UNIT-5

RAM ANALYSIS

5.1 RELIABILITY, AVAILIABILITY& MAINTAINABILITY

(RAM ANALYSIS)

Introduction

The word reliability means different things to different people. Trustworthy, dependable and consistent are the words, which can be used to give an indication of why the characteristic of reliability is valued.

A simple example to understand the reliability is human behavior, a person who attends his work place or attends his work without failure is considered as more reliable.

Reliability engineering is a combination of management and technical disciplines whose objective is the assurance of maximum time stability of a product`s specified performance. A person who completes his work in time is said to be more reliable than the other who does not. Concept of reliability is not only associated with human behavior or activity but can also be applied to other inventions. The reliability of a product is directly measured with its performance or by knowing the failure rates of the product.

To face the present competitive world on organization needs efficient, economic and continuous running equipments. The basic need of any organization is to achieve their targeted production at a minimum cost.

It must be noted that reliability engineering received its original impetus from military requirements, as during world war II the failure of many military operations gave rise to the need of reliability. As a result, the US department of defense and the electronics industry set up a joint task force-AGREE (the Advisory Group on Reliability of Electronic Equipment) in 1950. AGREE was the formal beginning of current reliability thinking.

Definition of Reliability

The reliability of a system is the probability that the system performs its specified function under specified operating environmental conditions without any failure for a specified time period. Quantitatively, reliability is the probability of success.

The objective of reliability engineering is to increase the capacity of a equipment/system to function under extreme conditions for a long period of time and without failures.

Causes of Failure

A product or system may fail due to various reasons. It is necessary to find all the possible causes, as far as possible, in order to prevent or minimize them.

The main reasons for occurrence of failure are as follows:

1. **Poor design:** Poor design is the primary reason behind the failure of any system or product. A poor system design might be inherently incapable to carry out the task assigned. It might be too weak for applied stress, and can suffer with malfunctioning at given temperature and so.
2. **Overstressed:** The component may be overstressed in some way. If applied stress exceeds strength of component then failure will occur. Designers provide some margin to decrease the chances of occurrence of such failures. In most cases, it is ensured that in-service worst case stress does not surpass the rate stress value. This is known as derating.
3. **Wearing out:** Wearing out is the process that causes an item to become weaker with age. For example, material fatigue, wear between surfaces in moving contact, corrosion etc.
4. **Errors:** Errors can cause failures such as incorrect specification, designs or software bug., by faulty assembly or test, by inadequate or incorrect maintenance, or by incorrect use.
5. **Poor maintenance:** If component or a subsystem is not properly maintained, then failures may occur due to breakdown of components. Proper maintenance is necessary to avoid such failures.
6. **Improper installation:** Improper foundation, excessive vibration, inadequate environment, wrong inputs, poor accessories all these factors affect the life of a component and increase failure rate.
7. **Complexity:** Complex systems have more number of components which makes it difficult to understand, operate, and maintain them as compared to simple systems. Hence complexity decreases the overall system reliability.
8. **Improper testing:** Wrong methods of testing, improper burn-in, inadequate data management and usage of improper modes for quantification are some other reasons for failure of equipments.
9. **Human error:** Lack of understanding of system/equipment, carelessness, forgetfulness, poor judgements, lack of skills, physical disability and fatigue are the causes of human errors that in turn result in increased failure rate.
10. **Operational instructions:** Wrong instruction, poor language manual and lack of clarity in instructions because of which they are difficult to understand are also the reasons that are responsible for increase in number of failures.
11. **Others:** Failures can be caused by other time dependant mechanisms. Battery run down, deformations caused by simultaneous high temperature and tensile stress, as in turbine discs, and fine solder joints etc. are the examples of such mechanisms.

5.2 Failure Data Analysis

Failure data analysis involves organization of data for specific components or subsystems and identification of their failure events and rates.

For the evaluation of various parameters, failure data is obtained for the components. This is done through either experiment or simulation. Various tests are carried out on the items to study the failure behaviors and then failure data is obtained. This data is then used for further estimation of required parameters.

Failure Rate

Failure rate is the ratio of number of failure to the average population (number of items) during a particular time interval. This is generally denoted by '$\boldsymbol{\lambda}$'. Failure rate is defined as the probability that a failure per unit time occurs in the interval $(t_2 - t_1)$ given that a failure has not occurred prior to 't_1'. Thus.

$$\lambda(t) = \frac{R(t_1) - R(t_2)}{(t_2 - t_1)R(t_1)}$$

If interval $[t_2 - t_1]$ is redefined as $[t, t + \Delta t]$ then

$$\lambda(t) = \frac{R(t) - R(t + \Delta t)}{\Delta t. R(t)}$$

Mean Failure Rate

Mean failure rate is the average value of all the failure rates in successive unit time intervals during a complete operation cycle. In other words, it is the ratio of sum of all failure rates to the total up time i.e., total operation time. Mathematically, mean failure rate is given by:

$$Mean\ failure\ rate = \frac{\lambda_1 + \lambda_2 + \ldots + \lambda_n}{T}$$

Where, T = total time of operation.

Failure Density

Failure density is defined as the ratio of total number of failures during a given time interval to the total number of items at the beginning of test. Total number of items at the beginning is called total initial population.

Thus, failure density

$$f_d = \frac{total\ failures\ durig\ \Delta t}{Total\ items\ before\ \Delta t}$$

$$f_d = \frac{n}{N}$$

Hazard Function or Hazard Rate

We have seen that failure rate is defined for a finite time interval. Hazard rate is defined as the limit of failure rate as the interval approaches towards zero. In other words, hazard rate $h(t)$is the instantaneous failure rate, and is defined as:

$$h(t) = \lim_{\Delta t \to 0} \lambda(t)$$

$$= \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{\Delta t. R(t)}$$

$$= \frac{1}{R(t)} \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{\Delta t}$$

$$h(t) = \frac{1}{R(t)} \left[-\frac{d}{dt} R(t) \right]$$

Mathematical Analysis

Suppose n_0 identical components are subjected to a design operating condition test. During the interval of time $(t - \Delta t, t)$, it is observed that number of failed components is $n_f(t)$ and that of surviving components is $n_s\ (t)$. Thus

$n_s\ (t) + n_f(t) = n_0$.now, since reliability is defined as the cumulative probability function of success, then at time t, the reliability $R(t)$is:

$$R(t) = \frac{n_s(t)}{n_s(t) + n_f(t)} = \frac{n_s(t)}{n_0}$$

If ‘T’ is a random variable denoting the time to failure, then the reliability function at time ‘t’ is expressed as:

$$R(t) = P(T > t)$$

The cumulative distribution function (cdf) of failure is the complement of R(t), i.e.

$$F(t) = 1 - R(t)$$

$F(t)$ is also known as unreliability.

If probability density function of time to failure (T) is $f(t)$ then

$$F(t) = \int_0^t f\,(\tau)d\tau$$

Equation can be written as:

$$R(t) = 1 - \int_0^t f\,(\tau)d\tau$$

Differentiating with respect to t

$$\frac{dR(t)}{dt} = -f(t)$$

For a given interval $[t_1, t_2]$,

$$-\int_{t_1}^{t_2} f\,(t)dt = R(t_2) - R(t_1)$$

$$\int_{t_1}^{t_2} f\,(t)dt = R(t_1) - R(t_2)$$

Thus we define the failure rate in time interval $[t_1, t_2]$ as the probability that a failure per unit time occurs in the interval given that no failure has occurred prior to t_1, the beginning of the interval.

Thus the failure rate is expressed as:

$$\lambda(t) = \frac{R(t_1) - R(t_2)}{(t_2 - t_1)R(t_1)}$$

Similarly hazard rate

$$h(t) = \frac{1}{R(t)}\left[-\frac{d}{dt}R(t)\right]$$

$$h(t) = \frac{f(t)}{R(t)}$$

now, integrating both sides with respect to ‘t’ between 0 to t

$$\int_0^t h\,(t).\,dt = -\int_0^t \frac{1}{R(t)}\frac{d[R(t)]}{dt}dt$$

$$-\int_0^t h(t).\,dt = \int_0^t \frac{dR(t)}{R(t)}$$

$$1n[R(t)]|_o^t$$

Using $\quad R(0) = 1$

$$-\int_0^t h(t).dt = 1n[R(t)]$$

$$R(t) = e^{-\int_0^t h(t)dt}$$

Mean Time to Failure (MTTF)

Mean Time To Failure (MTTF) is the expected time to failure of a component or system. That is, the mean of the Time To Failure (TTF) for that component or system.

If we have life tests information on a population of N items with failure times $t_1, t_2 \dots \dots, t_n$ then MTTF is defined as the expected value of the random variable 'time to failure' and it can be expressed as:

$$MTTF = \frac{1}{N}\sum_{i=1}^{N} t_i$$

Integral form: Let there be a random variable (lifetime) T having probability density function $f(t)$and reliability function $R(t)$, then MTTF would be

$$MTTF = E(T) = \int_0^\infty tf(t)dt$$

Using equation

$$= \int_0^\infty t\left(-\frac{dR(t)}{dt}\right)dt$$

$$= [-tR(t)]_0^\infty + \int_0^\infty R(t)dt$$

If $\lim_{t\to\infty} R(t) = 0$; which is true for practical distributions, then $[tR(t)]_0^\infty = 0$. So we get

$$MTTF = \int_0^\infty R(t)dt$$

Mean Time Between Failure (MTBF)

The MTBF is the expected time to failure after a failure and repair of the component or system. MTBF is similar to MTTF, but it is used for repairable items.

Down time: It is the time taken to repair the system. It is calculated from the time of breakdown to the time the system is put back into operation.

Up time: It is the period for which an equipment remain operational without any failure. The "time between failures" is the time for which the system remains operational between two successive failures.

Hence, MTBF is the ratio of the sum of the time periods for which system remain operational to the number of observed failures.

$$\rightarrow \qquad MTBF = \frac{Total\ up\ time}{number\ \ of\ failures}$$

$$= \frac{Total\ time - total\ down\ time}{number\ of\ failures}$$

$$= \frac{NT - \sum_{i=1}^{N_f} T\,D_i}{N_f}$$

Where, N_f = number of failure

TD_i = down time in i_{th} repair

$$or \qquad MTBF = \frac{NT - N_f(MDT)}{N_f}$$

Where MDT = mean down time

$$\frac{1}{N}\sum_{i=1}^{N_f} T\,D_i$$

MTTF v/s MTBF

Mean time to failure is a basic measure of reliability for non-repairable system. It is the mean time taken by the system before the first failure occurred or in other words it is the expected time to failure of a system. Thus MTTF is generally used for the non-repairable system. That is system cannot be repaired once deployed. On the other hand, MTBF is the mean time between successive failures. Hence it is directly connected to repairable systems as repairable systems can fail several times. It denotes the availability of system. Following diagram clarifies the basic idea.

Failure Modes and Bathtub Curve

In general, failures can be grouped into three different modes depending upon the nature of failure.

1. **Initial Failures or Infant Mortality**

When we put a large collection of units into operation, it is likely that there are a large number of failures initially. These early failures are called initial failure or infant mortality. The main causes behind these failures are manufacturing defects, poor insulation, bad assembly, poor fits, etc. Since the defective units are eliminated during the initial failure period, this period is known as debugging or burn-in period.

2. **Random Failures or Catastrophic Failure**

After initial failures, for a long period of time of operation fewer failures are reported. It is difficult to uncover the reason behind their cause and they usually occur due to sharp change in parameters determining the performance of units, either as a result of the change in the working stresses or environment conditions. To predict the amplitude of stress variation and their time of occurrence is a difficult job, hence the failures during this period are called random failures.

3. **Wear Out Failures**

As time passes on, the units get outworn and begin to deteriorate. Failure rate increases because most of the components have exceeded their service life. The changes are irreversible physio-chemical in nature. Failures in this time region are called wear out failures.

A typical curve showing all these modes The graph is used for showing hazard rate.

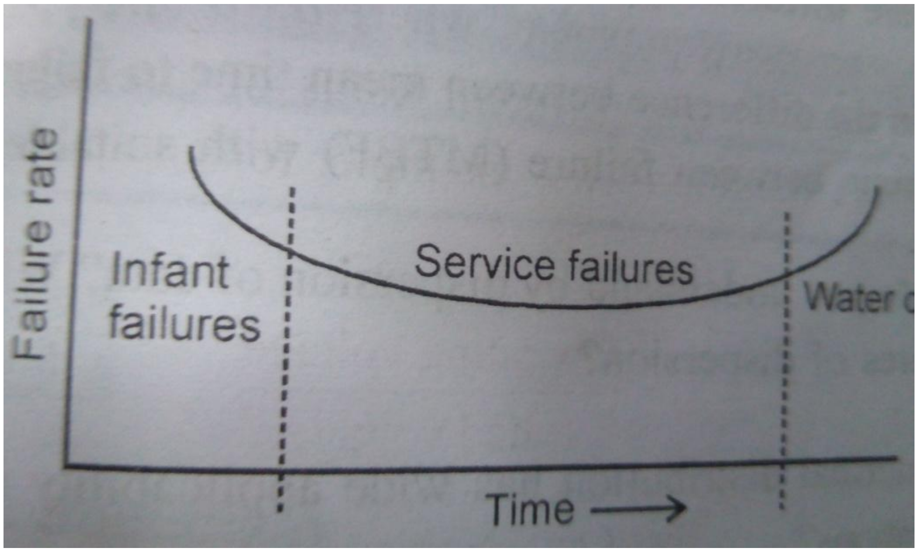


Figure - Bathtub curve

It has been observed that if we conduct life test on any type of product or system, and plot the hazard rate as a function of time, it follows a pattern similar to a bathtub and hence it is known as bathtub curve due to its special shape. As shown in figure this curve can divided into three distinct regions. The first region shows initial failures caused due to bad design, wrong manufacturing process, inadequate selection of material and poor quality. This region shows high hazard rate. The hazard rate then gradually reduces and stabilizes to a constant value in the second region, which corresponds to the useful life period. The second region shows catastrophic failures and therefore it is difficult to find any specific reasons behind their occurrence. To avoid these type of failure due care must be taken in design phase. After this period, the hazard rate again starts increasing rapidly due to fatigue, material deterioration, stresses, ageing, etc. which are caused by prolonged use of the equipment/system. This region is known as wear-out failure can be delayed by following well designed maintenance strategies that extend the useful life of the equipment by delaying the start of ageing phenomenon. Many manufacturers of high-reliability components subject their products to an initial burn-in period of t_1 time to eliminate the products having initial manufacturing defects. The period t_2-t_1 is the useful life time of the product and after t_2 time, the item must be replaced by another pretested item. It is because, the value of reliability R(t) is one for t = 0 and decreases continuously with the passage of time.

Failure or Hazard Rate Models

A failure or hazard rate model can be any probability density function (PDF), $f(t)$, defined over the range of time from $t = 0\ to\ t =\propto$. The most commonly used failure rate models are the constant failure rate and the weibull failure rate models.

Constant Failure Rate Model

Constant failure rate model are very easy to calculate and generally used to describe a system.

If a system has constant failure rate, i.e. failure rate is independent of time, then various expressions can be derived as following:

Consider that failure rate is

$$\lambda(t) = \boldsymbol{\lambda} = constant$$

Then hazard rate

$$h(t) = \lim_{\Delta t \to 0} \boldsymbol{\lambda}(t) = \boldsymbol{\lambda}$$

since '$\boldsymbol{\lambda}$' is independent of time, and $h(t)$is the instantaneous value of $\lambda(t)$, they both are equal for this model.

System reliability:

$$R(t) = e^{-\int_0^t h(t)dt}$$

$$= e^{-\int_0^t \lambda.dt}$$

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

Thus, system reliability varies exponentially. Hence, this model is also called "Exponential distribution model".

Mean time to failure

$$MTTF = \int_0^\infty R(t)dt$$

$$= \int_0^\infty e^{-\lambda t} dt$$

$$= \left[\frac{e^{-\lambda t}}{-\lambda}\right]_0^\infty$$

$$= \frac{-1}{\lambda}[0 - 1]$$

$$\therefore \qquad MTTF = \frac{1}{\lambda}$$

Thus, MTTF is the inverse of failure rate in case of constant failure rate system.

Weibull Distribution

The weibull distribution is a continuous probability distribution named after Waloddi Weibul. The weibull distribution is perhaps the most widely used of all the failure time distributions and it is noted for its flexibility as a model.

In general, the probability density function of a weibull random variable x is defined as:

$$f(x, \eta, \beta) = \begin{cases} \dfrac{\beta (x-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(x-\delta)}{\eta}\right]^{\beta}} & x \geq \delta \\ & x < \delta \end{cases}$$

Where, $\beta =$ shape parameter.

$\eta =$ scale parameter.

$\delta =$ location parameter.

the various plots of weibull distribution for different values of shape parameter β and scale parameter η.

If we use it to describe "time-to-failure" (t) then:

$$f(t) = \begin{cases} \dfrac{\beta (t-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} & t \geq \delta \\ & t < \delta \end{cases}$$

Where, $\beta =$ failure pattern parameter

$\eta =$ characteristic life parameter.

$\delta =$ minimum life parameter.

Then,

(a) $\beta < 1$ indicates that the failure rate decrease over time. This denotes the "infant mortality" region of "bath tub" curve.

(b) $\beta = 1$ indicates that the failure rate is constant over time which denotes the "Random/catastrophic failure" region of bath tub curve.
(c) $\beta > 1$ indicates that the failure rate increases over time. It denotes "wearout/ageing" region on the bathtub curve.

Location or minimum life parameter δ: if can be considered as a guarantee period within which no failures occur, and a guaranteed minimum life could exist. This means that no appreciable or noticeable degradation is evident before δ hours of operation. However, when a component is subjected to failure immediately after being put to service, no guarantee or failure-free period is apparent, then $\delta = 0$.

Scale or characteristic life parameter η: This parameter is a constant and is the mean operating period. In terms of system unreliability, it is the operating period during which at least 63% of the system`s equipment is expected to fail.

Shape or failure pattern parameter $\boldsymbol{\beta}$: It determines the contour of the weibull PDF. By finding the value of β for given set of data, the particular phase of an equipment`s characteristic life may be calculated.

Weibull Analysis

1. **Three Parameter Weibull**

The general form of weibull distribution is known as 3-parameter weibull. If we consider weibull distribution of "time-to-failure" then its probability density function (pdf) would be:

$$f(t) = \begin{cases} \dfrac{\beta(t-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} & t \geq \delta \end{cases}$$

The cumulative distribution function (cdf) of the three-parameter weibull distribution can be obtained by integrating pdf between 0 to t.

$$F(t) = \int_0^t f(t)dt$$

$\because for f(t), \geq \delta,$ therefore limits will change from $o\ to\ t, to\ \delta\ to\ t$

$$now \qquad f(t) = \int_{\delta}^{t} \frac{\beta(t-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} dt$$

$$= \frac{\beta}{\eta^{\beta}} \int_{\delta}^{t} (t-\delta)^{\beta-1} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} dt$$

$$F(t) = 1 - e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}}$$

Now, $R(t) = 1 - F(t)$

$$\therefore \qquad R(t) = e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}}$$

Also hazard rate is given by

$$h(t) = \frac{f(t)}{R(t)}$$

$$\therefore \qquad h(t) = \frac{\beta(t-\delta)^{\beta-1}}{\eta^{\beta}}$$

This is known as three parameter weibull because $f(t)$varies with three parameters $\beta, \delta\ and\ \eta$.

2. **Two Parameter Weibull**

This is the special case of three parameter weibull with location parameter $\delta = 0$. Hence we can obtain result by putting $\delta = 0$ in respective expressions.

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} e^{-(t/n)^{\beta}}$$

$$F(t) = i - e^{-(t/n)^{\beta}}$$

$$R(t) = e^{-(t/n)^{\beta}}$$

$$h(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}}$$

Mean and Variance of Weibull

Probability density function for weibull is:

$$f(t) = \frac{\beta(t-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} t \geq \delta ,$$

Mean of a continuous distribution function whose pdf is $f(t)$is given by:

$$E(T) = \int_{-\infty}^{\infty} t f(t) dt$$

$$E(T) = \int_{-\infty}^{\infty} t.\frac{\beta(t-\delta)^{\beta-1}}{\eta^{\beta}} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} dt$$

$$= \int_{-\infty}^{\infty} t\frac{\beta}{\eta}\left(\frac{t-\delta}{\eta}\right)^{\beta-1} e^{-\left[\frac{(t-\delta)}{\eta}\right]^{\beta}} dt$$

By putting $\left[\frac{(t-\delta)}{\eta}\right]^{\beta} = z,$

And then differentiating it we get

$$\beta\left(\frac{t-\delta}{\eta}\right)^{\beta-1}\frac{1}{\eta}dt = dz$$

$$\rightarrow \qquad \beta z^{\frac{\beta-1}{\beta}}\frac{1}{\eta}dt = dz$$

$$\rightarrow \qquad \frac{\beta}{\eta}dt = z^{\left(\frac{\beta-1}{\beta}\right)}dz$$

Using equation (3.31) and (3.32) in equation (3.30)

$$E(T) = \int_{0}^{\infty} \left[z^{\frac{1}{\beta}}\,\eta + \delta\right] e^{-z}dz$$

$$= \int_{0}^{\infty} \left[z^{\frac{1}{\beta}}\,\eta + \delta\right] e^{-z} + \int_{0}^{\infty} \delta e^{-z}dz$$

$$= \int_{0}^{\infty} z^{\left[\left(\frac{1}{\beta}+1\right)-1\right]}\eta e^{-z}dz + \delta$$

$$\eta\,\Gamma\left(\frac{1}{\beta}+1\right) + \delta$$

where $\Gamma(x)$ denotes Gamma function, defined as:

$$\Gamma(x) = \int_{0}^{\infty} e^{-t}t^{x-1}dt$$

$$\Rightarrow \qquad Mean = E(T) = \delta + \eta\,\Gamma\left(\frac{1}{\beta}+1\right)$$

For two parameter weibull, we can obtain expression for mean by putting $\delta = 0$;

$$\therefore for\ 2\ parameters\ E(T) = \eta\,\Gamma\left(\frac{1}{\beta}+1\right)$$

$$now, \qquad E[T^2] = \int_{-\infty}^{\infty} t^2 f(t) dt$$

$$\Rightarrow \qquad = \int_{\delta}^{\infty} t^2 \frac{\beta}{\eta} \left(\frac{t-\delta}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\delta}{\eta}\right)^{\beta}} dt$$

As previously, putting $\left(\frac{t-\delta}{\eta}\right)^{\beta} = z$ and differentiating we get

$$\Rightarrow \qquad dt = z^{-\left(\frac{\beta-1}{\beta}\right)} \frac{\eta}{\beta} dz$$

$$\Rightarrow \qquad E[T^2] = \int_0^{\infty} \left[z^{\frac{1}{\beta}} \eta + \delta\right]^2 e^{-z} dz$$

$$= \eta^2 \int_0^{\infty} z^{\frac{2}{\beta}} e^{-z} + 2\delta\eta \int_0^{\infty} z^{\frac{1}{\beta}} e^{-z} dz + \delta^2 \int_0^{\infty} e^{-z} dz$$

$$= \eta^2 \int_0^{\infty} z^{\left[\left(\frac{2}{\beta}+1\right)-1\right]} e^{-z}\, dz + 2\delta\eta \int_0^{\infty} z^{\left[\left(\frac{1}{\beta}+1\right)-1\right]} e^{-z}\, dz + \delta^2$$

$$= \eta^2\, \Gamma\left(\frac{2}{\beta}+1\right) 2\eta\delta\, \Gamma\left(\frac{1}{\beta}+1\right) + \delta^2$$

Now variance

$$\sigma^2 E(T^2) - [E(T)]^2$$

Using equations

$$\sigma^2 = \eta^2\, \Gamma\left(\frac{2}{\beta}+1\right) 2\eta\delta\, \Gamma\left(\frac{1}{\beta}+1\right) + \delta^2 + \left[\delta + \eta\, \Gamma\left(\frac{1}{\beta}+1\right)\right]^2$$

$$= \eta^2\, \Gamma\left(\frac{2}{\beta}+1\right) 2\eta\delta \left(\frac{1}{\beta}+1\right) + \delta^2$$

$$- \left[\delta^2 + 2\eta\delta\, \Gamma\left[\frac{1}{\beta}+1\right] + \eta^2 \left(\Gamma\left[\frac{1}{\beta}+1\right]\right)^2\right]$$

$$\sigma^2 = \eta^2 \left[\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right]$$

From the above expression it is clear that variance is independent of location parameter ‘δ’. Hence, it is same for 2 parameter wiebull and 3 parameter weibull.

5.3 MAINTAINABILITY AND AVAILABILITY

INTRODUCTION

The increasing complexity and high technology of present equipment has brought into focus two unique aspects known as Maintainability and Availability. Both of these are closely related to reliability. The word of maintainability occurs frequently in everyday usage. When we say that a particular equipment is easy to maintain, indicates that repairs can be easily and readily carried out if the equipment breakdowns.

Similarly, when we say that a particular equipment is available, we mean that the equipment is functioning and is available for use. On the other hand, it might not be available for use due to breakdown or malfunction. In the case, when equipment is breakdown or malfunctions and the repairs are undertaken, the ease with which it is brought back into operation reflects in some manner, the maintainability character of the equipment. Therefore if the system is capable of being repaired easily, then it has maintainability factor. As such the Availability factor will also be high. Moreover if the system reliability is high, then it means that breakdowns will be less frequent and availability factor will be high.

Hence, looking to above factors, a quantitative definition of maintainability and availability is necessary, so that, maintainability and availability requirements can be prescribed and efforts undertaken to achieve them. Further, a quantitative definition will enable a comparison of the characteristics of different systems.

MAINTAINABILITY

In broad terms, maintainability can be defined as:-"The ability and ease to repair and maintain equipment in the least amount of time at the lowest cost."

This can also be defined as:- "The relative ease and economy of time and resources with which an equipment can be retained in , or restored, to a specified condition when maintenance is performed by using prescribed procedures and resources."

Maintainability is also a Probability in the same way as reliability and its value lies between zero and one. Hence, in terms of probability, we can define maintainability as: "Maintainability is the probability that a unit or a system will be restored to specified conditions within a given period of time, when maintenance action is taken in accordance with prescribed procedures and resources. It is a characteristic of design and installation of the unit system."

Hence maintainability involves the following elements:

1. The specified condition to which the unit is restored with reference to its performance characteristics after it is repaired.

2. The time within which, the item is restored to the specified condition. Time element is related to the adopted procedures of maintenance.
3. Prescribed resources must be provided for maintenance and repairs. These would include the necessary tools, replacement parts such as bolts, screw, nuts etc. and the maintenance skills.
4. Characteristics of the design and installation of a complex system. The time taken to repair a system depends on, how it has been designed. Design and installation characteristics will also dictate the maintenance policies.
5. Maintenance policy – It is possible to define some of the maintenance policies in advance and take design decisions accordingly. The design and maintenance policies also control the technician requirements.

The maintenance policy will cover issues regarding general repairs, repair or discard policies, emergency re-order policies, inventory control, provisioning of spares etc. The technician requirements involve education, experience, training, capability and skill etc.

DESIGNING FOR MAINTAINABILITY

The objective of designing for maintainability is to provide equipment and facilities that can be serviced and repaired efficiently and effectively if they should fail. The successful design of majority of the equipments are based upon the ability and case of maintenance and repairs for providing good maintainability and reliability. Sufficient degree of maintainability and reliability will determine the equipment effectiveness and customer satisfaction.

Equipment should be designed with sufficient reliability, so that it will be operable for an anticipated life cycle at optimum availability. Thus reliability is a function of design. Once the design has been completed and released for manufacturing, the reliability of the equipments has been determined, or it cannot be altered without redesign.

The functional designs, where the technology of maintainability has been given considerable consideration, will result in simplified maintenance that can be performed both effectively and economically. As such the equipment will be down for service or repairs for a considerably smaller proportion of time, and the anticipated operative life of the equipment will be longer. Hence we see hat maintainability is affected by its reliability characteristics. Since improving maintainability is both difficult and costly after development, it is extremely desirable that reliability requirements of facilities be included in design specification and that design give attention to maintainability.

Most major maintenance problems are better solved at the equipment design level rather than at the level of maintenance personnel training. Maintainability problems solved at the design level are much less costly than teaching technicians to deal with countless problems faced during maintenance and also the problems which may arise during the life of the equipments.

Maintainability implies a built in characteristic of the equipment design and installation, which imparts to the cell an inherent ability to be maintained. It keeps the equipment productively operating by employing a minimum number of maintenance men hours, skill levels and maintenance costs.

OPERATIONS FOLLOWED IN DESIGN

Following are the sequences of the operations generally followed while design concepts are reviewed before detailed engineering proto-type development and final production:

1. Value Engineering : Should ask, is this the correct design?
2. Constructability : Should ask, can this design be cost effectively built?
3. Commissioning : Should ask, does this design and installation meet design intent?
4. Maintainability : Should ask, can this design be cost effectively operated

For equipments like aircraft, which are of high risk operation, designers take into account human factors. This is basically known as "HCD" Human Centered Design. Such a design encompasses requirements of all those personnel involved, such as the Pilots, maintenance crews, cabin crew, airport ground staff, air traffic controllers and air fuel supplies.

GENERAL PRINCIPLES OF MAINTAINABILITY

The following fundamental principles should be considered by the functional designers in the development of components, equipments and systems, so that, both reliability and maintainability are designed and built into the component:-

1. Endeavour to eliminate or minimize the need for maintenance.
2. Minimize the frequency and complexity of required maintenance tasks.
3. Endeavour to require maintenance that utilizes low skill levels and minimum training to perform the function adequately. Parts requiring maintenance should be easily accessible and should also be able to be maintained by using standard tools and requiring low skill levels and low physical and mental effort.
4. Determine the optimum preventive maintenance that should be performed.
5. Establish complete information to be used in the education and training for maintenance.
6. Provide optimum accessibility to all equipments and components requiring frequency maintenance, inspection, removal, replacement or adjustment.
7. Design trouble shooting chars.
8. All parts and components should be able to be positively identified so that they can be repaired easily or replaced.
9. Design for interchangeability of parts.
10. In heavy components, provide for the facilitication of transport such as toeing, hoisting, lifting and jacking.

11. Provide such bearings and seals that require the minimum of replacement and servicing on life cycle basis.
12. On instruments and other components that are easily damaged by shock and vibration, provide for isolation to avoid such conditions.
13. Specify corrosion resistant materials and protective coatings, plating and metalizing.

BENEFITS OF “DESIGN FOR MAINTAINABILITY”

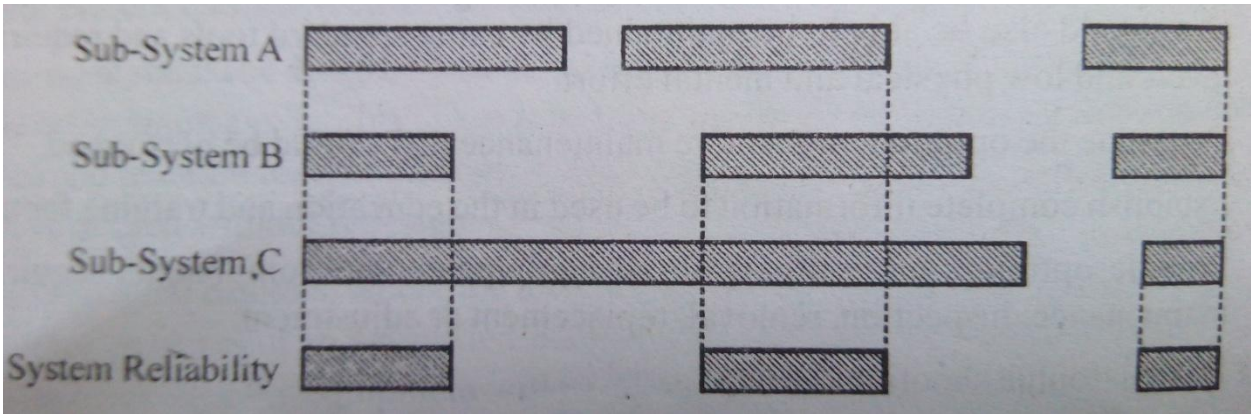
Following are the benefits of giving the option of “Design for maintainability” in any product cycle.

1. Greater task efficiency and reduced mean time to repair.
2. Improved system performance and reliability.
3. Increased process tool utilization.
4. Less operational errors.
5. Decreased stress on maintenance staff.
6. Reduced fatigue, reduced training time and costs.
7. Less reliance on maintenance manuals.
8. Reduced installation and maintenance costs.
9. Reduced maintenance manpower.

SYSTEM DOWN TIME

Before we take up the quantitative description of availability it will be better if we understand and define system downtime.

The system downtime is total time for which a system is down for active maintenance. This downtime varies from one type of failure to another. Further when a complex system consisting of several sub assemblies is said to be operating or available, then it can be said to be available only, when all the sub assemblies function successfully. We take an example of missile, consisting of 3 sub assemblies A,B,C. Each of the assemblies is in one of the two possible state i.e. operative or non operative.



Availability of the sub system has been shown by lined sections. Gaps indicate downtime. Here the downtime of each sub system varies.

System availability is only for the time when all three sub systems are operationally acceptable.

MTBF (MEAN TIME B/W FAILURE)

When a system is often unavailable due to breakdown and is put back in to operation after each breakdown with proper repairs the mean time b/w breakdowns was defined as mean time between failures (MTBF).

MTBR (MEAN TIME TO REPAIR)

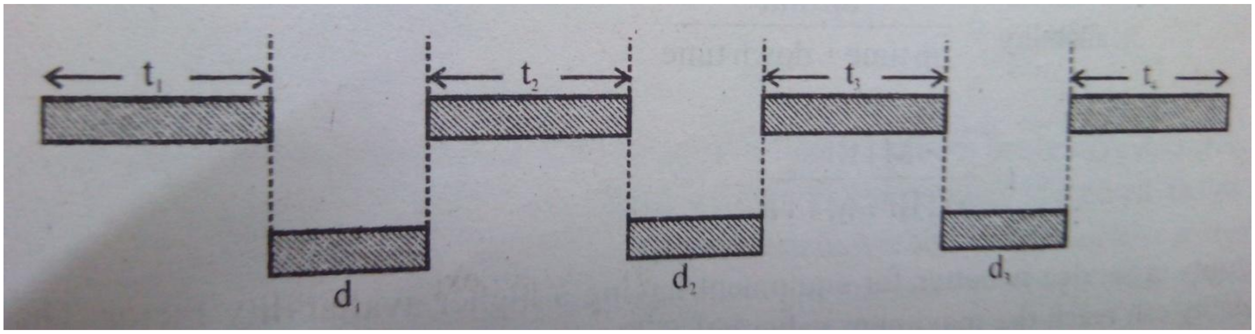
If we consider only the active time for repairs, i.e. the time spent for actual repairs then, mean time to repair (MTTR) is statistically mean time for active repair. It is the total active repair time during a given period divided by the no of malfunctions during the same interval.

MTBM (MEAN TIME B/W MAINTENANCE)

Frequently, a system may become unavailable on account of periodic inspections and not because of break down. By the systematic inspection or preventive maintenance for the detection of defects and prevention of failures, the system is kept in a satisfactory operational condition. The time spent on inspection and preventive maintenance is termed as preventive maintenance downtime. We have to distinguish between the mean time between maintenance (MTBM) & (MTBF) Mean time between failures. When preventive maintenance downtime is not considered & is taken as zero, then MTBM & MTBF are same or only MTBF is defined.

EXAMPLE

The following figure shows the profile for availability and downtime for a hypothetical system.



(1) The availability periods are shown by t_1, t_2, t_3 & t_4
(2) The downtime period are shown by d_1, d_2 & d_3
(3) In these profiles d_1 is the preventative maintenance downtime. d_2 and d_3 are the repairs tie in ease of failure of the equipment.

T3 = time for which the system is available for operation b/w the failures d_2 & d_3.

The statistical mean time of t periods give the MTBM. Downtime d_2 & d_3 will consist of

1. Supply time: That portion of non active maintenance time during which maintenance is delayed solely because a required item is not readily available.
2. Administrative time: That portion of non active maintenance time that is not included in supply time.
3. Active repairs time: That time during which repairs are done and the equipment is put back into operation.

AVAILABILITY

The percentage of time the equipment is available under operation is called the steady state availability. It characterizes the main behavior of the equipment. The availability function A(t) is defined as the probability that the equipment is operating at time t.

Although the definition appears to be very similar to the reliability function R(t), the two have different meanings. While reliability places emphasis on failure free operation up to time t, availability is concerned, with the status of the equipment at time t. The availability function does not say anything about the number of failures that occurred during time t. This means the two equipments A & B can have different numbers of failures in a given time interval & can still have the same availability.

EXAMPLE

In a period of 100 hours an equipment of 0.8 availability might have two failures, each of ten hour downtime or 3 failures one of ten hour downtime & rest of the two of 5 hours each downtime.

The availability can be expressed by reliability parameters, such as MTBF(Mean Time Between Failures) & MTTR(Mean Time To Repair)

Hence,

$$Availability = \frac{up\ time}{up\ time + down\ time}$$

$$= \frac{MTBF}{MTBF + MTTR}$$

Utility or service is better for equipment having a higher availability factor. Theoretically, availability can reach the maximum value either by achieving a very high MTBF (compared to MTTR) or by bringing down MTTR to a negligible value (compared to MTBF). This means that either the equipment reliability should be near unity or the repair rate of the equipment should be very high. This means that failures should be completely eliminated, if they occur they should be repaired within a negligible amount of time.

TYPES OF AVAILABILITY

It is possible to define three types of availability depending on the time elements we take into consideration. These are

(i) Inherent availability
(ii) Achieved availability
(iii) Operational availability

INHERENT AVAILABILITY

This is the probability that a system or equipment shall operate satisfactorily when used under stated conditions in an ideal support environment, without consideration for any scheduled or preventive maintenance at any given time. It excludes ready time, (that is the period during a mission when the item is available for operation, but is not required to operate), preventive maintenance downtime, supply downtime & administrative downtime.

Inherent availability may be expressed as:

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

By "ideal support environment" we mean the ready availability of tools, parts, man power, manuals etc. Thus A_i is the inherent characteristics of the equipment, since it ignores the downtime due to other sources & that which is not directly caused by the equipment.

ACHIVED AVAILABILITY

In the inherent availability we considered MTBF which does not take into account the downtime caused by preventive maintenance. If we take this into account, we get the achieved availability. Hence it may be defined as a probability that a system or equipment shall operate satisfactorily when used under stated conditions in an ideal support environment at any given time. It may be expressed as

$$A_a = \frac{MTBM}{MTBM + M}$$

Where M = Mean active maintenance down time resulting from both preventive & corrective maintenance. MTBM becomes MTBF if preventive maintenance downtime is ignored. In this we have considered both the preventive & corrective maintenance downtime. Administrative & supply downtime, which are not directly caused by the equipment are ignored. In other words, when the indirect downtime tends to zero, the availability factor achieved is A_a.

OPERATIONAL AVAILABILITY

In any real operation, we can`t reduce administrative & supply downtime to zero. By these a certain amount of delay will always be caused. Hence if we take into account these downtimes, we obtain the operational availability of the system. This is defined to be the probability that a system or equipment shall operate satisfactorily when used under stated conditions & in an actual supply environment at any given time. It may be expressed as

$$A_o = \frac{MTBM}{MTBM + MDT}$$

Where MDT = mean down time of the system.

It may be seen that we have mentioned the actual supply environment in the definition and that, therefore, AO is the availability factor achieved in operation.

All three availability factors defined are probability like maintainability and reliability.

AVAILABILITY IN TERMS IF FAILURE RATE AND REPAIR RATE

Let $\boldsymbol{\lambda}$ = Failure rate (failure per unit time)

μ = repair rate (repair per unit time)

Hence $\frac{1}{\lambda}$ = mean time between failure (MTBF)

$\frac{1}{\mu}$ = mean repair time or mean time to repair (MTTR)

Then availability $= \frac{MTBF}{MTBF+MTTR}$

Hence $A = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda}+\frac{1}{\mu}} = \frac{1}{1+\frac{\lambda}{\mu}}$

Or $A = 1 - \frac{\lambda}{\mu} + \frac{\lambda 2}{2\mu^2} + \cdots$

Or $A \simeq 1 - \frac{\lambda}{\mu}$

Or availability $= 1 - \frac{failure\ \ rate}{repair\ \ rate}$

EXAMPLE

An air compressor has to be so designed that its minimum reliability value is 0.90 for an operation time of 1000 hours. The minimum availability value over the same period has to be 0.99. Estimate the time to failure and mean repair time. Assume constant hazard for failure and repair.

Solution: The reliability is

$$R(t) = e^{-\lambda t} \geq 0.9 \quad 0 < t < 1000$$

Therefore $e^{-\lambda 1000} = \frac{1}{e^{-1000\,\lambda}} \approx 1 - 10^3\boldsymbol{\lambda} = 0.9$

Or $\lambda = 10^{-4}$

Now availability $A(t) = 1 - \frac{\lambda}{\mu} = 0.99$

$$\mu = 100\boldsymbol{\lambda} = 100 \times 10^{-4} = 10^{-2}$$

Or $\frac{\lambda}{\mu} = 10^{-2}$

Hence compressor should be designed.

Such that $MTTF = \frac{1}{\lambda} = 10^{-4}$ hours

And mean time to repair $\frac{1}{\mu} = 100$ hours

Probability of failure within 1000 hours

$$= 1 - 0.9 = 0. i. e. 10\%$$

As minimum availability = 0.99

Hence probability that compressor is down and under repair at any time between

$t = 0$ *and* $t = 1000$ hours is

$$1 - 0.99 = 0. i.e. 1\%$$

5.4 FAILURE DISTRIBUTION

TYPES OF FAILURES

- **(i)** **Catastrophic failures:** These failures are ones, which immediately stop the working of a system or component and it cannot be used without proper repair.
- **(ii)** **Deliberate failure:** These failures are caused by the personnel with bad intention of work.
- **(iii)** **Performance failures:** These failures are related with the performance of the systems. Sometimes, the system will remain operative inspect of failure of any component but performance reduces.

FAILURE DATA

For the equation of reliability the information about failure of units it's required which can be obtained by experiments or simulation. Tests are carried out on identical items to study the failure behavior of the components. These tests give failure data.

We can consider a series of these conducted certain stipulated condition on 1000 electronic components for 20 hours. The results of the test are tabulated below:

(1) Time Δt	**(2) No. of Failures f**	**(3) Cumulative Failures F**	**(4) No. of Survivors S**	**(5) Failure Density fd**	**(6) Failure Rate z**	**(7) Reliability R**
0	0	0	1000	0	0	1
1	130	130	870	0.130	0.139	0.870
2	83	213	787	0.083	0.101	.787
3	75	288	712	0.075	0.100	.712
4	68	356	644	0.068	0.100	.644
5	62	418	582	0.062	0.101	0.582
6	56	474	526	0.056	0.101	0.526
7	51	525	475	0.051	0.101	0.475
8	46	571	429	0.046	0.101	0.429
9	41	612	388	0.041	0.100	0.388
10	37	649	351	0.037	0.100	0.351
11	34	683	317	0.034	0.101	0.317
12	31	714	286	0.031	0.103	0.286

13 14 15 16 17 18 19 20	28 64 38 38 62 40 12 4	742 806 844 882 944 984 996 1000	258 194 156 118 56 16 4 0	0.028 0.064 0.038 0.038 0.062 0.040 0.012 0.004	0.103 0.283 0.243 0.243 0.714 1.110 1.200 2.000	0.258 0.194 0.156 0.118 0.056 .016 .004 0
20	1000	1000	0	1.00	Mean 0.376	0

(i) The first column denotes time interval in this case one hour.

(ii) The second column indicates the no of failures in each hour & expressed as f.

(iii) The third column indicates the cumulative failures and expressed as F.

(iv) The 4th column indicates the number of survivors and expressed as S.

(v) The 5th column indicates failure density and expressed as $fd = f/N$

(vi) The 6th column indicates failure rate expressed as

$$Z_1 = \frac{f}{(s_0 + s_1)/2}$$

Sometime $Z_1 = \frac{f}{s_1}$ only

(vii) Seventh column indicates reliability

$$R = \frac{s}{N}$$

Here, N indicates the total number of components.

The time is reckoned from the start of the test.

Based on the failure data or survival test results, we can now define failure density, failure rate, reliability and probability of failure.

Failure Density

This is the ratio of the number of failures during a given unit interval of time to the total number t of items at the very beginning of the test. In the above example, the total number of items at t beginning of the test was 1000. This is also known as the total initial population,

No. of components failed during the 1st unit interval

$$f = 130$$

$$\therefore \textit{Failure density} \qquad fd_1 = \frac{130}{1000} = 0.130$$

2nd unit interval

No. of terms failures =83

Failure density in second unit interval

$$fd_2 = \frac{83}{1000} = 0.083$$

10th unit interval

$$Failure\ density \qquad\qquad fd_{10} = \frac{37}{1000} = 0.037$$

The value of the failure density in the different interval of time is given in the fifth column sometimes the failure density is also called the ratio part failure rate.

Let n_1 be the number of components that fail during the first unit interval and n_2 the number components that fail during second unit interval and so on.

Let N = total population.

Then the failure density during the first unit interval= $\frac{n_1}{N}$

The failure density during the second unit interval = $\frac{n_2}{N}$

Then the failure density during the ith unit interval= $\frac{n_i}{N}$

Let i be the last interval, after which there are no survivors, then $fd_1 = \frac{n_1}{N}$ and so on

$$\therefore \quad fd_1 + fd_2 + fd_3 + \ldots\ldots + fdi = \frac{n_1}{N} + \frac{n_2}{N} + \frac{n_3}{N} + \frac{n_i}{N} = \frac{N}{N} = 1$$

Hence some of the density shall be one.

Failure Rate

This is the ratio of the number of failures during a particular unit interval to the average population during that interval. (The rate at which failures occur in a certain time interval $(t_2 - t_1)$ is called failure rate.

In the above example, failure rate in the first unit interval is

$$Z(1) = \frac{130}{(1000 + 870)/2} = \frac{130}{935} = 0.135$$

Similarly $\qquad Z(2) = \frac{31}{(317+286)/2} = 0.103$

Sometime the population at the beginning of the interval is taken. The rate at which failure curs in a certain interval of time $(t_2 - t_1)$ is called the failure rate during that interval, in terms of probability. Failure rate is defined as the probability that a failure per unit time occurs in the interval, given that a failure has not occurred prior to t_1, the beginning of the interval, thus

Failure Rate $\quad Z = \frac{R(t_1)-R(t_2)}{(t_2-t_1)R(t_1)}$

Here the failure rate is a function of time

If the interval is redefined as $[t, t + \Delta t]$

Then $\quad Z = \frac{R(t)-R(t+\Delta t)}{\Delta t.R(t)}$

The rate in the above definition is expressed as failure per unit time, time being in hours, kilometers or revolutions etc.

Mean Failure Rate

In the above example, we have seen that failure rate Z varies with time. In the first hour failure rate is 0.139 and in the second hour it is 0.101 and so on. It is also possible to calculate the mean failure rate for the entire test cycle. If Z_1, be the failure rate of the first hour, Z_2 for second hour and so HI. Then the mean failure rate, for T-hours shall be.

$$Mean\ failure = \frac{z_1 + z_2 + z_3 \ldots + z_n}{T}$$

If the interval is made much smaller than one hour, then we get a more accurate value of the mean failure rate.

MEAN TIME TO FAILURE (MTTF)

- **(i)** **Total up time:** The period for which a system or equipment remain operational without any failure.
- **(ii)** **Main Time to Failure (MTTF):** MTTF is the time period between two failure of system.
- **(iii)** MTTF is used for non repairable items.

We are more interested to know the mean time to failure of a component instead of complete failure details. It is assumed that MTTF will be same for all the components which are identical in the design and operate under identical conditions. If we have life teste information on a populations of N items with failure times, then we can calculate MTTF.

If t_1 is the time of first failure and t_n of n^{th} failure of N items then the MTTF is defined as

$$MTTF = \frac{(t_1 + t_2 + t_3 + \ldots + t_n)}{N}$$

$$or \qquad MTTF = \sum_{i=1}^{n} t_i$$

However, if a component is described by its reliability function and haggard model, then the MTTF if given by the mathematical expectation of the random variable T describing the time to failure of the component.

$$Therefore, \qquad MTTF = E(T) \int_0^\infty t f(t) dt$$

$$or \qquad f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt}$$

$$Hence, \qquad MTTF = -\int_0^\infty td\, R(t)$$

$$= -t\, R(t) \int_0^\infty + \int_0^\infty R(t) dt$$

$$= \int_0^\infty R(t) dt$$

The MTTF can also be computed using Laplace transform of R(t).

$$Thus, \qquad MTTF = \int_0^\infty R(t) dt = \lim_{t \to \infty} \int_0^\infty R(x) dt$$

$$So, \qquad \lim_{t \to \infty} \int_0^\infty R(x) dt = \lim_{s \to 0} R(s)$$

Where, R(s) is the Laplace transform of R(t)

$$Thus, \qquad MTTF = \lim_{s \to 0} R(s)$$

MEAN TIME BETWEEN FAILURE (MTBF)

(i) MTBF is used for repairable items, as MTTF is used for non-repairable items.

(ii) Down time: It is the time taken to repair a system. Down time is reckoned from the time of breakdown to the time, the system is put into operation.

(iii) Mean time between failure (MTBF) is the average time of breakdown until the component is beyond repair.

If N_f is number of failures of a system in the lift time of this system and T_{Dt} is down time in the successive repairs, then,

$$Mean\ Down\ Time\ (MDT) = \frac{1}{N}\sum_{t=1}^{N_f} T_{Dt}$$

Total UP Time = Total available time – Total down time

$$Total\ UP\ Time \quad = NT - \sum_{t=1}^{N_f} T_{Dt}$$

$$NT - N_f \times MDT$$

$$\therefore \qquad MTBF = \frac{NT - N_f \times MDT}{N_f}$$

So, mean failure rate= $\frac{N_f}{NT - N_f \times MDT}$

Hence, mean failure rate is directly reciprocal of MTBF. Also, failure rate is a functions of time.

MTTF IN TERMS OF FAILURE DENSITY

The mean time of failure is given by

$$MTTF = \frac{1}{N}\sum_{k=1}^{N_f} n_k\, k\Delta t$$

Where N is the initial total population n_1 is the number of specimens that fail during the first interval, n_2 the number of specimens that fail during the second interval and n_k the number of failure during the –th interval. If f_d is the failure density then by definition.

$$fd_k = \frac{n_k}{N\Delta t}$$

Hence $\frac{n_k}{N} = \Delta t\, fd_k$

Further $k\Delta t$ is the elapsed time t, hence the equation can be written as

$$MTTF = \sum_{k=1}^{i} d_{d_k} (k\Delta t)\Delta t$$

Where the summation is for the period from the first interval to the i^{th} interval.

5.5 REPAIRABLE AND NON REPARIABLE SYSTEMS

In general all mechanical systems can be classified in to two systems:

(i) Repairable system.
(ii) Non-Repairable system.

(i) **Non-repairable Systems:** these are those systems, whose lives are over as soon as the first failure occurs. These cannot be repaired and reused. For example: A missile is a non-repairable system. An electric bulb, satellite, chemical cell, are one-shot devices. We may call them use throw type devices.

(ii) **Repairable system:** These are those, systems, which undergo many cycles of failures and consequent repairs within the duration of their design life. Most of the industrial machines and consumer products are repairable systems. For example:- A lathe machine, an automobile vehicle, a bridge, air conditioners etc., the life of such systems does not end with a single failure. It is much longer. For repairable systems, instead of term “reliability”, it is more appropriate to the term “availability” and “maintainability” for measuring the system performance.

5.5 RELIABILITY IMPROVEMENT TECHNIQUES

OBJECTIVE OF RELIABILITY

One of the main objectives of carrying out reliability studies is to assess the present status of our system or the system under design and development. To check whether our systems are able to meet the design and mission requirements, a gap analysis is then carried out and strategies are planned to improve reliability.

A large number of reliability studies have brought out the fact that many failures are an account of improper design and over stressing of the components. Therefore it is one of the most important factor, which reliability engineers have to look into. The following methods are used to improve the reliability of engineering components and systems.

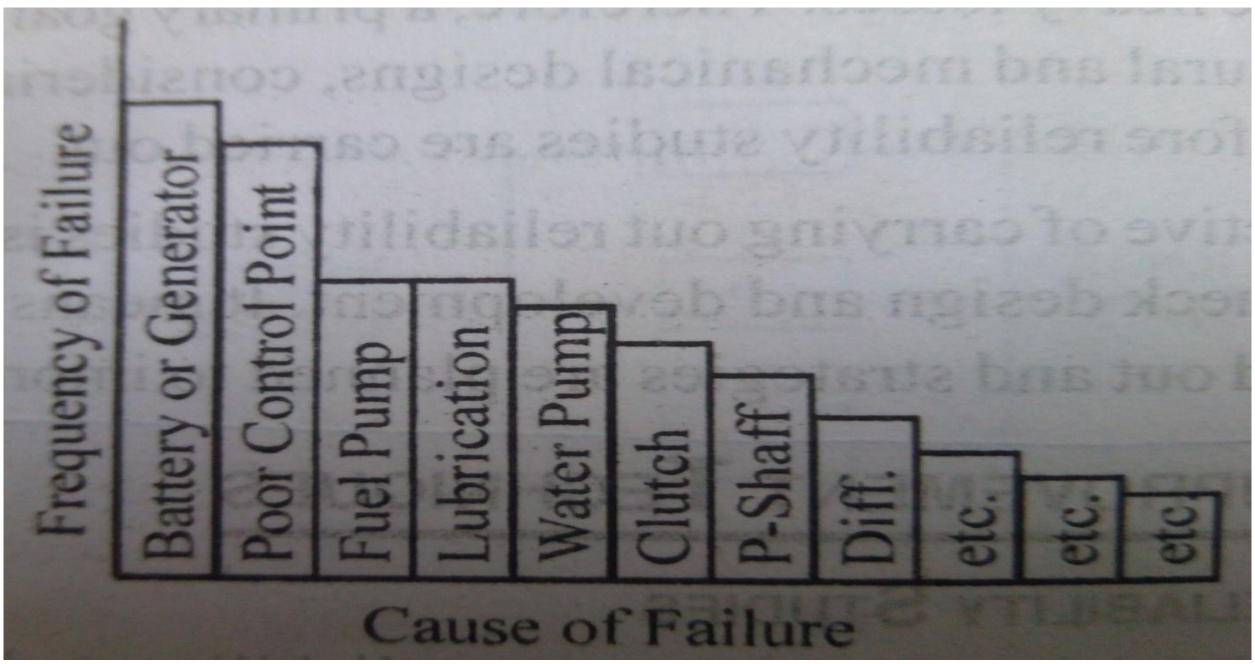
1. Use of Pareto analysis.
2. Usage of better components or improvement of components.
3. System simplification (removing complexities).
4. Derating.
5. Redundancy.
6. Controlling the environment.

7. Maintenance.
8. Removing early failures by burn-in.
9. Worst ease design (to minimize sensitivity to variations in parameters and operating condition).
10. Process control and quality assurance.
11. Human reliability.

PARETO ANALYSIS

Pareto was a famous nineteenth century economist. He carried a number of studies on the failure of components of a system. He observed that factors loading to a majority of the defects, which cause the failure of a system are relatively very few. A study on the failure of a automobile indicates the following facts:

We draw a graph between the frequency of failure and causes of failure as given below:



(i) Failures on account of causes of failure of battery or generator very high.
(ii) Failures on account of ignition circuit i.e. contact points were next to battery.
(iii) Failures on account of fuel pump, lubrication, water pump, gear box, clutch etc. were on decreasing side.

Therefore if the failures on these very few causes can be arrested, then the reliability of the system can be improved to a greater extent. Therefore after analyzing the failure data, it is necessary to identify these very few causes and then to take action to minimize these failures.

USAGE OF BETTER COMPONENTS

Components are the building blocks of a system. Component reliability can be improved by the following methods.

(i) High quality level (design and manufacturing).
(ii) Minimum variations in specifications.
(iii) Lower failure rates.
(iv) Factor of safety (FS) margin.
(v) Better materials.

The above things can be achieved by the following actions:

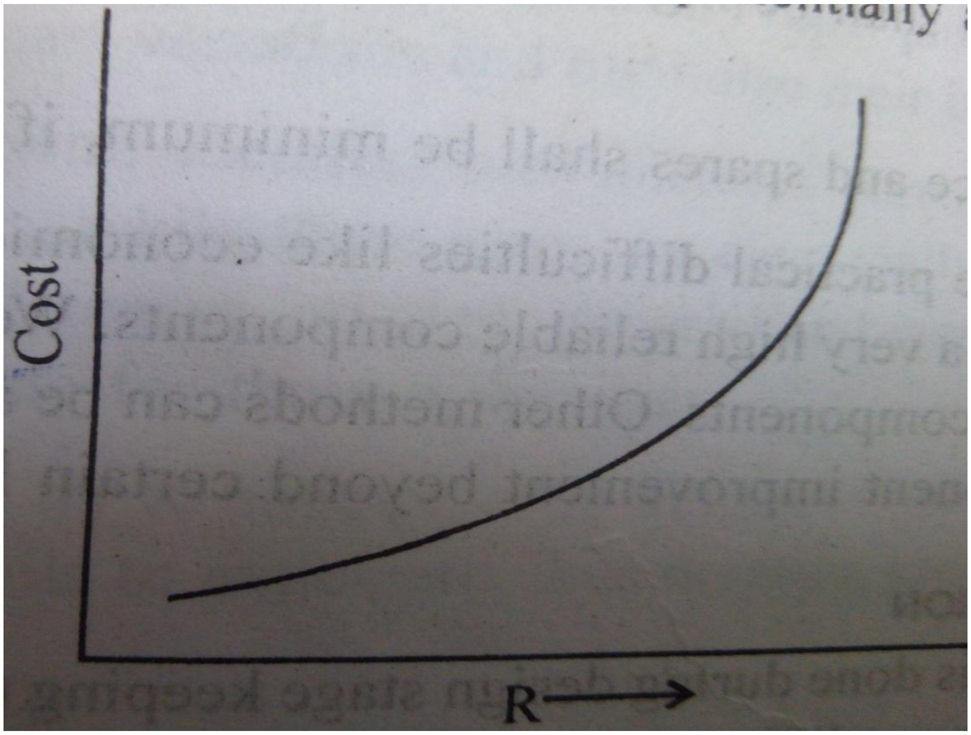
(a) Good engineering design.
(b) Selection of proper materials.
(c) Adequate technology of manufacturing.
(d) Strict quality control.
(e) Continuous updation and improvement.
(f) Proper vendor evaluation and selection.

As an initial step, the critical components in the system can be identified and improved. Reliability improvement of other components can be tried in the next stage. This is a costly affair but quite effective.

While attempting to improve reliability of components, we must keeping mind two important factors.

First is the effect of reliability improvement on cost and secondly the technical and manufacturing feasibility of such improvements.

Cost of the components increase, when their reliability is improved. The cost function has an exponential relationship to reliability. After attaining a certain level of reliability, if further improvements are carried out, the cost will increase exponentially as shown below in graph.



Therefore an adequate trade off policy must be planned before attempting to improve component reliability.

Reliability and cost can be related as

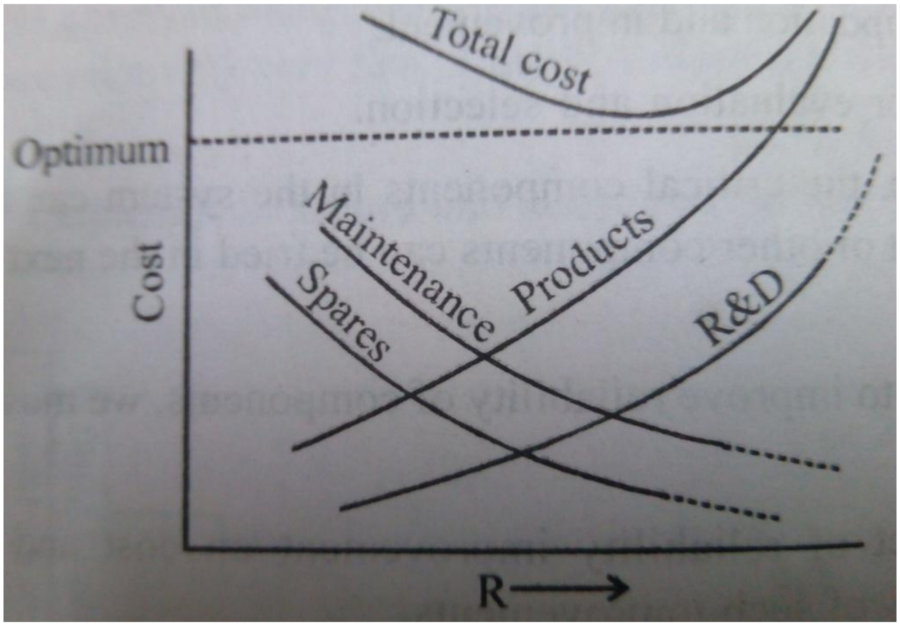
$$C = ae^{b/1-R}$$

Where C = design and development cost

R = reliability of the equipment a and b are positive constants.

The level of operational reliability is to be decided by cost constraints and operational requirements.

Generally, the objective is not merely to produce a system with the highest reliability but to involve a system which reflects an optimum total cost. The major items contributing to the total cost are research and development, production, spares and maintenance. The cost of these items varies with reliability as shown below



(i) To design and develop a highly reliable component, cost on R and D shall be high.
(ii) Cost on production shall be high, on a account of using modern machines.
(iii) Cost of maintenance and spares shall be minimum, if reliability is high.

Besides above there are practical difficulties like economic and design and manufacturing constants for manufacturing a very high reliable components. We may say that it is not profitable to manufacture high reliable components. Other methods can be applied to improve the reliability of the system besides component improvement beyond certain level.

SYSTEM SIMPLIFICATION

System simplification is done during design stage keeping the intended function same. Most systems can be designed in many different ways. Therefore to simplify a system, creative thinking and design is necessary. The variety of components and number of components in design should be as few as possible.

The following factors should be taken care of:

(i) Usage of standard ports.
(ii) Interchangeable of parts, as maximum as can be possible.
(iii) The design should be easily understandable.
(iv) Complexity should be eliminated.
(v) Parts and components should be easily available.
(vi) Components used in design should be of required reliability.

DERATING

(a) Derating is the reduction in electrical and thermal stresses to a part in order to decrease the part failure rate, which enhances the equipment reliability. Derating can be defined as a design strategy to improve the reliability of a part by operating the part at stressed value less than its maximum rated value. The rated parameters can be voltage, current, power, forces, torque, speed, temperature humidity. It has some similarities to the traditional design strategy of factor of safety (SF).

$$Factor\ of\ safety = \frac{maximum\ allowable\ load}{actual\ load}$$

As a thumb rule, most of the electronic components are used at their 50% rated strength or FS = 2. In mechanical systems, the FS = 1.5. Derating results in higher cost of the system. Therefore, trade off policy should be planned.

(b) Importance of Derating

1. Derating is the most effective tool for the designer to decrease the failure rates of parts. This can help to compensate for many of the variable inherent in any design.
2. All electronic parts produced is an assembly line are not identical. Large differences and variations exist from one part to next. Proper part derating will help to compensate for .0these part to part variations and minimize their impact on the equipment reliability.
3. Electronic parts with identical manufactures part numbers may be purchased from different suppliers, while these items are electrically in-teach arguable, but there may be significant differences in design, material and manufacturing process. Derating will help to compensate for these differences.
4. The designer will try to anticipate the impact of various electrical and environmental extremes. If he fails to anticipate, thus derating can provide an additional margin of safety.
5. The critical parameters are not stable of a part/component during the life of components. If these parameters change, thus proper derating will help to ensure the continuity of function properly.

(c) Effect of Derating on Part Stress Reliability Production:

During the useful life of an electronic part, its reliability is a function of both the electrical and thermal stresses. Increase in thermal stresses directly increases the junction temperature, which will increase failure rate according to the mathematical model of failure rate calculation. Similarly increase in electrical stresses results in increase in failure rate. Both the stresses increase failure rate and decreases reliability.

Some parts are temperature sensitive, so failure may occur sometimes due to temperature. In such type of components, reduction in temperature by improvement in thermal design will decrease failure rate.

(d) Method of Deratng

Derating of the component is done with reference to the absolute maximum ratings. The manufacturer in the specification or data sheet defines these ratings. Usually, a part has several different absolute maximum ratings such as voltage, current, power as so on. Each of these absolute maximum rating is unique and must be applied individually, and not in combination with any after absolute maximum ratings.

Derating must be cost effective. It should not be conservative to the point where the cost rises excessively. Derating can be accomplished by either:

(i) Reducing the stresses on the part.
(ii) By increasing the strength of the part.
(iii) By selecting a part having greater strength.

Different types of components are derated by different parameters. For example:

(i) Resistors are derated by power, by the ratio of the operating power to the rated power.
(ii) Capacitors are derated by reducing the applied voltage compared to the rated voltage.
(iii) Semi-conductors are derated by limiting their power dissipation, hence derating their junction temperature below the rated level.
(iv) Silicon-switching and small signal diodes are derated for temperature, voltage and current.
(v) Supply voltage, power dissipation and output current are derated in linear integrated circuits.

REDUNDANCY

Redundancy is another method for system reliability improvement. This is a technique in which more number of components than actually required for operation are connected in parallel. This is the easiest method of improving reliability. This shall be discussed in detail afterwards.

CONTROLLING THE WORKING ENVIRONMENT

The failure rate of the component increases many times when the working environment becomes more and more server. This is because the material properties change with operating environment and as a result, strength reduces.

This leads to higher failure rates. For example for every i.e. rise in temperature, the failure rate of most electronic components becomes double.

Humid and salty environment results in faster rates of Corrosion and oxidation. Sever vibration, acceleration and shocks ensure breakage, loose contents, unbalance and change of control settings.

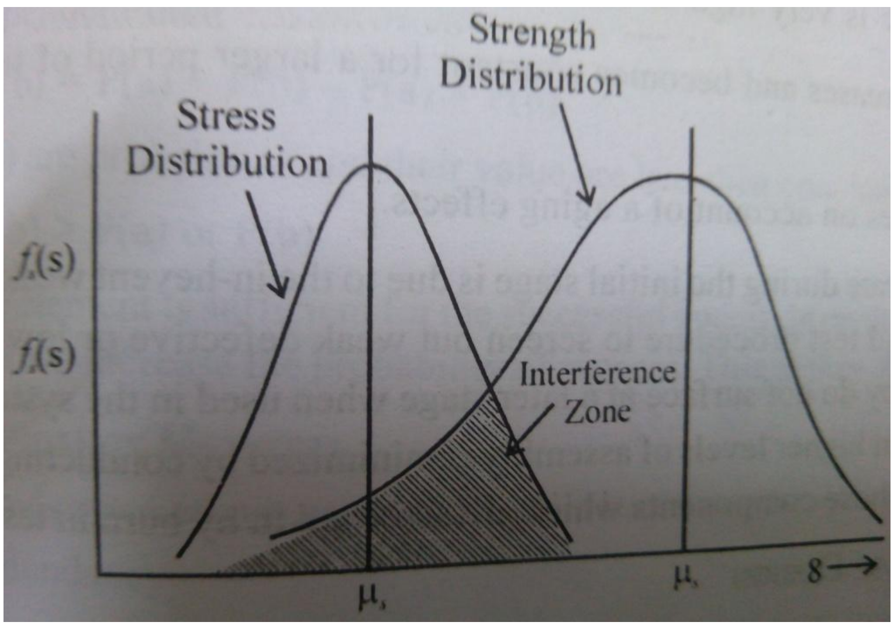
Therefore, controlling the environment is one of the most important methods for reliability improvement. In some cases, controlling the environment is not possible. In such cases, go for preventive measures, such as anti-oxidized, anti-corrosion agents, protective covers and insect repellants.

System mean life an components mean life are related in series system

$$\frac{1}{T} = \frac{1}{T_1} + \frac{1}{T_2} + \cdots \frac{1}{T_n}$$

PROCESS CONTROL AND PRODUCT RELIABILITY

Famous stress strength concepts can be used for reliability improvement. Both stress and strength follow same distribution. The interference area of stress strength distribution represents the unreliability zone. That means, reducing the interference area is a feasible method for reliability improvement.



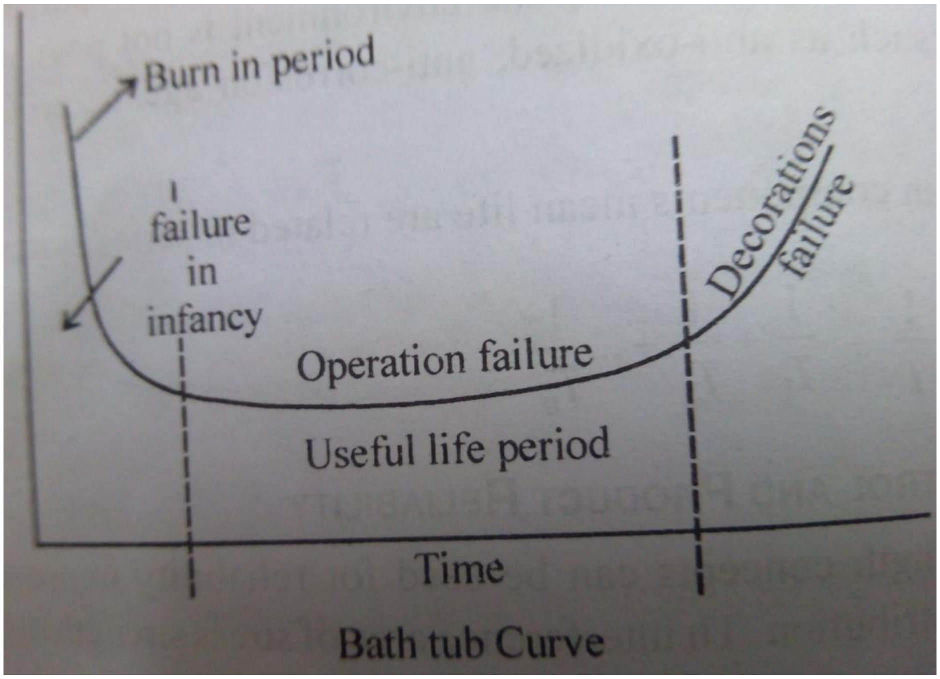
The interference area can be reduced by applying the following techniques:

- By increasing the gap between mean stress and mean strength.
- By reducing the variance of the stress strength distribution.
- By the combination of the two.

The first approach is basically similar to using a factor of safety or using the principle of derating. The second approach is either by controlling the variations in environment and applied load or by controlling the variations in strength by process control approach. This means that a better quality control mechanism will improve the product reliability. The third approach is by combining all other approaches.

APPLICATION OF BURN IN TEST

Bath tub curve between failure rate and time is shown below we see that:



(i) Failure rate is very high at the initial stages.
(ii) It then decreases and becomes constant for a larger period of time, i.e. operation time failure.
(iii) It again rises on account of a aging effects.

The high failure rate during the initial stage is due to the weakness of the component. Burn in is a design and test procedure to screen out weak defective or low quality items form the population, so that they do not surface at a later stage when used in the system assembly. Thus, the possibility of rework at higher levels of assembly is minimized by conducting burn in tests. It will be ideal, if we use only those components which are screened in by burn in tests in our assembly.

WORST CASE DESIGN

A system is composed of a large number of components. The components performance degrades over a period of time for various reasons such as manufacturing variations, environmental effects and types of failure mechanisms. This will directly affect the performance if the system. Therefore when a system is designed, all possibilities of component degradation and their effect on the system should be considered. If a system is designed while considering a worst possible variations of performances of each component and worst combination of this on the system, then it shall improve the reliability of the system. Hence design for a worst case design.

HUMAN RELIABILITY

Human beings are directly or indirectly involved in the operations of any system. Actual performance of the system is a function of system reliability and human reliability.

Or Achieved reliability = system reliability × Human reliability.

Therefore if human involvement is not properly addressed, we may not get the expected performance of the system. Hence it is necessary to increase the human reliability.

5.6 Reliability Testing

Objectives

- Reliability testing
- Accelerated life testing
- RET testing
- Reliability growth testing
- Test, analyse and fix
- FRACAS

What is a test?

• A test has been defined as "a subjection to conditions that show the real character of the thing "However, testing is a continuing operation to provide information throughout the complete evolution of the system

What should be testing?

Define exactly what requires testing - bearing in mind that the objective is to minimize the number of tests required for cost reasons The test types may be categorized as follows: -
Mandatory Testing based on pedigree or experience Data driven test requirements

Testing based on pedigree or experience: -
A historical product with similar physical and performance attributes and similar testing may be referred to as a guide. Manufacturing and development engineers may have a 'feel' for the type of testing required based on previous experience

Frequency of testing

Need to determine the frequency of testing.
Each and every product
Each and every product for a limited period
Periodic testing
Regulatory requirement testing at a specified interval/frequency

Time based testing

When an item fails, which part in a component causes failure which component in a system fails? The mode or modes of failure as exemplified by performance drift, erratic performance, catastrophic failure, etc., the mechanism of failure that is, the reasons for failure caused by poor design, part misapplication etc

Event testing

In this case samples of the equipment are tested repeatedly through their cycle of operation until failure. This testing, which is analogous to time-to-failure testing, becomes the more meaningful test when starting and stopping operations are more destructive than the more accumulation of time. The important parameter in this form of testing is mean number of cycles to failure.

Environmental testing

As its name implies, this form of testing represents a survey of the reaction of the item to the various environments. It is usually required in qualification tests and is frequently introduced in the development stage, usually at less numerous or less severe environmental levels.

Testing for reliability and durability

- Test to cause failures
- Not test to demonstrate successful achievement
- Use concepts of load and strength to determine test conditions

Types of Accelerated Test

This consists of running a product at a higher than normal level of some accelerating stress or stresses to shorten product life or to degrade product performance factor. Typical accelerating stresses are temperature, voltage, mechanical load, thermal cycling, humidity and vibration. Over-stress testing is the most common form of accelerated testing

Constant stress

- The most common form
- Each specimen is run at a constant stress level.
- Mimics the stresses seen in actual use in many cases and can be simple.
- The advantages are a constant stress level is easy to maintain Models for acceleration are well developed and tested

Methods of applying stress

• Progressive Stress Tests

In progressive stress testing, a specimen undergoes a continuously increasing level of stress. The method has similar advantages and disadvantages to the step stress test.

• Cyclic Stress

In use some products repeatedly undergo a cyclic stress loading, for example all AC electrical products see a sinusoidal stress. A cyclic stress test for a product repeatedly loads a specimen with the same stress pattern at high stress levels. For many products this cycle is sinusoidal, for others the duty cycle repeats but is not sinusoidal.

• Random Stress

In a random stress test, a random stress loading is applied to the specimen for a random time and then removed another random stress for some other random time and so on. This type of test simulates the real use of a number of products.

Reliability Enhancement Tests

Tests that are carried out in the design and development phase of a product to remove defects. The standard approach is

– TEST
– ANALYSE
– FIX

5.7 Reliability Prediction Basics

Reliability predictions are one of the most common forms of reliability analysis. Reliability predictions predict the failure rate of components and overall system reliability. These predictions are used to evaluate design feasibility, compare design alternatives, identify potential failure areas, trade-off system design factors, and track reliability improvement.

The Role of Reliability Prediction

Reliability Prediction has many roles in the reliability engineering process. The impact of proposed design changes on reliability is determined by comparing the reliability predictions of the existing and proposed designs. The ability of the design to maintain an acceptable reliability level under environmental extremes can be accessed through reliability predictions. Predictions can be used to evaluate the need for environmental control systems. The effects of complexity on the probability of mission success can be evaluated by performing a reliability prediction analysis. Results from the analysis may determine a need for redundant systems, back-up systems, subsystems, assemblies, or component parts.

Reliability and Unreliability

First, let us review some concepts of reliability. At a given point in time, a component or system is either functioning or it has failed, and that the component or system operating state changes as time evolves. A working component or system will eventually fail. The failed state will continue forever, if the component or system is non-repairable. A repairable component or system will remain in the failed state for a period of time while it is being repaired and then transcends back to the functioning state when the repair is completed. This transition is assumed to be instantaneous. The change from a functioning to a failed state is failure while the change from a failure to a functioning state is referred to as repair. It is also assumed that repairs bring the component or system back to an “as good as new” condition. This cycle continues with the repair-to failure and the failure-to-repair process; and then, repeats over and over for a repairable system.

Reliability (for non-repairable items) can be defined as the probability that an item will perform a defined function without failure under stated conditions for a stated period of time. One must grasp the concept of probabilities in order to understand the concept of reliability. The numerical values of both reliability and unreliability are expressed as a probability from 0 to 1 and have no units.

Reliability stated in another way:

The Reliability, $R(t)$, of a component or system is defined as the probability that the component or system remains operating from time zero to time $t1$, given that it was operating at time zero. Or stated another way for repairable items: The Reliability, $R(t)$, is defined as the probability that the component or system experiences no failures during the time interval zero to $t1$ given that the component or system was repaired to a like new condition or was functioning at $t0$. And: The Unreliability, $F(t)$, of a component or system is defined as the probability that the component or system experiences the first failure or has failed one or more times during the time interval zero to time t, given that it was operating or repaired to a like new condition at time zero.

The Unreliability, F(t), of a component or system at a given time is simply the number of components failed to time t divided by the total number of samples tested. The following relationship holds true since a component or system must either experience its first failure in the time interval zero to t or remain operating over this period.

$R(t) + F(t) = 1$ or Unreliability $F(t) = 1 – R(t)$

Availability and Unavailability

In reliability engineering and reliability studies, it is the general convention to deal with unreliability and unavailability values rather than reliability and availability. The numerical value of both availability and unavailability are also expressed as a probability from 0 to 1 with no units. The Availability, A(t), of a component or system is defined as the probability that the component or system is operating at time t, given that it was operating at time zero. Reliability Prediction Definitions Failure Rates Reliability predictions are based on failure rates. Conditional Failure Rate or Failure Intensity, $\lambda(t)$, can be defined as the anticipated number of times an item will fail in a specified time period, given that it was as good as new at time zero and is functioning at time t.

It is a calculated value that provides a measure of reliability for a product. This value is normally expressed as failures per million hours (fpmh or 106 hours), but can also be expressed, as failures per billion hours (fits or failures in time or 109 hours). For example, a component with a failure rate of 2 failures per million hours would be expected to fail 2 times in a million-hour time period. Failure rate calculations are based on complex models which include factors using specific component data such as temperature, environment, and stress. In the prediction model, assembled components are structured serially. Thus, calculated failure rates for assemblies are a sum of the individual failure rates for components within the assembly

There are three common basic categories of failure rates:

Mean Time Between Failures (MTBF)
Mean Time To Failure (MTTF)
Mean Time To Repair (MTTR)

Mean Time Between Failures (MTBF)
Mean time between failures (MTBF) is a basic measure of reliability for repairable items. MTBF can be described as the time passed before a component, assembly, or system fails, under the condition of a constant failure rate. Another way of stating MTBF is the expected value of time between two consecutive failures, for repairable systems. It is a commonly used variable in reliability and maintainability analyses. MTBF can be calculated as the inverse of the failure rate, λ, for constant failure rate systems. For example, for a component with a failure rate of 2 failures per million hours, the MTBF would be the inverse of that failure rate, λ,

Mean Time To Failure (MTTF)
Mean time to failure (MTTF) is a basic measure of reliability for non-repairable systems. It is the mean time expected until the first failure of a piece of equipment. MTTF is a statistical value and is intended to be the mean over a long period of time and with a large number of units. For constant failure rate systems, MTTF is the inverse of the failure rate, λ. If failure rate, λ, is in failures/million hours, MTTF = 1,000,000 / Failure Rate, λ, for components with exponential distributions. Or failures hours. For repairable systems, MTTF is the expected span of time from repair to the first or next failure.

Mean Time to Repair (MTTR)
Mean time to repair (MTTR) is defined as the total amount of time spent performing all corrective or preventative maintenance repairs divided by the total number of those repairs. It is the expected span of time from a failure (or shut down) to the repair or maintenance completion. This term is typically only used with repairable systems.

5.9 **MONTE-CARLO SIMULATION**

SIMULATION AND ANALYTIC MODELS

Analytic means exist for performing calculations using RBDs, but these calculations are only valid under certain restrictive assumptions such as independence of the blocks, no queuing for repair, etc. There are a number of modeling techniques which may be used to overcome these restrictions, and two such techniques are Markov analysis and simulation.

Reliability models, by the nature of the process that they represent, have a significant probabilistic content. These processes usually involve the combination of two or more input random variables to produce output random variables. There are two approaches to the solution of these problems; one using analytical methods and the other using a technique called Monte-Carlo simulation.

In the analytical method, the probability distributions associated with the output random variables are *calculated* from the probability distributions associated with the input variables. In Monte-Carlo simulation, the value of a distributed parameter is selected by the generation of a random number, with the probability of a given value being determined by the association of random numbers to that variable. By repeating this process a large number of times, a picture of the distribution of the output random variable may be built up, from which estimates of the parameters of interest may be calculated, e.g. their mean, standard deviations, etc. A more detailed explanation of the Monte-Carlo simulation method, together with worked examples is given by Jones.

The two modeling methods are best explained by means of an example. Consider two items connected in series which have constant failure rates. The times to failure of individual items are governed by the negative exponential distribution with the probability density function.

However, the system MTBF can also be estimated using Monte-Carlo simulation methods. A time is sampled from each failure time distribution for both elements, say T1 and T2. (Tocher1 describes methods of how this can be performed in practice) . By performing these operations a large number of times, the distribution of TS is obtained and an estimate of the system MTTF is given by the mean of the sample values TS.

COMPARISON OF METHODS

Each technique has its advantages and disadvantages; the main ones are listed in Table Broadly, for complex systems that may be subject to change later, the Monte-Carlo method is preferred because of its flexibility. For simpler systems, or studies to get a 'feel' for a problem, analytical methods may suffice

The decision as to whether the modeler should use analytical (e.g. deterministic equations) or simulation (i.e. Monte-Carlo) methods may be influenced by the following factors:

complexity. Simulation often gives better physical visibility of a complex system analysis than a set of equations, aiding interpretation of the output.

Cope. For example, complex repair policies are easier to deal with in simulations than analytical models.

Accuracy. Although analytical models are deterministic, they usually involve simplifying assumptions to make the model analytically tractable. Such assumptions have to be justified.

Future development. If a model is likely to be further refined ad developed, an initial model that may be initially tractable analytically may not be so when further development requirements are placed. A simulation model may therefore be appropriate from the start.

Application. For quick look analysis, analytical models may be preferred, because of their speed of execution. The repeated running involved in Monte-Carlo simulation can cause long execution times before estimates of system parameters of interest are obtained

Monte-Carlo Simulation Method		
Advantages	**Analytical**	**Monte-Carlo**
	a. Gives exact results (given the assumptions of the model).	a. Very flexible. There is virtually no limit to the analysis. Empirical distributions can be handled.

	b. Once the model is developed, output will generally be rapidly obtained.	b. Can generally be easily extended and developed as required.
	c. It need not always be implemented on a computer – paper analyses may suffice.	c. Easily understood by non-mathematicians.
Disadvantages	a. Generally requires restrictive assumptions to make the problem tractable.	a. Usually requires a computer.
	b. Because of a. it is less flexible than Monte-Carlo. In particular, the scope for extending or developing a model may be limited.	b. Calculations can take much longer than analytical models.
	c. The model might only be understood by mathematicians. This may cause credibility problems if output conflicts with preconceived ideas of designers or management.	c. Solutions are not exact, but depend on the number of repeated runs used to produce the output statistics. That is, all outputs are estimates.

Table:- Main Advantages and Disadvantages of Analytical and Monte-Carlo Simulation Models

TATISTICAL ACCURACY OF RESULTS

The Monte-Carlo simulation method is a type of sampling procedure, thus any output is not exact but a statistical estimate whose accuracy depends on the number of missions or failures generated. For example if mission parameters are of prime important (e.g. probability of mission survival failure free) then the number of missions to be simulated is the important parameter. The number of system failures generated is not necessarily important, e.g. if in 1000 mission simulated only 5 system failures are generated, mission reliability is none the less reasonably well established. However, if MTBF estimates are the prime consideration then a sufficient number of system failures must be simulated to yield the desired accuracy.

REVIEW QUESTIONS

Q.1. Explain the term reliability and also explain the failure data analysis.

Q.2. Explain the term availability & maintainability with suitable example.

Q.3. Give the RAM failure Mechanism and there failure distribution.

Q.4. Explain the repairable and non repairable system.

Q.5. Define the improvement of reliability with complete example.

Q.6. Explain the term reliability testing and give the name of types of testing process used.

Q.7. What is meant by reliability prediction technique and where it is used?

Q.8. What is MONTE CARLO SIMULATION explain with detail and give the advantage and disadvantages of this.