THE CERTIFIED RELIABILITY ENGINEER

HANDBOOK

Third Edition

Mark Allen Durivage, editor

THE CERTIFIED RELIABILITY ENGINEER HANDBOOK

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Preface

The chapters and sections are numbered by the same format used in the Body of Knowledge (BoK) for the Certified Reliability Engineer (CRE) examination. This format makes for some awkward placement and, in some cases, redundancy. However, it also facilitates access for readers who might be struggling with some particular point in the BoK, which more than balances the disadvantages.

The CRE Certification will provide valuable credentials to reliability and quality engineering professionals in the growing field of reliability engineering. The purpose of this handbook is to assist individuals preparing for the CRE examination and to provide a reference for the practitioner. Throughout this handbook, several "typical" examples are provided based on the collective experience and knowledge of the authors and editor. However, these "typical" examples are not explicitly specified in regulations, leaving decisions and the burden of justifying practices using sound scientific principles, which provide the context of the rationale, up to the company.

Acknowledgments

I would like to acknowledge the previous work of Donald W. Benbow and Hugh W. Broome for their previous versions of *The Certified Reliability Engineer Handbook*. Several sections of this book come directly from their previous work. Some changes have been made to clarify and augment some of their points and present the topics in a consistent manner.

Additionally, the Reliability and Risk Division leadership team should be acknowledged for supporting the update to this handbook. The division helped secure volunteer members who are CREs to contribute to the writing and editing processes.

The following individuals are to be recognized as contributing chapter authors for this handbook: David Auda, Jim Breneman, Dan Burrows, Mark Durivage, Tim Gaens, and Rong Pan. By using several individual subject matter experts, the overall quality and technical content of this handbook has been greatly enhanced.

I would like to thank those who have inspired, taught, and trained me throughout my academic and professional career. Additionally, I would like to thank ASQ Quality Press, especially Paul O'Mara, Managing Editor, for his expertise and technical competence, which made this project a reality. I also appreciate the fine copyediting and typesetting by Westchester Publishing Services. Lastly, I would like to acknowledge my wife Dawn and my sons Jack and Sam, whose patience allowed me time to organize, write, and edit this handbook.

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Part I

Reliability Fundamentals

Chapter 1 A. Leadership Foundations
Chapter 2 B. Reliability Foundations

Chapter 1

A. Leadership Foundations

The structure of this book is based on the Body of Knowledge (BoK) specified by ASQ for the Certified Reliability Engineer (CRE). Before the formal BoK is presented, a definition of reliability is needed. *Reliability* is defined as the probability that an item will perform a required function without failure under stated conditions for a specified period of time. A statement of reliability has four key components:

- *Probability*. For example, a timing chain might have a reliability goal of 0.9995. This would mean that at least 99.95% are functioning at the end of the stated time.
- *Required function*. This should be defined for every part, subassembly, and product. The statement of the required function should explicitly state or imply a failure definition. For example, a pump's required function might be moving at least 20 gallons per minute. The implied failure definition would be moving fewer than 20 gallons per minute.
- *Stated conditions*. These include environmental conditions, maintenance conditions, usage conditions, storage and moving conditions, and possibly others.
- *Specified period of time*. For example, a pump might be designed to function for 10,000 hours. Sometimes it is more appropriate to use some other measure of stress than time. A tire's reliability might be stated in terms of miles, and that of a laundry appliance in terms of cycles.

1. BENEFITS OF RELIABILITY ENGINEERING

> Describe the value that reliability has on achieving company goals and objectives, and how reliability engineering techniques and methods improve programs, processes, products, systems, and services. (Understand)
>
> Body of Knowledge I.A.1

The following are among the influences that have increased the importance of the study of reliability engineering:

- Customers expect products to not only meet the specified parameters upon delivery, but to function throughout what they perceive as a reasonable lifetime.
- As products become more complex, the reliability requirements of components increase. Suppose, for instance, that a system has 1000 independent components that must function in order for the system to function. Further suppose that each component has a reliability of 99.9%. The system would have a reliability of $0.999^{1000} = 0.37$, an obviously unacceptable value.
- An unreliable product often has safety and health hazards.
- Reliability values are used in marketing and warranty material.
- Competitive pressures require increased emphasis on reliability.
- An increasing number of contracts specify reliability requirements.

The study of reliability engineering responds to each of these influences by helping designers determine and increase the useful lifetime of products, processes, and services.

2. INTERRELATIONSHIP OF SAFETY, QUALITY, AND RELIABILITY

> Describe the relationship of and distinguish between reliability and quality, and describe the importance of safety in reliability engineering and how reliability impacts safety. (Understand)
>
> Body of Knowledge I.A.2

In most organizations the quality assurance function is designed to continually improve the ability to produce products and services that meet or exceed customer requirements. Narrowly construed, this means, in the manufacturing industries, producing parts with dimensions that are within tolerance. Quality engineering must expand this narrow construction to include reliability considerations, and all quality engineers should have a working knowledge of reliability engineering. What, then, is the distinction between these two fields?

- Once an item has been successfully manufactured, the traditional quality assurance function has done its job (although the search for ways to improve is continuous). The reliability function's principal focus is on what happens next. Answers are sought to questions such as:
  - – Are components failing prematurely?
  - – Was burn-in time sufficient?

  - Is the failure rate acceptable?
  - What changes in design, manufacturing, installation, operation, or maintenance would improve reliability?

- Another way to delineate the difference between quality and reliability is to note how data are collected. In the case of manufacturing, data for quality engineering are generally collected during the manufacturing process. Inputs such as voltages, pressures, temperatures, and raw material parameters are measured. Outputs such as dimensions, acidity, weight, and contamination levels are measured. The data for reliability engineering generally are collected after a component or product is manufactured. For example, a switch might be toggled repeatedly until it fails, and the number of successful cycles noted. A pump might be run until its output in gallons per minute falls below a defined value, and the number of hours recorded.
- Quality and reliability engineers provide different inputs into the design process. Quality engineers suggest changes that permit the item to be produced within tolerance at a reasonable cost. Reliability engineers make recommendations that permit the item to function correctly for a longer period of time.

The preceding paragraphs show that although the roles of quality and reliability are different, they do interrelate. For example, in the product design phase both quality and reliability functions have the goal of proposing cost-effective ways to satisfy and exceed customer expectations. This often mandates that the two functions work together to produce a design that both works correctly and performs for an acceptable period. When processes are designed and operated, the quality and reliability engineers work together to determine the process parameters that impact the performance and longevity of the product so that those parameters can be appropriately controlled. A similar interrelationship holds as specifications are developed for packaging, shipment, installation, operation, and maintenance.

Reliability will be impacted by product design and by the processes used in the product's manufacture. Therefore, the designers of products and processes must understand and use reliability data as design decisions are made. Generally, the earlier reliability data are considered in the design process, the more efficient and effective their impact will be.

Safety considerations pervade all aspects of both the quality engineering and reliability engineering fields. When a process/product change is proposed, the proposal should be accompanied by a thorough study of the impact the improvement will have on safety. Questions to investigate include:

- *Could this change make the production process less safe? How will this be mitigated?*

  Example: Workers accustomed to doing things the old way may be more at risk with the proposed changes.

- *Could this change make the use of the product less safe? How will this be mitigated?*

  Example: The new dishwasher latch, if not engaged properly, allows steam to escape into the electronic timer, causing a fire hazard.

- *With the failure of another component now more likely, are there new safety risks?*

  Example: Proposals for increasing the useful life of a component should be accompanied by a study on the effect the increased life will have on other components.

- *As the product reaches its wear-out phase, could this change introduce safety risks? How will this be mitigated?*

  Example: The new lighting system contains chemical compounds that are toxic when improperly disposed of.

When conducting a failure modes and effects analysis (FMEA) study, all failure modes should be investigated for possible safety risks. And once a reliable product is designed, quality engineering techniques are used to make sure that the processes produce that product.

3. RELIABILITY ENGINEER LEADERSHIP RESPONSIBILITIES

Describe how to be a reliability champion by influencing program decisions and facilitating cross-functional communication. (Understand)

Body of Knowledge I.A.3

John Quincy Adams said it best: "If your actions inspire others to dream more, learn more, do more, and become more, you are a *leader*."

This idea applies to a reliability leader as well, whether a senior reliability engineer, supervisor, manager, or reliability fellow. It is the reliability leader's primary job to:

- Instill a vision of "giving the most accurate answer with the data available"
- Influence the behavior of either an individual or a group, regardless of the reason, in an effort to achieve reliability goals in a given situation
- Understand the business ramifications of a reliability question or solution
- Explain in clear terms the reliability and safety risks involved in a management decision so that management can make an informed decision
- Remind people working on your team of their ethical responsibilities, in documentation and face-to-face communication
- Support the decision of the reliability position to management

Key "facets" of leadership[1] include:

- **F**ocus—get the job done
- **A**uthenticity—have "constancy of purpose" (Deming)
- **C**ourage—stand up to criticism, support reliability decisions
- **E**mpathy—understand all areas of a problem and people interaction
- **T**iming—know when to make a critical decision

4. RELIABILITY ENGINEER ROLE AND RESPONSIBILITIES IN THE PRODUCT LIFECYCLE

> Describe how the reliability engineer influences the product lifecycle, and describe a reliability engineer's role in the design review process in order to anticipate how reliability can impact risk and costs and ensure performance over time. (Understand)
>
> Body of Knowledge I.A.4

Producing a product that is safe must be a top priority for every organization. The responsibility of the reliability engineer in meeting this priority includes the following:

1. Collecting and analyzing data regarding failures and failure rates
2. Presenting those data and analyses in an understandable format
3. Making sure that the key decision makers have an understanding of the analyses

In discharging these responsibilities, the following are among the additional items that must be considered:

1. *Could the failure of the product cause some chain of events with safety/liability implications?* This analysis should be done in conjunction with the safety organization, since the safety organization is responsible for defining risk (human injury or death or accidents).

   Example: The product is installed as part of a system in which the failure of the product was not contemplated in system design.

2. *What aspects of the product could possibly cause safety/liability hazards even though the product hasn't failed?*

   Example: During normal maintenance, the product must be partially disassembled, which may expose energized electrical conductors.

3. *What misuse of the product might cause safety/liability issues?*

   Examples: The product, when stacked more than three high for shipping, can cause damage to nearby items. If the product is exposed to temperatures below –15°F, the seals will fail. If the product is not installed within one degree of level, it presents possible hazards. If the pH of the solvent used in the product is below 3.2, the product will develop hazardous leaks. When used on a windy day, the product functions correctly but endangers downwind organisms.

In any of these situations the reliability engineer must work with the safety organization to perform a safety hazard analysis.

4. *Can the final disposition of the product present safety/liability issues?*

   Example: The product, when crushed for recycling, releases gases that produce a reaction in some people.

5. *Can the malfunction of other parts of the system cause safety/liability issues for the product?*

   Example: When exposed to fluid pressures outside its operating range, the product will act unpredictably.

6. *What is the impact of government regulation, current or contemplated, on safety/liability issues?*

   Example: Several states are contemplating legislation that will declare some types of metallurgical content of a component hazardous.

7. *Does the product design compromise the reliability of components?*

   Example: An electronic component has an acceptable reliability based on a minimum level of air circulation, but its enclosure is not properly ventilated.

5. FUNCTION OF RELIABILITY IN ENGINEERING

> Describe how reliability techniques can be used to apply best practices in engineering (e.g., measuring reliability early), how industry standards can impact reliability, and how reliability can inform the decision analysis process. (Analyze)
>
> Body of Knowledge I.A.5

The study of reliability engineering is usually undertaken primarily to determine and improve the useful lifetime of products. Data are collected on the failure rates of components and products, including those produced by suppliers. Competitors' products may also be subjected to reliability testing and analysis.

Reliability techniques can also help other facets of an organization:

- Reliability analysis can be used to improve product design. Reliability predictions provide guidance as components are selected. Derating techniques aid in increasing a product's useful lifetime. Reliability improvements can be effected through component redundancy.
- Marketing and advertising can be enhanced as warranty and other documents that inform customer expectations are prepared. Warranties

that are not supported by reliability data can cause extra costs and inflame customer ire.

- It is increasingly important to detect and prevent or mitigate product liability issues. Warnings and alarms should be incorporated into the design when hazards can't be eliminated. Products whose failure can introduce safety and health hazards need to be analyzed for reliability so that procedures can be put in place to reduce the probability that they will be used beyond their useful lifetime. Failure rates typically escalate in the final phase of a product's life. Components whose useful lifetime is shorter than the product's should be replaced on a schedule that can be determined through reliability engineering techniques.
- Manufacturing processes can use reliability tools in the following ways:
  - The impact of process parameters on product failure rates can be studied.
  - Alternative processes can be compared for their effect on reliability.
  - Reliability data for process equipment can be used to determine preventive maintenance schedules and spare parts inventories.
  - The use of parallel process streams to improve process reliability can be evaluated.
  - Safety can be enhanced through the understanding of equipment failure rates.
  - Vendors can be evaluated more effectively.
- Every facet of an organization, including purchasing, quality assurance, packaging, field service, logistics, and so on, can benefit from a knowledge of reliability engineering. An understanding of the lifecycles of the products and equipment they use and handle can improve the effectiveness and efficiency of their function.

6. ETHICS IN RELIABILITY ENGINEERING

Identify appropriate ethical behaviors for a reliability engineer in various situations. (Evaluate)

Body of Knowledge I.A.6

The ASQ Code of Ethics (Figure 1.1) provides useful guidelines. Some relevant illustrative examples are given below.

[I] will do whatever I can to promote the reliability and safety of all products that come within my jurisdiction. This indicates that the reliability engineer's responsibilities are not limited to crunching numbers and producing good analyses but include the promotion of product reliability and safety.

Fundamental Principles

ASQ requires its members and certification holders to conduct themselves ethically by:

1. Being honest and impartial in serving the public, their employers, customers, and clients.
2. Striving to increase the competence and prestige of the quality profession.
3. Using their knowledge and skill for the enhancement of human welfare.

Members and certification holders are required to observe the tenets set forth below:

Relations with the Public

Article 1—Hold paramount the safety, health, and welfare of the public in the performance of their professional duties.

Relations with Employers, Customers, and Clients

Article 2—Perform services only in their areas of competence.

Article 3—Continue their professional development throughout their careers and provide opportunities for the professional and ethical development of others.

Article 4—Act in a professional manner in dealings with ASQ staff and each employer, customer, or client.

Article 5—Act as faithful agents or trustees and avoid conflic of interest and the appearance of conflicts of interest.

Relations with Peers

Article 6—Build their professional reputation on the merit of their services and not compete unfairly with others.

Article 7—Assure that credit for the work of others is given to those to whom it is due.

Figure 1.1 ASQ Code of Ethics.

EXAMPLE 1.1

A design team has decided on a more hazardous configuration against the recommendation of the reliability engineer. What should the reliability engineer do? The engineer must answer the question, “Have I done whatever I can to promote the reliability and safety of all products?” If the answer is “no,” then the code of ethics requires further action. If the design team decided on a more hazardous configuration against the recommendation of the reliability engineer, that decision should be brought to the attention of the reliability engineer’s manager and director for their review.

[I] will be dignified and modest in explaining my work and merit. This phrase requires that all who subscribe to this code of ethics recognize that their efforts should be expended on objective analysis of facts and not on self-promotion.

[I] will preface any public statements that I may issue by clearly indicating on whose behalf they are made. Engineers are frequently called on to apply their expertise to issues not directly related to their employer. These opportunities vary from service on a committee in a professional organization to providing advice on public works projects. When it is necessary to issue a statement in this capacity, the code of ethics

requires a disclaimer separating one's views from those of the employer. On the other side of the coin, when the engineer is asked to speak for the employer, the statement should make that fact clear as well.

[I] will inform each client or employer of any business connections, interests, or affiliations which might influence my judgment or impair the equitable character of my services. Professionals of all types make value judgments as part of their responsibilities. This section of the code of ethics requires a conscious search to identify any connections that might bias conclusions. In some situations, especially public service, any connection that could even be perceived as a conflict of interest should be divulged.

[I] will indicate to my employer or client the adverse consequences to be expected if my professional judgment is overruled. The reliability engineer is required to present both good news and bad news scenarios when making recommendations. This equips the decision maker with options, complete with the likely outcomes of each. If hypothesis tests were used to reach conclusions, the significance level should be disclosed. For sampling reports, the confidence level and margin of error should be included.

[I] will not disclose information concerning the business affairs or technical processes of any present or former employer or client without his consent. This clause says that even in the absence of a confidentiality agreement, the individual is honor bound to act as if one is in place. As a practical matter, it may be advisable to have a signed statement from the former employer or client releasing the information.

[I] will take care that credit for the work of others is given to those whom it is due. This clause requires action on the part of the person preparing or presenting a report. Rather than leaving the report uncredited, which might imply that the credit is due the presenter, the "take care" phrase requires an acknowledgment of those involved. If a team is due credit, the team members should usually be named.

The entire ASQ Code of Ethics should be studied and used as a basis for action by all in this field.

7. SUPPLIER RELIABILITY ASSESSMENTS

> Explain how supplier reliability impacts the overall reliability program and describe key reliability concepts that should be included in supplier reliability assessments. (Analyze)
>
> Body of Knowledge I.A.7

In an ideal world, every supplier would have an excellent reliability engineering program with regular, dependable reports delivered to customers. While awaiting this state of affairs it is essential that the customer choose between three scenarios:

1. The customer assumes all responsibility for the reliability engineering function and requires supplier compliance with all specifications. With this arrangement the supplier must report any proposed changes in the process or product so that the potential impact on reliability can be studied. This option is more common in situations where the customer has full design responsibilities and outsources relatively minor components.

2. The supplier assumes responsibility for reliability engineering and reports its analysis and decision-making process to the customer for agreement. The customer is, of course, ultimately responsible to its customers, but the supplier may share financial responsibility for warranty claims and so on. This option is more common when the supplier has design control of the supplied component.
3. Some sort of shared responsibility for the reliability engineering analysis and interpretation exists, perhaps involving a third party. Third-party involvement is more common when the supply chain is long geographically.

With any of these options the arrangement must be clearly spelled out in the contractual agreement between the parties. The customer will want to conduct assessments customized to that agreement.

Examples:

- For suppliers with a long-term relationship based on mutual trust and understanding, the reliability functions conducted by the supplier can be verified at the time of a quality audit. At least one auditing team member should be familiar with reliability engineering functions. The supplier's collection and analysis of lifecycle cost data should be studied, and the mechanism for feedback of this information to the product/design functions should be confirmed.
- For suppliers without a strong favorable history with the components involved, the customer should consider performing actual testing and evaluation of the products. This could vary from a full-fledged reliability program to less elaborate programs, depending on the situation.

The full reliability program would begin with establishing goals and translating goals into product/process design requirements and continue through validating production output. Less elaborate programs could consist of monitoring the reliability engineering function at the supplier's location, training supplier personnel, and/or testing random samples from production to assure that reliability requirements are being met.

8. PERFORMANCE MONITORING

Describe the importance of performance monitoring to ensure that product reliability or safety requirements continue to be met, and identify lifecycle points in which process and product reliability data are collected and evaluated. (Understand)

Body of Knowledge I.A.8

Performance monitoring involves periodically measuring a project's progress toward explicit short- and long-term reliability, maintainability, and safety (RMS) objectives and giving feedback on the results to decision makers who can use the information in various ways to improve performance.

Uses of Performance Indicators

Strategic Planning

For any program, incorporating performance measurement forces greater consideration of the critical assumptions that underlie that program's relationships and the paths it is following. So, performance indicators help clarify the RMS objectives and logic in the program.

Performance Accounting

Performance indicators can help inform resource allocation decisions if they are used to direct RMS resources to the most successful activities and thereby promote the most efficient use of those resources.

Forecasting and Early Warning During Program Implementation

Measuring progress against indicators points toward future performance, providing feedback that can be used for planning, identifying areas needing RMS improvement, and suggesting what can be done.

Measuring Program Results

Good performance indicators measure what a program has achieved relative to its RMS objectives, not just what it has completed, thus promoting RMS accountability.

Program Marketing and Public Relations

Performance indicators can be used to demonstrate program RMS results to satisfy an external audience/customer. RMS performance data can be used to communicate the value of a program or project.

Benchmarking

Performance indicators can generate RMS data against which to measure other projects or programs. They also provide a way to identify good RMS applications, thus learning from success and from experience how to improve the RMS performance of other projects or programs.

Quality Management

Performance indicators can be used to measure customer satisfaction relative to customer requirements. Performance can be monitored through administering satisfaction surveys and reviewing complaints.

How Are RMS Performance Indicators Developed?

Performance indicators must be based on the unique objectives of individual projects and the customer's requirements. Identifying the RMS objectives—indeed all project objectives—can flow from the customer's requirements via a quality function deployment (QFD).

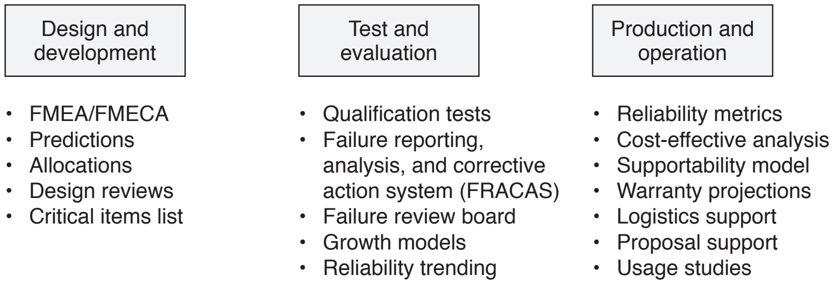
As the project's RMS objectives are developed, the best mix of outputs to achieve these objectives and components is derived. Tracking parameters for these outputs (e.g., mean time between failures, reject rates, number of defectives, aborts, material defects per item, etc.) can be set up for regular, timely reporting.

For example, looking at a typical product development cycle, the reliability (and indeed, closely related safety) tools and methods are used/modified/developed for the product (see Figure 1.2).

Some performance monitoring examples are shown in Figures 1.3 through 1.6.

NOTE

1. Paraphrased from Brian Ward, *Lead People, Manage Things* (Edmonton, AB: Affinity Consulting, 2009), 93–97.



Design and development

- FMEA/FMECA
- Predictions
- Allocations
- Design reviews
- Critical items list

Test and evaluation

- Qualification tests
- Failure reporting, analysis, and corrective action system (FRACAS)
- Failure review board
- Growth models
- Reliability trending

Production and operation

- Reliability metrics
- Cost-effective analysis
- Supportability model
- Warranty projections
- Logistics support
- Proposal support
- Usage studies

Figure 1.2 Reliability tasks occur throughout the life of the program.

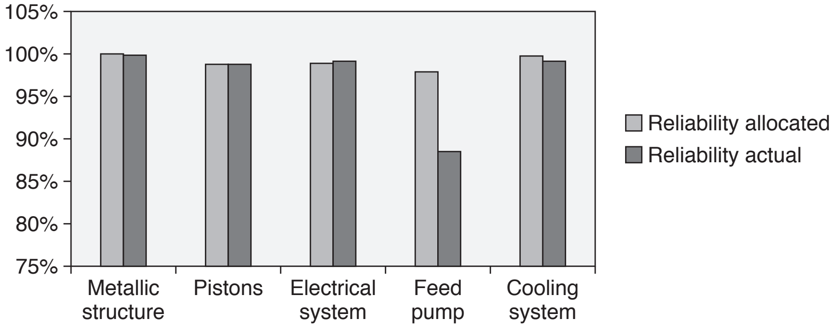


Figure 1.3 Reliability allocations.

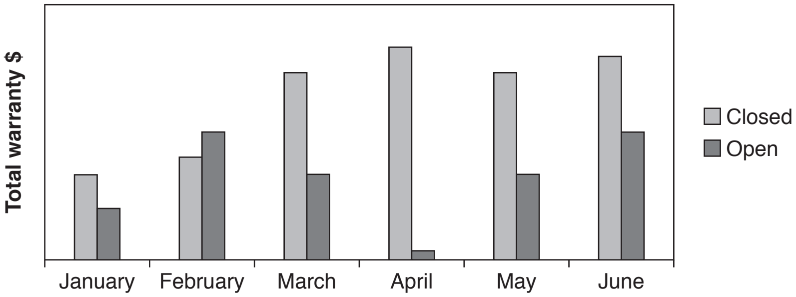


Figure 1.4 Warranty predictions (predicted vs. actual).

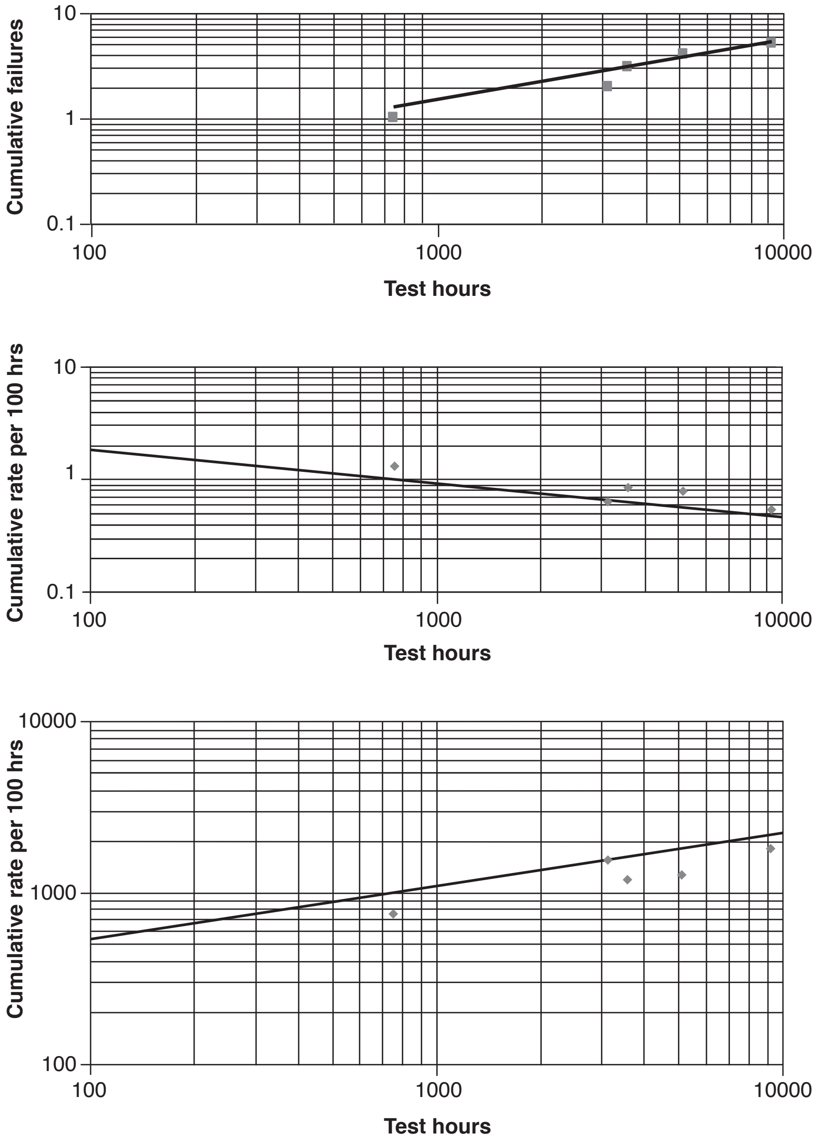


Figure 1.5 Reliability growth models.

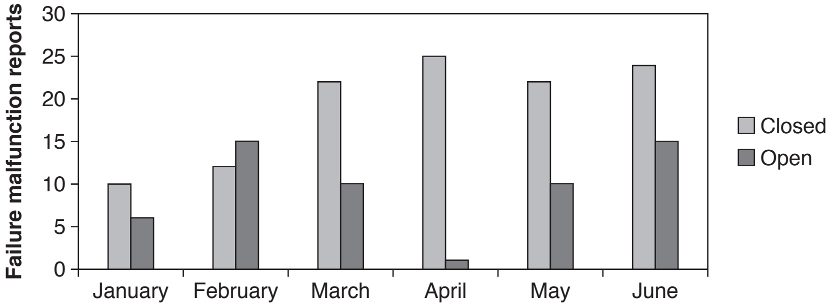


Figure 1.6 FRACAS.

Chapter 2

B. Reliability Foundations

1. BASIC RELIABILITY TERMINOLOGY

> Explain basic terms related to reliability and the associated metrics (e.g., MTTF, MTBF, MTTR, service interval, maintainability, availability, failure rate, reliability, and bathtub curve.). (Apply)
>
> Body of Knowledge I.B.1

Reliability is the probability that an item can perform its intended function for a specified interval under stated conditions. There are several measures of reliability, including *mean time to failure* (MTTF) and *mean time between failures* (MTBF).

The *mean life* of a product is the average time to failure of identical products operating under identical conditions. Mean life is also referred to as the expected time to failure. Mean life is denoted by MTTF for non-repairable products and MTBF for repairable products. The reliability engineer should exercise care in the use of the terms MTTF and MTBF. These terms are usually used when the underlying failure distribution is the exponential and the failure rate is constant. The relationships given in the remainder of this chapter are based on this assumption. MTTF and MTBF are often denoted with the Greek theta (θ). "Time" as used here refers to some measure of life units for the product. In the case of automotive products, the life units may be miles. In other equipment, life units may be cycles, rounds fired, and so forth. Some documents, for instance, replace MTBF with *mean cycles between failures* (MCBF). For a particular set of failure times, the mean life is obtained by averaging the failure times. This value serves as an estimate for θ. If n items are tested to failure, the general formula is

$$\mathrm{MTTF} = \theta = \frac{\sum t_i}{n}$$

where

n = Number of items

t_i = Failure times

EXAMPLE 2.1

Ten randomly selected non-repairable products are tested to failure, and their failure times in hours are: 132, 140, 148, 150, 157, 158, 159, 163, 163, 168.

$$\text{MTTF} = \theta = \frac{132+140+148+150+157+158+159+163+163+168}{10} = 153.8 \text{ hours}$$

The general formula for the situation where a number of repairable items are tested for a given amount of time, with failed items being promptly replaced, is

$$\text{MTBF} = \frac{nm}{r}$$

where

n = Number of items

m = Number of hours in the test

r = Number of failures

Suppose 100 repairable items are tested for 1000 hours each, and failed items are promptly repaired and returned to the test. Suppose 25 failures occurred during the test. Then,

$$\text{MTBF} = \theta = \frac{100{,}000}{25} = 4000 \text{ hours}$$

Censored Data

There are four types of failure data:

1. *Exact failure times,* in which the exact failure time is known.
2. *Right-censored* data, in which it is known only that the failure happened or would have happened after a particular time. This occurs if an item is still functioning when the test is concluded.
3. *Left-censored* data, in which it is known only that the failure happened before a particular time. This occurs if the items are not checked prior to being tested but are periodically examined, and a failure is observed at the first examination.
4. *Interval-censored* data, in which it is known only that the failure happened between two times; for example, if the items are checked every five hours and an item was functioning at hour 145 but had failed sometime before hour 150.

Failure rate is the reciprocal of the mean life and is defined as the number of failures per unit of time. Failure rate is usually denoted by the letter *f* or the Greek letter lambda (λ). We will denote failure rate as λ or $\lambda(t)$. $\lambda(t)$ is also called the *hazard function*. So,

$$\lambda = \frac{1}{\text{MTBF}}$$

or

$$\lambda = \frac{1}{\text{MTTF}}$$

and, of course,

$$\text{MTBF} = \frac{1}{\lambda}$$

and

$$\text{MTTF} = \frac{1}{\lambda}$$

Availability can be defined as the probability that a product is operable and in a committable state when needed. In other words, it is the probability that an item has not failed or is not undergoing repair. This measure takes into account an item's reliability and its maintainability. Another way to express this is the proportion of time a system is in a functioning condition. This can be written as the fraction

$$A = \frac{\begin{array}{c}\text{Total time a functional unit is capable}\\ \text{of being used during a given interval}\end{array}}{\text{The length of the interval}}$$

The *mean time to repair* (MTTR) is the average time to fix a repairable system. If the product is repairable and needs no preventive maintenance, and if repair can begin immediately when failure occurs, availability can be defined as

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

A more general formula for availability can be written as the ratio of the average value of the uptime of a system to the sum of the average values of uptime and downtime:

$$\text{Availability} = \frac{\text{Average uptime}}{\text{Average uptime} + \text{Average downtime}}$$

Dependability is a very similar concept. It is defined as the probability that a product will function at a particular point in time during a mission.

Maintainability is the probability that a failed product will be repaired within a given amount of time once it has failed. Thus, maintainability is a function of time. If there is a 95% probability that a product will be operable within three hours, then M(3) = 0.95. In defining maintainability it is necessary to describe exactly what is included in the maintenance action. The following items are typical: diagnosis time, part procurement time, teardown time, rebuild time, and verification time.

Preventive maintenance (PM)—that is, the replacement, at scheduled intervals, of parts or components that have not failed rather than waiting for a failure—is frequently more cost-effective. Preventive maintenance reduces the diagnosis and part procurement times and thus may improve maintainability.

As component and product design decisions are made, the reliability engineer can aid in calculating the cost–benefit relationships by providing life expectancies for various design options.

MTTF is defined as the average time elapsed until the product is no longer performing its function. If the item is repairable, MTBF is the metric used. MTTF and MTBF are reciprocals of λ:

$$\text{MTTF} = \frac{1}{\lambda} \text{ or } \text{MTBF} = \frac{1}{\lambda}$$

EXAMPLE 2.2

If $\lambda = 0.00023$ failures per hour, MTBF ≈ 4348 hours.

Reliability R(t) is defined as

$$\text{R}(t) = \frac{\text{Number of units functioning at the end of the time period}}{\text{Number of units that were functioning at the start of the test}}$$

BX *life*, or B*(X) life*, is the amount of time that has elapsed when X% of the population has failed. For example B(10) = 367 hours means R(367) = 0.90.

Mean time between repairs (MTBR) provides another measure of the reliability of a product. MTBR data should include information about the type of repair and resources required. These data are helpful in determining spare parts inventories, planning for resources, and scheduling preventive maintenance.

Mean time between unplanned maintenance action (MTBUMA) indicates the level of confidence that can be placed in the machine when it is placed in a vital role. If MTBUMA is relatively short, redundant equipment may be needed.

Service interval refers to the recommended time between routine checks and replacements. Familiar examples include lubrication and filter change schedules.

EXAMPLE 2.3

A set of 283 non-repairable units are tested, and the number of failures during each 100 block of time is recorded. The test produced the following data:

Time interval (hrs)	# failures
0–99	0
100–199	2
200–299	10
300–399	30

Calculate $\lambda(t)$, MTBF, and R(t) for each time block.

Solution:

Using the formulas given in the definitions:

Time interval (hrs)	# failures	# surviving	$\lambda(t)$	MTBF (hrs)	R(t)
0–99	0	283	0.0000	Undefined	1.000
100–199	2	281	0.0001	10,000	0.993
200–299	10	271	0.356	28.1	0.958
300–399	30	241	0.1107	9.0	0.852

Relationship to Product Specifications

It is customary to specify dimensions, weights, carbon content, and so forth, for products. From the reliability engineering standpoint, it would often be more productive to specify one or more of the reliability metrics listed previously. This has proved especially useful when specifying purchased parts because suppliers often know more about the characteristics of their products than the customer. Although Example 2.4 is anecdotal and somewhat subjective, it illustrates this point.

EXAMPLE 2.4

An automotive company had specified black rubber door seals, giving content, hardness, profile dimensions, and other characteristics. Instead, they now specify reliability requirements such as resistance to ultraviolet (UV) exposure for specified amounts of time and passing rain tests for specified time periods. The customer has left other details up to the supplier and has found that its research requirements are reduced, the new seal does a better job, and the price is slightly reduced because the rubber supplier designed a product that is also easier to manufacture.

Maintainability

Maintainability is a metric usually specified as a probability that a particular maintenance activity can be accomplished in a stated period of time. It is made up of two components: serviceability and repairability. *Serviceability* refers to the level of difficulty encountered when performing the maintenance activity, and *repairability* refers to the level of difficulty when returning a failed item to usefulness. The ultimate goal is to develop a *reliability-centered maintenance* (RCM) program. Steps in that direction include:

1. Develop a functional hierarchy of the machines and their components
2. Make a complete list of failure modes for the machines
3. Perform an evaluation of each PM activity to determine whether it really aids in preventing failure modes
4. Reorganize PM activities to align with the information from steps 1–3

Product Lifecycle

Reliability engineers identify three stages in the lifecycle of a product:

1. The first stage is referred to variously as the *early failure* stage, the *infant mortality* stage, or the *decreasing failure rate* stage. The failures that occur during the early failure stage are usually associated with manufacturing rather than design. Examples of causes of failure include inadequate test or burn-in time, poor quality control, poor handling, weak materials or components, and human error in fabrication or assembly. Ideally, all these failures should occur in-house and be corrected before the customer takes possession.
2. The second stage is called the *constant failure rate* stage, the *random causes* stage, or the *useful life* stage. During the useful life stage the failure rate is approximately constant. Note that the failure rate is not necessarily zero. During this stage the failures have random causes and can't usually be assigned to production problems. Reducing the failure rate during this stage usually requires changes in product design.
3. The third stage is called the *wear-out* stage, *fatigue* stage, or the *increasing failure rate* stage. The wear-out stage is characterized by an increasing failure rate over time. These failures are caused by product or component fatigue.

A graph of the failure rate is shown as the *bathtub curve* in Figure 2.1. Note that although the useful life stage is sometimes referred to as the random causes stage, random causes are generally present during all three stages.

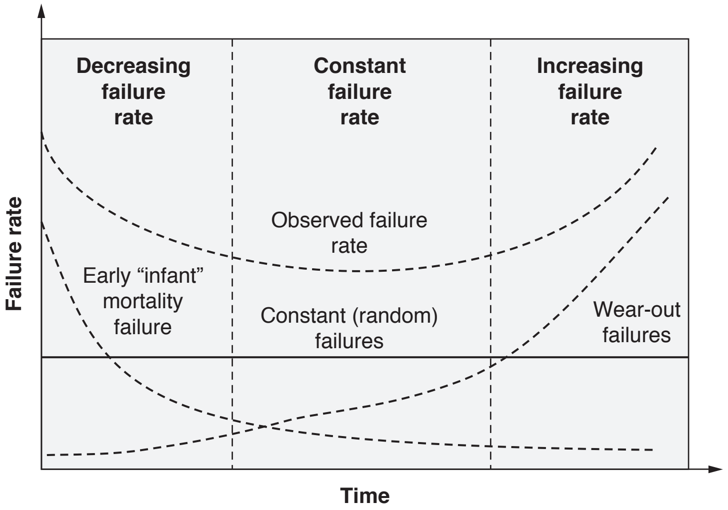


Figure 2.1 Reliability bathtub curve.

Source: Adapted from M. A. Durivage, *Practical Engineering, Process, and Reliability Statistics* (Milwaukee, WI: ASQ Quality Press, 2014).

2. DRIVERS OF RELIABILITY REQUIREMENTS AND TARGETS

> Describe how customer expectations and industry standards, safety, liability, and regulatory concerns drive reliability requirements. (Understand)
>
> Body of Knowledge I.B.2

Reliability analysis provides estimates of the probability of failure. The reliability engineer must go beyond these calculations and examine the consequences of failure. These consequences typically represent costs to the customer. The customer finds ways of sharing these costs with the producer through the warranty system, loss of business, decrease in reputation, or the civil litigation system. Therefore, an important reliability function is the anticipation of possible failures and the establishment of reliability acceptance goals that will limit their occurrence and consequent costs. The acceptance criteria associated with these goals generally fall into three categories:

- Functional requirements (such as 20 gallons per minute for a pump)
- Environmental requirements (such as temperature, radiation, pH)
- Time requirements (such as failure rate during useful life, time elapsed before wear-out phase begins)

Once component, product, and system reliability goals have been set, a testing protocol should be implemented to provide validation that these goals will impact the failure rates and the associated consequences as planned. These reliability goals typically impose specifications on the product. In anticipation of the start of production, reliability engineers provide further testing procedures to provide verification that these specifications are being met.

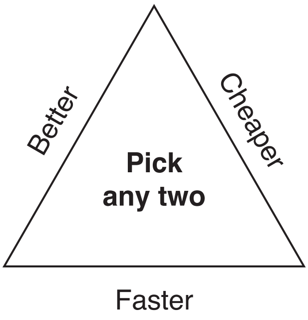
A reliability program should impact many functions in an enterprise, including research, purchasing, manufacturing, quality assurance, testing, shipping, and field service, among others. A reliability program should have the following elements:

1. *Established reliability goals and requirements.* The general goal of reliability efforts is to delight customers by increasing the reliability of products. The reliability program accomplishes this goal by establishing reliability goals and meeting them. Customer input and market analysis typically determine minimum reliability requirements. In general, consumers have rising expectations for reliability. The minimum reliability requirements are time dependent because reliability changes throughout the life of the product.
2. *Product design.* The reliability program must have a mechanism for translating the minimum reliability requirements into design requirements. Reliability requirements should be documented for each stage of a product's design and for all subsystems and components.
3. *Process design.* As the product design firms up, attention can shift toward the design of the processes that will produce it. Reliability requirements must be finalized for components, whether produced in-house or

purchased from suppliers. These requirements must be linked to manufacturing process parameters by determining what processes and what settings will produce components with the required reliability.

4. *Validation and verification.* As either prototypes or the first production pieces become available, the reliability program must facilitate tests that are conducted to validate that the reliability requirements do indeed produce the desired product reliability. When these requirements have been validated it is necessary to verify that the production processes can produce products that meet these requirements.
5. *Post-production evaluation.* The reliability program must make provisions for collecting and analyzing data from products during their useful life:
    a. Random samples from regular production should be collected and tested for reliability.
    b. Customer feedback should be actively solicited and analyzed.
    c. Field service and warranty records should be studied.
6. *Training and education.* Although listed last, this is certainly not the least important element of a reliability program. No reliability program can succeed without a basic understanding of its elementary concepts by people at all levels. Support from key managers is essential because their cooperation is needed for the testing and analysis process. Top-level management must see the importance of the program to the success of the enterprise. So, this element of the reliability program must sometimes be given first priority if the rest of the program is to succeed.

Design requirements originate from customer needs. These requirements, as determined by the marketplace, customer input, organizational objectives, and other sources, must often be prioritized. A classic example is the motto NASA adopted in the 1990s, "faster—better—cheaper," to which the engineers famously replied, "We can do any two."



Meeting reliability design requirements within time and resource constraints requires an efficient testing and documentation program. The tasks associated with the program must be accomplished in synchronization with other design, development, and manufacturing functions. These tasks must be given adequate priority at each stage of design if unpleasant late-term surprises are to be avoided.