Chapter 7
Mining Equipment Reliability and Maintainability Testing

7.1 Introduction

Testing is an important element of any engineering product development program. It may simply be stated as subjecting a product to conditions that highlight its weaknesses, behavior characteristics, and modes of failure.

Reliability testing is an important element of testing and is basically concerned with obtaining information regarding failures, in particular the product/equipment's tendency to fail as well as the failure consequences. A good reliability test program is one that requires a minimal amount of testing and provides the maximum amount of information on failures [1, 2].

The main objective of maintainability testing and demonstration is to verify the maintainability features that have been designed and built into a piece of equipment/product [3]. In addition, maintainability testing and demonstration provides customers with confidence, prior to making production-related commitments, that the piece of equipment/product under consideration meets the specified maintainability-associated requirements.

This chapter presents various important aspects of reliability and maintainability testing considered useful for application in the areas of mining.

7.2 Reliability Test Classifications

Reliability tests may be grouped into three categories, as shown in Fig. 7.1 [4]. These are reliability development and demonstration testing, qualification and acceptance testing, and operational testing.

Three main objectives of reliability development and demonstration testing are as follows:

- To identify necessary changes in design.

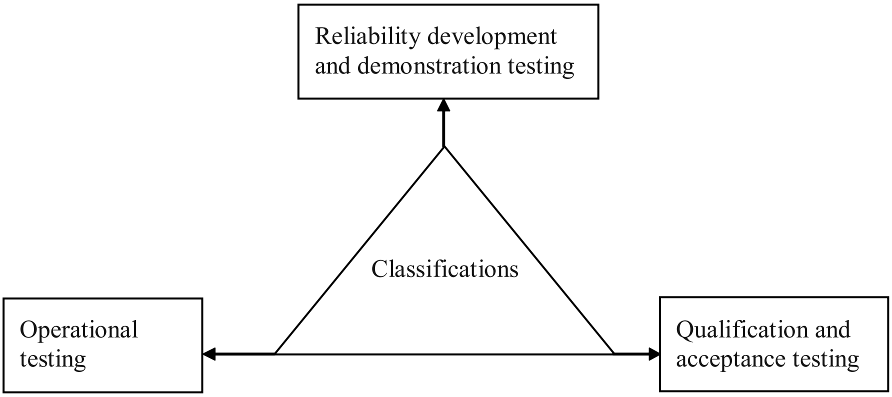

Fig. 7.1 Reliability test classifications

- To determine if there is any need to improve design to meet reliability specifications.
- To verify improvements in design reliability.

Note that the nature of this type of testing depends on various factors including the type of system/equipment/subsystem being investigated and the level of complexity under consideration.

Two main objectives of the qualification and acceptance testing are as follows:

- To determine if the item under consideration should be accepted or rejected individually or on a lot basis.
- To determine if the design under consideration qualifies for its specified objective.

Note that the above two objectives differ from the objectives of other reliability tests, particularly with respect to the accept-or-reject approach.

Finally, three main objectives of the operational testing are as follows:

- To verify the results of reliability analyses performed during the system/equipment design and development phase.
- To provide data for use in subsequent activities.
- To provide data indicating necessary changes to operational policies and procedures with respect to reliability and maintainability.

7.3 Success Testing

This type of testing is normally used in receiving inspection and in engineering test laboratories where a no-failure test is specified; thus it could be quite useful for application in the mining industry. Nonetheless, the main goal of success testing is to ensure that a specified reliability level is achieved at a given confidence level.

Thus, in this case for zero failures, the lower 100 $(1-\alpha)\%$ confidence limit on the desired reliability level can be expressed as follows [5]:

$$R_{\mathrm{L}} = \alpha^{1/m}\,, \tag{7.1}$$

where

m is the total number of items/units placed on test,
α is the consumer's risk or the level of significance.

Thus, with 100 $(1-\alpha)\%$ confidence, we may write

$$R_{\mathrm{L}} \leq R_{\mathrm{t}}\,, \tag{7.2}$$

where

R_{t} is the true or actual reliability.

Taking the natural logarithms of both sides of Eq. (7.1) yields

$$\ln R_{\mathrm{L}} = \frac{1}{m}\ln\alpha\,. \tag{7.3}$$

Rearranging Eq. (7.3) we get

$$m = \frac{\ln\alpha}{\ln R_{\mathrm{L}}}\,. \tag{7.4}$$

The desired level of confidence, C, may be expressed as follows:

$$C = 1-\alpha\,. \tag{7.5}$$

Rearranging Eq. (7.5) we obtain

$$\alpha = 1-C\,. \tag{7.6}$$

Substituting Eqs. (7.2) and (7.6) into Eq. (7.4) we get

$$m = \frac{\ln(1-C)}{\ln R_{\mathrm{t}}}\,. \tag{7.7}$$

Thus, Eq. (7.7) can be used to determine the total number of items/units to be tested for a given reliability and confidence level.

Example 7.1

Assume that a manufacturer of a certain part used in a piece of mining equipment is required to demonstrate 95% reliability of that part at a 90% confidence level. Determine the total number of parts to be tested when only zero failures are allowed.

Substituting the given data values into Eq. (7.7) we get

$$m = \frac{\ln(1-0.90)}{\ln 0.95} \cong 45\,\text{parts}\,.$$

This means a total of 45 parts must be tested.

7.4 Accelerated Testing

Accelerated testing is concerned with reducing the duration of the test time by varying parameters such as frequency of cycling, voltage above regular levels, or temperature or by simply conducting sudden-death testing. There are a number of ways to perform accelerated testing including those listed below [6–11].

- Perform sudden-death testing.
- Increase the sample size.
- Increase the test severity.

When performing sudden-death testing, the test sample is divided into various groups containing an equal number of items or units, and all items/units in each of these groups start their operation simultaneously. Whenever any one of the group units fails, all units are considered failed and the testing of nonfailed units is terminated immediately. Furthermore, in the event of failure of the first unit in the last and final group, the entire testing process is terminated.

With respect to increasing the sample size, the size of the sample is increased when the item/unit life distribution does not exhibit a wear-out characteristic during its (*i.e.*, item's) predicted lifespan. Note that the increase in the sample size decreases the test time as the test time is inversely proportional to the sample size.

Finally, increasing the test severity involves increasing the stress acting on the test unit/item. The stress may be classified under two distinct areas: application and operational. The application area includes items such as voltage, self-generated heat, and current; the operational area includes humidity and temperature. The following equation can be used to calculate the acceleration factor for this type of accelerated testing [10–13]:

$$F_a = \exp\left[-(E/k)\left\{\frac{1}{T_{ac}} - \frac{1}{T_{us}}\right\}\right], \tag{7.8}$$

where

F_a is the acceleration factor,
T_{ac} is the acceleration temperature expressed in degrees Kelvin,
T_{us} is the use temperature expressed in degrees Kelvin,
E is the activation energy, and its value is taken as 0.5 eV,
k is the Boltzmann constant, and its value is taken as 0.00008623 eV/degree.

Example 7.2

A sample of 20 identical engineering items used in mines were tested to failure at a temperature of 130 °C, and their mean time between failures (*MTBF*) was 2500 h. Calculate the *MTBF* of these items at the normal operating temperature of 85 °C.

Using the given data values we get

$$T_{ac} = 273 + 130 = 403\,\text{degrees Kelvin}$$

and

$$T_{us} = 273 + 85 = 358\,\text{degrees Kelvin}\ .$$

Substituting the above-calculated values and the other given data values into Eq. (7.8) yields

$$F_a = \exp\left[-\left(\frac{0.5}{0.00008623}\right)\left\{\frac{1}{403} - \frac{1}{358}\right\}\right] = 6.10\ .$$

Thus, the *MTBF* of the engineering items, used in mines, at 85 °C is

$$MTBF = (6.10)\,(2500) = 15{,}250\,\text{h}\ ,$$

where

MTBF is the mean time between failures of the engineering items at 85 °C.

7.5 Confidence Interval Estimates for Mining Equipment Mean Time Between Failures

Usually, in reliability studies conducted for practical purposes, including in the area of mining, times to item failure are assumed to be exponentially distributed. Consequently, the item failure rate becomes constant and, in turn, the item mean time to failure (*MTTF*) or mean time between failures (*MTBF*) is simply the reciprocal of the item failure rate.

Thus, in testing a sample of items with exponentially distributed times to failure, one can make a point estimate of the *MTBF*. Unfortunately, this approach does not provide any surety of measurement because it provides only an incomplete picture. Therefore, it would be more meaningful if we said, for example, that after testing a sample of identical items for T hours, n number of failures occurred and the actual *MTBF* lies somewhere between certain upper and lower limits with a certain degree of confidence.

The confidence interval on *MTBF* can be calculated with the aid of a χ^2 (chi-square) distribution. The following notation is used to obtain chi-square values:

$$\chi^2\,(p, df)\ , \tag{7.9}$$

where

df	is the degrees of freedom,
p	is a quantity, which is a function of the confidence coefficient.

The symbols listed below are used in subsequent associated formulas [2,4]:

α	is the acceptable error risk,
θ	is the mean time between failures (*MTBF*),
n	is the number of items that were placed on test at time $t = 0$,
K	is the number of failures accumulated by time t^*, where t^* is the life test termination time,
K^*	is the number of pre-assigned failures,
$C = 1 - \alpha$	is the confidence level.

Confidence intervals are estimated under the following two conditions:

- Testing is terminated at a pre-assigned number of failures, K^*.
- Testing is terminated at a pre-assigned time, t^*.

The following two formulas are used to calculate upper and lower limits for the above two conditions, respectively [2,4]:

- Pre-assigned number of failures, K^*:

$$\left[\frac{2Y}{\chi^2\left(\frac{\alpha}{2}, 2K\right)}, \frac{2Y}{\chi^2\left(1-\frac{\alpha}{2}, 2K\right)}\right] ; \tag{7.10}$$

- Pre-assigned truncation time, t^*:

$$\left[\frac{2Y}{\chi^2\left(\frac{\alpha}{2}, 2K+2\right)}, \frac{2Y}{\chi^2\left(1-\frac{\alpha}{2}, 2K\right)}\right] . \tag{7.11}$$

The value of Y is determined by the type of test: replacement test (*i.e.*, the failed item/unit is repaired or replaced) or nonreplacement test. Thus, for the replacement test, the value of Y is expressed by

$$Y = nt^* . \tag{7.12}$$

Similarly, for the nonreplacement test, the value of Y is expressed by

$$Y = (n-K)t^* + \sum_{j=1}^{K} t_j , \tag{7.13}$$

where

t_j is the jth failure time.

In the case of censored items/units (*i.e.*, withdrawal or loss of nonfailed items/units) the value of Y, for replaced failed units/items but nonreplacement of censored

Table 7.1 Chi-square distribution values

Degrees of freedom (df)	**Probability**					
	0.99	**0.95**	**0.9**	**0.5**	**0.05**	**0.01**
2	0.02	0.1	0.21	1.38	5.99	9.21
4	0.29	0.71	1.06	3.35	9.44	13.27
6	0.87	1.63	2.2	5.34	12.59	16.81
8	1.64	2.73	3.49	7.34	15.50	20.09
10	2.55	3.94	4.86	9.34	18.30	23.20
12	3.57	5.22	6.3	11.34	21.02	26.21
14	4.66	6.57	7.79	13.33	23.68	29.14
16	5.81	7.96	9.31	15.33	26.29	32
18	7.01	9.39	10.86	17.33	28.86	34.80
20	8.26	10.85	12.44	19.33	31.41	37.56
22	9.54	12.33	14.04	21.33	33.92	40.28
24	10.85	13.84	15.65	23.33	36.41	42.98
26	12.19	15.37	17.29	25.33	38.88	45.64
28	13.56	16.92	18.93	27.33	41.33	48.27
30	14.95	18.49	20.59	29.33	43.77	50.89
40	22.14	26.50	29.06	39.33	55.75	63.70
50	29.68	34.76	37.70	49.33	67.50	76.16
60	37.46	43.18	46.47	59.33	79.08	88.39

items/units, is expressed by

$$Y = (n-m)t^* + \sum_{i=1}^{m} t_i\,, \tag{7.14}$$

where

t_i is the ith censorship time,
m is the number of censored items/units.

Similarly, the value of Y, for nonreplaced failed and censored items/units is expressed by

$$Y = (n-m-K)t^* + \sum_{i=1}^{m} t_i + \sum_{j=1}^{K} t_j\,. \tag{7.15}$$

Table 7.1 presents some tabulated values of $\chi^2(p, df)$ [1,2].

Example 7.3

Assume that a total of 20 identical items used in mines were placed on test at time $t = 0$ and none of the failed items were replaced. The test was terminated after 200 h. Five items failed after 50, 70, 120, 130, and 150 h of operation.

Estimate the items' *MTBF* and its upper and lower limits with 90% confidence level.

Substituting the given data values into Eq. (7.13) we get

$$Y = (20-5)200 + (50+70+120+130+150) = 3520\,\mathrm{h}\,.$$

Thus, the items' *MTBF* is expressed by

$$\theta = \frac{3520}{5} = 704\,\mathrm{h}\,.$$

Substituting the specified and calculated values into relationship (7.11) and using Table 7.1, we get the following upper and lower limits for the items' *MTBF*:

$$\begin{aligned} \mathit{Upper}\ \text{limit} &= \frac{2\,(3520)}{\chi^2\,(0.95,10)} \\ &= \frac{2\,(3520)}{3.94} \\ &= 1786.8\,\mathrm{h}\,; \\ \mathit{Lower}\ \text{limit} &= \frac{2\,(3520)}{\chi^2\,(0.05,12)} \\ &= \frac{2\,(3520)}{21.02} \\ &= 334.9\,\mathrm{h}\,. \end{aligned}$$

Thus, the items' *MTBF* is 704 h. Its (*i.e.*, *MTBF*'s) upper and lower limits with a 90% confidence level are 1786.8 h and 334.9 h, respectively. In other words, the true *MTBF* of the items with a 90% confidence level will lie within 334.9 h and 1786.8 h or $334.9 \le \theta \le 1786.8$.

7.6 Documents on Reliability Testing

Over the years, many publications have appeared on reliability testing that could be directly or indirectly useful in the reliability testing of mining equipment. Some of the important ones are as follows:

- MIL-STD-781D, Reliability Design, Qualification and Production Acceptance Tests: Exponential Distribution, US Department of Defense, Washington, DC
- IEC 605, Equipment Reliability Testing, International Electrotechnical Commission (IEC), Geneva, Switzerland
- MIL-STD-2074, Failure Classification for Reliability Testing, US Department of Defense, Washington, DC
- IEC 1123, Reliability Testing Compliance Test Plans for Success Ratio, International Electrotechnical Commission (IEC), Geneva, Switzerland

- MIL-HDBK-781, Reliability Test Methods, Plans, and Environments for Engineering Development, Qualification, and Production, US Department of Defense, Washington, DC
- MIL-HDBK-H108, Sampling Procedures and Tables for Life and Reliability Testing (Based on Exponential Distribution), US Department of Defense, Washington, DC
- MIL-STD-202F, Test Methods for Electronic and Electrical Component Parts, US Department of Defense, Washington, DC
- MIL-STD-2165, Testability Program for Electronic Systems and Equipment, US Department of Defense, Washington, DC

7.7 Planning and Control Requirements for Mining Equipment Maintainability Testing and Demonstration

These requirements may be divided into the following six distinct categories [14, 15]:

- **Following MIL-STD-471 guidelines.** These guidelines were developed by the United States Department of Defense in 1966 for manufacturers to carefully consider in the planning and control of equipment maintainability demonstrations. They cover areas such as establishing test teams, selecting a test method, and data collection and selection, performance, and sampling of corrective and preventive maintenance tasks.
- **Providing appropriate manpower.** This is concerned with ensuring that individuals performing maintainability demonstrations have backgrounds and skill levels similar to those of a product's final users, operating, and maintenance personnel.
- **Developing a demonstration plan.** This is concerned with developing a demonstration plan that conforms to the specifics described in MIL-STD-471 [16] and covers areas such as test planning, administration, and control; test conditions; and test analysis, documentation, and reporting.
- **Specifying appropriate parameters.** As the basic purpose of a formal maintainability demonstration is to verify compliance with defined parameters, it is essential to have specifications for demonstration parameters in quantitative terms. A typical example of a measurable time parameter is mean time to repair ($MTTR$).
- **Developing a demonstration model.** This model is used to demonstrate a product's proposed quantitative parameters and qualitative design features for maintainability.
- **Taking environment into consideration.** Environment is an important factor in maintainability testing as equipment downtime may vary significantly between laboratory-controlled conditions and actual operational conditions. Therefore, it is essential to take into consideration factors such as test facilities, support resource needs, and limitation simulations.

7.8 Test Methods to Obtain Maintainability-related Test Data for Mining Equipment

There are numerous points in mining equipment life cycle and in related maintainability program tasks that need test data. This type of data may be necessary to make decisions about maintainability design requirements, to evaluate equipment life cycle maintenance support, or for administrative and logistic control to update corrective actions or modifications.

Test methods that can provide such data may be grouped under six categories as follows [15]:

- **Closed-loop tests.** These tests generate useful information to evaluate equipment-design effectiveness, tolerance adequacy, performance, and other important issues.
- **Functional tests.** These tests simulate normal operating conditions to establish a product's or piece of equipment's state of readiness to perform its stated mission.
- **Static tests.** These tests provide information on the transient behavior of the product under consideration.
- **Dynamic tests.** These tests simulate a typical application of a given piece of equipment so that each and every item involved can be checked properly.
- **Open-loop tests.** These tests represent a refinement of static and dynamic tests and usually provide better maintenance-related information than closed-loop tests because they make a direct observation of the system transfer function without the modifying influence of feedback.
- **Marginal tests.** These tests are used to isolate potential difficulties through the simulation of abnormal operational conditions.

7.9 Test Methods for Demonstrating Diverse Maintainability Parameters

The main objective of demonstrating maintainability is to determine whether a development program or a manufacturer has satisfied qualitative and quantitative maintainability requirements. A successful maintainability demonstration depends on many factors including quality of equipment design for testability, quality of written maintenance manuals, and quality of training of repair technicians.

A total of 11 test methods addressing many diverse maintainability parameters considered useful for application in the mining industry are shown in Fig. 7.2 [16, 17]:

The median equipment repair time method is used when the requirement is defined in terms of an equipment repair time median and is based on log-normally distributed corrective maintenance task times. The mean maintenance time and maximum maintenance time method is used to demonstrate indexes such as mean corrective maintenance time and mean preventive maintenance time.

The mean method is used when the requirement is stated in terms of a mean value and there is a corresponding value of design goal. The preventive maintenance times method is used when the specified index involves the mean preventive maintenance task time and/or maximum preventive maintenance task time at any percentile. The critical percentile method is used when the requirement is expressed in terms of a required critical percentile and a corresponding value of design goal.

The percentiles and maintenance method utilizes a test of proportion for demonstrating fulfillment of maximum preventive maintenance task time at any percentile, median corrective maintenance task time, median preventive maintenance task time, and maximum corrective maintenance task time at the 95th percentile, when preventive and corrective maintenance repair time statistical distributions are not known.

The critical maintenance time method is used when the requirement is stated in terms of required critical maintenance time and a corresponding design-goal value. The man-hour rate method (using simulated faults) is used to demonstrate man-hour rates per operating hour and is based on the predicted equipment failure rate, total accumulative simulated demonstration operating hours, and total accumulative chargeable maintenance man-hours.

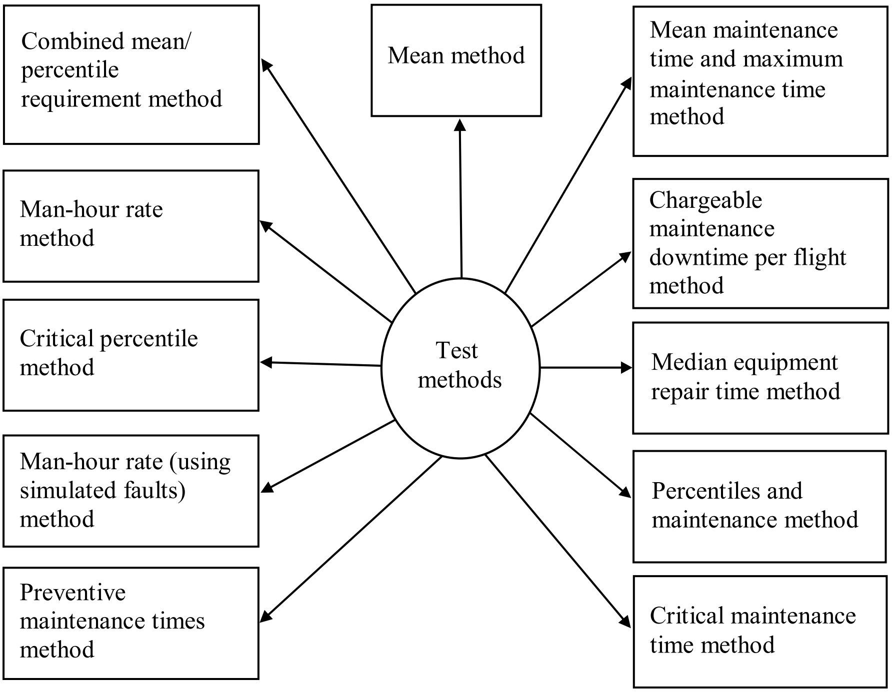

Fig. 7.2 Test methods for demonstrating diverse maintainability parameters

The combined mean/percentile requirement method is used in situations where the requirement is a dual requirement for the mean and for either the 95th or 90th percentile of maintenance times, when maintenance times are log-normally distributed. The chargeable maintenance downtime per flight method is used in testing aircraft; it makes use of the central limit theorem. Furthermore, the chargeable downtime per flight is the allowable time, expressed in hours, to perform the maintenance activity.

The man-hour rate method is used to demonstrate man-hour rates, particularly man-hours per flight hour. Finally, the preventive maintenance time method is used in situations when the specified index involves the mean preventive maintenance task time and/or maximum preventive maintenance task time at any percentile, as well as when all possible preventive maintenance tasks need to be completed.

Information on statistical aspects of many of the above methods is available in Ref. [16].

7.10 Useful Guidelines for Avoiding Pitfalls in Maintainability Testing of Mining Equipment

Some of the useful guidelines to avoid pitfalls in maintainability testing of mining equipment are as follows [18]:

- Tailor MIL-STD-471 [16] for the program and equipment under consideration with care and avoid relying on it totally.
- Aim to perform some "dry run" testing.
- Improve the technical manual verification and validation process well before the maintainability demonstration test.
- Define, rectify, and verify discovered shortcomings/deficiencies and the associated requirements for corrective action.
- Carry out a new and different trial for each and every trial that identifies a shortcoming or deficiency.
- Limit the permissible trial repetitions as a requirement for canceling the test, moving into an "evaluate and fix" phase, and then repeating the complete test with newly stated faults.

7.11 Problems

1. Discuss the following two reliability test classifications:
    - Qualification and acceptance testing
    - Operational testing
2. What is success testing?

3. A manufacturer of a part used in a piece of mining equipment is required to demonstrate 98% reliability of that part at a 95% confidence level. Determine the number of parts to be tested when only zero failures are allowed.
4. What are the ways to perform accelerated testing?
5. A sample of 30 identical engineering items used in mines was tested to failure at a temperature of 120 °C, and their mean time between failures (*MTBF*) was 3000 h. Calculate the *MTBF* of these items at the normal operating temperature of 80 °C.
6. List the five most important documents used, directly or indirectly, in reliability testing.
7. Discuss the following items in regard to maintainability testing:
   - Functional tests
   - Marginal tests
   - Static tests
8. Discuss at least seven test methods for demonstrating diverse maintainability parameters.
9. Discuss the four most useful guidelines for avoiding pitfalls in maintainability testing.
10. Compare reliability testing with maintainability testing.

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