CHAPTER 13

RELIABILITY

13.1 INTRODUCTION

The concept of reliability has been known for a number of years, but it has assumed greater significance and importance during the past decade, particularly due to impact of automation, development in complex missile and space programmes. The manufacture of highly complex equipment has served to focus greater attention on reliability. The complex products, equipments are made up of hundreds or thousands of components whose individual reliability determines the reliability of the entire equipment. Using various types of materials and fabricating operations, the industry has to build reliable performance into equipment and the products manufactured.

As regards the Indian industry, the reliability concept is yet to find a footing. The solutions to many of the problems of quality and economy remain handicapped because of inadequate appreciation of the reliability principles and techniques. However, reliability is only one of the tools of the management which must be supplemented by other tools like quality control and design of experiments for the solution of problems of quality and cost.

13.2 QUALITY CONTROL AND RELIABILITY

Quality control maintains the consistency of the product and thus affects reliability. But it is entirely a separate function. Reliability is associated with quality over the long term whereas quality control is associated with the relatively short period of time, required for manufacture of the products. The task of reliability is to see that in a product design, full account has been taken of every contingency which may cause a breakdown in use and to forecast the components or assemblies that are likely to become defective in service. However well, the equipment is designed, still it may be unreliable, if some component has not been fully evaluated under all service conditions, even if the production standards have been maintained by quality control during manufacture.

Figure 13.1 shows the integration of quality and reliability function.

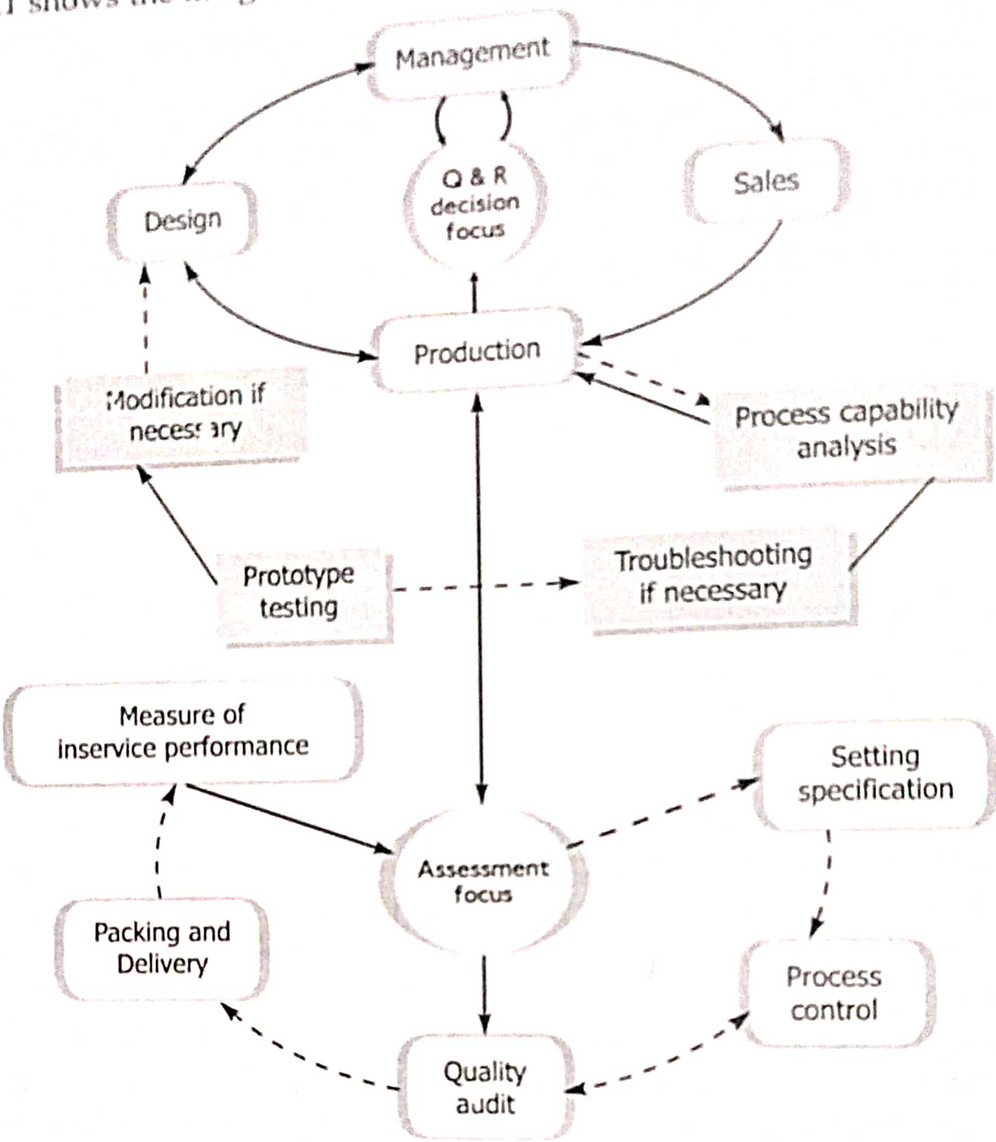


Fig. 13.1 Integration of Quality and Reliability Functions.

Need for a Reliable Product

The reliability of a system, equipment or product is very important aspect of quality for its consistent performance over its expected life span. In fact, uninterrupted service and hazard free operation is the essential requirement of large complex systems like electric power generation and distribution plants or communication network such as railways, aeroplane, automobile vehicles etc. In these cases a sudden failure of even a single component, assembly or system results in a health hazard, accident, or interruption in continuity of service.

Thermal power plants provide electric power for domestic, commercial, industrial and agricultural use. Reliability problems may cause shut down or reduced generation of power resulting in load shedding and many other problems including loss of productive activities.

Failure of any one system of an air-craft may result in forced landing or an accident.

Sudden stoppage of suburban railway train due to fault in the single system faulty carriage, interruption in the power supply or faulty track, sets up a chain of events leading to disruption of service or accidents.

Similarly, sudden failure of a car break system while it is running may cause severe accident.

Unpredicted failure of a single critical component may be cause of any one of the above.

What is true of power plants, air-crafts, railways etc. is also true for other products like washing machine, mixer grinder, T.V. sets, Refrigerators etc. though failure of such products may cause inconvenience on a smaller scale.

The problem of assuring and maintaining has many responsible factors, including original equipment design, control of quality during manufacture, acceptance inspection, field trials, life testing and design modifications.

Therefore deficiencies in design and manufacture of products which go to build such complex systems needs to be detected by elaborate testing at the development stage and later corrected by a planned programme of maintenance.

Definitions of Reliability

Reliability is ordinarily associated with the performance of the product. However, there would be little point in having an electric lamp which may light at the time of purchase but which may burn off after 200 hours of use. Whenever the customer purchases a product he expects that it should give satisfactory performance over a reasonably long period. Hence, what is important is that a product should function and continue to function for a reasonable time.

In practice, in majority of the cases, it may not be possible to test each and every product for its life or other performance requirements. Nevertheless, it is a well known experience that each individual unit of product varies from the other units ; some may have relatively long life. In view of the existence of this variation, there would always be a chance or probability that the product would function in the intended manner for the intended length of time. More specifically,

> Reliability is the probability of a product functioning in the intended manner over its intended life under the environmental conditions encountered.

From this definition, there are four factors associated with reliability. These are :

1. Numerical value
2. Intended function
3. Life
4. Environmental conditions.

The introduction of this element of probability really makes the quantitative measurement of reliability possible. In other words, such measurements help to make reliability a number – a probability – that can be expressed as a standard. They make it possible to objectively evaluate the reliability to predict it and to balance it with the other quality requirements, such as maintainability and appearance.

The second consideration for a product to be reliable is that it must perform a certain function or do a certain job when called upon. The phrase 'functioning in the intended manner' (satisfactory performance) implies that the device is intended for certain application. For example, in the case of electric iron, the intended application is that of applying intended degree of heat to the various types of fabrics. If instead it is used to keep a room at a certain temperature, the electric iron might be inadequate because of the greater area to be heated and the change in environment.

The third element in the definition of reliability is that of time which ensures that the product is capable of working satisfactorily throughout the expected life. Many companies frequently concentrate on testing their product at the start only and do not evaluate the performance at the various stages during the life of the product. As a result they experience extremely difficult reliability problems when their increasingly complex products are put to use by the consumers.

The fourth consideration in the definition is that of the environment conditions which have to be viewed broadly so as to include storage and transport conditions. Since these conditions too have significant effect on product reliability.

Many formal definitions of reliability have been proposed that are similar in their general intent but differ a bit in their exact phrasing.

Some of the other definitions are as follows :

"Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered".

"The reliability of a system or device, is the probability that it will give satisfactory performance for a specified period of time under specified conditions".

Reliability of a product is

"a measure of the ability of the product to function successfully, when required for the required period in the specific manner".

Stated simply,

"reliability is the capability of an equipment not to breakdown in operation".

When an equipment works well, and works whenever called upon to do the job for which it is designed, such equipment is said to be reliable.

Failure is defined as the inability of an equipment not to breakdown in operation.

"Reliability may also be defined as the probability of no failure throughout a prescribed operating period".

The causes of unreliability of the product are many : one of the major causes is the increasing complexity of product. The multiplication law of probability illustrates this very simply. Given an assembly made up of five components, each of which has a reliability of function of 0.95, the reliability of function of assembly is $(0.95)^5$ or about 0.78. Many assemblies which are electronic in nature involve thousands of parts (a ballistic missile has more than 40,000 parts). Therefore, to have reasonable chance of survival for such assemblies the component reliability is of prime importance.

13.3 BASIC ELEMENTS OF RELIABILITY

The basic elements required for an adequate specification or definition of reliability are as follows:

1. Numerical value of probability.
2. Statement defining successful product performance.

3. Statement defining the environment in which the equipment must operate.
4. Statement of the required operating time.
5. The type of distribution likely to be encountered in reliability measurement. Reliability follows the distribution of Poisson $e^{-T/\theta}$.

where θ mean life,

T required life.

Failure Pattern for Complex Product

Complex products often follow a familiar pattern of failure. When the failure rate (number of failures per unit time) is plotted against a continuous time scale, the resulting chart is known as "bath tub curve" (because of its shape).

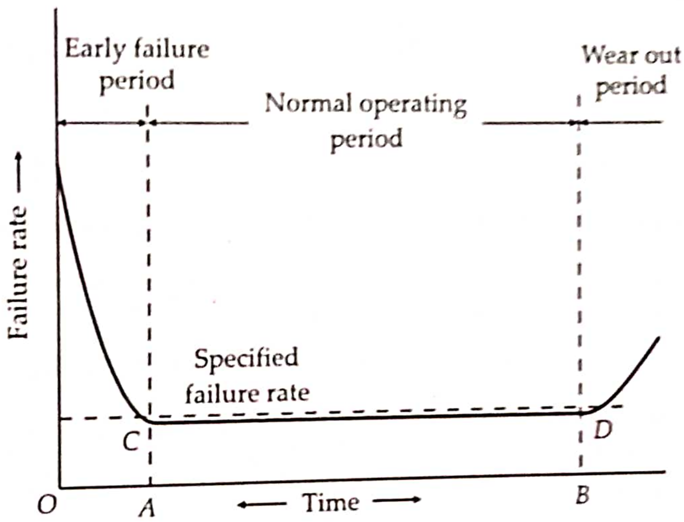


Fig. 13.2 Failure rate curve.

This curve exhibits three distinct zones. These zones differ from each other in frequency of failure and in the cause of failure pattern. These are as follows :

1. ***Infant mortality period (or burn in or the debugging period).*** This is characterised by high failure rates. It begins at the first point during manufacture that total equipment operation is possible and continues for such a period of time as permits (through maintenance and repairs), the elimination of marginal parts initially defective though not inoperative, and unrecognizable as such until premature failure.

Commonly, these are early failures resulting from defect in manufacturing, or other deficiencies which can be detected by debugging, running on or extended testing.

2. ***The constant failure rate period.*** Upon replacement of all prematurely failing items, the failure rate will have reached a lower value (point C). From this point the failure rate remains fairly constant.

These are chance failures which may result from the limitations inherent in the design plus accidents caused by usage or poor maintenance or hidden defects which escape inspection. The period from A to B is the normal operating period in which the average failure rate remains fairly constant. It represents the effective life of the product. In effect the use of sampling plans based on a constant failure rate implies that only the region from A to B need to be considered.

3. ***The wear out period.*** These are failures due to abrasion fatigue, creep, corrosion, vibration etc., *e.g.*, the metal becomes embrittled, the insulation dries out. A reduction in failure rate requires preventive replacement of these dying components before they result in catastrophic failure.

13.4 ACHIEVEMENT OF RELIABILITY

There are five effective areas for the achievement of reliability of the product. They are

(*i*) Design (*ii*) Production
(*iii*) Measurement and testing (*iv*) Maintenance and
(*v*) Field operation.

Design is the main cause of unreliability and a greater percentage of causes of unreliability can be traced out in this area.

Designing for Reliability

The following factors should be considered for achieving a reliable design :

1. ***Simplicity of product.*** The design should be as simple as possible. Error rate is directly proportional to complexity. The greater the number of components the greater the chance of failure. Increased reliability is a natural by-product of equipment simplification.

2. ***Derating.*** Derating means providing a large safety margin. It is also used as a method of achieving design reliability. For example, a material with tensile strength of 10,000 kg/cm^2 might be prescribed where only 7,000 kg/cm^2 is required.

3. ***Redundancy.*** Redundancy is the provision of stand-by or parallel components or assemblies to take over in the event of failure of the primary item.

Even though we use most reliable components and keep their number a minimum, there may be one or two such components which may have lesser reliability. To overcome this, more number of such components are included and so arranged that the whole equipment will continue to survive so long as at least one of these components survives. This technique is known as redundancy.

Auxiliary power generators are examples of redundant items. They are put in service when the primary system fails.

4. ***Safe operation.*** Part should be designed with fail safety in mind. How the component fails is of importance. If possible, failure should occur in non-catastrophic manner and should do no harm to operator.

5. ***Protection from extreme environmental conditions.*** An item protected from extremes of environmental conditions will have increased reliability. For example, pilots of supersonic space-craft are protected from the effects of extremes of heat and cold. Electric motors of common household appliances are rubber mounted to protect them from vibration.

6. *"Maintainability"* and *"serviceability"* are important considerations in designing for reliability. Ease of maintenance and service contributes to higher field reliability. It is evident that an item which is easy to maintain naturally receives better maintenance and service.

Methods for Improving Design Reliability

Design is the most important of the key areas and the greater percentage of causes of unreliability can be traced to this area.

Except by pure chance, a product will not have a greater reliability than the designer has engineered into it. The designer builds up a model, he subjects the model to tests, usually very limited tests in terms of actual service requirements, he revises his design to correct the deficiencies. When he has repeated this performance until he arrives at a result with which he is satisfied he tries to define his design in terms of words, lines and figures.

Action to change design to improve their reliability is best taken by designer himself. The following actions indicate some approaches used by the designer working jointly with the reliability engineer to improve a design.

1. Review the index selected to define product reliability to make sure that it reflects customer needs.
2. Question the function of the unreliable parts with a view of eliminating them entirely if the function is found to be unnecessary.
3. Review the selection of any parts which are relatively new. Use standard parts whose reliability has been proved by actual field usage (making sure that the conditions of previous use are applicable to the new product).
4. Conduct a research and development programme to increase the reliability of the parts which are contributing most to the unreliability of the equipment.
5. Specify corrective replacement times for unreliable parts and replace the parts before they fail.
6. Select parts which will be subjected to stresses which are lower than the parts can normally withstand (Derating).
7. Control the operating environment so that a part will be operating under conditions which yield a lower failure rate.
8. Use redundancy so that if one unit fails a redundant unit will be available to do the job.
9. Consider possible trade-offs of reliability with functional performance ; weight or other parameters.

Some of these actions can be taken by the designer himself others require management consideration.

Reliability Tests. Reliability testing means the tests conducted to verify that a product will work satisfactorily for a given time period. Reliability testing therefore, consists of functional test, environmental test and life testing.

Functional Test. Functional testing involves a test to determine if the product will function at time zero.

Environmental Test. Environmental conditions (temperature, humidity, vibration, etc.) are critical to many products. Environmental test consists of determining the expected environmental levels and then carrying the functional test under the environments under which the product has to operate.

Measurement of Reliability

A basic measurement of the reliability of a product *i.e.*, its probability of survival is that of mean time between failures. Suppose that 'n' products are taken at random from a large group, and 'nt' of them fail (end their life) during the time period t, then the probability of failure during the period 't'.

$$P_t = \frac{n_t}{n}$$

For the determination of reliability however, it is necessary to evaluate the performance of the product over the intended length of time, say T.

Therefore, $$P_t = \sum_{t=0}^{T} \frac{n_t}{n}$$

Reliability $$R_T = 1 - \text{Probability of failure}$$

$$= 1 - P_t$$

$$= 1 - \sum_{t=0}^{T} \frac{n_t}{n} \qquad \text{...(1)}$$

When a large number of products is tested so that the relative frequency $\frac{n_t}{n}$ becomes a smooth function $f(t)$ of times then reliability can be expressed by :

$$R_T = 1 - \int_0^T f(t) \cdot dt \qquad \text{...(2)}$$

In practice, it is found that if the failure rate (*i.e.*, the percentage of failure during each time interval) is approximately constant, then the function $f(t)$ assumes the form of the exponential probability density function

$$f(t) = \frac{1}{0} e^{-t/0} \qquad \text{...(3)}$$

where, 0 stands for the mean life or mean time between failure (MTBF).

Therefore, $$R_T = 1 - \int_0^T \frac{1}{0} \cdot e^{-t/0} \cdot dt$$

or $$R_T = e^{-T/0} \qquad \text{...(4)}$$

where T denotes the required life.

The failure rate λ can be shown in this case to be the reciprocal of the mean time to failure *i.e.*, $\lambda = \frac{1}{\theta}$.

Therefore the expression for reliability becomes

$$R_T = e^{\lambda T} \qquad ...(5)$$

In case the failure rate is not constant, there are other density functions like Normal, Gamma, Weibull which accommodate most of the patterns in practice.

OC curve for an acceptance sampling plan based on a stipulated maximum number of test hours

The OC curve represents the probability of acceptance for a given mean life. Considered the following lot-by-lot acceptance sampling plan (taken from "Hand book H 108").

Select 22 items at random from a lot. Place these items on test. Whenever an item fails, replace it with another item selected at random from the lot. If the test continues for 500 hours with 2 failures accept the lot. If 3 failures occur before 500 hours of testing reject the lot and terminate the test.

Acceptance under this plan requires 22 (500) = 11,000 item hours of test with an acceptance number of 2. Under the assumption that the probability of failure is the same for every item hour, the calculations of the OC curve is the same as if having an ordinary single sampling attributes plan with an n of 11,000 and 'c' of 2.

Table 13.1 illustrates the use of Table G to calculate the OC curve of this plan. The method of calculations is identical as that of ordinary single sampling plan (attribute). However, the failure rate λ' takes the place of the fraction defective p', and this example 11,000 λ' is equivalent to np'. Table 13.1 shows the value of θ' corresponding to each value of λ'. Fig. 13.3 shows the OC curve plotted in the usual manner.

Table 13.1 and the OC curve of Fig. 13.3 are valid for all plans requiring 11,000 items hours for acceptance and having an acceptance number 2.

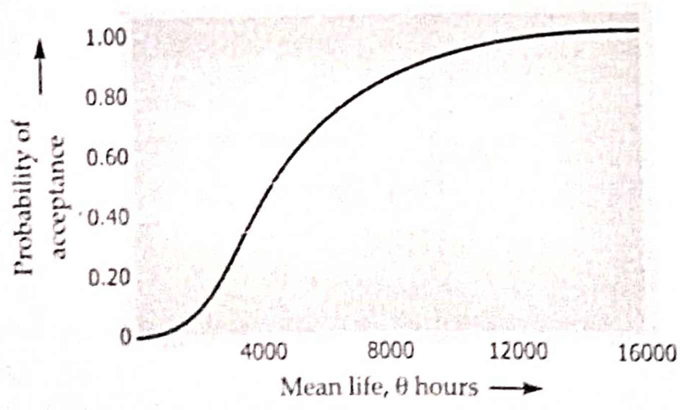


Fig. 13.3 OC Curve.

Table 13.1 : *Calculation of OC curve for acceptance sampling plan requiring 11,000 item hours of life testing with an acceptance number of 2.*

Failure rate per hour λ'	*Mean life hour* $\theta = 1/\lambda'$	*Expected average number of failures in 11,000 test hours (11,000* λ'*)*	*Probability of acceptance (probability of 2 or less failures, read from Table 9)*
0.00002	50,000	0.22	0.999
0.00005	20,000	0.55	0.982
0.00006	16,667	0.66	0.971
0.00008	12,500	0.88	0.939
0.00010	10,000	1.1	0.900
0.000125	8,000	1.375	0.839
0.00015	6,667	1.65	0.770
0.00020	5,000	2.2	0.623
0.00025	4,000	2.75	0.480
0.00030	3,333	3.3	0.360
0.00040	2,500	4.4	0.185
0.00050	2,000	5.5	0.088
0.00060	1,667	6.6	0.040
0.00080	1,250	8.8	0.007

Cost of Reliability

Before actually designing for high reliability the cost of obtaining the desired reliability must be considered. The investment in reliability is exponentially proportional to the return on investment. Therefore, in the case of highly reliable products, the cost of development and maintenance of reliability would be quite high.

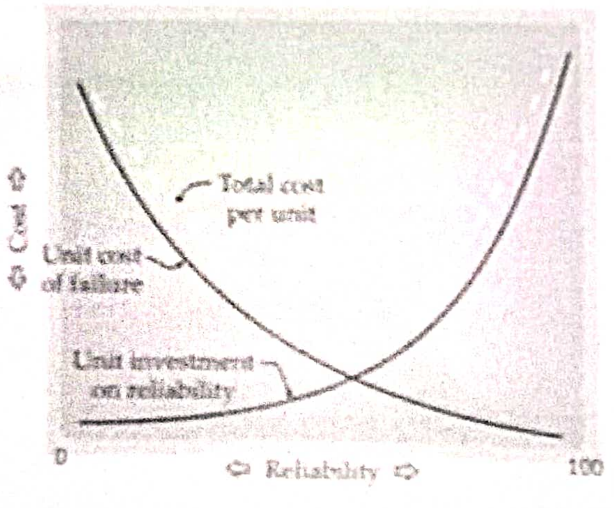


Fig. 13.4 Optimum reliability.

However, for most industrial and consumer products, the cost problem would not be so difficult. There would generally be an optimum value of reliability which is most economical to meet consumer requirements.

If the specified reliability is much lower than the optimum, the actual costs to the consumer may be high due to excessive repairs and maintenance. On the other hand if an unduly high reliability value is specified the total cost may still be excessive due to greater and stricter requirements for components and assemblies. Hence, efforts will have to be made by balancing various factors in such a way as to ensure adequate reliability at an economic level.

When reliability requirements become quite high and it is desired to establish these values in practice, an almost unbelievable amount of testing may be required. On the other hand if the conclusions are drawn by taking just a few samples then certain amount of risk would always be involved. The only practical solution in such cases appears to be to design the product with adequate design margins, manufacture them with satisfactory precision and control including effective quality control, and evaluate the reliability requirements, wherever possible, under simulated conditions.

Maintenance and Reliability

Approximately twice the original cost of complex equipment is expended each year to support the equipment. Much of this cost is the result of upkeep and maintenance. The total reliability of the equipment in the field is a function of design, maintenance and field operation reliability ; that is,

$$R_F = f(D, M, FO)$$

Maintenance is a production type of activity at or near the place of use, which is confined to repair or replacement of failed, marginal or time change units.

Maintainability. "Maintainability" is defined as the probability that a device will be restored to its operational effectiveness within the given period : when maintenance action is performed in accordance with the prescribed procedure.

Maintenance action is the prescribed operation to correct an equipment failure.

Mean Time Between Failures (MTBF). The MTBF is the mean (or average) time between successive failures of a product. This definition assumes that the product in question can be repaired and placed back in operation after each failure. An increase in an MTBF does not result in a proportional increase in reliability (the probability of survival). If $t = 1$ hour, the following table shows the mean time between failures required in order to obtain various reliabilities.

MTBF	*R*
5	0.82
10	0.90
20	0.95
100	0.99

A large increase in MTBF from 20 to 100 hours is necessary to increase the reliability by 4 percentage points as compared with a doubling of the MTBF from 5 to 10 hours to get 8 percentage points increase in reliability. This is important because MTBF is often used as the criterion for making important decisions affecting reliability.

$$\text{MTBF} = \frac{1}{\lambda} = \frac{\text{Total test time}}{\text{Number of failures during test}}$$

MTBF is used for repairable items.

Mean Time to Repair (MTTR). It is the arithmetic mean of the time required to perform maintenance action.

$$\text{MTTR} = \frac{\text{Total maintenance time}}{\text{Number of maintenance action}}$$

Maintenance action rate (μ). It is a numerical value representing the number of maintenance action that can be carried out on a particular equipment per hour.

$$\mu = \frac{1}{\text{MTTR}}$$

Mathematically Mean Time for Repair,

$$\text{MTTR} = \frac{\sum ni\,\lambda i\,tmi}{\sum ni\,\lambda i}$$

where, ni = number of similar parts

λi = failure rate

tmi = predicted maintenance action time

In addition to the desired inherent design effect on maintainability the environment conditions and operating personnel at the place of use have substantial effect on maintainability.

The most significant maintenance and filed support factors are the following :

Criteria of adequate performance. Both operators and maintenance personnel must possess the necessary skill and knowledge to make correct decision about the performance of equipment. Maintainability is dependent upon correct and consistent decisions regarding whether or not maintenance is required. These decisions can be made in the monitoring phase, preventive phase, or by the operator as a result of actual unsatisfactory operation.

Maintainability may be enhanced by designing into the equipment various measuring devices to detect unsatisfactory performance as soon as it occurs.

Marginal Testing. Marginal testing is a technique for detecting potential failures so as to shortcut them. It consists of testing the equipment at maximum and minimum values required by the specifications. This testing at the margins of the acceptable specifications range will often be helpful in detecting whether a deteriorating unit will fail before the next maintenance period.

Provision of Spares. If replacement is needed, right spare parts must be available in sufficient quantity and equal or better quality. In planning for spares in addition to failure rate replacement resulting from marginal testing, parts damaged in maintenance, and secondary failures should also be considered.

Training. For each type of failure, maintenance hand-books should contain instructions on how to trace the failures and what corrective action should be taken. Random sequential replacement of parts until trouble disappears is very undesirable. It may result in serious reduction in reliability through accidental damage, improper re-assembly, misalignment, and other malpractices. Detailed step-by-step procedure for locating troubles is necessary. Maintenance training programmes should provide for thorough introduction in various methods of detecting and correcting the troubles.

Manuals and Technical Orders. Simple adequate understandable maintenance instructions are essential to proper maintenance of equipment and to proper operation. They should be clear, concise and sufficiently direct to allow the maintenance man to proceed through a step-by-step routine towards fault isolation. Whenever possible, requirements for maintenance quality should be expressed in quantitative rather than qualitative terms.

Test Equipment and Facilities. Maintenance of equipment may require the use of precision test equipment for a variety of measurements. Such equipment should be at least as accurate as the test equipment used in original production and test. They should be calibrated as often as necessary and uniform maintenance standard should be followed.

Finally, the test equipment should be adequate to perform the necessary test and it should be available at the time of need.

Availability

"Availability" is sometimes a more appropriate measure than reliability. Whereas reliability is a measure of performing without failure, availability recognizes both reliability and maintainability :

1. Time availability is the percentage of operating time that an equipment is operational. This is usually computed as :

$$P_A = \frac{\text{MTBF}}{\text{MTBF} + \text{MRT}}$$

where MTBF = mean time between failures

MRT = mean repair time.

2. Equipment availability is the percentage of equipments which will be available for use after t hours of operation due to combined effect of units which did not fail and failed units which were restored to service within a specified maximum down-time.
3. Mission availability is the percentage of time t which will have any failure which cannot be restored within a specified maximum down-time.

These definitions recognize that failures will occur but that a good maintainability programme can improve the overall effectiveness of the product.

13.5 FAILURE MODE, EFFECT AND CRITICALITY ANALYSIS (FMECA)

FMECA can be explained as a group of activities intended to :

- Recognize and evaluate the potential failure of a product or process and its effects.
- Identify actions that could eliminate or reduce the chance of potential failures.
- Document the process.

For each potential failure, an estimate of its effect on the total system and its seriousness is made. A review of the action being taken (or planned) is also made to minimize the probability of failure or the effect of failure.

FMECA analysis includes such matters as :

- **Safety.** Injury is the most serious of all failure effects. In consequence safety is handled through special programmes.
- **Effect on down time.** Whether the repairs can be made during an off-duty time or the system must stop until repairs are made.
- **Access.** What hardware items must be removed to get at the failed component.
- **Repair planning.** What is the anticipated repair time ? What special repair tools are needed ?
- **Recommendations.** What changes in designs or specifications should be made ? What tests should be added ?

  What instructions should be included in manuals of inspection, operation, or maintenance ?

There are several types of FMECA :

- Design FMECA,
- Process FMECA,
- Equipment FMECA,
- Maintenance FMECA,
- Service FMECA, etc. and system FMECA is a combination of design and process FMECA.

Design FMECA aids in the design process :

(*i*) By identifying known an foreseeable failure modes and then

(*ii*) Ranking failures according to relative impact on the product.

(*iii*) It helps to establish priorities based on expected failures and severity of those failures.

(*iv*) It also helps to uncover oversights, misjudgement and errors that might have been made.

(*v*) Furthermore design FMECA reduces development time and cost of manufacturing processes by eliminating many potential failure modes prior to operation of the process by specifying the appropriate tests to prove the designed product.

Process FMECA is used to identify potential failure modes by ranking failures and helping to establish priorities according to the relative impact on the internal and external customer.

Implementing process FMECA helps to identify potential manufacturing or assembly causes in order to establish controls for occurrence, reduction and detection.

Furthermore, design and process FMECA document the results of the design and production processs, respectively.

Procedure

Design FMECA should always begin with a block diagram. The block diagram can be used to show different flows (information, energy, force, fluid and so forth) involved with the component being analysed. A block diagram is started by first listing all the components of the system, their functions, and the means of connection or attachment between components. Then, the components of the system are placed in blocks, and their functional relationships are represented by lines connecting the blocks.

A ranking procedure is usually applied in order to assign priorities to the failure modes for future study. The ranking is three-fold :

(*i*) the probability of occurrence.

(*ii*) the severity of the effect.

(*iii*) the likelihood of detection by design control.

For each of these, a scale of 1 to 10 usually used. If desired a risk priority number (RPN) can be calculated as the product of the three ratings mentioned above.

For most products, it is not economical to conduct the analysis of failure mode and effect for each component. In such cases, engineering judgement is used to single out items which are critical to the operation of the product.

In addition to design and process, FMECA analysis are also useful in planning for inspection, assembly, maintainability and safety.

Stages of FMECA

The four stages of FMECA are as given below :

1. Specifying possibilities :
   (*a*) Functions.
   (*b*) Possible failure modes.
   (*c*) Root causes.
   (*d*) Effects.
   (*e*) Detection/prevention.
2. Quantifying Risk
   (*a*) Probability of cause.
   (*b*) Severity effect.
   (*c*) Effectiveness of control to prevent cause.
   (*d*) Risk priority number.
3. Correcting High Risk Causes
   (*a*) Prioritizing work.
   (*b*) Detailing action.
   (*c*) Assigning action responsibility.
   (*d*) Check points on completion.
4. Re-evaluation of Risk
   (*a*) Recalculation or Risk Priority Number.

Terms used in the format for design FMECA are as follows :

1. Item Function. In this section, the name and number of the item being analysed are recorded.

2. Potential Failure Mode. It may be the method in which the item being analysed may fail to meet the design criteria. It may be the method that may cause potential failure in a higher level system or may be the result of failure of a lower level system. Some typical failure modes may include cracked, deformed, loosened, leaking, sticking, short-circuited, oxidized, fractured etc.

3. **Potential Effect of Failure.** The effect of failure must be described in terms of what the customer will notice or experience (as perceived by the customer) some typical effects of failure may include noise, erratic operation, poor appearance, lack of stability, impaired operation etc.

4. **Severity (S).** It is the seriousness of the effect of the potential failure mode. Severity should be rated on a 1-to-10 scale, with one being none and 10 being the most severe.

5. **Classification (Class).** It records any special product characteristics for components, subsystems or systems that may require additional process controls.

6. **Potential Cause Mechanism of Failure.** Every potential failure cause and/or mechanism must be listed completely and concisely. Typical failure causes are : incorrect material specified, inadequate design, inadequate life assumption, over-stressing, poor environment protection etc.

   Typical failure mechanisms are : yield, creep, fatigue, wear, material instability and corrosion.

7. **Occurrence (O).** The chance that one specific cause/mechanism will occur. The likelihood of occurrence is based on a 1-to-10 scale, with one being the least chance of occurrence and 10being the highest chance of occurrence.

8. **Current Design Controls.** In this portion of the form, the activities that assure the design. Sufficiency for the failure mode or mechanism is listed. These may include prevention measures, design validation and design verification.

9. **Detection (D).** It is the ranking of likelihood of detection by design control for design FMECA. It is the relative measure of the assessment of the ability of the design control to detect either potential cause/mechanism or the subsequent failure mode before the component, subsystem or system is completed for production. It is ranked from 1 to 10.

10. **Risk Priority Number (RPN).** By definition, the risk priority number is the product of the severity (S), occurrence (O) and detection (D) rankings *i.e.*, $RPN = (S) \times (O) \times (D)$.

11. **Recommended Actions.** After every concern has been examined and given a risk priority number, the team should begin to examine the corrective actions that may be employed, beginning with the concern with the greatest RPN and working in descending order according to RPN.

12. **Responsibility and Target Completion Date.** Here the individual or group responsible for the recommended actions and the target completion date should be entered as reference for future document users.

13. **Action Taken.** A brief description of the actual action and its effective date should be entered.

14. **Resulting RPN.** After the corrective action has been identified the resulting severity, occurrence, and detection ranking should be re-estimated. Then the resulting RPN should be recalculated and recorded.

Table 13.2 shows the format for design FMECA

Table 13.2 : *Format for Design FMECA*

FAILURE MODE AND EFFECT ANALYSIS (DESIGN FMECA)

FMECA Number ______

Page ______

Date ______ Design Responsibility ______ Prepared By ______

Model Number/year ______ Key Date ______ FMECA DATE (Original) ___ Revised ___

Item / Funtion	*Potential Failure Mode*	*Potential Effect(s)of Failure*	*S*	*CLASS*	*Potential Cause(s) Mechanism(s) of Failure*	*O*	*Current Design Control*	*D*	*RPN*	*Recommended Action*	*Responsibility and Target Completion Dates*	*Action Results* *Action Taken*

Benefits of FMECA

Continually measuring reliability of a machine, product, or process is an essential part of T.Q.M. When acquiring new machines, creating a new product, or even modifying an existing product, it is always necessary to determine the reliability of the product or process. One of the most powerful methods available for measuring the reliability of the process or product is FMECA.

Design (product) FMECA or process FMECA can provide the following benefits :

1. The systematic review of component failure modes in FMECA ensures that any failure produces minimal damage to the product or process.
2. It is possible to determine the effects that any failure will have on either items in the product or process and their functions.
3. Determining those parts of the product or the process whose failure will have critical effects on the product or process operation.
4. Calculating the probabilities of failures in assemblies, sub-assemblies, products and processes from the individual failure probabilities of their components and the arrangements in which they have been designed. Since, components have more than one failure mode, the probability that one will fail at all is the sum of the total probability of the failure modes.
5. Establishing test programme requirements to determine failure mode and rate data not available from other sources and also to verify empirical reliability predictions.
6. Eliminating or minimising the adverse effects that assembly failures could generate and indicating safeguards to be incorporated if the product or the process cannot be made fail-safe or brought within acceptable failure limits.
7. Helping uncover oversights, misjudgements, and errors that may have been made.
8. Helping reduce development time and cost of manufacturing processes by eliminating many potential modes prior to operation of the process and by specifying the appropriate tests to prove the designed product.

13.6 TOTAL PRODUCTIVE MAINTENANCE (TPM)

In today's manufacturing environment, employing high tech, expensive machines backed by computer control of manufacture and advanced manufacturing concepts, there is virtually no room for breakdown of any type. Thus maintenance management is now under an all time high pressure, the aim now being "Zero Breakdowns". Thus, starting with conventional repair of the machines, maintenance now has reached a stage of "Total Productive Maintenance", a concept which aims at "Zero Down Time". This demands a devoted participation of all concerned units and individuals at all levels.

The total maintenance function should be directed towards the elimination of unplanned equipment and plant maintenance. The objective is to create a system in which all maintenance activities can be planned and do not interfere with the production process. Surprise breakdown should not occur.

Applying TPM in to *three* words, we have,

Total = All encompassing by maintenance and production individuals working together.

Productive = Production of goods and services that meet or exceed customer's expectations.

Maintenance = Keeping equipment and plant in as good as or better than the original condition at all times.

TPM is an extention of the 'Total Quality Management' philosophy to the maintenance function. In fact TPM combines the American practice of preventive maintenance with the Japanese concept of TQC, Total Employee Involvement (TEI) and Continuous Process Improvement (CPI) and zero defects. The result is an innovative system for equipment maintenance that optimises effectiveness, eliminates breakdowns and promotes autonomous operator maintenance through day-to day activities.

TPM aims to use equipment at its maximum effectiveness by eliminating waste and loss caused by failure of the equipment, setup and adjustment, reduced speed, process defects and reduced yield. Failure occurs because of the way equipment is manufactured, used and maintained. TPM aims at improving the productivity by improving its personnel and plant by changing the corporate culture

Autonomous work groups are established based on the natural flow of activity. The operator is made responsible for daily maintenance work such as clean up, lubrication, tightening and external inspection so that the equipment does not break down. Operators and maintenance personnel are brought together, resulting in a autonomous work groups. Maintenance technicians are also consultants to the operating personnel. They train operators in how to do certain tasks, such as oiling, minor troubleshooting and set-ups. The maintenance personnel are responsible for carrying out periodical inspections, precision diagnosis and repairs.

A comprehensive definition of TPM involving company wide activities includes the following main elements :

- TPM aims to change corporate culture in order to maximize overall effectiveness of production systems.
- It establishes a sound system to prevent all kinds of losses (zero accidents, zero defects, zero breakdowns) based on actual equipment and workplace.
- TPM is implemented not only by production related departments but also by other departments such as product development, sales, administration etc.
- TPM involves every employee, from top management to workers on the shop floor.

The following measurements were adopted by the Japanese and are accepted by most practitioners.

Accordingly, six major loss areas need to be measured and taken care of :

(A) Down Time Losses

1. *Planned*
   (*a*) Start ups
   (*b*) Shift changes
   (*c*) Coffee and lunch breaks
2. *Unplanned down time*
   (*a*) Equipment breakdown
   (*b*) Change overs
   (*c*) Lack of material.

(B) Reduced Speed Losses

3. *Idling and minor stoppages*
4. *Slow downs*

(C) Poor Quality Losses

5. *Process non-conformities*
6. *Scrap.*

These losses can be quantified into three metrics and can be summarised into one equipment effectiveness metric.

Down time losses are measured by equipment availability using the equation

$$A=\left(\frac{T}{P}\right)\times 100$$

where, A = Availability
T = Operating time (P.D.)
P = Planned operating time
D = Down time.

Reduced speed losses are measured by tracking performance efficiency using the equation,

$$E=\left(\frac{C\times N}{T}\right)$$

where, E = Performance efficiency
C = theoretical cycle time
N = processed amount (quantity)

Poor quality losses are measured by tracking the rate of quality products produced using equation,

$$R = \left(\frac{N-Q}{N}\right) \times 100$$

where, R = rate of quality products

N = processed amount

Q = non-conformities

Equipment effectiveness is measured as the product of the decimal equipment of three previous metrics using the equation

$$EE = A \times E \times R$$

where EE = Equipment effectiveness or overall equipment effectiveness (OEE).

The target for improvement is 85% equipment effectiveness.

Hazard Analysis

Hazard analysis is similar to FMECA but the failure event is one that causes an injury. Three forms of hazard analysis can be prepared : design concept, operating procedures and hardware failures.

Fault Tree Analysis

The fault tree analysis is one of the approaches to reliability analysis of complex system. This method is based on the causes (events) that will lead to system failure. A fault tree is a diagrammatic representation of all possible fault events, their logical combinations and their relationship to the system failure. The faults at the lowest level of the system are normally represented at the bottom of the tree and the system faults at the top.

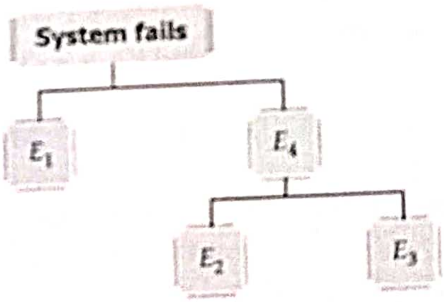


Fig. 13.4(a) Fault Tree Analysis.

The technique is called "fault tree" analysis due to the branching out of origins and causes. The technique is reverse of FMECA, which starts with origins and causes and looks for any resulting bad effects.

The events (causes) at the lowest level are known as basic events. There could be other events resulting from combinations of basic events. Such events are represented as intermediate events. The failure possibilities of the basic events are combined to obtain the failure possibilities of intermediate events and finally the top events.

In the example, E_1, E_2 and E_3 are the basic events. E_4 is an intermediate event which occurs when both E_2 and E_3 occur.

Therefore, $E_4 = E_2 \cap E_3$

The top event *i.e.*, system failure occurs when either E_1 or E_4 occurs.

Then top event $= E_1 \cup E_4 = E_1 \cup (E_2 \cap E_3)$

The probability of system failure is

$$P_r(\text{Top event}) = P_r\,[E_1 \cup (E_2 \cap E_3)]$$

i.e.,
$$P_r(\text{Top event}) = P_r(E_1) + P_r(E_2 \cap E_3) - P_r(E_1)\,P_r(E_2 \cap E_3)$$

If the events E_2 and E_3 are independent,

$$P_r(\text{Top event}) = P_r(E_1) + P_r(E_2)\,P_r(E_3) - P_r(E_1)\,P_r(E_2) \cdot P_r(E_3)$$

Let q_i = the probability of occurring E_i, the system unreliability can be expressed as

$$Q = P_r\ (\text{Top event})$$
$$= q_1 + q_2 \cdot q_3 - q_1 q_2 q_3.$$

Detailed checklists are often developed to provide the designer with information on potential failures, the bad effects/injuries that can result, and specific types of design actions that can be taken to minimize the failure.

Failure Rate and Hazard Function

The rate at which failure will occur in a certain interval of time $[t_1, t_2]$ is known as failure rate for that period. In other words, failure rate is the probability that a failure per unit time occurs in the interval given that a failure has not occurred prior to the beginning of this interval.

Let us analyse the failure of a system in a given time interval, which is between times t_1 and t_2. For the time interval $[t_1, t_2]$ the probability of failure is expressed by an unreliability function as :

$$\int_{t_1}^{t_2} f(t)\,dt = \int_0^{t_2} f(t)\,dt - \int_0^{t_1} f(t)\,dt$$

where, $f(t)$ is the failure function.

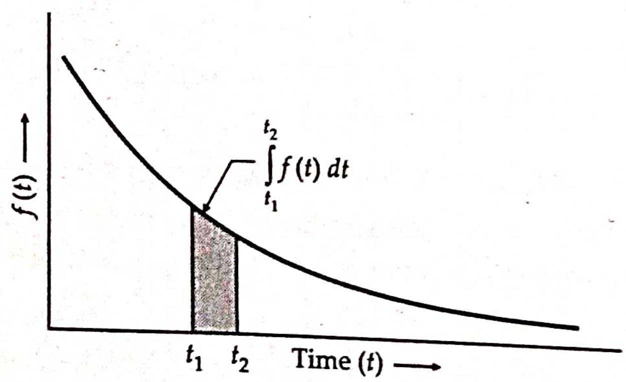


Fig. 13.4(b)

In terms of reliability function, it is expressed as :

$$\int_{t_1}^{t_2} f(t)\,dt = F(t_2) - F(t_1)$$
$$= [1 - R(t_2)] - [1 - R(t_1)]$$
$$= R(t_1) - R(t_2)$$

Here, $F(t)$ is unreliability function and is the integration of failure density function.

Reliability function is complementary to unreliability function and thus equal to one minus the unreliability function.

Now, according to the definition as already stated, failure rate can be expressed as

$$\text{Failure rate} = \frac{R(t_1) - R(t_2)}{(t_2 - t_1)\, Rt_1}$$

If, t_2 is $(t_1 + \Delta t)$ and $t_1 = t_2$, then,

$$\text{Failure rate} = \frac{R(t) - R(t + \Delta t)}{\Delta t\,(Rt)}$$

Hazard Function $h(t)$

Hazard function is the limiting value of the failure rate as the interval approaches to zero.

Thus,
$$h(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{\Delta t \cdot R(t)}$$

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

i.e.,
$$h(t) = \frac{1}{R(t)} \cdot -\left[\frac{d}{dt} R(t)\right] \qquad ...(1)$$

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

Differentiating both sides we get,

$$\frac{d}{dt} F(t) = -\frac{d}{dt} R(t) \qquad ...(2)$$

From equations (1) and (2) we can write

$$h(t) = \frac{1}{R(t)} [f(t)]$$

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

Thus, hazard rate is the ratio of failure rate and reliability.

Thus product of $h(t)$ and Δt represents the probability that a device which has survived till an age of time 't', will fail in the small interval $[t, t + \Delta t]$.

Constant Hazard Model

If we consider an exponential probability distribution and constant failure rate ;

Failure rate ; $\quad f(t) = \lambda^{e-\lambda t}$

Reliability function $R(t) = e^{-\int_0^t \lambda . dt} = e^{-\lambda t}$

then, hazard function,

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda.e^{-\lambda t}}{e^{-\lambda t}} = \lambda$$

Thus, for a constant failure rate, hazard rate is also constant and is equal to failure rate.

Linear Hazard Model

Many components that are under mechanical stresses, fail due to wear out or deterioration. The hazard rate of such components increases with time. The linear-hazard model is the simplest time-dependent model and is of the form

$$h(t) = bt,\ t > 0$$

where, b is a constant

$$R(t) = \exp\left[-\int_0^{\infty} bt \cdot dt\right] = \exp\left(-\frac{bt^2}{2}\right)$$

$$f(t) = bt \exp\left(\frac{-bt^2}{2}\right)$$

Mean Time to Failure (MTTF)

For one-shot systems such as missiles or other non-repairable items such as bulb, fuse etc. It is more appropriate to assess reliability in terms of mean time to failure or probability of survival.

MTTF is the average time that an item or equipment may be expected to function before failure

$$\text{MTTF} = \int_0^{\infty} t\, f(t)dt$$

$$= \int_0^{\infty} t(\lambda e^{-\lambda t})dt = \left[-te^{-\lambda t} - \left\{-\frac{-e^{-\lambda t}}{\lambda}\right\}\right]_0^{\infty} = \frac{1}{\lambda}$$

Thus, MTTF is the reciprocal of constant hazard rate.

13.7 QUALITY AND RELIABILITY

There exists a close relationship between quality and reliability. A good quality without reliability is of little use and reliable product is quite likely to be of good overall quality. However, if a minute distinction is to be made, reliability is not concerned itself with such quality aspects as appearance. It is essentially concerned with the functioning or performance of the product and may have a different method of measurement (for example, mean time between failure).

Further, for the products satisfying the same quality requirements, the degree of reliability may be different. Thus in the case of electric lamps, if the specified requirement for life is minimum of 1000 and 1500 hours, they would be quality lamps. Yet it can be said that the lamps of the second supplier are likely to be more reliable as the probability of their survival at the specified period would be more. In other words, reliability is that 'some time extra' which turns a satisfactory (trouble-free) service not only when it is purchased but throughout its intended life. That is,

Quality now + Quality later = Reliability

Statistical techniques have an important part to play in reliability. They are extremely useful in setting standards for reliability, in process improvement and control to meet these standards and in testing and analysis of manufactured products for ascertaining their reliability.

System Reliability

A system or a complex product is an assembly of a number of parts or components. The components may be similar or dissimilar. The components may be connected in series or in parallel, or it may be a mixed system, where the components are connected in series as well as in parallel.

1. Components connected in series

If the components of an assembly are connected in series the failure of any part causes the failure of the assembly or a system. In this type of system the reliability of the assembly is given by the product of the reliabilities of the individual components.

Suppose a system consists of three mechanical devices, *A*, *B* and *C* that operate in series in such a way that a failure in any one device causes a failure in the system. Assume that the probability that *A* will operate without failure for 100 hours is estimated to be 0.95 and that corresponding probabilities for *B* and *C* are 0.90 and 0.80, respectively. If the failures in *A*, *B* and *C* are completely independent, the probability that the system will operate without failure for 100 hours should be estimated to be

$$(0.95) \times (0.90) \times (0.80) = 0.684$$

Therefore, in general, if the system consists of *n* parts,

Fig. 13.5 Components in series.

Reliability of the system,

$$Rs(t) = R_1(t) \times R_2(t) \times R_3(t) \times \ldots R_n(t)$$

In terms of failure rate,

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

where λi = failure rate of *i*th component

or

$$Ri(t) = \int_{i=1}^{n} e^{-\lambda t.s} \times dt = e^{-\lambda s.t}$$

where $\lambda s = \sum_{i=1}^{n} \lambda i$. Summation of individual failure rate.

2. Components connected in parallel (Parallel system)

When the components are connected in parallel, let

q_i = probability of failure of ith component

$P_i = 1 - q_i$ = probability of successful operation.

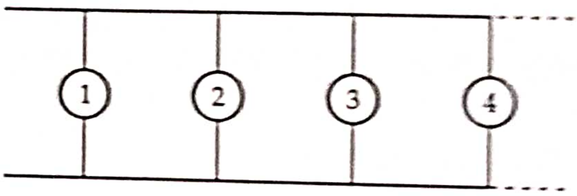


Fig. 13.6 Components in parallel.

Then probability of failure of the system is given by

$$F(t) = q_1 \times q_2 \times q_3 \ldots \times q_n$$

Reliability of the system,

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

$$= 1 - (1 - P_1)(1 - P_2)(1 - P_3)\ldots(1 - P_n)$$

3. Mixed system

Figure below shows two devices A and B connected in series. Device A consists of two parts 1 and 2 connected in parallel. Similarly, device B consists of two parts 3 and 4 connected in parallel.

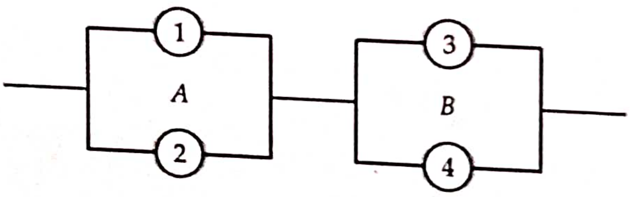


Fig. 13.7

The reliability of the device A,

$$R_A(t) = 1 - (1 - P_1)(1 - P_2)$$

The reliability of the device B,

$$R_B(t) = 1 - (1 - P_3)(1 - P_4)$$

And the reliability of the system

$$R_S(t) = R_A(t) \times R_B(t)$$

i.e., System reliability $= [1 - (1 - P_1)(1 - P_2)]\,[1 - (1 - P_3)(1 - P_4)]$.

Reliability of switches

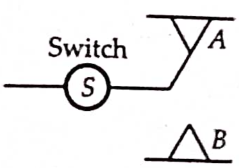


Fig. 13.8 Switch

Switches are also incorporated in electrical systems. A system may fail to work if the switch is imperfect, hence the reliability of switches should also be considered.

Consider a switch having two elements (contact points A and B) as shown in Fig. 13.8, whenever, A fails, switch operates and makes connection with B and system operates.

Switch can fail in *three* ways :

1. Switch does not make connection when operated.
2. Failure to operate when energized.
3. Operates when not required.

System will operate successfully if the following events occur :

1. *Element A fails*, switch operates connection is made and element B functions.
2. *Element B fails*, switch does not operate connection is maintained B and element A functions.
3. Elements A and B are both functional and connection is maintained.

If, P_C = probability of connection being maintained

P_S = probability of switch not operating when energized

P_f = probability of switch not operating when not required

P_A = probability of element A being functional

$(1-P_A)$ = probability of element A being not functional

P_B = probability of element B being functional

$(1-P_B)$ = probability of element B being not functional.

Then reliability of the system,

$$R_S(t) = (1-P_A)\cdot P_S \cdot P_C \cdot P_B + (1-P_B)\cdot P_f \times P_C \times P_A + P_A \cdot P_B \cdot P_C$$

If we assume

$$P_A = P_B = P_1$$

and

$$R_S(t) = P_C[P_1^2 + 2P_1P_2(1-P_1)]$$

13.8 AVAILABILITY OF SINGLE REPAIRABLE SYSTEM USING MARKOV MODEL

The availability of a single repairable system can be computed using familiar Markov model. It is assumed that the failure and repair rates are constants. The Markov graph for the availability of single component with repair is shown in Fig. 13.9. The repair starts as soon as the component fails.

Let, λ = failure rate

μ = repair rate

State O denotes that no failure has occurred and state 1 denotes that one failure has occurred (*i.e.*, the component is down). If the component has not failed at time t, then the probability that the component will fail in the time interval $(t, t+\Delta t)$ is equal to $\lambda\Delta t$. On the other hand, if the component is in state 1 (*i.e.*, failed state), then the probability that the component will enter into state O is equal to $\mu\Delta t$.

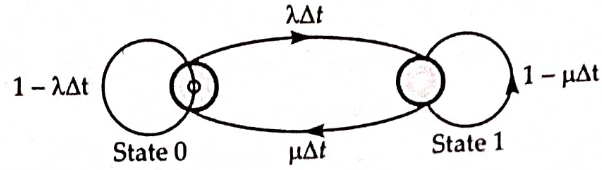


Fig. 13.9 Markov graph for availability.

From the Markov graph (Fig. 13.9), the probability that the component will be in state 0 at time $t + t\Delta$ is

$$P_0(t+\Delta t) = P_0(t)(1-\lambda\Delta t) + P_1(t)\mu\Delta t \quad \text{—(i)}$$

Similarly, the probability that the component will be in state 1 at time $t + \Delta t$ is

$$P_1(t+\Delta t) = P_1(t)(1-\mu\Delta t) + P_0(t)\lambda\Delta t \quad \text{—(ii)}$$

The above equations can be rewritten as :

$$\frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} = -P_0(t)\lambda + P_1(t)\mu \quad \text{—(iii)}$$

and

$$\frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = P_0(t)\cdot\lambda - P_1(t) - \mu \quad \text{—(iv)}$$

The resultant differential equations are :

$$\frac{dP_0(t)}{dt} = P_0'(t) = -P_0(t)\lambda + P_1(t)\mu$$

and

$$\frac{dP_1(t)}{dt} = P_1'(t) = P_0(t)\lambda - P_1(t)\mu$$

At time $t = 0$ $\quad P_0(0) = 1$ and $P_1(t) = 0$

The solution of this set of two differential equations yields

$$P_0'(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t}$$

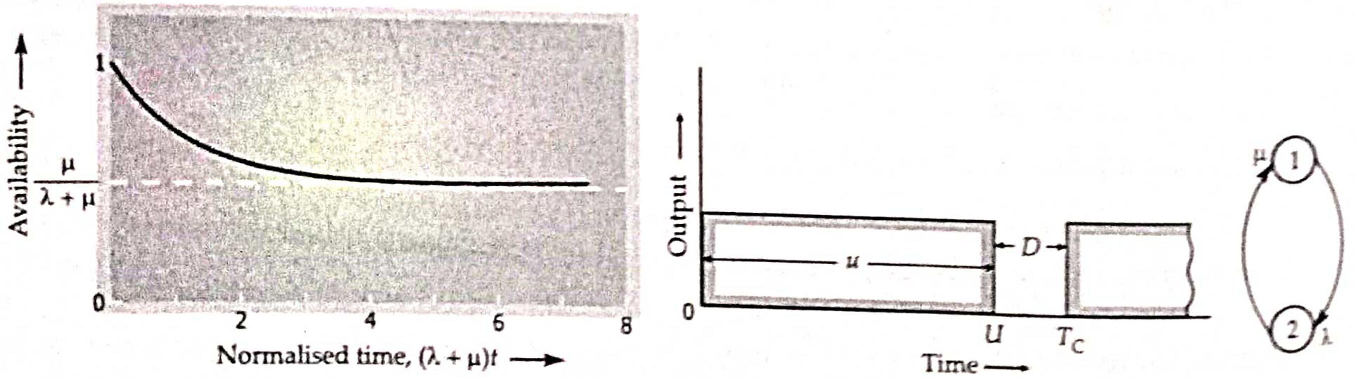
and

$$P_1(t) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t}$$

As per definition of availability,

$$A(t) = P_0(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t}$$

The availability function is plotted in Fig. 13.10.



(a) Availability of the unit

(b) Average history of output of the unit

(b) Two-state transition diagram

Fig. 13.10 Behaviour of a single repairable unit.

As the time becomes large, the availability function reaches some steady-state value. The steady-state or long-term availability of single component is

$$A = A(\infty) = \frac{\mu}{\lambda + \mu}$$

This equation can be modified as :

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

Here, $\frac{1}{\lambda}$ is the mean time between failures (MTBF). It may be noted that this has been defined as the mean time to failure (MTTF) in the case of non-repairable components. $\frac{1}{\mu}$ is the mean repair time or mean time to repair (MTTR). Fig. 13.10(*b*) characterizes the expected or mean behaviour of the component. *U* represents the mean up-time (MTBF) and *D* represents the mean down-time (MTTR). T_c is known as the cycle time. Here

$$U = \frac{1}{\lambda}$$

$$D = \frac{1}{\mu}.$$

The steady-state availability is a number greater than zero and less than one. It is equal to zero when no repair is performed ($\mu = 0$) and equal to one when the equipment does not fail ($\lambda = 0$). Normally, $\frac{1}{\mu}$ is much smaller than $\frac{1}{\lambda}$ and therefore the availability can be approximated as

$$A = \frac{1}{1 + \frac{\lambda}{\mu}} \simeq 1 - \frac{\lambda}{\mu}$$

when $\frac{\lambda}{\mu}$ approaches zero, *A* approaches unity

$P_1(t)$ defines the unavailability of the equipment and hence

$$\bar{A}(t) = \frac{\lambda}{\lambda + \mu}[1 - e^{-(\lambda+\mu)t}]$$

$$\bar{A} = \bar{A}(\infty) = \frac{\lambda}{\lambda + \mu}$$

The equipment should be either at state 0 or in state 1 and this is proved by the fact that

$$P_0(t) + P_1(t) = 1$$

or

$$A + \bar{A} = 1.$$

Life Test

The life of the component is the time period during which it retains its quality characteristics. Life tests are carried out to access the working life of a product, its capabilities and hence to form an idea of its quality level. The life test aims to measure the time or period during which the product will retain its desired quality characteristics. This may apply to either (*a*) shelf life (*b*) and life during use or both.

For perishable products such as food products, self life is important. On the other hand, products which lasts for a considerable period life during use is an important factor in addition to shelf life.

Life tests are carried out in different manners under different conditions as follows :

- Tests under Actual Working Conditions.
- Tests under Intensive Conditions.
- Tests under Accelerated Conditions.

Tests under Actual Working Conditions

The life test of the component under actual working conditions for full duration is quite labourious, cumbersome, time-consuming and impracticable. Moreover such full duration tests do not lend any help in controlling a manufacturing process.

Tests under Intensive Conditions

Let us take an example of a household mixer which works for say 1 hour every day. It is to be tested under actual working conditions, it would be operated for only one hour per day to find out after how many days it fails. This is impracticable and time-consuming.

Therefore, it is worked continuously at rated specifications and thus the life can be estimated in a much shorter duration of time. However, it may be switched off for some period during intensive testing.

Tests Under Accelerated Conditions

These tests are conducted under severe operating conditions to quicken the product failure or break down. For example, an electric circuit may be exposed to high voltages or high currents, a lathe may be subjected to severe vibrations and chatter, a refrigerator performance may be checked under high ambient temperature conditions, etc.

Acceptance Sampling Plan Based on Life Tests

The data of life (destructive) tests can be analysed by sampling techniques and control charts. Sometimes, it may not be necessary to subject all the sample pieces to destructive testing. In these cases the results can be concluded from the time of first and middle failure. However, the potential capability of the product can be determined only through destructive testing.

Sometimes management may not like to destroy their good products, but destructive testing is essential to reveal to the designer the weakest component of the chain. In development testing, a designer should get the component fabricated exactly under those conditions and specifications with which it will be manufactured, once tested okay. He should incorporate even the minute design changes in the sample fabricated for testing.

Dr. Davidson developed a table (given below), which shows, for a life test, the relationship between the sample size, probability and percent of units which will fail before their shortest life. According to the table, if we want to be 95% sure (probability) that not more than 5% of component would fail before their shortest life of X hours, we should conduct life tests on 59 components. However, if we want to be 95% sure that not more than 1% of component would fail before their shortest life of X hours we should conduct life test on 299 components.

Dr. Weibull evolved Probe Testing with which it is possible to plan tests and get maximum information as can be had from pure statistical techniques, but by conducting comparatively lesser number of tests.

Table 13.3 : *Sample Size Required in a Life Test*

The sample size required in a life test to be sure (with probability P%) that fever than K% of future units will fail in a time shorter than the shortest life in the sample.

P in % / K%	99.9	99	95	75	50
0.1	6977	4652	3026	1401	701
1	689	459	299	139	70
2	343	229	149	69	35
3	227	152	99	46	23
4	170	113	74	34	17
5	135	90	**59**	28	14
10	66	44	29	14	7
15	43	29	19	9	5
20	31	21	14	7	4
25	25	17	11	5	3
30	20	13	9	4	2
35	16	11	7	4	2
40	14	10	6	3	2
45	12	8	6	3	2
50	10	7	5	2	1

Table 13.4 : *Terms Related to Reliability*

S.No.	Terms	Meaning
1.	MTBF (Mean Time Between Failures)	Mean time between successive failures of a repairable product.
2.	MTTF (Mean Time to Failure)	Mean time failure of a non-repairable product or mean time to first failure of a repairable product
3.	Mean life	Mean value of life (life may be related to major overhaul) wear out time, etc.
4.	Mean Time to First Failure (MTFF)	Mean time to first failure of a repairable product.
5.	MTBM (Mean Time Between Maintenance)	Mean time between a specified type of maintenance action.
6.	Longevity	Wear-out time for a product.
7.	MTTR (Mean Time to Repair)	It is the arithmetic mean of the time required to perform maintenance action.
8.	System Effectiveness	Extent to which a product achieves the requirements of the user.
9.	Probability of Success	Same as reliability (but often used for one short or non-time oriented products).
10.	Availability	It is the percentage of operating time that an equipment is operational. (It is expressed as % of operating and repair time).
11.	Derating	Derating means providing a large safety margin. It is a method of achieving design reliability.
12.	Redundancy	The provision of stand-by or parallel components or assemblies to take over in the event of failure of the primary item.
13.	b_{10} life	Life during which 10% of the population would have failed.
14.	b_{50} life	Median life, or life during which 50% of the population would have failed.
15.	Repairs/100	Number of repairs per 100 operating hours.
16.	FMECA (failure mode, effect and criticality analysis)	A methodical way of examining a design for possible ways in which failure can occur.
17.	Failure rate $f(t)$	The rate at which failure will occur in a certain interval of time $[t_1, t_2]$.
18.	Hazard rate $h(t)$	The limiting value of the failure rate as the interval approaches to zero $h(t) = \frac{f(t)}{RT}$ *i.e.*, Hazard rate is the ratio of failure rate and reliability.
19.	Risk priority number (RPN)	RPN is the product of the severity (*S*), occurrence (*O*) and defection (*D*) *i.e.*, $RPN = (S) \times (O) \times (D)$

Solved Problems

Problem 13.1 *A certain type of electric component has a uniform failure rate of 0.00001 per hour. What is its reliability for a specified period of service of 10,000 hours ?*

Solution. Given
$$\lambda = 0.00001 \text{ per hr}$$
$$T = 10,000 \text{ hr}$$

Reliability
$$R_i = e^{-\lambda T}$$
$$= e^{-0.00001 \times 10,000}$$
$$= e^{-0.1}$$
$$= 0.90483 \text{ or } 90.483 \text{ per cent}$$

Problem 13.2 *Given a θ′ of 5,000 hours and a uniform failure rate, what is the reliability associated with a specified service period of 200 hours ?*

Solution. Given
$$\theta' = 5000 \text{ hr}$$
$$T = 200 \text{ hrs}$$

Now,
$$\lambda = \text{failure rate} = \frac{1}{\theta'} = \frac{1}{5000}$$
$$Rt = e^{-\lambda T}$$
$$= e^{-\frac{1}{5000} \times 200}$$
$$= e^{-0.04}$$
$$= 0.96079 \text{ or } 96.079 \text{ per cent.}$$

Problem 13.3 *The following reliability requirements have been set on the sub-systems of a communication system :*

Sub-system	Reliability (for a 4-hour period)
Receiver	0.970
Control system	0.989
Power supply	0.995
Antenna	0.996

What is the expected reliability of the overall system ?

Solution.
$$R_s(t) = R_1(t) \times R_2(t) \times R_3(t) \times R_4(t)$$
$$= 0.970 \times 0.989 \times 0.995 \times 0.996$$
$$= 0.950 \text{ or } 95 \text{ per cent.}$$

Therefore, the chance that the overall system will perform its function without failure for a 4-hour period is 95 per cent.

Problem 13.4 *A unit has a reliability of 0.99 for a specified mission time. If two identical units are used in parallel redundancy, what overall reliability will be obtained ?*

Solution. When parallel redundancy is used, the overall reliability is calculated as follows:

$$R_s(t) = 1 - (1 - R_1)^n$$

where $R_s(t)$ = reliability of the system

R_1 = reliability of the individual elements in the redundancy

n = number of identical redundant elements

Therefore,
$$R_s(t) = 1 - (1 - 0.99)^2$$
$$= 1 - (0.01)^2$$
$$= 0.999 \quad \text{or } 99.9 \text{ per cent}$$

Problem 13.5 *It is desired to have a reliability of atleast 0.990 for a specified service period of 8,000 hours on the assumption of a uniform failure rate. What is the least value of θ' that will yield this desired reliability ?*

Solution. Given $R_t = 0.990$, $T = 8000$ hours, $R_t = e^{-\lambda T}$

Therefore,
$$0.990 = e^{-\lambda(8000)}$$

i.e.,
$$-\lambda(8000) = \log_e 0.990$$

i.e.,
$$-\lambda(8000) = -0.01005$$

or,
$$\lambda = \frac{0.01005}{8000} = 1.25625 \times 10^{-6}$$

Hence,
$$\theta = \text{mean life} = \frac{1}{\lambda} = \frac{8000}{0.01005} = 7.96 \times 10^5$$

Problem 13.6 *An element has a probability of successful operation over a given period of 60 per cent. If four such elements are connected in parallel estimate the improvement factor.*

Solution. Given $P_i = p_1 = p_2 = p_3 = p_4 = 0.6$

System reliability $R_s(t) = 1 - F(t)$

i.e.,
$$R_s(t) = 1 - (1 - p_1)(1 - p_2)(1 - p_3)(1 - p_4)$$
$$= 1 - 0.4 \times 0.4 \times 0.4 \times 0.4$$
$$= 0.9744.$$

Therefore, improvement factor
$$= \frac{0.9744}{0.6} = 1.624$$

Problem 13.7 *An equipment is subjected to a maintenance time constraints of 30 minutes. What is the probability that it will meet the specification if MTTR is 0.262 hours ?*

Solution. *Given* $tm = 30$ min

MTTR = 0.262 hr

Now, probability of maintaining the equipment is given by

$$M = 1 - e^{-\mu \cdot tm}$$

where $\mu = \dfrac{1}{\text{MTTR}}$

Therefore,

$$M = 1 - e^{-\frac{1}{0.262} \times 0.50}$$

$$= 1 - e^{-1.9083}$$

$$= 1 - 0.14833$$

$$= 0.85167 \text{ or } 85.167\%$$

Problem 13.8 *In one life testing plan 63 items tested for 500 hours with replacement and with an acceptance number of 5. This plan was stipulated for an approximate value of 0.10 for the producer's risk of rejection of a lot having a mean life of 10,000 hours and for an approximate value of 0.10 for the consumer's risk of acceptance of a lot having a mean life of 3333 hours. Compute the respective values of these two risks.*

Solution. Given :

No. of test hours $= 500$

No. of items $= 63$

$$c = 5$$

Producer's risk $= 0.1$ for mean life 10,000 hours

Consumer's risk $= 0.1$ for mean life 3333 hours

(*i*) Now, item hours required for acceptance for mean life 10,000 hours $= 500 \times 63 = 31{,}500$

Therefore, expected average number of failures in 31,500 test hours $= 31{,}500\,\lambda$

$$= \frac{31{,}500}{10{,}000} = 3.15$$

Corresponding probability

$$P_a = 0.9$$

Therefore, producer's risk

$$= 1 - P_a = 0.10$$

(*ii*) Expected average number of failures for mean life of

3333 hrs $= 31{,}500 \times \dfrac{1}{3333}$

$$= 9.4509$$

Corresponding probability,

$$P_c = 0.0917$$

i.e., Consumer's risk $= 0.0917$

Exercises

Theoretical Questions

1. (*a*) Define Reliability.
   (*b*) Explain the importance of reliability.
2. (*a*) What are the basic elements of reliability ?
   (*b*) Explain the failure pattern for complex products.
3. (*a*) State and explain the factors to be considered in designing for reliability.
   (*b*) Explain the reliability tests.
4. Explain the following in connection with reliability :
   (*i*) Quality and reliability (*ii*) Cost of reliability
   (*iiii*) System reliability (*iv*) Availability
5. Write short notes on the following :
   (*i*) MTTR (*ii*) MTBF
   (*iii*) Marginal testing (*iv*) Maintenance and reliability.
6. What is FMECA ? State the benefits of design FMECA.
7. Define FMECA. Describe the procedure used for design FMECA.
8. Describe "Fault Tree Analysis" briefly with a suitable example.
9. Define the terms :
   (*i*) Failure rate (*ii*) Hazard rate
   (*iii*) FMECA (*iv*) RPN
10. What is TPM ? Explain its importance.
11. Describe briefly the avaiiability of single repairable system using Markov model.
12. Write short notes on :
    (*i*) Life Test (*ii*) Acceptance sampling plan based on Life Test.

Numerical Questions

13. Given component reliabilities as indicated, calculate the probability of survival of the assembly.

Component	*Reliability*
A	0.999
B	0.980
C	0.990
D	0.870
E	0.920
F	0.84