Reliability

Principles of reliability prediction and factors affecting the life of components

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Reliability is the responsibility of the engineer concerned with the design of a system or a sub-system, yet it seems to be one of the least understood concepts which he has to use. Engineers in general seem to prefer not to get involved in any calculations of the reliability of the equipment which they are designing. The reasons for this are probably a lack of understanding of the techniques involved — considered to be bordering on the "Black Arts" by some, and is probably largely due to the fact that the data used in reliability prediction has been derived statistically — and prediction infers crystal balls. But those who shudder at the thought of anything statistical should be reminded that even the value of a resistor is really a statistical statement and not an exact value.

MANY DESIGNERS will say "I don't need to do all those calculations. I design reliable equipment by using the best components". On the face of it this argument is quite sound, but it can only be at all valid in a situation where cost is of no consequence. Cost and reliability are closely related, and cost can be of equal, if not greater importance. There is also another aspect to be considered. The user of an equipment also has to maintain it. Nothing, however reliable, will work for ever and a prediction of failure rate is a useful indication of future maintenance effort required and likely store's holdings (today's components will not be available for ever, particularly in the rapidly developing world of electronics). These considerations may be of no importance where Grandma's portable telly is concerned, but it is a different story where a data-processing installation or a telephone exchange is concerned.

Certain aspects of reliability calculations can be a little involved. The object of this article is to present some of the fundamental ideas. Excellent works are available on the subject, of which references 1 and 2 are considered by the author to be the best.

What is reliability?

Every component, whether electronic, electro-mechanical or purely mechanical, has a finite life. After a certain period of operation there will be signs of deterioration in its performance until a point is reached where it no longer performs satisfactorily. We then say that it has reached the end of its life. These last two sentences should pose some questions in the reader's mind. Such a definition is rather loose. Unless the device ceases to function completely, that which means failure for one application may not be so for another. Again, in a test situation where a device's parameters are being measured, the end-point of its life may be different to an application where negative feedback might mask the fall-off in performance to give an extended life. We can escape this quandary by recognising that the test situation has the advantage that it yields the more pessimistic estimate of device life and furthermore, that it is application-independent.

Reliability information comes from two main sources; the component manufacturer and the user. Firstly from the component manufacturer, and this applies mainly to active electronic components, e.g., semi-conductors. Batches of components are taken from the output of the production line according to a pre-determined sampling scheme. These components are placed on life-test during which they are exposed to various types and levels of stress, according to the specification of the device, and key parameters are monitored. When any of these parameters fall outside prescribed limits the component is deemed to have failed. The cause of failure is determined in order that the mechanism of failure can be better understood. In most cases this simple picture of life testing would be impracticable due to the length of life of most electronic components; reliability data would not be available in time for it to be of any use to the designer. For this reason, accelerated life testing is used. Considerable knowledge of the relationship between the life of a component and the temperature of operation, particularly in the case of semi-conductor components, has been accumulated. Thus by testing components at a suitably elevated temperature the life can be reduced to a lower, measurable value, and the component's life at other lower temperatures may be computed.

As stated above, the type of life testing conducted by component manufacturers is application-independent. Furthermore, the test environment is closely controlled and the results which have been obtained over many thousands of device hours, enable the designer to predict the behaviour of his system even under different environmental and operational conditions. One possible draw-back with the reliability data produced by component manufacturers is that for economic reasons the number of devices of any one type that can be tested at a time is limited. Thus, it still requires a considerable length of time for the number of device-hours of testing for any particular component to reach the level required for the data to be statistically 'reliable'.

The second main source of reliability information comes from component users. In general most large organisations in the electronic and electro-mechanical sphere keep some record of the reliability of the components which they use. Some of the information may have been accumulated over many device-years and is therefore 'reliable'. These data are, however, extremely application-dependent and in the general case the published information drawn from these sources does not give details of environment, levels of stress, etc, under which the device concerned was operated. Indeed, the published information may in fact be the grand average of many different applications, etc.

This information is, in fact, very valuable. Because it is drawn from a very wide range of applications and operating conditions, it tends to present an average value and because in most cases the environment is not defined, the net result is very much more pessimistic than the data obtained from the manufacturer. Furthermore, because of the very much greater number of device-years encompassed in this type of information one may have more (statistical) confidence in it. Although the method of derivation of this information is the very antithesis of the scientific approach adopted by the manufacturer's quality control organization, i.e., it does not set out to separate and control or limit the many factors which affect reliability, this is, of course, far more typical of many industrial applications where little control can be exercised over, for example, environment. In many cases, particularly with electro-mechanical components, this may be the only source of information.

Before pursuing the subject of component life data further and its application to the prediction of equipment life we should now look more closely at some of the terms used and how they are related. We have spoken, thus far rather loosely, of reliability, when most published data tends to be in terms of 'failure rate' and 'mean time between failures' (m.t.b.f.).

Since the behaviour of most physical systems follows some sort of exponential law it will come as no surprise to the reader that the probability of a failure occurring is also an exponential function of time. Reliability is the probability that a component will perform its function correctly for a given period of time under the specified operating conditions. The term probability is used here in its mathematical sense, where complete certainty that an event will occur is given the probability value 1 and complete certainty that the event will *not* occur is given the value zero. The probability of an event occurring must therefore always be between 0 and 1[3].

We cannot simply consider the failure of a single component, since this is a single event in time: instead, we must consider what happens in the general case where a number of a given type of component operates in an equipment. If we plot the number of failures against time we get a curve similar to that of Fig 1 – often referred to as the 'bath-tub' curve. This curve has three distinct areas, the first being known as the burn-in period. During this time the number of failures is high and these are due to infant mortalities caused by component weaknesses, for example fragile leads, leakages in case seals, high leakage currents, etc. For electronic equipment this period is typically of the order of 200-300 hours and is not amenable to mathematical prediction.

At the end of the burn-in period the number of failures will have fallen to a low level and the failure rate – the number of failures per unit time – then remains sensibly constant for a very much longer period of time until the components near the end of their life, the third area where the failure rate rises due to 'wear-out' failures.

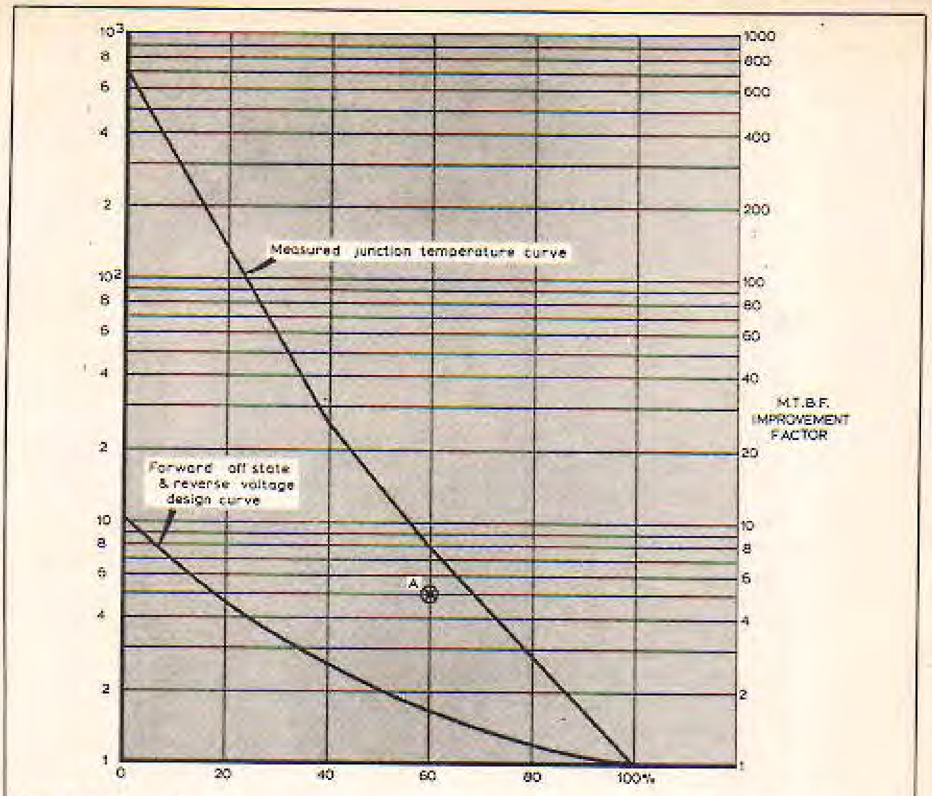

Fig. 2. *Effect of junction temperature and voltage on m.t.b.f. for silicon thyristors.*

In this article we are concerned primarily with electrical applications and of the above period that represents the useful life period. Failure studies have shown that in this period components tend to fail randomly with time and that the number of failures after a given operating time is exponentially related to time and the number of components in service. Thus:

$N_f = N_T e^{-t/m}$ .... (1)

where N_f = number of failures after time t

N_T = total number of the component in service and e = 2.71828, the base of Naperian logarithms.

The constant m was found to be the arithmetic average of the time to failure for the component concerned or m.t.b.f. Equation (1) can be rewritten in the more useful form:

$R(t) = N/N_T = e^{-t/m}$ where $R(t)$ is the probability that the component will not fail within time t, (the probability of survival). In this form $R(t)$ ranges in value from 0 (zero probability of survival) for $t = \infty$ to 1 (complete certainty of survival) for $t = 0$. From the above equation, it will be seen that, in a similar fashion to the charge/discharge curve for a capacitor resistor circuit the controlling parameter is the 'time-constant' m. For example, for $t = m$, $R(t) = 0.37$. That is, the probability of survival for a time equal to the m.t.b.f. m is 0.37 (or 37%). The probability of survival for a time of $t = 0.2m$ is $R(t) = e^{-0.2m/m} = e^{-0.2} = 0.82$ or 82%. Conversely, we can find the value of t for which the probability of survival is, say, 98%. By taking logarithms we can rearrange the equation to give:

$t = m\log_e(1/R) = m\log_e(1/0.98) = 0.02m$

That is to say we can be 98% certain that the component or equipment will operate without failure for $0.02m$ hours. Alternatively one can use the last form of the equation in a similar way to find what the equipment m.t.b.f. must be to achieve a given survival time with the required level of confidence.

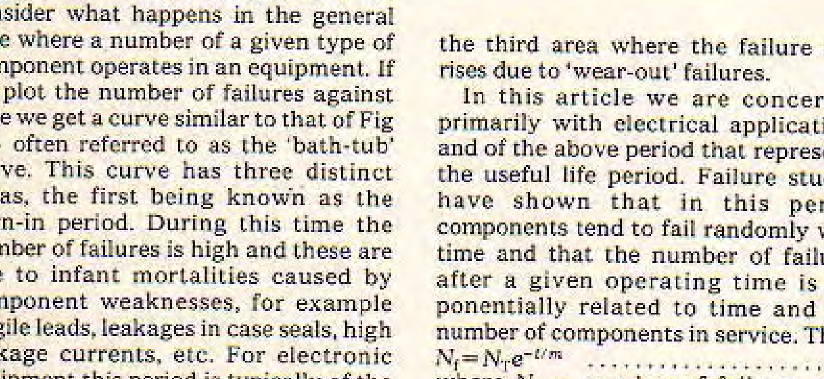

Fig. 1. *The "bath-tub" curve of failures plotted against time*

It is seen from the above that the probability of survival, that is, of operation without failure is determined by the parameter m, the m.t.b.f. It must be remembered that m.t.b.f. is, as the term implies, an average value – which in turn implies that there will be components whose time to failure will

Table 1. Component list of typical photo-electric system discussed as an example.

Component list for Photo-electric Beam Control Unit

Section	Component	Quantity	Unit Failure Rate %/1000 hours	Joint Failure Rate %/1000 hours
1. **Amplifier**	Resistors ¼ w composition	20	0.021	0.0042
	Capacitors:			
	polystyrene	9	0.0008	0.0001
	electrolytic	5	3.33	0.1665
	Transistors			
	low power 150mW	6	0.017	0.001
	Diodes signal GaAs	1	0.008	0.00008
	light source	2	0.02	0.0004
	Soldered joints	120	0.18	0.216
	Printed circuit board	1	0.01	0.0001
	Output transformer	1	0.1	0.001
2. **Relay Driver**	Resistors composition ¼ w	6	0.021	0.0013
	Capacitors polystyrene	3	0.0008	0.00002
	Transistors medium power	1	0.6	0.016
	Diodes Zener	2	0.7	0.034
	Soldered Joints	30	0.18	0.054
	Printed circuit board	1	0.01	0.0001
	Relay (2 c/o contacts)	1	1.57	0.0157
3. **Power Supply**	Power Transformer 100 VA	1	0.2	0.002
	Diodes power	4	0.7	0.028
	Capacitors electrolytic	2	3.333	0.066
	Power connector	1	0.005	0.00005
	Soldered Joints	30	0.18	0.054

be less than m and also those whose time to failure will be greater than m. It is a common misconception that the m.t.b.f. m, when quoted for an equipment, is the life which one can expect before a failure occurs. As one can see from the survival equation, one can only be 37% certain that such a life will be achieved.

Failure rate, which we have already mentioned, is related to m.t.b.f. The average failure rate of a component is $\lambda = 1/\text{m.t.b.f.}$ or $1/m$ per unit time. If m is in hours then λ is failure rate/hour. Failure rate is usually expressed as the percentage component failures per 1000 hours. For example, in a data-processing installation, 500 integrated circuits of a particular type were in service for five years. In this time only two failures were recorded. The percentage failure was, therefore,$(2/500) \times 100 = 0.4\%$. The total number of operating hours was 43680 (5 yrs). Thus, failure rate $= (0.4/43680) \times 1000 = 0.0092\%/1000$ hours. This form is useful when comparing the performance of components, but must be converted to failures per unit time when performing failures rate calculations.

Equipment reliability

So far we have only considered what happens in the life of a single component or equipment. In practice we are concerned more with the reliability of equipment which contains numbers of different components and systems which comprise more than one equipment. These two cases are in many respects the same and what follows can be applied to both. However, the reliability of a system can be complicated by the presence of duplicate elements (redundancy) such that the failure of a single one of these elements will not result in failure of the equipment.

Since an equipment will contain numbers of components of varying types and individual reliabilities we would expect the overall reliability to be lower than that of the worst (least reliable) component. The relationship above gives the probability of a component's life extending to time t. If we have two components with individual probabilities of survival of $R_1(t)$ and $R_2(t)$ respectively, their joint probability of survival to time t will be $R_E(t) = R_1(t) \times R_2(t)$. If we substitute in this expression the exponential relationship for $R(t)$ we get:

$R_E(t) = \exp(-\lambda_1 t) \times \exp(-\lambda_2 t)$ where λ_1 and λ_2 are the failure rates of the two components.

Then $R_E(t) = \exp -(\lambda_1 + \lambda_2)t = \exp(-\lambda_E t)$. Clearly $E = \lambda_1 + \lambda_2$, and the m.t.b.f. of the combination is $1/\lambda E = 1/(\lambda_1 + \lambda_2)$. This leads to a very simple rule; to find the failure rate of an equipment in which failure of the equipment results from the failure of any one of the constituent components we simply add together the individual failure rates of all the components. For example, let us consider the case of a simple photo-electric system in which a beam of modulated infra-red radiation is generated by a gallium arsenide diode and is detected by a silicon diode. A typical system with a self-contained mains power supply might contain the components shown in Table 1.

Summing the joint failure rates in the right-hand column of Table 1 yields the overall failure rates of 0.6605/1000 hours. The m.t.b.f. will therefore be $1000/0.6605 = 1514$ hours. Using the survival equation we see that we could only expect around 160 hours (with 90% confidence) of fault-free operation and this ignores, for example, failures due to the build-up of dust on the optical system. If this equipment were in use in a process-control installation with, say, nine other identical equipments and a failure of any one equipment would mean failure of the installation, then the overall failure rate would be ten times greater. The m.t.b.f. is therefore reduced to 151.4 hours. We could expect, with 90% confidence, a period of fault-free operation of only 16 hours.

Suppose that it is essential that the installation shall operate with 90% certainty for a minimum period of 22 hours without a failure. We can use the survival equation to find what overall m.t.b.f. is required; in this example we get $\text{m.t.b.f.} = 22/\log_e(1/0.9) = 208.83$, say 209 hours. This requires that the m.t.b.f. of the individual equipments must be at least ten times this value — 2090 hours.

At this stage we might reasonably question the design of this unit and consider what improvements, if any, we can make to its reliability. The first step is to examine Table 1 to see how the failure rates are distributed over the different parts of the equipment. There are three distinct parts to this equipment; the photo-cell, light source and amplifier, the relay driver and the power supply. The joint failure rates and m.t.b.fs for each are shown in Table 2.

TABLE 2
Approximate Distribution of Failure Rates

Item	Failure rate	mtbf hours
photo-cell light source and amplifier	0.3894	2568
relay driver	0.1211	8258
power supply	0.1501	6662

In this case the photo-cell, light source and amplifier contributes most to the unreliability of the system. One now has to decide whether any worthwhile improvements can be made.

The m.t.b.f. of the relay driver and power supply together is 3687 hours and this represents the highest m.t.b.f. which can be achieved — by reducing the failure rate of the amplifier to zero. Although this is not possible, this calculation does enable one to answer the question 'is any improvement likely to be significant?'. In this case, if the amplifier failure rate were zero the m.t.b.f. of the system would be increased by a factor of 2.5. In practice, of course, we cannot expect to achieve such a vast improvement, but at least the scope is there. Had the ratio been much smaller, it is doubtful whether any practical improvement could be made which would be significant when compared with the rest of the system.

The two components with the highest failure rates are the electrolytic capacitors and the soldered joints. Provided the required values are not high the electrolytics can be replaced by Mylar film types with a unit failure of 0.0008%/1000 hours. This results in an overall m.t.b.f. for the amplifier of 4485. The overall m.t.b.f. for the equipment becomes 2023 hours; an improvement of 34%. The likely cost of this modification would be small, so a worthwhile improvement would be obtained.

As far as the other high failure rate component is concerned — the soldered joints — a significant reduction could only be achieved by a pro-rata reduction in the number of components. For example, if the amplifier could be replaced by two operational amplifiers in dual-in-line integrated packages, then the number of soldered joints would be reduced to about 60, but there would be a considerable reduction in the other components also. An estimate of the resulting failure rate (assuming the integrated circuits to each have failure rates of 0.0005%/1000 hours) is 0.1097/1000 hours. The resulting m.t.b.f. of the amplifier is therefore 9115 hours, and the overall m.t.b.f. of the equipment becomes 2625 hours, making the overall improvement due to both modifications about 1.7:1. This second modification is quite drastic however and would only be considered at the design stage of the equipment.

The time for which we could expect fault-free operation of ten units (with 90% confidence) is now increased to 27.7 hours. Clearly this is a considerable improvement but it is still hardly a satisfactory situation. In the original example we quote the case of ten such units, the failure of any one unit causing system failure. In such a situation we would be justified in looking for further improvements, but some of these may affect the design of the rest of the installation and would require careful consideration. Redesigning the relay driver to eliminate the relay, for example; although it would increase its intrinsic reliability, it would mean a drastic change in the interface with the rest of the system. Undoubtedly the power supply is another high failure rate area with its electrolytic capacitors and high power level devices. If the overall system design would permit, since 10 such photo-electric units are used, the use of a common power supply would make a significant change to the overall reliability. The joint m.t.b.f. for 10 units would become (assuming the improvements to the amplifier discussed above) 422 hours, nearly a 3:1 improvement over the original situation.

The above example serves to bring out one or two important points. The overall failure rate of an equipment will be greater, sometimes very much greater than that of any of the components used. Whether or not this overall failure rate is acceptable depends upon the system in which it is being used. Failure implies maintenance and calculation of the expected annual maintenance cost is often the best criterion for determining whether the expected failure rate is acceptable or not. It may seem a defeatist attitude to even consider that a failure rate could be acceptable but we must not lose sight of another factor — that the capital cost and the failure rates of components are closely related. For example, in the case of t.t.l. integrated circuits, when the costs and reliabilities of different packages are compared it is seen that by using Class A devices the cost is increased by a factor of 3:1 over that of industrial devices, whilst the m.t.b.f. is increased by a factor of 5.

Unfortunately there is no easy solution to this problem. A process of trial and error must invariably be used, employing a table similar to that of Table 1, but with an additional column giving the cost of each type of component, so that each component change will enable not only the effect upon reliability but also upon cost to be calculated. This table is inspected to identify those components which significantly affect the overall failure rate and alternative components and/or circuit redesign considered to improve the reliability bearing in mind the effect this might have on the overall capital cost. It may well pay to trade-off increased capital cost against reduced maintenance costs since the former is a 'once only' cost whereas the latter is a continuing cost.

It has already been remarked that failure rate of an equipment is not always due to complete failure of a component but instead is due to parameters varying with age and falling outside acceptable limits. It follows therefore that a positive contribution to reliability can be made by proper attention to equipment design. Electronic circuits should be designed to be as tolerant of component parameter variation as possible. Computer programmes are available which enable circuits to be simulated and the effect of component parameter variations to be accurately determined as well as power dissipations and stress levels. As well as making for a more reliable equipment these design techniques can lead to cheaper designs using wider tolerance components. The design of circuits which are tolerant of component parameter degradation is also very dependent upon the equipment performance specification. Performance specifications should not be unnecessarily tight since this is immediately reflected in component tolerances.

Choice of components

The reliability of a component is determined by various factors and the degree to which these factors are operative in a given equipment must be decided by the equipment designer before an accurate assessment of reliability can be made. Some of the factors which affect the reliability of a component are:

— component quality and type of construction
— temperature
— vibration
— humidity
— electrical stress level.

Component manufacturers aim their products at various application fields and often have separate product lines for each – military and aero-space, industrial, domestic consumer, etc. Particularly in the semi-conductor industry the specifications for each of these fields are well defined. For example, in the case of t.t.l. integrated circuits the military product line differs from the industrial version in packaging as well as the performance testing to which the finished product is exposed (on a batch-sampling basis). There are significant differences in the reliability obtained but there are also equally significant differences in cost.

Capacitors are another example of a component field in which there are many types of construction. Here the constraints on the designer are not only cost and reliability but also physical size, maybe weight, and electrical performance. One may for example be faced with the quandary of requiring a silver-mica construction from stability considerations, a polystyrene in order to meet space requirements, etc.

The effect of temperature upon the life of a component may be judged in a qualitative fashion by remembering that the rate at which a chemical reaction takes place doubles for every 10°C rise in temperature. In general, electrical components show an increase in their useful life as their operating temperature is reduced. Fig. 2 shows the relationship between junction temperature and m.t.b.f. for silicon transistors.

At high temperatures other effects come into play which affect the mechanical structure of the device in addition to affecting its electrical operation; for example, thermo-plastics soften and distort at temperatures around 95°C, metal-glass seals rupture due to differential expansion and dielectrics change their characteristics. Under these conditions it is difficult also to maintain stable temperature levels and thermal run-away often occurs. For these reasons electronic equipment should be designed so that it operates well within the temperature ratings of its components with adequate ventilation to remove excess heat. In calculating the expected operating temperature of an equipment the effect of external sources of energy such as solar radiation should also be considered in addition to the expected range of ambient temperatures.

At the other extreme, operation of equipments at low temperatures can also adversely affect the life expectancy. For example, differential contraction of materials in seals, hardening of oils and grease in bearings. Complete failure of electrolytic capacitors, primary and secondary cells (except the Nickel-Cadmium type) in which the electrolyte has a very much lower freezing point than the lead-acid type.

Associated with the effects of operating temperature is the electrical stress level at which a component is operated. In the case of semiconductors, reduction of the applied bias and operating current and voltage levels results in a significant increase in useful life. Tungsten filament lamps which typically have useful lives of some 2,000 hours at full rating, show an increase of up to five times this value for a derating of only 10%.

Closely associated with temperature is humidity. The absolute humidity is determined primarily by the air temperature and is highest at high temperatures and generally decreases with the temperature. Of all the various environmental factors humidity has probably the greatest effect upon component life, and performance. Absorption of moisture by a material used as a dielectric or just as an insulant causes an increase in loss angle with consequent local generation of heat and reduction in performance. Absorption also leads to dimensional changes, lowering of flexural strength and, over a period of time, corrosion of metallic parts, which is exacerbated by galvanic action where the contact of dissimilar metals is involved.

Any equipment which moves or in which there are moving parts will suffer vibration. The design of mechanical structures to minimise the effects of induced vibration upon the components is a complex exercise. To be carried out effectively the precise nature of the induced vibration in individual components must be known. In certain cases the effects of vibration may be alleviated by the use of anti-vibration mounts. Joints of all kinds and connectors are particularly vulnerable, as also are potentiometers, variable capacitors, switches, lamps and lamp-holders.

In this context particularly one must also consider the effects of maintenance work. This is one of many aspects of reliability where there is intersection with the subject of maintainability. In this particular case any component which may be moved in the course of testing may be subjected to damage.

For example, it is often necessary to remove printed circuit boards in order to mount them on extender boards or to effect a repair. Apart from affecting the electrical contact between the mating contacts of the edge connector due to disturbance of dirt and oxidation layers — which should be cleared anyway before re-insertion — physical damage may also occur during the removal/replacement process. Careful selection of board connectors and design of their mounting plays an important part here. Similar problems arise where it is necessary to replace components. The quality of soldered joints must be controlled and the damaging effects to printed-circuit tracks and the board minimised.

It is, of course, an intractable problem as far as reliability is concerned to include the above and similar effects in any reliability equations at the design stage, unless one has available historical records for similar equipment operated and maintained under similar conditions. However, one is able at the design stage to design with the maintainability of the equipment in mind. The process whereby a faulty component is located should be made as direct as possible thus minimising the amount of speculative board removal and replacement for testing which otherwise occurs in practice.

It is not possible to consider these and other topics which affect reliability in greater detail within the scope of this paper. The subject is very adequately and explicitly dealt with in reference 2, which also goes a long way towards formulating the whole process of reliability calculations.

System reliability

Much of the foregoing discussion on equipment reliability applies also to system reliability. The system designer will be concerned with integrating a number of equipments into a complete system. When he has some control over the design of the individual equipments also, he will have the necessary data from which to assess the overall system reliability. A difficulty arises, however, with proprietary equipment, for example, a digital processor, where the system designer must rely to a large extent upon the information provided by the equipment supplier, weighted by any previous experience.

The system designer's work does not start when all the separate equipments comprising the system have been designed, it must start, before any detailed design can begin, with the complete specification of the system for which he must state the required minimum overall system performance objectives. These objectives must include minimum reliability and maximum cost boundaries. It would be super-idealistic to suggest that such boundaries can be fixed absolutely at this early point in the design but an initial feasibility study would indicate where they should be.

The overall design of a system from a reliability point of view requires more than the simple integration of a number of component equipments and the calculation of the overall reliabilities. In the earlier example of a photo-electric system the reliability which was calculated referred only, in this case, to its electrical performance. In practice the system designer must consider the overall operation of the system. In this example, experience shows that in most industrial applications of photo-electric systems an important contributory factor to the un-reliability of the system, is the accumulation of dust on to the exposed optical surfaces. Prior knowledge of this factor could be taken into account in the design of the optical system and any recorded data relating to failure due to this cause used when calculating the expected m.t.b.f.

Furthermore, the remarks made above regarding the effects of maintenance work on the reliability of an equipment apply equally to a complete system. It is, therefore, equally imperative that the quality control of maintenance work should be at least, as vigorous as that employed at the manufacturing stage. This consideration together with the rising cost of maintenance for complex electronic systems has made the employment of centralised repair depots economically viable. First-line servicing is thus reduced to the task of identifying and replacing a faulty module.

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