at the start of the period}} \times 100\%$$

(b) Plot the 'bath tub' diagram (failure rate plotted against time).
(c) Estimate the duration of the early-failure (burn-in) period.
(d) Estimate the failure-rate at mid-term (i.e. during the constant failure rate period).
(e) Estimate the time at which the wear-out (burn-out) period starts.

3 Some simple statistics

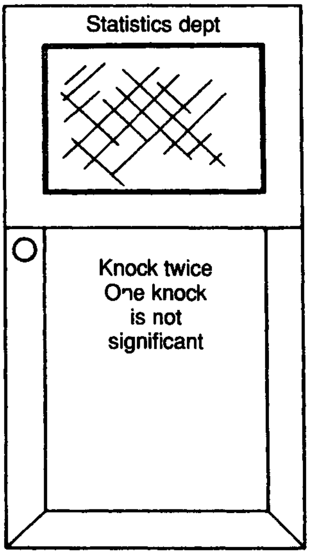


Figure 3.1 Statistics department.

Reliability is concerned with quantities, e.g. How many units are in use? How many parts? How many fail? What proportion is this to the total? Statistics are used in analysing these quantities. Statistics are also an essential tool in calculating probabilities of failures. Mathematically, 'probability' can be expressed in three ways, all of which in practice mean the same thing.

(1) As a percentage, e.g. 99%
(2) As odds, e.g. 99:1
(3) As a 'ratio', e.g. 0.99.

What most intending users want to know is the probability of survival of all the parts in an equipment, i.e. the reliability. If we start (time = 0) and see what the probability of failure is some time later (time = t), we find that practical experience of faults in equipments suggests some form of mathematical equation. This equation is based on what is known as the exponential law of reliability. This says that, for a given initial population, the rate of failure decreases with time only in so far as there are progressively fewer survivors left to fail.

The probability of no failures occurring in a given time can be expressed as follows:

$$R = e^{-\lambda t}$$

where R is the probability of no failures in time t, e is the base of the natural system of logarithms and equals 2.718, and λ is the constant failure rate.

As MTBF (mean time between failures) = $1 / \lambda$
or $\lambda = 1 / \text{MTBF}$
then Reliability = $e^{-t/m}$

where m = MTBF and t = time.

Self-assessment Question 3.1

A light aircraft manufacturer requires an avionic system to have a reliability (R) of at least 90% after 10 000 hours of service. Determine the minimum acceptable MTBF for the system.

Calculation of MTBF is described more fully in the next chapter, but at this point it would be useful to look at some simple statistics in faults analysis. If an equipment is operating and failures occur, the number of failures can be recorded at the time at which they happen as shown in Table 3.1.

These observations can be plotted in the form of a graph from which more simple statistics can be discussed (see Figure 3.2). Line (1) records the actual failures as they occur with time. Line (2) shows the cumulative total as time goes on.

Only seven observations were made in this simple example, but supposing a very large number of observations were made – for example resistors, capacitors or transistors, or any small part where large quantities are involved. Then the frequency distribution of the measurements will be important.

It is generally convenient to group the measurements in the form of Table 3.2. If this is plotted, it will show the scatter of the measurements (see Figure 3.3).

Table 3.1

	Time (hours)	*Failures*	
	0	0	
	5	1	
	12	2	
	18	1	= 7 observations
	26	3	or measurements
	38	2	
	56	5	
Totals	56	14	

As 14 failures in 56 hours, the MTBF is $^{56}/_{14}$ = 4 hours.

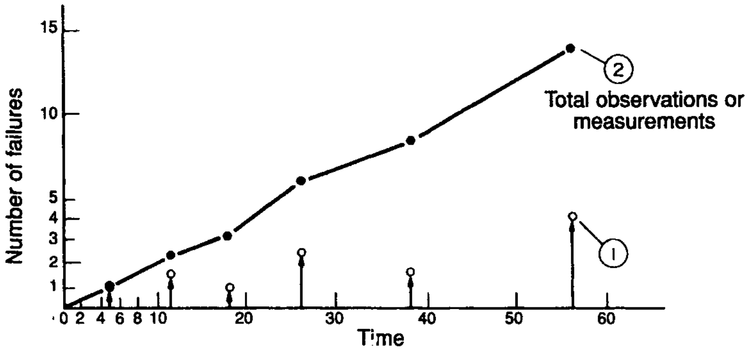


Figure 3.2 Simple rate and cumulative graph.

Table 3.2

Measurement value	*Number of times (or frequency) that this value occurs*
1	1
2	3
6	4
22	7
31	9
34	8
39	4
43	3
49	2
64	1

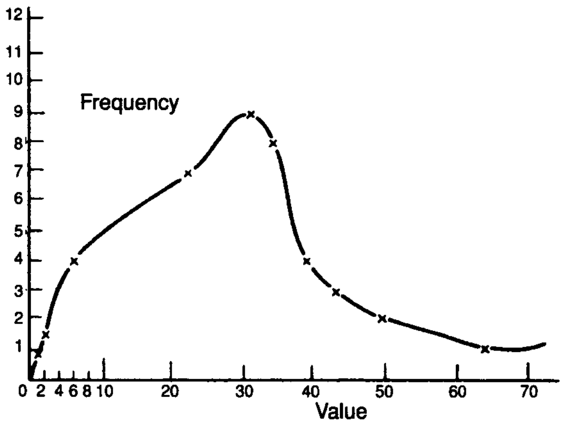


Figure 3.3 Frequency curve showing scatter of measurements.

Self-assessment Question 3.2

The number of reported failures of an automated canning plant are recorded against time in the table shown below. Use this data to plot rate and cumulative frequency graphs and estimate the MTBF.

Time (hours)	*Failures reported*
0	0
100	1
200	2
300	1
400	3
500	2
600	1
700	2
800	4
900	2
1000	5

If the frequency of observation is plotted against the value of observations, a curve similar to that shown in Figure 3.4 is obtained. This gives a graphical representation of a type of distribution known in statistics as 'Normal' or 'Gaussian'. The curve is symmetrical about the centre line and the frequency at the centre line of symmetry is the most frequently occurring observation (or 'Mode').

The 'standard deviation' is a measure of the scatter of observations about the centre line and is usually represented by the Greek letter σ (sigma).

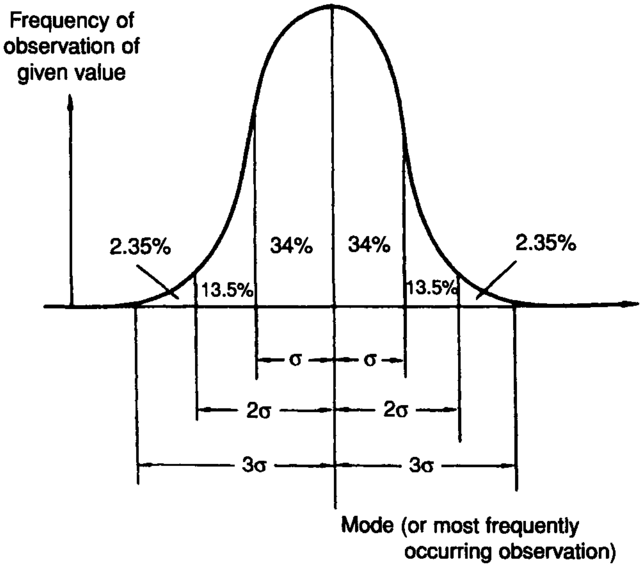

Frequency of observation of given value
2.35%
34%
34%
2.35%
13.5%
13.5%
σ
σ
2σ
2σ
3σ
3σ
Mode (or most frequently occurring observation)

Figure 3.4 Deviations of area from the mode.

If we consider the area under the curve in Figure 3.4, the proportion of the total area which lies between +σ and –σ = 68% or in other words 68% of the measurements may deviate from the centre line (mode) by amounts equal to less than ±σ. Similarly:

95% of the measurements lie between +2σ and –2σ
99.7% of the measurements lie between +3σ and –3σ

so that a standard deviation of ±3σ is often used to cover well over 99% of all measurements.

The Normal or Gaussian distribution is used when the number of observations is large.

Another type of distribution encountered in reliability work is the 'Poisson' and this is used to describe the situation when events occur at random but at a constant 'rate', e.g. to individual failures of equipment with a known MTBF, which is much more important than the 'Normal' in reliability work.

Other types of distribution, e.g. 'Gamma' and 'Weibull' are also of considerable interest to the reliability engineer, but these fall outside the scope of the book and full descriptions of them can be found in references 8 and 10 on page 88. Some more technical terms used by statisticians are given later in this chapter in the section on 'The language of reliability statisticians'.

The product law of reliability

It is obvious that the more parts there are in any machine or equipment the more risk there is of any one failing.

With only two parts such as a motor car engine and a motor car chassis, let us suppose that tests on six of each are made. If the six tests on the engine result in five engines passing the tests and one failing this could be simply represented as in Figure 3.5.

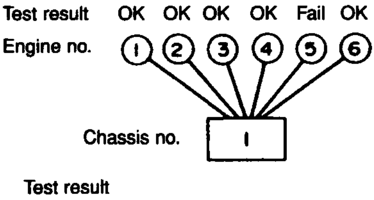


Figure 3.5 One engine failure in six.

As there are six chassis, suppose the tests on the chassis result in five passes again, and one failure, then the combination of engine and chassis failures can be represented pictorially as shown in Figure 3.6.

The reliability of each engine or each chassis is that five pass the test out of six or 5/6 = 0.833 or 83%. Engine No. 5 and chassis No. 2 fail and we can therefore indicate a failure against any combination including one of these (Figure 3.6). There are, therefore, 11 failure combinations in the 36 tests. The reliability of the complete system (engine and chassis) is that, on average, 25 out of 36 will pass, i.e. a reliability of 25/36 (or 5/6 × 5/6) = 0.694 or 69.4%.

Thus, even with only two parts the reliability of a system will be less than the reliability of any one part and, as has been seen, is determined by multiplying the two parts' failure rates together, not by adding them.

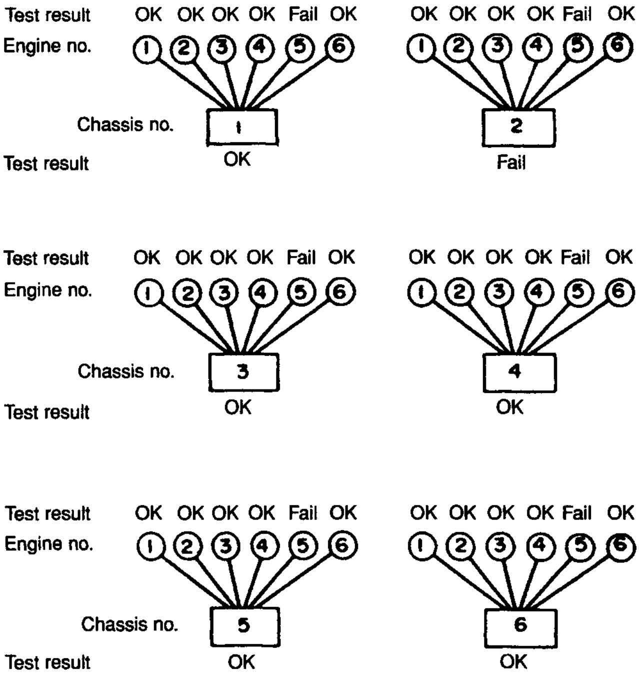


Figure 3.6 Combinations of engine and chassis failure.

Self-assessment Question 3.3

A small manufacturing company assembles a range of vehicle battery chargers from components and sub-assemblies bought in from subcontractors. The latest product to go into manufacture involves the components listed in the table below which also shows the average number of faulty components per batch of 100 received from each supplier. Assuming that no goods inward testing takes place prior to assembly of a product, estimate the reliability (R) of the new battery charger.

Component part or sub-assembly	*Average number of faulty parts or sub-assemblies (per batch of 100)*
Switch/voltage selector	2
Transformer	4
Rectifier	1
Ammeter/terminal panel	5

Confidence levels

It will be remembered that reliability is defined as the probability that an item will perform a required function under stated conditions for a stated time. What confidence can be given to this probability? It can vary between 0 (none) and 100 (certainty).

If an item is for general use, the confidence level (CL) may be reasonably low (say 60%), but for equipment involving life safety may be much higher (say 99%).

The degree of confidence is tied up with statistics, and this, in turn, is concerned with the amount of evidence – in particular, the size of the sample taken for testing. The effect of confidence levels on reliability calculations can be very significant. For instance, for an electronic equipment to have a failure rate of 1% per 1000 hours, the minimum test hours required with no failures for 60% confidence level would be 92 000, but for 90% CL, 230 000 unit test hours would be required.

Sampling schemes are also used for tests in which a certain number of a total quantity (or population) are selected according to the quantity and the acceptable quality level (AQL) determined, but these are again discussed in references 1, 3 and 8 (see page 88).

The language of reliability statisticians

Exponential, Normal or Gaussian, Poisson, Gamma and Weibull distributions are commonly used in estimating reliability. The reader will, however, come across a number of unfamiliar terms which are used by statisticians, such as contingency, goodness of fit, Chi-square (χ^2) distributions, 'students t' variance ratio, etc. Some of the language used by modern statisticians is defined below for interest:

(1) *Algorithm*
A prescribed set of well-defined rules or processes for the solution of a problem in a finite number of steps.

(2) *Cut sets and tie sets*
Cut set is a set of components in a system whose failure results in the system failure. Tie set is a set of components in a system whose success ensures system success.

(3) *Duane model*
A model which provides a deterministic approach to reliability growth such that the system MTBF versus operating hours falls along a straight line when plotted on log-log paper.

(4) *Fault tree*
A fault tree is a graphical representation of logic associated with the

development of an undesired system event in terms of the factors that contribute to its occurrence.

(5) *Fuzzy sets*

Fuzzy sets refer to a class of set with continuous grade of membership involving a gradual (rather than abrupt, as in the case of conventional sets) transition from membership to nonmembership.

(6) *k-out-of-m:G*

The system consists of *m* redundant units of which at least *k* units should be good for the system to be good.

(7) *k-out-of-m:F*

The system consists of *m* redundant units of which at least *k* units will fail before the system will fail.

(8) *Heuristics*

These pertain to exploratory methods of problem solving in which solutions are devised by evaluation of the progress made towards the final result. These are generally discovered intuitively.

(9) *Markov chain*

When the behaviour of a system is described by saying it is in a certain state at a specified time, the probability law of its future states of existence depends only upon the present state and not on how the system reached that state, the system state behaviour can be described by a process called the Markov process. A Markov process whose state space is discrete is called a Markov chain.

(10) *Modelling*

A technique of system analysis and design using mathematical or physical idealizations of all or a portion of the system based on the state of knowledge of the system and its environment.

(11) *Petri nets*

A bipartite directed graph modelling containing places, transitions and tokens used for studying the structure and control of a complex concurrent information processing system.

(12) *Stochastic analysis*

An analysis or procedure employed for the determination of certain parameters of a stochastic/random process, using some system modelling equations and boundary conditions.

(13) *Truth tables*

A table that describes a logic function by listing all possible combinations of states of system component and indicating, for each combination, the state of the system.

Note: The reader should refer to Chapter 12 for additional definitions of technical terms.

4 How reliability is calculated

It is important to remember that one cannot calculate the exact period for which an equipment will work without failure. All that can be done is to calculate the probability of an equipment working without failure for a particular period of time.

The concept of probability is fundamental to an understanding of what is meant by reliability, so it is vital to be quite clear just what 'probability' means.

Suppose we have a bag containing an equal number of well-mixed black and white marbles. If you put your hand in without looking and take out the marbles one by one, the probability would be that if you took out a certain number you would remove equal quantities of black and white marbles. The more marbles you took out, the higher the probability that the quantities of each would be equal. But this is only a probability; it is what we expect to happen. But we cannot rule out that you might, for instance, take out all the black marbles first.

Again, if the bag contains twice as many white marbles as black, then the probability would be that after taking out a certain number of marbles you would have removed twice as many white marbles as black. Here again, the more marbles you took out the higher the probability that you would have removed twice as many white as black, but there is no certainty that this would be so.

In reliability, the average period an item will function without failure is most often represented by the mean time between failures (MTBF). But there is no certainty that it will not fail before the end of this period; it might fail within a much shorter period, or perhaps run for longer without failure. But as with our marbles, the longer we go on, the more likely is our probability to prove true taken over the whole period; that is to say, if an item is run for a period which is long compared with its MTBF, the more likely is the MTBF to represent the true average period between failures. But note carefully that this is not the same thing as saying that the period between individual failures will approximate to the MTBF more closely at the end of a long run than it did at the beginning.

The MTBF has, however, become a useful measure of reliability for comparison purposes. There are two ways of calculating or predicting this measure of reliability. Taking, as an example, electronic equipments:

(i) By estimating failure rates for all the parts in the equipment, multiplying these by the number of parts, then relating this to the total equipment MTBF.
(ii) From previous experience with similar equipment, set up equations which can be used to predict an MTBF for a new equipment.

The first system is the one most used and the conventional method for expressing the failure rate of parts is in percentage per thousand hours (%/1000 hours). In some circumstances a failure rate of the number of failures in 10^9 component hours (a FIT) is used.

Taking a detailed example, let us list the parts in a typical transistorized equipment before integrated circuits were introduced and their possible failure rates as shown in Table 4.1.

Table 4.1

Part	*Failure rate (f)* *% per 1000 hours*	*No. in use* · *(n)*	*Product of* *(n) × (f)*
Transistors	0.003	100	0.3
Diodes	0.002	200	0.4
Connectors	0.15	5	0.75
Resistors	0.001	150	0.15
Capacitors	0.006	100	0.6
Switch	0.03	1	0.03
Relay	0.04	1	0.04
Sockets	0.03	6	0.18
Potentiometers	0.06	20	1.20
Transformers	0.04	2	0.08
Total		585	3.73

From Table 4.1 the total equipment failure rate is thus 3.73% per 1000 hours of operation.

The relation between failure rate and MTBF is

$$\begin{aligned} \text{failure rate} &= 1 / \text{MTBF} \\ \text{or MTBF} &= 1 / \text{failure rate} \end{aligned}$$

So in 1000 hours 3.73 out of 100 parts may be expected to fail. So

$$\begin{aligned}\text{MTBF} &= 1 \,/\, \text{failure rate}\\ &= 1 \,/\, (3.73 \times (1 \,/\, 100\,000))\\ &= 100\,000 \,/\, 3.73\\ &= 26\,810 \text{ hours.}\end{aligned}$$

This is the simplest form of prediction of MTBFs and in practice many other factors have to be considered, the component part stresses, the environmental conditions, special operating conditions, etc., but these are usually taken into account in the design. The total number of parts used has a bearing on reliability, as obviously an equipment with 2000 parts will have a higher failure rate than one with 200 similar parts assuming they are operated under comparable conditions.

The main factors taken into account in calculating reliability are illustrated pictorially in Figure 4.1.

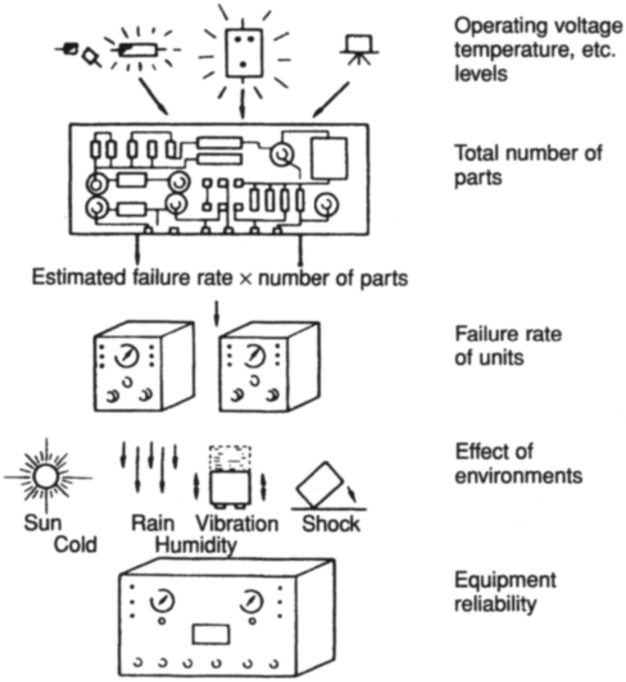


Figure 4.1 Factors taken into account in estimating electronics reliability.

Typical failure rates for electronic parts are discussed later in this chapter, but it must be emphasized that these are given as a guide only. They will vary with component stresses, environment, operating conditions, etc., and will change with any alteration in materials or processing employed in the manufacture of the component, hence the necessity of continually up-dating failure rates.

Some values of MTBF are given on page 28.

The number of component parts used varies widely. For a television set 200 to 400 parts may be used, for a large computer 250 000 to 500 000, while for space operations such as a manned moon mission up to 15 million parts may be required; many of these are now combined in the form of integrated circuits, or 'chips'.

Self-assessment Question 4.1

Determine the MTBF for a satellite navigation system that has a failure rate of 2.5% per 1000 hours of operation.

Self-assessment Question 4.2

A cellular telephone has an MTBF of 12 500 hours. Determine its failure rate expressed as a % per 1000 hours of operation.

Physics of failure

A difficulty in estimating reliability statistically is the very large number of components which must be tested to get a meaningful number of failures. For instance, if 330 000 specimens of a component with a failure rate of 0.001% per 1000 hours were tested for 1000 hours (nearly 42 days) there would be only three failures on average. It is unlikely that the production run would be large enough to justify testing on this scale, and the time, equipment and expense involved is considerable.

For high reliability items such as integrated circuits a new approach has therefore been developed, termed the physics of failure, which sets out to prevent the manufacture of faulty components, in contrast to detecting and rejecting them. The active silicon chip of the integrated circuit itself is extremely reliable; faults occur in encapsulating it, mounting it, and connecting it to lead-out wires. Through careful investigation and analysis, faults in these areas can be avoided.

Failure rates of electronic components and microelectronics

As a general guide, fixed resistors and fixed capacitors have fairly low failure rates of the order of 0.001–0.05% per 1000 hours; transformers about 0.01–0.05% per 1000 hours for each winding. Relays have to be calculated on failures in contact pairs and on coils and depend on many factors (as each type of relay has a different failure rate). Higher failure rates are expected from variable resistors, approximately 0.02–0.06% per 1000 hours, again depending on type, while switches are rated on contacts, being approximately 0.015% per 1000 hours per contact. Thermionic valves used to have much higher failure rates, ranging from 0.5% to 3.0% per 1000 hours, as also have some mechanical devices such as blower motors (4% per 1000 hours). Connections, although having extremely low failure rates, are numbered possibly in thousands so that hand-soldered connections may have a failure rate of 0.001% per 1000 hours while machine-soldered connections can be as low as 0.0005% per 1000 hours. Crimped connections are approximately 0.002% and welded 0.004% per 1000 hours, while wrapped connections are regarded as the most reliable, having a very low failure rate, of the order of 0.0001% per 1000 hours. Transistors range from about 0.003–0.01% per 1000 hours.

Integrated circuits (ICs) or 'chips' are now used in virtually all electronic equipment.

The introduction of silicon integrated circuits in the late 1950s and early 1960s produced a revolution in electronics so far-reaching that it can be likened to the invention of printing from movable type in the late fifteenth century.

With the virtual elimination of the thermionic valve (vacuum tube) and of large numbers of individual resistors, capacitors, etc., reliability, size, weight and cost were greatly reduced. This made possible the production of complex modern digital computers, pocket calculators, very complicated airborne electronic equipment and other innovations.

Because of the multiplicity of technologies employed in integrated circuits (TTL, ECL, MOS, NMOS, CMOS, etc.) and differing encapsulation techniques it is impossible to give any overall generic failure rates for integrated circuits. In the first 15 years after their introduction, however, the failure rates for all types of device decreased by approximately one hundred times. This reduction in failure rates is still continuing and reliability calculations should use only the most up-to-date figures available. For this reason no attempt is made in this book to tabulate precise failure rates as any values given would soon be outdated. One example that may offer some indication of present trends can, however, be quoted. A very complex integrated circuit containing over 5 000 000 'components' is reputed to have a failure rate of 0.01% per 1000 hours at a junction temperature of 125°C.

The measure of failure rates normally used today is the FIT which is the number of failures in 10^9 component hours. The above failure rate would, for instance, be 100 FITs. Less complex circuits or circuits operated at lower junction temperatures would have a considerably smaller failure rate.

Self-assessment Question 4.3

An integrated circuit has a failure rate of 45 FIT. Express this failure rate as a % per 1000 hours.

To summarize reliability assessment procedure

To calculate MTBFs list the component parts accurately, find out the basic failure for each, and multiply this by the number of components. Add all products and divide into 100 000. This estimates the MTBF of the equipment in hours. The basic failure rates are modified by a weighting factor (due to the environment in which the equipment is operated), a possible rating factor (depending on whether the components are fully loaded or not), and also temperature. It is quite difficult to give an accurate estimate but it is often necessary to predict an approximate MTBF in the early stages of equipment design. For the sake of simplicity and uniformity, failure rates have been given in % per 1000 hours (i.e. failures in 10^5 hours) in this book; however, failure rates may also be given as failures in 10^6, 10^8, 10^9 or 10^{12} hours.

Derating to improve reliability

Manufacturers' ratings are usually based upon safe working loads for a reasonable performance. A bridge may be rated to carry 30 tonnes, but could probably carry 60 tonnes. A mechanical hoist may be rated at 10 tonnes, but could be used for more than this. A 5-watt resistor could be loaded for more than 5 watts, but would not be so reliable. A balance must always be obtained between rating, cost and reliability.

Values of MTBF

Some approximate MTBFs for electronic equipments are given in Table 4.3 as a rough guide, but again conditions vary considerably and are different for each individual equipment.

Table 4.2 Some typical component failure rates (% per 1000 hours)

Capacitors	(plastic film dielectric)	0.01
	(electrolytic)	0.2
Connections	(crimped)	0.002
	(flow soldered)	0.001
	(hand soldered)	0.005
	(welded)	0.004
	(wrapped)	0.0001
Connectors	(coaxial)	0.1
	(multi-way)	0.005 per way
	(direct edge connectors)	0.05 per way
	(indirect edge connectors)	0.01 per way
Crystals	(quartz)	0.05
Diodes	(signal diodes)	0.005
	(power diodes)	0.05
Inductors		0.05
Integrated circuits	(MSI)	0.003–0.005
	(LSI)	0.005–0.01
	(VLSI)	0.01–0.02
Lamps	(signal lamps)	0.2
	(general illumination)	2.0–5.0
Meters	(moving coil)	0.1–0.5
	(digital)	0.02
Motors	(small)	0.5–1.0
	(large)	1.0–5.0
Relays		0.01–0.03 per contact
Resistors	(carbon film – fixed)	0.01-0.05
	(carbon track – variable)	0.05
	(metal film)	0.001–0.005
	(wirewound – fixed)	0.01
	(wirewound – variable)	0.02
Switches	(rotary)	0.02 per contact
	(slide)	0.1 per contact
	(toggle)	0.02 per contact
Transformers		0.02–0.1
Transistors	(low power)	0.0025–0.01
	(high power)	0.01–0.1
Valves	(amplifier)	0.5–2.0
	(magnetron)	5.0
	(rectifier)	2.0
	(transmitting)	2.5

Table 4.3 Approximate MTBFs for electronic equipments

Equipment	*MTBF (approximate)*
Repeater amplifiers in undersea cables	40 years
Satellites (some)	10/20 years
Computers and electronic equipment in laboratories	5000–10 000 hours
Military ground equipment	1000–5000 hours
Shipboard electronics	500–2500 hours
Airborne electronics	100–1000 hours
Missile electronics	1–500 hours

MTBFs for lifts, radios, TV sets, refrigerators, washing machines, cars and so on are not readily available, but an idea of approximate MTBFs is as follows:

Washing machines	approx. 10 000 hours
Personal computers	approx. 16 000 hours
TV sets	approx. 20 000 hours
Refrigerators	approx. 30 000 hours
Lifts (elevators)	approx. 44 000 hours (5 years)

Life expectancy = mean life

It is of interest to compare the life expectancies of some well-known objects with that of a modern integrated circuit.

Butterfly	2 weeks
Ordinary domestic light bulb	1 year
Motor car	10 years
Undersea cable	40 years
Man	75 years
House	100 years
Personal computer	4 years
Single integrated circuit	Hundreds of years

(In a firm of 500 employees about one will die on average each year.)

Self-assessment Question 4.4

The following components and sub-systems are used in a robotic system:

Proximity sensor (2)	(each having a failure rate = 0.025% per 1000 hours)
Signal processor (2)	(each having a failure rate = 0.075% per 1000 hours)
Power controller	(failure rate = 0.12% per 1000 hours)
Linear actuator	(failure rate = 0.21% per 1000 hours)
Power supply	(failure rate = 0.08% per 1000 hours)
CPU	(failure rate = 0.19% per 1000 hours)

(1) Which of the components and subsystems is:
   (a) most reliable?
   (b) least reliable?
(2) Which of the components and subsystems has:
   (a) least MTBF?
   (b) greatest MTBF?
(3) Determine the overall reliability of the robotic system (expressed in % per 1000 hours).
(4) Determine the overall MTBF for the robotic system.
(5) Estimate the probability that the robotic system will operate without failure for:
   (a) a period of 5000 hours
   (b) a period of 20 000 hours
   (c) a period of 100 000 hours.

Redundancy

In general, redundancy means more than one way of accomplishing a required function. It can take many forms: partial, active, stand-by, etc.

Partial redundancy can be illustrated by spokes in a bicycle wheel; even if some of them are broken the wheel will not fail. A lift suspension may consist of more than one rope so that in case one fails the lift can still operate. A further example is that of a four-engine aeroplane, capable of taking off on three engines.

In the case of equipment used in space missions, satellite communications, complex military systems, etc., when failure would have far-reaching effects, defence, safety or financial consequences, redundancy is employed. This means that part or the whole of a particularly vulnerable equipment is replicated in order to reduce the probability of loss of system function. A simple example of redundancy is the use of stand-by electrical generators in a factory or hospital to ensure continuity of supply in the event of a mains failure. A system of this type is known as stand-by redundancy, i.e. in the event of the failure of A, then B, a replacement device, can be switched into the system either manually or automatically (see Figure 4.2).

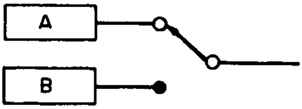


Figure 4.2 Stand-by redundancy.

Another form frequently employed particularly in signal processing applications is 'parallel redundancy'. In Figure 4.3, A and B are identical devices, both capable of performing their function independently. In the event of failure of either of the elements A or B, the overall system function will not be lost.

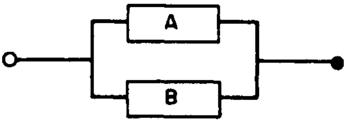


Figure 4.3 Parallel redundancy.

Many other configurations are possible; a parallel system of say three or more elements where the overall function is unaffected by the loss of one element, but the loss of two elements may result in reduction of function but not complete loss.

It is obvious that in the employment of redundancy techniques and therefore duplication of system elements both the size and cost of an installation are increased. This limits their application to cases of absolute necessity. One typical example of a situation where redundancy is highly desirable, but in practice is frequently prevented by space/weight considerations, is that of the transmitter in an airborne radar installation. The transmitter is usually the area of greatest reliability hazard in any such system because of the particularly severe environment associated with high power (hence high temperature) and high voltage combined with vibration. The limited space and load carrying capacity available in most aircraft prohibit the replication of transmitters in the majority of cases.

The calculation of MTBF for a system employing redundancy is obviously complex and is beyond the scope of this book; however, guidance on the mathematical techniques required can be found in most standard works on reliability.

Reliability in manufacture

By the time an equipment has passed from development into the production stage, most, if not all of the design deficiencies should have been eliminated. Under ideal conditions only random component failures would then be experienced and the MTBF should be that produced by the prediction calculation; this represents the full reliability potential of the equipment. Any errors in manufacture, e.g. badly made soldered joints, locking devices or materials, screws omitted, etc., will reduce the MTBF from the predicted value. 'Burn-in' can, and does, eliminate many of these problems, but in practice it has been found that a considerable number of manufacturing errors require a considerably longer time than that economically possible for burn-in before they cause failure. For this reason, strict quality control including rigorous inspection is essential if the full reliability potential is to be achieved.

Quality control

The quality of any manufactured product is determined by its design, the materials from which it is made and the processes used in its manufacture. The BSI formal definition of quality is 'The totality of features and characteristics of a product or service that bear on its ability to satisfy a given need'. This means that the item must meet its specification. How well it meets its specification is called 'conformity', defined as 'the ability of an item to meet its stated performance and/or characteristic requirements, the assessment of which does not depend essentially on the passage of time'. This is the 'zero' time element of quality, whereas the 'future' time element is the reliability.

Acceptance testing is mainly a question of economics. To provide a high degree of conformity requires a great deal of testing and therefore is very costly, and this must be balanced against the value of trouble-free operation by the customer. As mentioned in Chapter 1, this importance varies widely and the cost of quality control must be carefully estimated.

Acceptance testing is carried out by taking a sample from every batch manufactured and subjecting it to a wide range of measurements under various conditions. The size of the sample selected varies according to the AQL (acceptable quality level) value chosen. The AQL is the maximum average percentage of defective items which is considered tolerable. The lower the AQL value, the larger the sample must be. Tables known as 'sampling tables' are provided which statistically give the number to be tested, and the number accepted (which pass all the tests), against the AQL value.

Quality of a product, therefore, is determined by conformity and reliability.

Calculation is not everything

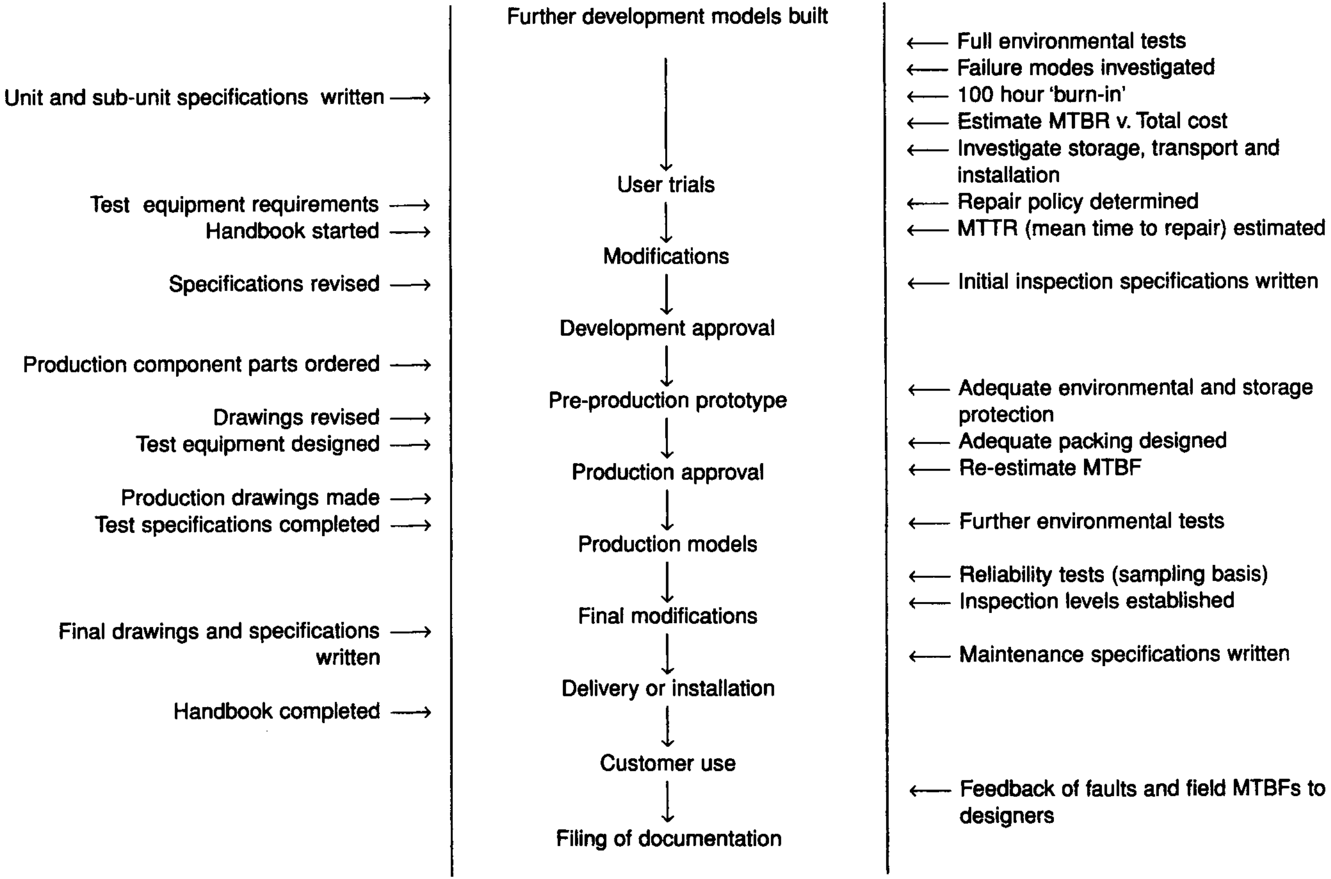
This chapter has dealt with calculating the reliability of components, and has touched on the reliability of equipments and of systems. However, for some designs there is an additional factor which the engineer may need to take into account in assessing reliability and safety. This additional factor is public opinion, a variable, emotional, non-quantifiable factor, set smouldering by major accidents to nuclear installations, aircraft and ships, often fanned into flame by the media. Public opinion can overwhelm calculated engineering design, as was shown in 1988 by the closure of a nuclear power station on Long Island in the US before it had ever generated even one watt of electricity. The closure was forced by public opinion on the major grounds that if there were an accident in the installation it would be impossible to vacate Long Island quickly enough.

Stages in producing a typical electronic equipment

Before discussing the effect of operating conditions and environments on electronic equipments in the next chapter, it must be emphasized that the design, development and production of any electronic or mechanical equipment is extremely complex.

To illustrate this, the following chart has been produced which not only shows the various stages in design, development and production, but also the stages necessary in ancillary and reliability work. Even with computer designed equipment, with assembly by robots, similar complex work has to be carried out from the initial idea to the final filing of documents.

Anciliary work required	*Stages in design, development and production*	*Reliability work required*
(1)	(2)	(3)
	↓	
	Initial idea	
	↓	
	Tentative requirement	
Market research →	↓	
	Design proposals	
Initial calculations →	↓	
	Initial specification	
Literature review →	↓	← Estimate likely reliability requirement
	Circuit design	← Determine likely environments ← Use 'worst-case' design ← Select likely best component parts ← Investigate redundancy
Initial component choice →	↓	
	Breadboard model	
Tests and modifications →	↓	
	Design approval	← Estimate approx MTBF
Component parts ordered →	↓	
	Development model	← Evaluate component part reliability ← Establish possible failure modes ← Estimate MTBF
Development component parts ordered →	↓	
	Mechanical design	← Mechanical tests – Resonance tests – Bump tests
Drawing office work started →	↓	
	Layout of units and system design	← Best ergonomic layout ← Adequate cooling ← Good accessibility for maintenance ← Best interconnection
	↓	


Further development models built
User trials
Modifications
Development approval
Pre-production prototype
Production approval
Production models
Final modifications
Delivery or installation
Customer use
Filing of documentation
Unit and sub-unit specifications written
Test equipment requirements
Handbook started
Specifications revised
Production component parts ordered
Drawings revised
Test equipment designed
Production drawings made
Test specifications completed
Final drawings and specifications written
Handbook completed
Full environmental tests
Failure modes investigated
100 hour 'burn-in'
Estimate MTBR v. Total cost
Investigate storage, transport and installation
Repair policy determined
MTTR (mean time to repair) estimated
Initial inspection specifications written
Adequate environmental and storage protection
Adequate packing designed
Re-estimate MTBF
Further environmental tests
Reliability tests (sampling basis)
Inspection levels established
Maintenance specifications written
Feedback of faults and field MTBFs to designers

5 The effect of operating conditions and environments

Equipment has to be installed and operated in all parts of the world, and climatic conditions can have a considerable effect on reliability. For instance, in hot, wet climates such as the Tropics the humidity is very high. In desert areas the temperature is high and the humidity low. In the Arctic the temperature is low. Some of the effects of these and other environments on the number of failures of equipments and materials is shown in Table 5.1.

Table 5.1 Analysis of typical failures of military equipment and materials under various environments in a given time

Environment	*Temp. and humidity*	*Dust*	*Humidity*	*Radiation*	*Salt spray*	*High temp.*	*Low temp.*
Electronic and electrical equipment	17	3	10	1	–	14	14
Lubricants, fuels and hydraulic fluids	–	1	–	–	–	8	4
Metals	10	–	9	–	26	8	5
Optical instruments and photo components	5	1	3	–	–	–	–
Packaging and storage	9	–	9	–	–	–	–
Textiles and cordage	14	–	5	11	–	3	–
Wood and paper	12	6	4	–	–	2	–
Totals	67	11	40	12	26	35	23

It will be seen that temperature and humidity head the list of factors causing failure. In high humidity moisture can form films on insulating materials, producing electrical losses, penetrate into component parts and change their characteristics and also cause rust to develop on a variety of metals, reducing their mechanical strength. Equipment for use in the Tropics is therefore usually sealed up (although sometimes this produces heating problems) or heated continuously to drive off the moisture.

Operating in hot climates also produces problems. Most electronic equipment dissipates some heat and if to this is added the climatic temperature the total heat may affect the reliability of the equipment. Greases may melt and some low melting point plastics such as polythene may soften. Differential expansion of differing materials can cause distortion and binding of moving parts.

Low temperatures also have an effect on electronic and other equipments although in most cases equipment is operated in heated rooms because of the human operator. There are, however, some instances where it is not possible to heat the equipment, such as walkie-talkie sets and equipment in aircraft.

The effect of these environments on the failure rates of electronic equipments may be summarized and are shown in Table 5.2.

Table 5.2 The effect of environment on electronic equipment reliability

Equipment	*Environment*	*Approx. failure rate (% per 1000 hours)*
Underseas cable amplifiers	Extremely stable temperature, low humidity, no shock or vibration once laid	0.0004
Electronic telephone exchanges	Usually air-conditioned and well maintained	0.067
General-purpose computers	At room temperature Some air-conditioned	0.17
Civil airlines	Subject to vibration and temperature changes but well maintained	0.83
Laboratory equipments	At room temperature subject to handling	1.01
Radio and TV sets	Room temperatures. Not usually moved when installed but built at competitive prices	1.00
Military equipment	High temperatures High humidity Salt laden atmosphere Shock, vibration, etc.	2–4

Self-assessment Question 5.1

Consider each of the following applications and suggest the THREE environmental factors that are MOST likely to affect the reliability of the electronic and mechanical components (as appropriate):

(a) a fire detection system fitted into the engine bay of a Boeing 747 aircraft
(b) a pod-mounted TV camera fitted to a Formula 1 racing car
(c) an HF radio transceiver for use on a deep-sea fishing trawler
(d) a high-power sound reinforcement system used by a travelling rock band
(e) an automatic braking system fitted to a roller-coaster in a Florida theme park.

Burn-in

Reference back to Figure 2.1, page 8, shows that during the early failure period of components, the failure rate is considerably higher than during the useful life period. If components and sub-assemblies were incorporated directly from the production line into a complex equipment which was then shipped to the customer, an unacceptably high failure rate might be experienced during the first few hundred hours. In order to minimize this effect, a procedure known as 'burn-in' is frequently employed. The individual components (integrated circuits, transistors, diodes, capacitors, etc.) or sub-assemblies, e.g. printed circuit boards, are operated for a hundred or so hours under environmental conditions slightly more severe than those encountered during normal operation. The effect of this is to induce many of the 'early life failures' in the components or sub-assemblies before system integration. This is obviously a fairly costly operation, but a large overall saving is possible due to the reduction of the requirement for re-work on the final product and also customer goodwill is maintained.

Burn-in of the completed equipment is possible, but the diagnostic and re-work problems encountered can lead to a considerably larger expenditure in time and money than if the operation is conducted at a component level.

6 Mechanical reliability

The well-reported failures, such as the Space Shuttle *Challenger*, the Three Mile Island and Chernobyl nuclear accidents, and the Bhopal gas escape, emphasize vividly the necessity for mechanical reliability.

Buildings, bridges, transit systems, railways, automotive systems, robots, offshore structures, oil pipe lines and tanks, steam turbine plates, roller bearings, etc., all have their particular modes of failure affecting their reliability.

While this book deals mainly with electronics, there are a number of common modes of mechanical failures, which are worth listing, e.g. with structures:

(1) Corrosion failures
(2) Fatigue failures
(3) Wear failures
(4) Fretting failures
(5) Creep failures
(6) Impact failures

These may be considered the main failure modes, but there are of course many others, such as ductile rupture, thermal shock, galling, brinelling, spalling, radiation damage, etc., which are outside the scope of this book.

General mechanical failures

There are many causes of failure. Some have been listed by C. Lipson[1] as:

(1) Defective design
(2) Wrong application
(3) Manufacturing defect
(4) Wear-out
(5) Incorrect installation

[1] Lipson, C. 'Analysis and Prevention of Mechanical Failures', Course Notes 8007, University of Michigan, Ann Arbor, June 1980.

(6) Failure of other parts
(7) Gradual deterioration

Self-assessment Question 6.1

In each of the following scenarios, classify the causes of failure in terms of the seven causes of failure identified by Lipson:

(a) The jib of a tower crane suddenly fails when subjected to twice the maximum rated load.
(b) The brakes of a motor car become less efficient as they near the end of their working life.
(c) The pipe joints in a domestic central heating system develop leaks when assembled by an unskilled person.
(d) A motor shaft bearing overheats and seizes due to use of an inappropriate lubricant.
(e) A building collapses when a wrongly placed structural member fails.
(f) The front suspension of a motorcycle collapses when the motorcycle hits a kerb at speed.
(g) The anti-skid braking system of an articulated lorry overcompensates for heavy pressure applied to the brake pedal. This causes the lorry to overturn.

Some interesting sources of product failure in the following areas are given by Lipson[2] as:

(1) Steel industry. Manufacturing and metallurgy (34%), design (58%) and service (8%).
(2) Engines. Manufacturing (20%), engineering (40%), misuse in field (30%) and other causes (10%).
(3) Truck industry. Manufacturing (12%), design (55%) and materials (33%).
(4) Electrical industry. Manufacturing (37%), design (37%) and service (26%).

Guidelines for designers in order to achieve higher reliability are given in B. S. Dhillon's book: *Mechanical Reliability: Theory, Models and Applications.*[3]

(1) Make design as simple as possible.

[2] Lipson, C. *Ibid.*
[3] B. S. Dhillon. *Mechanical Reliability: Theory, Models and Applications.* AIAA Education Series. 370, L'Enfant Promenade, SW, Washington, DC 20024, United States of America. Published 1988.

(2) Avoid introducing cost-saving procedures at the expense of reliability.
(3) Make allowances for human error.
(4) Make use of well-tried parts and materials.
(5) Carefully test new designs.
(6) Perform analyses of data received from the field.
(7) Pay attention to data received from the field when making modifications and improvements.
(8) In the case of critical parameters, consider using safety margins of three to six standard deviations.
(9) Consider diagnosis of critical items.
(10) Include facilities for inspection in the design.
(11) Introduce redundancy whenever necessary.
(12) Pay attention to the maintenance aspect with respect to reliability (Active Maintenance).
(13) Take into account the effects of transport, handling and storage.
(14) Make use of standard parts as much as possible.
(15) Pay attention to the manufacturing aspects with respect to reliability.

Some of these are touched upon in sections of this book, e.g. in Chapters 5, 6, 7 and 8.

Human reliability is often discussed and it is a fact that, apart from war, the highest toll of human life is caused by car accidents. These, in turn, are mainly caused by errors of judgement, making the main cause of failure – lack of human reliability.

Self-assessment Question 6.2

A small engineering company has asked you to produce a design for a car jack. The jack must be reliable, simple to operate, and inexpensive. Select SIX items from Dhillon's guidelines that you consider to be most important in the design of the car jack.

7 Installation and operability

Installation

The ways in which the installation of an equipment or machine can affect its reliability may not be immediately apparent, especially since the method and means of fixing and putting into operation will have been largely laid down beforehand. There may be some latitude in the running, connecting up, and interconnecting of the necessary services such as electricity, air, water, etc., so that the following two points, for instance, must be watched.

(1) Care must be taken to ensure that pipes, cables and flexible connections will not be damaged by any vibration which may be present. They can be damaged by chafing against a support, against the machine, or against each other. For instance, electrical connections passing through access holes or supports must be protected by grommets or other means.
(2) Cables which run across the floor must be positioned so that they are not trodden on, either during installation or subsequently. This is especially liable to happen if the equipment or machine is being installed in a confined space.

If installation has to be carried out under adverse conditions the possibility of errors increases. In planning how an equipment will be installed, full attention must, therefore, be given to the environment in which the work will be done. Since installation involves the same type of operations as are performed in repair and maintenance, similar considerations of human engineering and of working conditions are involved. These are described in this chapter.

Operability

Neither operability nor maintainability (dealt with in Chapter 8) are features which are usually considered within the scope of reliability. Nevertheless, poor operability can lead to equipment failure, and poor maintainability can reduce the time during which an equipment is functioning normally. For these reasons both operability and maintainability have been included in this book.

Every equipment has to be controlled by a human operator. If the equipment does not perform its specified function, the result is a failure or lack of reliability. To be reliable equipments must, therefore, be so designed that the probability of the operator making an error is as small as possible, and this characteristic is called Operability.

To produce a design best suited to a human operator we must know the relevant facts about human capabilities and limitations. These facts come from investigations in the field of 'ergonomics', i.e. the study of man in relation to work. The design and specification of human beings, that is to say the way in which they control and move their limbs, react to various stimuli, and so on, are fixed, although human beings vary considerably from one to another and are also very adaptable. This specification must be carefully considered in designing a machine or equipment for human control, and ergonomics or 'human engineering', as it is sometimes called, lays down the rules which enable the best possible use to be made of the working human being.

For instance, standing up is tiring, so the operator should be seated whenever possible. When seated the height and design of the seat, backrest, footrest and armrest, the height of the working area and the position of the various parts which the hands and feet must reach must all be considered in relation to the job to be done and the average dimensions of the people doing it, in order that fatigue should be reduced to a minimum. As an example, the optimum distance to place controls is about 70 cm from the operator.

In cases where physical effort is required to operate controls, ergonomics has established rules which enable people to supply the effort with a minimum of fatigue. These rules lay down, for instance, that it is uneconomical to underload large muscles and dangerous to overload small ones; that however perfect a machine may be, it is not correctly designed if only an athlete or contortionist can operate it; and that needless fatigue must always be avoided. Some of these rules may seem obvious, but are nevertheless often overlooked.

Ergonomics also provides guidelines on the most comfortable working environment. For instance, a high noise level is extremely tiring, and high-pitched sounds are much more disturbing than low-pitched sounds. The maximum tolerable noise level is around 90 dB; at this level it is difficult to talk to a person 1 metre away. Two simple rules apply here – put the noisy parts of a machine as far from the operator's ears as possible, and find out when ordering an equipment what is its maximum specified noise level. Noise can be reduced by replacing worn components, by damping out vibration, by insulating the source of noise, or by insulating noise-reflecting surfaces such as walls and ceiling.

Another important consideration in the working environment is lighting. Either too much or too little can be tiring. Too much lighting can be caused by glare from highly polished or other reflecting surfaces, or from bright lights within the field of vision. Bright lights can be particularly tiring; windows fall into this category, and positioning an operator directly facing a window when viewing a control panel should be avoided. The need for adequate lighting is obvious, but the actual level and nature of the source must be related to the position and type of controls and indicators with which the operator is concerned, particularly operators who spend long hours at video display units (VDUs) and plan position indicators (PPIs).

Self-assessment Question 7.1

Carry out a detailed investigation of the lighting in a workshop, laboratory or computer suite that you have access to. Identify all sources of illumination (including natural light) and show them on a scaled plan of the area. Indicate areas where light levels are unsatisfactory and suggest ways in which the situation can be improved. You may also like to collect the opinions of other users. Present your recommendations in the form of a brief written report and include reasons why the correct level of illumination is important in the situation that you have chosen.

The human body is fairly sensitive to its environment. Muscular effort will generate heat; if the operator exercises little effort he or she may need heated surroundings. Body temperature is controlled through convection (the transfer of heat to or from the surrounding air) and through radiation (the transfer of heat to or from surrounding surfaces such as walls and windows). To make the operator comfortable both these conditions must be controlled. Attention must also be given to air velocity which may result from draughts, or from wind in outside locations, and to humidity. Humidity is related to body temperature, since excessive humidity reduces the body's ability to lose heat through the evaporation of sweat and so reduces its resistance to high temperatures.

Another source of human fatigue is vibration, which may be encountered particularly in large machines, or in aircraft, ships, or large vehicles. Vibration is tiring because it causes relative movement between the body and the points of contact with the surroundings, or between different parts of the body itself. Thus the effects of vibration depend on the nature of the vibration, and on its frequency. For instance, vibration may be periodic, as in aircraft, or non-periodic as in a ship in a rough sea. Intense and continuous vibration between 0.1 and 1 cycle per second (Hz) can produce a form of sea sickness. From 1 to 15 or even 30 Hz is the range of greatest importance, because it is here that the chief resonances occur in the human body; it is also the band of frequencies in which many machines and vehicles vibrate, and in which vibration is particularly difficult to suppress. Vibration above 30 Hz is generally not a serious hazard unless particularly intense; its effects are somewhat similar to noise.

To avoid excessive fatigue due to vibration the nature of the vibration must be predicted or measured, and an acceptable level defined. Both these steps may involve complex matters of design engineering, and the second may involve the intricacies of human engineering. The final step is to control the vibration in order to bring it into acceptable limits, and this again may be difficult and require considerable expense.

To sum up, the more comfortable the operator is, the less likely are mistakes which will introduce an element of unreliability into the equipment being controlled because, through faulty handling, it may fail to perform its specified function.

Ensuring correct operation, however, involves much more than just making the operator comfortable. The operator's main responsibility is to assess an equipment's performance through visual displays, meters, position indicators, counters or lamps, or in the case of vehicle control, for instance, through the assessment of external conditions, and control it through the movement of keys, knobs, levers, etc. The displays must be so designed that the operator will quickly and accurately understand the information they convey, and the controls must operate in a way which will as far as possible ensure that, when the operator uses them, the required change in the performance of the equipment will result.

The operator and the equipment in fact form a closed loop in which information output on the machine is received by the operator's input (eye or ear). The operator's output is in the form of an action which feeds into the machine input and operates a control mechanism which alters the performance of the machine in a manner which is again shown on the information output or by a change in its performance. Any failure in this loop is likely to result in the equipment failing to function correctly, thus introducing an element of unreliability. The way in which the equipment responds to its control mechanism is a function of the equipment design, and so is not relevant to operability. The overall reliability of an equipment thus depends on the integration of the equipment and the operator, and this means considering the type and position of information displays, and the position, movement, and type of controls in relation to operator comfort and movement.

Mistakes in operation will also be reduced if controls are grouped according to their function, and according to the particular part of the equipment which they influence. Controls which have to be operated in sequence must be placed near each other, and in the correct order. The various requirements to reduce operator errors can never be met by a symmetrical layout of controls with identical knobs. Unfortunately this type of panel, which is designed to look right and not designed for good operability, is often the rule rather than the exception.

Having received information from the display, the operator must use a control.

It is essential that he or she uses the control correctly, and the following are the more important considerations which will increase the probability that this will be done.

A similar layout for display and controls will assist in selecting the correct control. A further advantage is for the operator to associate a particular shape of knob or control with a particular function, by touch as well as by sight.

When a control is used it is essential that the operator can see the associated display. It must not, for instance, be placed round a corner or behind the operator's back.

The position in which a control is set must be clearly and quickly distinguishable. If the positions of a rotating control are numbered, then laying out the numbers in the same positions as on a clockface enables the operator to tell instinctively what position the control is in.

Complex systems contain many visible displays and some audible signals to indicate and warn of incorrect operation and of fault conditions in the equipment. In the event of a serious fault there can be so many warning signals that the operator can be presented with much more information than can be assimilated and acted on correctly under emergency conditions; for instance, in a nuclear power station. The operator is consequently unable to distinguish the actual fault, and the malfunctions arising from the fault, from the mass of warning information being presented. Designing a warning system which will be effective in all fault conditions is therefore complex and difficult, and must be closely related to human characteristics; it will involve such considerations as the nature and positioning of warning signals, the priority in which they require attention under various fault conditions, and the ability and speed with which an operator can be expected to respond to them correctly in an emergency.

The type of control chosen must be related to its function. Levers should preferably be long, so that less force is needed to move them, and the wrist and forearm should be supported if fine adjustment is required. Cranks are most suitable where a wide range of adjustment is needed, because they can be turned quicker than a wheel or a knob. Handwheels should only be used if considerable force must be transmitted.

To sum up. The critical moment in the operation of an equipment is when some decision is taken, and as a result some control is used. The reliability of the equipment is bound up with the decision the operator makes, the actual control he or she operates and how it is used, and these can all be affected by the operator's personal comfort and working conditions, in addition to his or her interpretation of a display, and the layout and design of controls.

Self-assessment Question 7.2

Figure 7.1 shows the window anti-icing arrangement in the flight deck of a modern airliner.

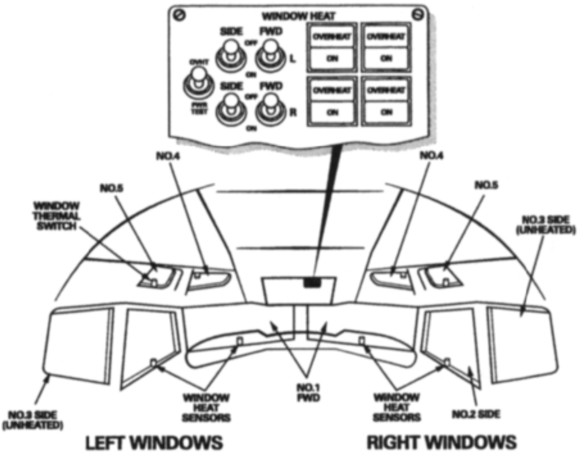


Figure 7.1

The anti-icing system prevents ice and fog build-up on cabin windows 1, 2, 4 and 5 and also improves the impact strength of the windows in case of bird strikes. Alternating current flows through a conductive material in the window and heats the pane. Forward-facing windows 1 and 2 are controlled at a temperature of 110 °F by a heat control unit for each of the windows. Each window has a temperature sensor embedded in it which sends a signal to the control unit. If control fails and the window temperature exceeds 145 °F, the heat control unit will cut off power to the window and turn on the oveheat warning light on the overhead control panel. Windows 4 and 5 on each side are heated together in a series circuit and a thermal switch mounted on window 5 regulates the temperature to between 90 °F and 110 °F. When either of the window 2 switches is turned on, current also flows to windows 4 and 5 on that side of the aircraft. A three-position test switch is fitted.

The build-up of ice on an unheated window can be a serious problem, particularly on the forward windows. Comments from pilots indicate that occasionally wrong switches are selected in which case forward visibility can become severely impaired.

Redesign the layout of the overhead control panel so as to improve ease of use and reduce the risks of mis-operation.

8 Maintainability

When an item of equipment or a machine fails, as it probably will sooner or later, since no design can be made absolutely reliable, it is important that it should be repaired quickly so as to become available for use again in the shortest possible time. Often, in fact, the user is more interested in availability, which is the percentage of time during which the equipment is functioning when required, as in television sets in the home.

As an example, an airline's principal source of revenue comes from its fare-paying passengers. Most civil aircraft must therefore be flown for many hours every day in order to earn their keep. For narrow-bodied aircraft on shorthaul routes, in-flight usage may be up to 10 hours each day but for wide-bodied jets like Boeing's 747, daily usage needs to amount to nearer 14 hours. Furthermore, when the aircraft is on the ground being serviced it is not earning income and, since the cost of taking a Boeing 747 out of service amounts to around £100 000 for each day that the aircraft is on the ground, maintenance must be very carefully planned!

Regardless of complexity, all equipment must have good maintainability – maintainability being a measure of the speed with which loss of performance is detected, the fault located, repairs completed, and a check made that the equipment is functioning normally again. Maintainability must be built into the original design since, like other reliability factors, attempts to incorporate it as an afterthought, by modifications to the manufactured equipment, will never produce a satisfactory solution. Features which improve maintainability can often be made part of the original design without a great deal of extra expense. The designer must, however, be careful not to improve maintainability by introducing features which reduce reliability – for instance, by enabling assemblies to be removed quickly by replacing soldered connections by plugs and sockets which are sometimes less reliable.

To obtain satisfactory maintainability the following factors must be considered:

(a) The equipment or machine could fail at some time or other.

(b) The positioning of maintenance displays, check points, gauges, meters and the position of one assembly with respect to others.
(c) The limitations imposed by the human frame.
(d) The environment in which maintenance or repairs will be carried out.
(e) The design of test equipment.
(f) The presentation of information in the maintenance and repair manual.

Good maintainability is just as important for routine maintenance as it is for repair, since maintenance can also represent a period of non-availability which must be made as short as possible.

Maintenance involves making a number of check measurements, or taking specified action such as lubrication, at particular points in the equipment or machine. It is essential that these points are easily accessible and are so situated that the required action can be easily taken. The check points must not be put in positions dictated by the physical design of the equipment rather than in the best position for maintenance. If they are, they may be difficult to get at, or be so placed that when an adjustment is made or a reading taken it is difficult or impossible to see the relevant meter or indicator. It is essential that all the displays, meters, component parts, adjustment points or other items which will be involved in a single maintenance operation should be so grouped that all are comfortably accessible, both manually and where the eyes can easily be placed in line with the pointer, to ensure an accurate reading.

Special attention must be given to the positioning of parts which must be regularly serviced, or which are known to have a high failure rate. They should be placed so that the maintenance points and the parts themselves are readily accessible, without first removing other components or assemblies. Covers on the part itself, or which must be opened or removed to get at the part, must be easily and quickly removable. Obviously replacement is quicker if a part can be replaced from the front of an equipment – a pilot lamp, for instance. Where there may be difficulty in identifying a part such as in electronic equipment, the part must be clearly marked in a place which is easily visible.

If colour coding is used, it must be remembered that about one in seven persons are sufficiently colour-blind to be unable to distinguish nearly identical shades, or dull colours. Colours must not fade, they must be used consistently, and whenever possible a standard code should be used, details of the code being displayed on the equipment. The eye finds it difficult to identify small areas of colour, so that the use of, for instance, a colour thread running through cable insulation is unsatisfactory. The use of colour coding on parts which are liable to get dirty or contaminated with oil should also be avoided.

Fixing devices must be readily accessible, so that a part can be removed easily and quickly for repair or replacement. Fixing devices must also be designed so that a part can be quickly released and quickly re-secured.

It must be remembered that what appears completely accessible, or very simple to adjust, or to undo and do up, when a part or assembly is on a bench may not turn out to be so when assembled into a complete equipment. It is, therefore, essential to visualize, at the design stage, exactly how each part will be situated in the complete assembly, equipment or system. The designer must constantly aim to cause the minimum of work for the maintenance engineer. This involves not only making it easy to 'get inside the black box' and doing the job when there, but also avoiding the use of non-standard or too wide a variety of fixing screws. Even such an apparently unimportant feature as the use of needlessly long screws, which increase the time taken to remove and replace the nuts, lengthens maintenance time unnecessarily and so reduces equipment availability.

Clearly, maintenance cannot be carried out so well, or perhaps cannot be carried out at all, if there are any actual or potential hazards such as high voltages or moving parts. If interlocks have to be made inoperative during maintenance or repair, a warning light should indicate if power is on. In the case of machinery, some means should be provided to prevent inadvertent operation.

Good maintainability also involves consideration of the conditions in which the human body can work best, such as the relation between manual ability and the senses, human lifting capacity, and the maintenance equipment environment. Our work skill actions are governed by the input of information received from our senses, the most efficient input coming from sight, then touch and lastly memory. This means that work is performed most quickly and accurately when one can see what one is doing; if it is only possible to work by feel the job is more difficult, and if parts can be neither seen nor felt but their position has to be memorized, a job becomes lengthy and tedious. To take a simple example – it is easy to place the blade of a screwdriver into a slot on a screw head which can be seen, rather more difficult if the screw cannot be seen and the blade must be guided by hand, but very much more difficult when the hand holding the screwdriver must place the blade in the screw slot aided only by what can be remembered of the screw and slot position.

It is a matter of personal experience that in certain positions of the body the hands can carry out certain movements easily, either when holding tools or by themselves. Equipment and machines should be so designed that maintenance and repair can be carried out with natural movements; unnatural movements of the hands, arms or body lead to strain, frustration, wasted time, and a greater possibility of error. In this connection it is especially important to have in mind how a part or assembly will be situated within a complete equipment.

The maximum weight which a human being can lift varies within wide limits, depending on the actual position of the body and its position in relation to the weight. For instance, most men can lift 50 kg or more if it is close to their body, but only about one-quarter of this weight can safely be handled if it is positioned over 60 cm away. Less weight can be handled if the body has to work in a space which is restricted because access is difficult, or because the equipment is installed in a small area. Lifting capacity will also be reduced in other circumstances – for instance, on a ship which is rolling.

These weight limitations must be considered in the equipment design, particularly in mechanical units, so that they are not exceeded by any single complete item which will have to be manhandled in or out of the equipment. Even when the weight is within the limits, all but the smallest and lightest units must be provided with some convenient handle or other facility for lifting. Not only does this make lifting easier, but if no provision is made the assembly may be moved by grasping some portion of it not designed to withstand its weight, with consequent damage, or it may be dropped.

Equipment is normally designed, built and tested in an environment with a comfortable temperature and good lighting. However, maintenance and repair may have to be carried out in a hostile environment. For instance, in the case of vehicles, ships, aircraft and equipment used by the Armed Forces, conditions may vary from below freezing to tropical temperatures accompanied by high humidity. Cold reduces human efficiency, chiefly because of the bulk of the additional clothing which is required, including gloves, and because of the effects of cold wind on exposed parts of the body. The bulk of additional clothing means that larger access openings are needed to work through, but the most serious effect is often that the use of gloves impairs the sense of touch, making it more difficult to use the hands. These factors must be considered during the design stage.

The effects of high temperature and humidity are rather different from the effects of cold. They reduce the amount of physical work which can be performed, and cause a deterioration of mental ability. Besides impairing performance and producing fatigue, extreme conditions can even lead to physical collapse. Temperatures inside a vehicle or aircraft parked in the open may be considerably higher than those outside. In a hot and humid environment it is more than ever necessary to ensure that all maintenance operations which may have to be carried out are the simplest possible, and that there is a good system of part identification, that access is easy, and that parts can be quickly detached and replaced.

Wind is another element which may have to be reckoned with in a hostile environment. Aperture coverings which stay open safely in the design laboratory may be slammed shut by high winds when the equipment is standing in the open. Devices used to lock covers must operate positively, and should show clearly whether or not the covers are locked in the open position.

Self-assessment Question 8.1

List the stages required to remove, examine and replace one of the road wheels of a motor car. For each stage list the tools required, access points, and the precautions that must be taken to prevent damage to the vehicle and to ensure personal safety. Perform the task on at least two different vehicles at the roadside using only the tools, equipment and information supplied with the vehicle. Comment on your findings and state at least THREE improvements that can be made to the vehicle and/or to the equipment in order to help make the task easier, quicker and safer.

Test equipment

A number of the features necessary for good equipment maintainability apply also to test equipment, since a failure here will also delay maintenance and repair work, thus shortening the equipment's availability. Test equipment instruments must be easy to see when in use, and operability must be good (see Chapter 7). In addition it must be possible for the test gear to be easily and safely positioned when in use, within comfortable manual and visual range. Test indicators should be as simple as possible. For instance, if only a 'Satisfactory-Not Satisfactory' indication is needed, the use of a lamp or buzzer is better than a meter. If a gauge or meter must be read, the dial should be as simple as possible and not capable of being read to a greater accuracy than the test requires. In more sophisticated types of special test equipment it may be desirable to incorporate some form of quick check to show that the equipment is functioning normally. Accessories, such as leads, should be permanently attached, and there must be stowage space for all loose ancillary items so that it can be seen at a glance which, if any, are missing.

The weight, portability, robustness, reliability, and even the maintainability of test equipment must be considered with reference to the skill and training of the staff who will use it, and to the environment in which it will be used. In addition, the variety of test equipment required should be kept to a minimum.

One of the most important contributions to good maintainability is a well-planned maintenance and repair manual, since this will often be the only available guide to the way the equipment works, and if information is not clearly presented, lengthy delays can result. It must be written with its purpose, and the conditions in which it will be used, firmly in mind. Thus constant page turning to refer to diagrams or tables of values must be avoided, and some guide to step-by-step fault tracing should be included. The manner in which the equipment operates must be clearly described and well illustrated, with simple cross-referencing between theoretical and practical working diagrams. One of the most valuable features in a maintenance and repair manual is a list of the failures which experience has shown are most likely to occur, together with their symptoms and the method of repair; such information can often save a great deal of time.

Maintenance must never involve 'poking about' inside an equipment, moving connecting cables, displacing parts, and perhaps even undoing or unsoldering parts. Experience has shown that such attempts to see if failures can be anticipated does far more harm than good, since interference with the working parts is likely to introduce an element of unreliability by creating conditions leading to failure. The maintenance and repair manual should lay down maintenance routines, and no maintenance in excess of these routines must be attempted.

A useful concept in considering maintainability is to estimate the total repair and maintenance man-hours needed in a given period. Such an estimate involves employing a representative technician with a specified education, training and experience, and timing him in the performance of the various maintenance tasks. From this the total maintenance man-hours in a given period can be calculated. The total repair man-hours can be derived in a similar way, but it is necessary to time the carrying out of various repairs and to make a reasonably accurate estimate of the failure rates of various parts, so as to establish how often each repair will be needed within the given period.

Planned maintenance

Planned maintenance normally involves a series of regular checks including the replacement of components that may be reaching the end of their working lives. A good example of this process is that which relates to the routine servicing of a motor car. Tyres, brakes, steering, lighting and lubrication fluids are often checked at a service interval (check cycle) of 4500, 5000 or 6000 miles. Clutch, gearbox, transmission, and other major items may be checked at a longer service interval (check cycle) of either 9000, 10 000 or 12 000 miles. More complex equipment may require a number of differently scheduled check cycles – those for a Boeing 747 are shown in Table 8.1.

Table 8.1 Boeing 747 check cycles

Check type	*Flying hours*	*Calendar days*	*Landings*
Service 1	1 060	85	160
Service 2	2 120	160	320
Intermediate	6 360	500	900
Major	24 000	1825	3800

Mean time to repair

The MTBF is a measure of the likelihood that an equipment will break down in a given period, but it is also necessary to know how long it will be out of service for maintenance and repair. This time is often designated MTTR (mean time to repair). Only by taking both these factors into account can the user estimate for how long within a given period an equipment is likely to be available, and how serious the effects of non-availability during maintenance and breakdown are likely to be. He or she will also be able to estimate what, if any, stand-by equipment is necessary to obtain a certain availability of service, and avoid both the unnecessary expense of stand-by equipment which is not required, and the extra costs due to the effects of the equipment being out of action for longer periods than might otherwise have been anticipated.

Self-assessment Question 8.2

Local area networks (LAN) provide a powerful and efficient means of sharing computing resources between a number of users. A small LAN (such as that found in a College or small company) usually consists of a number of workstations (each fitted with a network interface card) linked to a network file server via an arrangement of coaxial cables and connectors. In addition, a shared printer and other high-value peripheral devices may be made available to users through the medium of the network.

Consult your Network Manager or Information Services Manager and ask him or her to help you to complete the table shown below (note that the experience of individual Network Managers may vary widely):

Item	*Number in use*	*Estimated MTBF*	*Estimated MTTR*
File server			
Workstation or networked PC			
Network printers			
Cabling/connectors			
Network operating system (upgrade or 'bug fix')			

A record of 'downtime' may be available for you to examine. You may also like to ask the Network Manager whether he or she can give you an idea of the cost (to the College or company) of the non-availability of the network (in some cases this information may have to be treated as 'confidential').

9 Reporting failures

Serious accidents in the air, at sea, or on the railways are the subject of detailed examination to establish their cause. If an element of unreliability is involved, the investigation will reveal it, so that a suitable redesign can prevent a similar failure in the future. This process closes what is usually an open loop between the designer and the user. Normally the designer, having developed an equipment or machine to meet the user's needs in given working conditions, receives no regular and accurate information on how his or her design is performing. Such reports would, however, enable the designer to improve subsequent designs, with a resulting increase in reliability.

Reporting failures in use might well establish the shortcomings in one particular part, and so indicate how a minor and inexpensive modification could produce a substantial improvement in reliability. While it is true that information on a particular failure will usually get back to the manufacturers eventually if the failure is sufficiently widespread, they may in the meanwhile have produced and sold a substantial number of equipments which will be liable to the same failure. Furthermore, they may never hear about other failures which might otherwise have been eliminated in later models.

To improve reliability there is therefore a need to report back failures. Failure reporting should not be confined to those defects which actually lead to a breakdown. Unduly rapid deterioration in a part which may be revealed by normal maintenance procedure is clearly a failure of the part, even though it may be replaced while the equipment is still functioning normally and so not have caused a breakdown. The presence of such parts is obviously a potential cause of equipment unreliability, and in addition the need to replace them at relatively frequent intervals increases maintenance time and reduces the equipment's availability.

The most important aspects of failure reporting are accuracy and speed. If the designer receives wrong information about the nature of the failure, reporting it may do more harm than good. This means that the nature of the failure must be accurately diagnosed, the part which has failed must be identified, and the information incorporated in a report in a way which will convey the information clearly. The report should make it plain which are the facts and which are opinions or deductions about the cause of failure. If a special form has to be completed when reporting failures, it should not call for too much information, otherwise the accuracy of the details provided will depend unduly on the technical and descriptive ability of the writer and the time he or she has available to complete the report.

In reporting failures, or in devising forms or procedures whereby this can be done, the aim must always be to ensure that the information given is accurate, and this will usually mean that it is also necessarily limited. Manufacturers may not contemplate a redesign unless they have a number of reports all indicating the same failure. The information available in these reports collectively may be sufficient to indicate how the failure can be eliminated. If the information is not sufficient for this, it will provide a starting point for the designer to make his or her own investigations of the failure, and on which to base a redesign.

Reporting failures is a two-way business. Users must appreciate that accurate reports are the most important method of improving reliability of an equipment or machine after production; designers must realize that failure reports afford the chief source of data on which the reliability of future designs can be improved. Users must ensure that the facts of a failure are reported accurately and quickly; designers must not expect too much information to be provided, and must be prepared to find out for themselves any additional information they need to improve their design.

To sum up, however carefully a design has been conceived and manufactured, failures which reduce the reliability may nevertheless occur in particular parts when the equipment or machine is in use. If the nature of these failures is reported accurately to the designers, they can make improvements which can increase reliability.

This is particularly true when a Reliability Improvement Programme is operated during the development of an equipment. A prototype equipment or equipments are run for periods considerably in excess of the predicted MTBF (say 10–20 times). Each failure of the equipment is recorded and analysed; some of them will be random component problems (those accounted for in the MTBF prediction), others may be design related. Analysis shows up the design weaknesses, so that necessary modifications can be incorporated; therefore the MTBF should increase during the programme.

All those given the task of reporting failures should realize that it is not just a formality, but a vital procedure for improving reliability. If this is understood, reports are far more likely to be completed quickly and accurately.

Self-assessment Question 9.1

Consumer electronic products are invariably covered by a 'Manufacturer's Warranty' which offers the purchaser some protection against defective workmanship and component failure during a limited term (often either six or twelve months). During the warranty period, faulty equipment can usually be returned, free of charge, to the supplier or distributor who in turn sends the item to an authorized repair centre.

Information gleaned from the end-user and supplier can often prove useful in helping to pinpoint a fault and it may also help to identify modifications and improvements in the design of the equipment.

Devise a Fault Report Form for use when a computer printer is returned for repair under warranty. Your report form should be suitable for use by a non-technical user and should relate to a manufacturer's range of printers, including laser, ink jet and dot matrix types.

10 The cost of reliability

An important aspect of any equipment is usually its cost. Orders are normally placed with the supplier who can provide equipment or machines to the required specification at minimum initial cost, and there is no doubt in the minds of many of those who carry financial responsibility that this is the most economical way of running their business.

Nevertheless, this is very often a mistaken approach, because it takes into consideration only the initial cost and neglects the expense of keeping the equipment working satisfactorily once it has been purchased. How much maintenance and repair will cost depends on the reliability of the equipment; the more reliable an equipment is the cheaper will be the maintenance and repair bill, but the initial cost may tend to be higher.

Three separate cost factors are involved – the cost of design (including development), the cost of production, and the cost of repair and maintenance. As the reliability of an equipment increases, the cost of design and production may increase, whereas the cost of repair and maintenance will go down. Design may become more expensive because more precise assessments of the exact working conditions must be made, followed by more detailed development, possibly involving trials on prototypes, further environmental testing, etc. (see chart, pages 32 and 33).

On the production side higher reliability means better quality and therefore more expensive parts. It may be necessary to use costlier materials, to work to finer limits, and to provide additional and more elaborate test and inspection facilities. Usually more skilled and, therefore, more highly paid assemblers must be employed, and the completed equipment will in turn have to meet a tight and comprehensive test and inspection schedule.

To make an equipment more reliable may increase its initial cost. This increase can, however, be more, sometimes very much more, than offset by economies in maintenance and repair costs.

When an equipment fails there is a loss of production or of service, and often of goodwill, all of which involves some form of direct or indirect financial loss. If the results of a failure are likely to be serious, then it may be necessary to provide one or even more spare equipments as replacements. Clearly the lower the reliability the greater will be the number of equipments or machines which are out of action at any given time, and therefore the higher the number of replacements which must be provided. What is more, if the equipment is part of a system, entire spare systems may be required. Take, for instance, a weapons system such as that in a fighter aircraft. With the Service requirement that a specified number of fighters must be operational at one time, complete spare aircraft must be provided to replace those grounded by equipment failure. The need to maintain a specified service in, say, an electricity or telephone network will also require the provision of stand-by equipment or systems.

Besides the financial loss caused by an equipment failure, there is the cost of repair, which is far more than just the cost of the work and material involved, since it must also take into account the expense of educating and training the necessary skilled staff, the cost of test and repair apparatus and installations, and the cost of spares. The less reliable an equipment is, the more repair work is needed, and the greater the number of staff and the quantity of test apparatus and of spares which must be available.

With modern complex equipment, highly skilled technicians are normally required for repair work and training them can be a long and expensive process. No explanation is needed of the fact that more repair work will require more and larger workshop installations, and also more apparatus for carrying out the repairs, such as tools and test gear. But all the expenses involved in the provision of spares may not be quite so obvious. Quite apart from the cost of producing spares, they perform no useful function until they are used, in contrast to an actual equipment. The total value of the stock of spares thus represents money lying idle, which, if invested or used to pay for capital goods, could produce an income. The potential income which could be derived from the money value of the stock or spares must therefore be added to the price of the spares to represent their true cost. Furthermore, spares must be ordered, transported, perhaps tested, issued, and accounted for. All this requires administrative staff and facilities.

Maintenance costs may not only mean that it costs more to keep an item in working order. They may also add to the initial cost because something must be included in the selling price to cover the average amount of repair work which it is estimated will be necessary while the item is under guarantee. The less reliable the equipment, the larger this amount will be.

The manufacture may also be affected in another way. The rate at which an equipment can be produced may be lessened by the need to divert parts, which could be incorporated in complete equipments, for use as spares.

More often than not buyers are interested only in the initial cost of an equipment, instead of in its life-cycle cost, or total cost, namely how much it will cost them to buy the equipment and to keep it functioning normally throughout its working life. By paying more initially, to obtain a more reliable equipment, maintenance costs can be made lower and the total cost reduced. This is shown in Figure 10.1, which illustrates how production and design costs rise as reliability increases, but at the same time maintenance and repair costs fall. These three added together represent the total cost of the equipment. If the total cost is plotted it first falls with increasing reliability, and then rises again, showing that at a certain reliability the total cost is a minimum, as represented by the dotted lines in Figure 10.1.

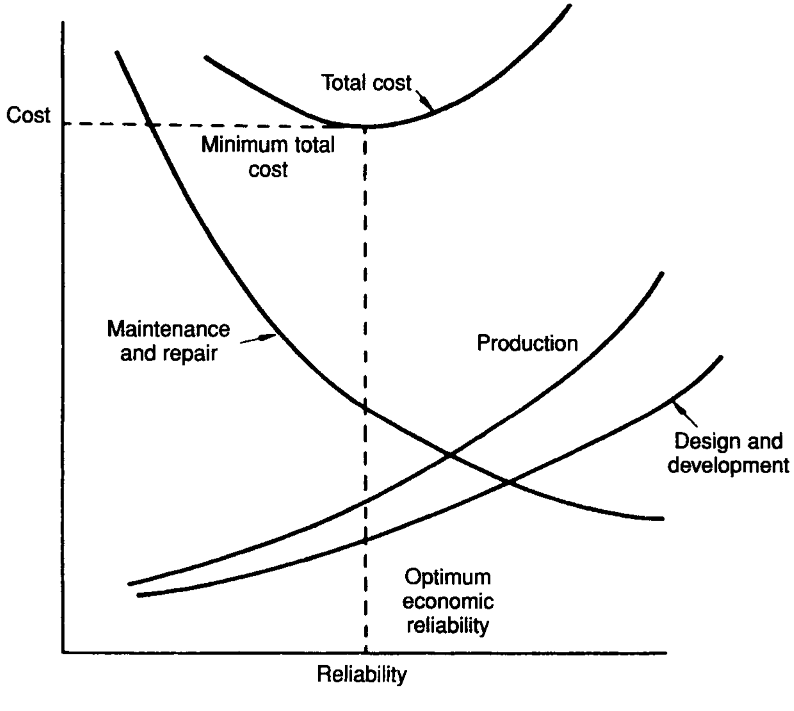


Figure 10.1 Variation of total cost with reliability.

Note particularly that when the initial cost, represented by the production and design costs, is lowest, the total cost, which represents the total which the buyer will have to spend on the equipment during its working lifetime, is higher.

Optimum economic reliability, which is the degree of reliability for which the total cost is a minimum, is difficult to realize in practice because it involves estimating how production, design and maintenance costs will vary for a given reliability, and this can only be done with any accuracy if there is a considerable amount of previous experience to draw on. It may therefore be extremely difficult to make such estimates for new types of product, or for products involving new design features, new techniques or new production methods.

Minimum total cost is of course not always the governing factor in deciding the degree of reliability of an equipment. For instance, it may be necessary to reduce reliability to the minimum acceptable to buyers whose main consideration is an initial cost within the price range they can afford, even though they realize that higher performance and reliability may be obtainable at a higher price. Many consumer goods fall into this category, which is usually highly competitive. Nevertheless, the reliability achieved by such equipment, for instance cars, television sets or refrigerators, is surprisingly high when viewed against the complexity of the item and its initial cost.

As an example, Table 10.1 shows an analysis of car maintenance carried out in the USA some years ago. Although the costs today could be higher, the principle is the same.

Table 10.1

Part	*Contribution to breakdown probability*	*Maintenance action*	*Maintenance cost (dollars)*
Ignition	0.03	Major tune up	25
Tyres	0.05	Replace	100
Engine	0.08	Overhaul	300

In terms of US dollars:

Ignition	0.03/\$25 = 0.0012 per \$
Tyres	0.05/\$100 = 0.0005 per \$
Engine	0.08/\$300 = 0.00027 per \$

This shows that reliability improvement is preferable by maintenance on ignition and tyres rather than engine overhaul. By spending only \$125 on the first two items, the same reduction in breakdown probability can be accomplished as by spending \$300 on the last one.

A case where total cost is not the most important factor in determining reliability is when buyers stipulate a high degree of reliability in the light of what they know of the exacting conditions of use and of the extreme results of failure. These are the circumstances which increasingly often govern the purchase of equipment to be used, for example, by the Armed Forces, by civil airlines or in space. To specify a particularly high reliability requires lengthy and careful consideration of a large number of factors, some of them conflicting, and usually requires very close cooperation between the user and the manufacturer, involving perhaps an initial feasibility study to determine the best design which can be realized in practice, as well as extensive field trials of prototypes to ensure that the chosen design meets the equipment specification and will have the expected degree of reliability.

Finally there is the case where the very highest reliability possible must be obtained almost irrespective of cost. This condition must be met, for instance, in amplifying equipment in an undersea cable, because of the extremely high cost of raising the faulty length of cable for repair. Another example which may be quoted is in space research, where a failure may endanger an astronaut's life, or render useless a project costing millions of pounds. It is in fields such as these, especially those concerned with space projects, that the frontiers of reliability knowledge are being advanced, with results which will eventually help to raise the reliability of many other products.

The relationship between reliability and cost illustrates the well-known rule that you only get what you pay for. By not paying for reliability built into the product a much greater cost may eventually be incurred by the necessity for frequent repair.

Self-assessment Question 10.1

The main component parts and subsystems of a PC are listed in the table below together with their contribution to overall breakdown probability and the average maintenance cost (in US dollars). Use the data in the table to determine the breakdown probability cost per $ and identify the THREE most cost-effective areas for reliability improvement.

Component part	*Contribution to breakdown probability*	*Average maintenance cost*
Central processing unit	0.05	$125
SIMM RAM	0.05	$150
Cache RAM	0.025	$150
BIOS and configuration software	0.1	$150
Other motherboard components	0.05	$250
Connectors and cables	0.075	$100
Interface cards	0.1	$200
Floppy disk drive	0.12	$100
Hard disk drive	0.35	$250
Power supply	0.08	$150

11 Design of fault tolerant systems

Previous chapters have dealt with methods by which reliability can be determined and improved. We have also introduced the concepts of maintainability and the cost of reliability. This chapter adopts a rather different approach by looking at ways in which an equipment or system can be made to operate within specification (or to some defined lesser specification) when a fault is present.

The human body is an excellent example of a fault tolerant system. If we should suffer an injury to a limb, the muscles on our other fully functional limbs will develop in order to compensate. If we suffer the loss of one of our senses, our other senses will develop in order to make up for that loss.

The concept of a fault tolerant system is quite simple – the important thing to remember is that fault tolerance has to be designed into a product. There are four basic stages in this process:

- Firstly, we need to know that a fault has occurred – this process involves some means of monitoring the current level of performance of the equipment or system and detecting abnormal conditions when they arise.
- Secondly, we need to identify the nature and source of the fault in order to safeguard the operation of the system.
- Thirdly, we need to take the necessary action in order to maintain the performance of the system to within specified limits or to a reduced specification (as appropriate). This can be achieved in a number of different ways, including modifying the way in which the system operates (e.g. by switching a power source from one part of the system to another or by routing signals in a different direction) or by bringing redundant components and subsystems into operation (e.g. by switching to a backup power supply or a standby processor).
- Lastly, we need to update the status of the system, reporting the fault by generating appropriate messages, displays or alarms so that the user is made aware of the current state of the system. At some later stage – perhaps during a routine check cycle – the fault can be rectified and the system made to revert to its original state.

Fault tolerance

Fault tolerance can be defined as the ability of a system to operate within specification (or to some lesser defined specification) when a fault is present. Clearly, the more complex and more critical an item of equipment or system is, the more it can benefit from a degree of fault tolerance. Simple, non-critical equipment is unlikely to be a candidate for the implementation of a fault tolerant system – even though some parts of the equipment may exhibit a degree of fault tolerance in their operation.

Examples of fault tolerant systems include:

- *Flight control systems* – the new Boeing 777 has no fewer than seven Inertial Reference Units (IRU) while the Boeing 747-400 has three. Since only three IRUs are necessary at any one time, the failure of one IRU on a Boeing 777 is not particularly serious.
- *Computer networks* – computer networks are made more robust by using adaptive, fault tolerant software. A token ring network, for example, involves passing 'tokens' between stations in the network. Network software can be made to detect lost or corrupt tokens or to render invalid duplicate tokens that may subsequently be generated. This process is quite transparent to the network user who is usually blissfully unaware that a fault has occurred.

There are two basic approaches to making equipment or systems fault tolerant. One method involves the use of additional hardware while the other involves the use of software.

Hardware methods

Hardware methods involve the use of additional logic or a programmed logic array (PLA) in order to make logical decisions concerning the state of the system at any time. Hardware methods are well suited to performing such basic tasks as:

- detecting missing signals
- indicating out-of-specification supply voltages
- identifying timing or framing errors.

On a system without fault tolerance, once a fault condition has been detected, the output signal would be typically used to drive a warning device such as a signal lamp, LED, magnetic indicator, electromechanical flag or piezoelectric transducer. Where a system has a degree of fault tolerance, the output signal is used to initiate changeover to a redundant component or subsystem or to modify the behaviour of the system in such a way as to safeguard essential aspects of its operation.

Figure 11.1 shows the simplified arrangement of a fault tolerant system based on hardware.

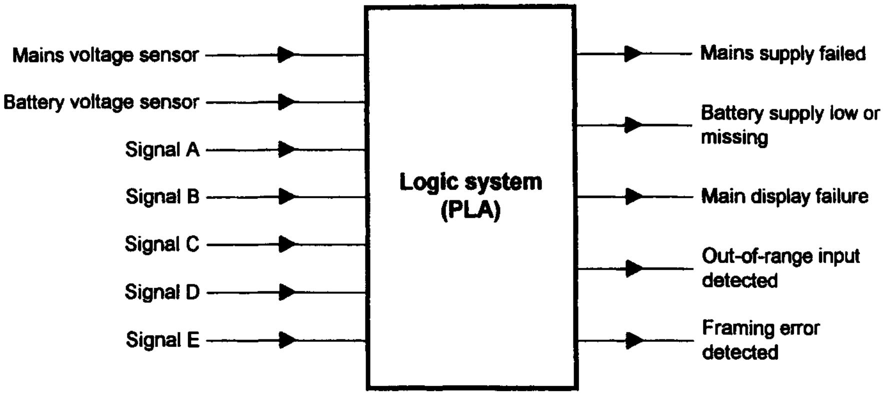


Figure 11.1.

Software methods

Software methods involve incorporating software routines, procedures or functions within control programs that will:

- perform full system diagnostics during initialization;
- perform periodic diagnostic checks during program execution (for example, periodically reading a status byte);
- ensure that out of range indications are recognized and erroneous data is ignored;
- log faults as they occur together, where possible, with sufficient information (including date and time) so that the user can determine the point at which the fault occurred and the circumstances that were prevailing at the time.

Certain fault conditions, such as loss of a power rail or a signal from a fire detection loop, are so important that they must be dealt with immediately upon detection. These signals can be given a high priority within the system of interrupt signals sent to the CPU – either directly or via an external interrupt controller.

Provided that the CPU is accepting interrupts at the current level (i.e. that its internal logic has not been placed in a state in which interrupts are 'masked' or 'disabled'), the processor will suspend its current operation (saving important data so that an orderly return can be made to the point at which it was interrupted) and then determine the source of the interrupt – for example, by polling each subsystem to establish which was the instigator of the interrupt request. Having established the source of the interrupting signal, the processor can then execute an appropriate interrupt fault correcting service routine (ISR) before returning to the previously suspended task.

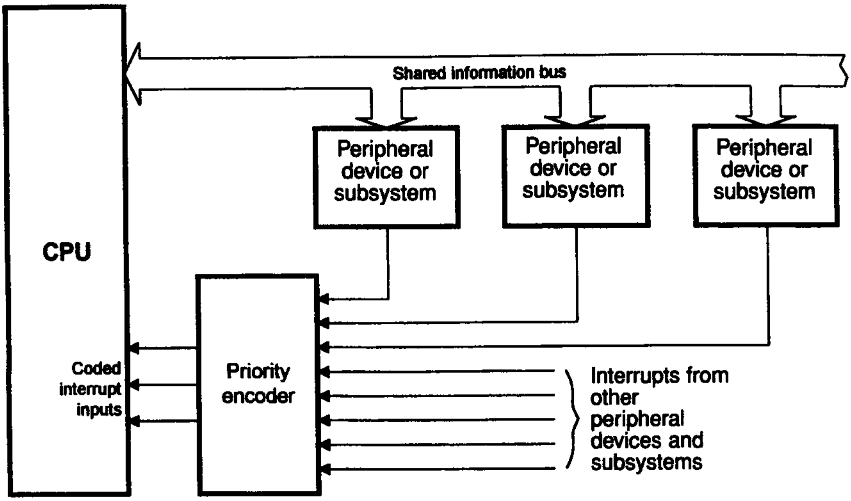

CPU
Shared information bus
Peripheral device or subsystem
Peripheral device or subsystem
Peripheral device or subsystem
Coded interrupt inputs
Priority encoder
Interrupts from other peripheral devices and subsystems

Figure 11.2.

Other, less important, fault conditions can be detected by generating one or more status bytes in which each bit represents the signal from an input or output, and then placing these bytes on the data bus where they can be read at regular intervals by the CPU. Since a very large number of fault conditions could potentially be present within a complex system, a 'look-up' table (LUT) can be used to contain a set of 'signature' bytes for each fault condition. When a fault is detected, this table is searched until a successful comparison is made and then the necessary corrective action is taken (see Figure 11.3).

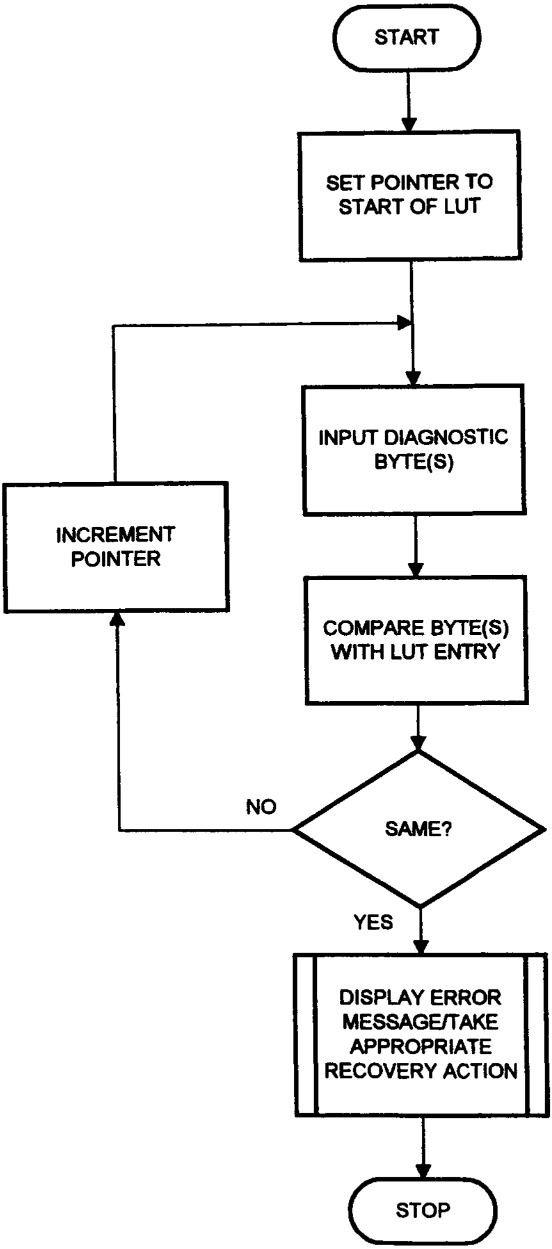

START
SET POINTER TO START OF LUT
INPUT DIAGNOSTIC BYTE(S)
INCREMENT POINTER
COMPARE BYTE(S) WITH LUT ENTRY
NO
SAME?
YES
DISPLAY ERROR MESSAGE/TAKE APPROPRIATE RECOVERY ACTION
STOP

Figure 11.3.

Finally, Table 11.1 below shows how hardware and software methods compare:

Table 11.1

	Advantages	*Disadvantages*
Hardware methods	Simple. Does not require computer processing time.	Not easy to modify or reconfigure. More suited to a limited number of fault conditions.
Software methods	Easy to modify and reconfigure. Easy to implement in systems that are already computer-based. Can easily cope with a large number of fault conditions.	Requires programming expertise. Higher initial cost. Requires computer processing time.

Self-assessment Question 11.1

For each of the following applications state whether fault tolerance is appropriate and whether it should be based on hardware or software methods:

(a) a computer controlled system designed to track a deep space probe
(b) the fire detection system in a nuclear fuel reprocessing plant
(c) a computer network used for air traffic control data
(d) a domestic satellite TV receiver.

Combination of methods

Finally, it is possible to combine software and hardware methods and enjoy some of the benefits of both hardware and software approaches. A typical example of this is a 'watchdog controller' within a programmable logic control (PLC) system or as part of a bus-based industrial controller.

The watchdog controller usually comprises an interface card or module which incorporates its own intelligent processor, interface logic, control program and timer. The watchdog controller has shared access to all the system bus lines and is therefore able to determine the status of the system at any point. The controller is also able to alert the main CPU (or current bus 'master' processor in a multiprocessing system) using one or more of the interrupt request (IRQ) or attention request (ATNRQ) lines. When these lines are asserted by the processor in the watchdog controller, the main CPU will suspend normal processing within the main control program and start to execute instructions that will initiate recovery.

The facilities available from a simple watchdog controller generally include:

- generating a status byte that is periodically read (typically every 1–2.5 seconds) by the main control program. This status byte provides an indication of the current state of the system. If the status byte is not read within a predetermined period, the watchdog controller assumes that a fault condition has been encountered and the board takes appropriate action. Typical situations which result in the watchdog status byte not being read involve major system failures, attempts to access inoperative peripheral hardware (a hardware hang) or the software running in an uncontrolled infinite loop (a software hang).
- monitoring one or more of the power rails and generating appropriate signals when the voltage present fails to meet the defined tolerances for the rail concerned. Typical actions in the event of a low voltage being detected involve preserving important system variables before switching over to backup supplies or stand-by batteries.
- the ability to exploit the multiprocessing capability of a system by making use of independent processors and, where necessary, duplicate I/O circuitry attached to independent signal conditioning boards. Typical actions in the event of detecting I/O failure involve momentarily suspending operation of the main control program, treating current data values as invalid, and switching to other multiplexed I/O lines or differently addressed devices.

12 Some useful reliability definitions

NB: There are two internationally agreed specifications on reliability definitions:

(1) IEC STD 271 and 271A 'List of basic terms, definitions and related mathematics for reliability'.
(2) MIL STD-721C 'Definitions of terms for reliability and maintainability'.

Some useful definitions for the reader are:

Accelerated test: A test in which the applied stress level is chosen to exceed that stated in the reference conditions, in order to shorten the time required to observe the stress response of the item or magnify the response in a given time. To be valid, an accelerated test must not alter the basic modes and/or mechanisms of failure or their relative prevalence.

Administrative time: That interval during which maintenance orders are being prepared. It includes all administrative delays prior to and subsequent to actual initiation of maintenance action.

Apportionment: Assigning reliability requirements to individual items within a system to attain the specified system reliability.

Assurance, quality: A technique or science which uses all the known methods of quality control and quality engineering to assure the manufacture of a product of acceptable quality standards.

Availability: The probability that the item (system) is operating satisfactorily at any point in time when used under stated conditions, where the total time includes operating time, active repair time and administrative time.

Availability, inherent: The probability that a system or equipment, when used under stated conditions, without consideration for any scheduled or preventative action, in an ideal support environment (i.e., available tools, spares, personnel, data, etc.), shall operate satisfactorily at a given point in time. It excludes ready time, preventative-maintenance downtime, logistics time, and waiting or administrative downtime.

Availability, operational: The probability that a system or equipment, when used under stated conditions in an actual operational environment, shall operate satisfactorily at a given point in time. It includes ready time, logistics time, and waiting or administrative downtime.

Burn-in: The operation of items prior to their ultimate application intended to stabilize their characteristics and to identify early failures.

Burn-in period: The beginning of the working life of a component during which the failure rate falls rapidly as items defective in manufacture are subject to early failure.

Burn-out period: The end of the working life of an item during which its failure rate increases rapidly as it becomes worn out.

Characteristic, operating: The curve which describes the probability of acceptance of a lot for various values of process average.

Component: An article which is normally a combination of parts, sub-assemblies, or assemblies and is a self-contained element of a complete operating equipment and performs a function necessary to the operation of that equipment.

Condition monitoring: Techniques used to determine the health of a set of equipments before they began to develop faults which may need attention.

Conformity: The ability of an item to meet its stated performance and/or characteristic requirements, the assessment of which does not depend essentially on the passage of time.

Control, quality: A scientific system involving the application of all known industrial and statistical techniques to control the quality of the manufactured article throughout its various production phases.

Corrective action: A documented design process, procedure, or materials change implemented and validated to correct the cause of the failure or design deficiency.

Cut set: Set of elements whose failure will cause the system to fail.

Cut set, minimal: A set of elements which has no proper subset whose failure alone will cause the system to fail.

Cycle time: The time interval from one system failure to the next system failure. The cycle time is the sum of an uptime and a downtime.

Debugging: The operation of an equipment or complex item prior to being put into service to detect and replace parts that are defective or expected to fail and to correct errors in fabrication or assembly.

Defect: A characteristic which does not conform to applicable specification requirements and which adversely affects or potentially effects the quality of a device.

Degradation: A gradual impairment in ability to perform the required function.

Derating: The intentional reduction of stress/strength ratio in the application of an item, usually for the purpose of reducing the occurrence of stress-related failures.

Design adequacy: The probability that the system will successfully accomplish its mission, given that the system is operating within design specifications.

Downtime: The total time during which the system is not in an acceptable operating condition.

Early failure period: That period during which the failure rate of some items is decreasing rapidly (sometimes also known as *burn-in period*).

Effectiveness, system: The probability that the system can successfully meet an operational demand within a given time under specified conditions.

Element: A term used generally to refer to a part, assembly, component, equipment, complete operating equipment, and/or system.

Environment: The aggregate of all external conditions either natural, manmade, or self-induced (such as temperature, humidity, radiation, magnetic and electric fields, shock, vibration, and so on) that influences the form, performance, reliability or survival of an item.

Environmental stress screening (ESS): A series of tests conducted under environmental stresses to disclose latent part and workmanship defects in order to execute corrective action.

Estimation: The evaluation of a statistical parameter for a population from a set of sample data in such a way so as to give the best indication to the true value of such a parameter.

Failure: The termination of the ability of an item to perform its required function within previously specified limits.

Failure analysis: Subsequent to a failure, the logical systematic examination of an item, its construction, application and documentation to identify the failure mode, and to determine the failure mechanism and its basic cause.

Failure, catastrophic: Failures that are both sudden and complete.

Failure, complete: Failures resulting from deviations in characteristic(s) beyond specified limits such as to cause complete lack of the required function. Note that limits referred to in this category are special limits specified for this purpose.

Failure, degradation: Failures that are both gradual and partial.

Failure density: At any point in the life of an item, the incremental change in the number of failures per associated incremental change in time.

Failure, early: The failures of components, equipments and systems which occur during the initial life phase of such devices and which are generally caused by initial production, assembly, test, installation or commissioning errors.

Failure effect: The consequence(s) a failure mode has on the operation, function or status of an item. Failure effects may be classified as local effects, next-higher effects and end-item effects.

Failure, gradual: Failures that could be anticipated by prior examination.

Failure, independent: A failure which occurs in a random manner and which has no relationship or association with any other failure.

Failure mechanism: A physical, chemical, thermal or any other process which results in failure.

Failure, misuse: Failures attributable to the application of stresses beyond the stated capabilities of the item.

Failure mode: The mechanism through which the failure occurs, that is, short, open, fracture, excessive wear, etc. Also, the effect by which a failure is observed, e.g. an open or short-circuit condition, or a gain change.

Failure mode and effects analysis (FMEA): A procedure by which each potential failure mode in a system is analysed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity.

Failure, partial: Failures resulting from deviations in characteristic(s) beyond specified limits but not such as to cause complete lack of the required function.

Failure, random: Any failure whose cause and/or mechanism makes its time of occurrence unpredictable.

Failure rate: The total number of failures within a population, divided by the total number of life units represented by that population, during a particular measurement interval under stated conditions.

Failure rate, assessed: The failure rate of an item determined within stated confidence limits from the observed failure rates of nominally identical items. Note that, alternatively, point estimates may be used, the basis of which must be defined.

Failure rate, constant: That period during which failures of some items occur at an approximately uniform rate.

Failure rate, instantaneous: At a particular time, the rate of change of the number of items that have failed divided by the number of items surviving.

Failure, secondary (dependent): Failure of an item caused either directly or indirectly by the failure of another item.

Failure, sudden: Failures that could not be anticipated by prior examination.

Failure, wear-out: A failure that occurs as a result of deterioration processes or mechanical wear and whose probability of occurrence increases with time.

Fault: An attribute which adversely affects the reliability of a device.

Fault tolerance: Ability of an equipment or system to continue to operate within specification when a fault condition is present.

Fault tree analysis: A deductive type of failure analysis that focuses on one particular undesired event at a time, and then provides a method for determining the possible causes of that event.

Free time: That interval during which the equipment is scheduled off duty.

Infant mortality: The initial phase in the lifetime of a population of a particular component when failures occur as a result of latent defects, manufacturing errors, etc., i.e. related to the early failure period.

Interval, confidence: The maximum and minimum limits which define the range within which it is expected that an observation will occur in accordance with a degree of certainty as dictated by the confidence level.

Interval, test: A specific period of time during which one or more units may be undergoing test simultaneously.

Item (in reliability): An all-inclusive term to denote any level of hardware assembly, i.e. system, segment of a system, subsystem, equipment, component, part, etc. Note that the item includes items, population of items, sample, etc., where the context of its use so justifies.

k-out-of-m: F system: That system which is failed if and only if at least *k* of its *m* items are failed.

k-out-of-m: F system, consecutive: A system which fails if and only if at least *k* successive items of the system are down, simultaneously.

k-out-of-m: F system, r-within-consecutive: A system which fails, whenever there exist *k* consecutive items, which include among them at least *r* failed ones.

k-out-of-m: G system: That system which is good if and only if at least *k* of its *m* items are good.

Latent defect: An inherent weakness that has a high probability of resulting in an early life failure.

Level, acceptable quality: The quality standard associated with a given producer's risk which is prescribed by the customer or quality engineer for the products on order. It is usually expressed in terms of per cent defective or defects per hundred units.

Level, confidence: The degree of uncertainty, expressed as a percentage, that a given hypothesis is true within a specified limit or limits.

Level of significance: A significance level associated with the test of a hypothesis which defines the expected number of times the hypothesis will be rejected even though it might be true.

Life cycle: All phases through which an item passes from conception through to disposal.

Life, shelf: The length of time an item can be stored under specified conditions and still meet specification or operational requirements.

Life, useful: The length of time an item operates with an acceptable failure rate.

Logistic time: That interval during which active repair has been suspended while awaiting the arrival of spare parts.

Lot: A collection or group of units of product from which a sample is drawn and inspected to determine compliance with applicable criteria or specifications and drawings.

Maintainability: The probability that when maintenance action is initiated under stated conditions, a failed system will be restored to operable condition within a specified total downtime.

Maintenance: All actions necessary for retaining an item in or restoring it to a specified condition.

Maintenance, corrective: All actions performed as a result of failure to restore an item to a specified condition. Corrective maintenance can include any or all of the following steps: localization, isolation, disassembly, interchange, reassembly, alignment and checkout.

Maintenance, preventive: A procedure of periodically reconditioning a product in accordance with specific instruments and scheduling to prevent or reduce the probability of failure or deterioration while the product is in service. This type of maintenance may be either scheduled or nonscheduled in nature.

Maintenance, scheduled: Preventive maintenance performed at prescribed points in an item's life.

Maintenance, unscheduled: Corrective maintenance required by item conditions.

Malfunction: Unsatisfactory operation of a device because of one or more faults.

Mean life: The arithmetic mean of the times that a group of nominally identical items spend before they cease to function permanently. This may include several cycles of failures and repairs in the case of repairable items.

Mean life, assessed: The mean life of a non-repaired item determined within stated confidence limits from the observed mean life of nominally identical items. Alternatively, point estimates may be used, the basis of which must be defined.

Mean life, predicted (for non-repaired items): The product of the number of items and their operating time divided by the total estimated number of failures.

Mean time between failures, assessed: The mean time between failures of a repairable item determined within stated confidence limits from the observed mean time between failures of nominally identical items. Alternatively, point estimates may be used, the basis of which must be defined.

Mean time between failures, predicted: The mean time between failures of a repairable complex item computed from its design considerations and from the failure rates of its parts under the intended conditions of use. The method used for the calculation, the basis of the extrapolation and the time-stress conditions should be stated.

Mean time to failure (for non-repairable items): The total operating time of a number of items divided by the total number of failures.

Mean time to failure, assessed: The mean time to failure of a non-repairable item determined within stated confidence limits from the observed mean time to failure of nominally identical items. Alternatively, point estimates may be used, the basis of which must be defined.

Mean time to failure, observed (for non-repairable items): For truncated tests for a particular period, the total cumulative observed time on a population divided by the total number of failures during the period under stated stress conditions. (1) Cumulative observed time is a product of units and time or the sum of these products. (2) The criteria for what constitutes a failure should be stated.

Mean time to failure, predicted: The mean time to failure of a non-repairable complex item computed from its design considerations and from the failure rates of its parts for the intended conditions of use. The method used for the calculation, the basis of the extrapolation, and the time-stress conditions should be stated.

MTBF (Mean time between failures): The average time an item logs in operating between its two successive failures. This is often used in the context of repairable items.

MTTF (Mean time to failure): The total operating time of a number of items divided by the total number of items.

MTTR (Mean time to repair): The average time taken to repair an item.

MTTFT (Mean time to first failure): Mean time interval from the system initiation to the first system failure.

Mission time: The period of time in which a device must perform a mission under the specified operating condition.

Operating time: The period during which the item (system) is operating in a manner acceptable to the operator.

Operational readiness: The probability that, at any point in time, the system is either operating or ready to be placed in operation on demand when used under stated conditions.

Operational time: That interval during which the equipment is in actual operation. This time is basic to reliability. Operational time is really a category related to equipment condition.

Path set: A set of elements whose functioning ensures the system success.

Path set, minimal: Set of elements which has no proper subset whose functioning alone would ensure the system success.

Quality: A measure of the degree to which a device conforms to applicable specification and workmanship standards.

Redundancy: The existence of more than one means of performing a given function.

Redundancy, active: Redundancy wherein all redundant items are operating simultaneously rather than being switched on when needed.

Redundancy, partial: Redundancy wherein two or more redundant items are required to perform the function.

Redundancy, stand-by: Redundancy wherein the alternative means of performing the function is inoperative until needed, and is switched on upon failure of the primary means of performing the function.

Reliability: (1) The ability of an item to perform a required function under stated conditions for a stated period of time. (2) The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time. Definition (2) is most commonly used in engineering applications. In any case, where confusion may arise, specify the definition being used.

Reliability, assessed: The reliability of an item determined within stated confidence limits from tests or failure data on nominally identical items. The source of the data should be stated. Results can only be accumulated (combined) when all the conditions are similar. Alternatively, point estimates may be used, the basis of which must be defined.

Reliability, extrapolated: Extension by a defined extrapolation or interpolation of the assessed reliability for durations or stress conditions different from those applying to the conditions of the assessed reliability.

Reliability growth: The improvement in a reliability parameter caused by the successful correction of deficiencies in item design or manufacture.

Reliability, inherent: A measure of reliability that includes only the effects of an item's design and its application, and assumes an ideal operation and support environment.

Reliability, predicted: The reliability of an equipment computed from its design considerations and from the reliability of its parts in the intended conditions of use.

Reliability, use: The probability that a device of known inherent reliability will perform its prescribed mission for a specified time when subjected to field human engineering factors and maintenance practices.

Repairability: A measure of the speed with which a faulty item can be repaired or replaced and a check made that the equipment is functioning normally again.

Risk, consumer's: The probability of acceptance of lots whose quality is of lot tolerance per cent defective.

Risk, producer's: The risk in a sampling plan that a lot of acceptable quality will be rejected because of sampling variations which occasionally result in a pessimistic-looking sample being drawn. This risk is usually of the order of magnitude of 5–10%.

Sample: A random selection of units from a lot for the purpose of evaluating the characteristics or acceptability of the lot. The sample may be either in terms of units or in terms of time.

Sampling, acceptance: The art or science that describes procedures which outline the criteria and method of examining samples for the purpose of determining whether to accept or reject.

Sampling distribution: The distribution of a parameter of a parent population which is obtained from the estimated values of such a parameter from the results of the total possible number of identical and independent samples.

Screening: A process for inspecting items to remove those that are unsatisfactory or those likely to exhibit early failure. Inspection includes visual examination, physical dimension measurement and functional performance measurement under specified environmental conditions.

Screening test: A test or combination of tests intended to remove unsatisfactory items, including those likely to exhibit early failures.

Serviceability: The degree of ease or difficulty with which a system can be repaired or maintained.

Step stress test: A test consisting of several stresses applied to a sample sequentially for periods of equal duration. During each period a stated stress level is applied and the stress level is increased from one step to the next.

Storage time: That interval during which the equipment is a spare – it is extra equipment intended for service only when required as a replacement.

Stress, component: The stresses on component parts during testing or usage which affect the failure rate and hence the reliability of parts. Voltage, power, temperature and thermal environmental stress are included.

Test, acceptance: Tests performed on equipment prior to shipment to a customer in order to ensure a satisfactory product.

Test, destructive: The intentional operation of a device to ultimate failure in order to discover design weaknesses which might adversely affect reliability.

Test, sequential: A series of tests taken in steps, after each of which a decision to accept, select additional samples or reject the lot is made, depending on the number of defects found with relation to the chart control limits.

Testability: A characteristic of an item's design which allows the status (operable, inoperable or degraded) of that item to be confidently and quickly determined.

Testing, nondestructive: Testing which in no manner affects the function or the life expectancy of the device undergoing test.

Tests, service: Tests which are conducted in the field under actual service conditions in order to evaluate the suitability of the device for the purpose intended.

Tie set: Same as *Path set.*

Tie set, minimal: Same as *Path set, minimal.*

Unbiased estimator: The estimated value of a parameter such that the mean value of such estimates over a large number of estimations should be equal to the true value of the parameter.

Undetectable failure: A postulated failure mode in the failure mode and effects analysis (FMEA) for which there is no failure detection method by which the operator is made aware of the failure.

Uptime: The total time during which the system is in acceptable operating conditions.

Wear-out: The third and final phase of the lifetime of a population of components when failures occur as they near the end of their working life.

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Answers to self-assessment questions

1.1 200 hours

1.2 Your three key factors might include:

- need to ensure that the customer's expectations are met (quality assurance)
- need to ensure safety of the end-user at all times (recall that these products are operated at mains potential)
- need to reduce costs associated with faulty manufacturing
- need to reduce the number of products returned under warranty.

2.1

	Cause		*Time*		*Degree*		*Combination*	
	Misuse	*Inherent weakness*	*Sudden*	*Gradual*	*Partial*	*Complete*	*Catastrophic*	*Degradation*
(a)	–	✓	–	✓	✓	–	–	✓
(b)	–	✓	✓	–	–	✓	✓	–
(c)	✓	–	✓	–	–	✓	✓	–
(d)	–	✓	✓	–	✓	–	–	✓

2.2 (a)

Time (hours)	*Calculated failure rate (% per 1000 hours)*
1 000	15
2 000	9.4
3 000	7.8
4 000	8.4
5 000	7.7
6 000	8.3
7 000	7.3
8 000	7.8
9 000	8.5
10 000	11.6
11 000	15.7

(b) Graph plotted as shown in Figure 2.1
(c) 2500 hours
(d) 7.7% per 1000 hours
(e) 9000 hours.

3.1 94 912 hours (i.e. approx. 11 years of continuous operation).

3.2 Graphs plotted as shown in Figure 3.2, MTBF = 43.47 hours.

3.3 88.5%.

4.1 40 000 hours.

4.2 8% per 1000 hours.

4.3 0.045% per 1000 hours.

4.4.1 (a) Proximity sensors
(b) Linear actuator

4.4.2 (a) Linear actuator
(b) Proximity sensors

4.4.3 0.8% per 1000 hours

4.4.4 125 000 hours

4.4.5 (a) 96%
(b) 85%
(c) 45%

5.1 (a) mechanical shock, vibration, high temperature
(b) mechanical shock, vibration, moisture
(c) salt water atmosphere, moisture, vibration
(d) rough mechanical handling, rough electrical handling (frequently over-driven), moisture
(e) mechanical shock, vibration, moisture and humidity

6.1 (a) wrong application
(b) wear-out
(c) incorrect installation
(d) failure of other parts and/or incorrect application
(e) incorrect installation
(f) defective design and/or wrong application
(g) defective design.

6.2 Items 1 to 5 and 8.

7.1 –

7.2 Figure A.1 shows the existing layout of the window anti-icing controls while Figure A.2 shows the improved layout used in a real aircraft.

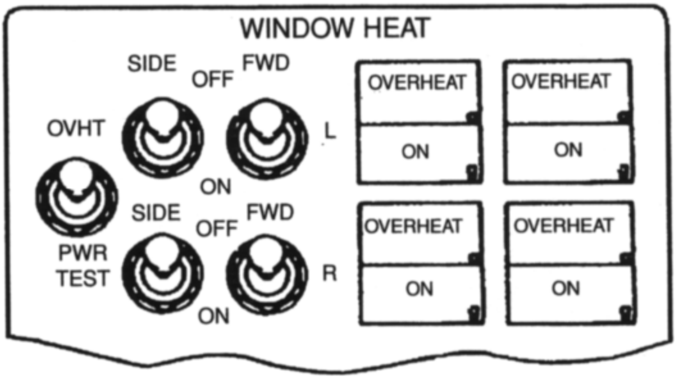

Figure A.1.

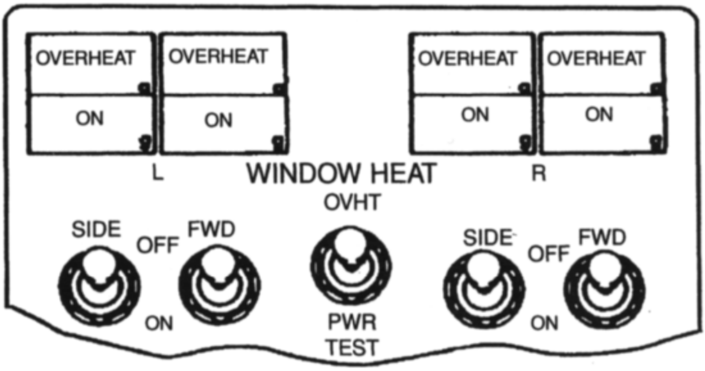

Figure A.2.

8.1 –

8.2 A typical answer might be:

Item	*Number in use (hours)*	*Estimated MTBF (hours)*	*Estimated MTTR*
File server	1	10 000	4
Workstation or networked PC	16	16 000	2
Network printers	2	8 000	3
Cabling/connectors	–	32 000	1
Network operating system (upgrade or 'bug fix')	1	6 000	2

9.1 –

10.1 Hard disk drive, floppy disk drive, connectors and cables.

11.1 (a) Fault tolerant – software
(b) Fault tolerant – hardware or software depending upon the complexity of

the system (number of sensors and automatic extinguishers)

(c) Fault tolerant – software

(d) No fault tolerance required (competitive, price-conscious market).

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(16) DEF STAN 00-41 – *MOD Practices and Procedures for Reliability and Maintainability.*

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