# 22

# Electronic Hardware Reliability

Arun Ramakrishnan
*University of Maryland*

Toby Syrus
*University of Maryland*

Michael Pecht
*University of Maryland*



## 22.1 Introduction

Reliability is the ability of a product to perform as intended (i.e., without failure and within specified performance limits) for a specified time, in its life cycle application environment. To achieve product reliability over time demands an approach that consists of a set of tasks, each requiring total engineering and management commitment and enforcement. These tasks impact electronic hardware reliability through the selection of materials, structural geometries and design tolerances, manufacturing processes and tolerances, assembly techniques, shipping and handling methods, operational conditions, and maintenance and maintainability guidelines.[1] The tasks are as follows:

1. Define realistic product requirements and constraints determined by the life cycle application profile, required operating and storage life, performance expectations, size, weight, and cost.

The manufacturer and the customer must jointly define the product requirements in the light of both the customer's needs and the manufacturer's capability to meet those needs.

2. Define the product life cycle environment by specifying all relevant assembly storage, handling, shipping, and operating conditions for the fielded product. This includes all stress and loading conditions.
3. Characterize the materials and the manufacturing and assembly processes. Variabilities in material properties and manufacturing processes can induce failures. A knowledge of the variability is required to assess design margins and possible trade-offs with weight, size, and cost.
4. Select the parts required for the product, using a well-defined assessment procedure that ensures that the parts selected have sufficient quality and integrity, are capable of delivering the expected performance and reliability in the application, and will be available to sustain the product throughout its life cycle.
5. Identify the potential failure sites and failure mechanisms by which the product can be expected to fail. Critical parts, part details, and potential failure modes and mechanisms must be identified early in the design, and appropriate measures must be implemented to assure design control. Potential architectural and stress interactions must also be defined and assessed.
6. Design to the usage and process capability of the product (i.e., the quality level that can be controlled in manufacturing and assembly), considering the potential failure sites and failure mechanisms. The design stress spectra, the part test spectra, and the full-scale test spectra must be based on the anticipated life cycle usage conditions. The proposed product must survive the life cycle environment, be optimized for manufacturability, quality, reliability, and cost-effectiveness, and be available to the market in a timely manner.
7. Qualify the product manufacturing and assembly processes. Key process characteristics in all the manufacturing and assembly processes required to make the part must be identified, measured, and optimized. Tests should be conducted to verify the results for complex products. The goal of this step is to provide a physics-of-failure basis for design decisions, with an assessment of all possible failure mechanisms for the anticipated product. If all the processes are in control and the design is valid, then product testing is not warranted and is therefore not cost-effective. This represents a transition from product test, analysis, and screening to process test, analysis, and screening.
8. Monitor and control the manufacturing and assembly processes addressed in the design, so that process shifts do not arise. Each process may involve screens and tests to assess statistical process control.
9. Manage the life cycle usage of the product using closed loop management procedures. This includes realistic inspection and maintenance procedures.

## 22.2 Product Requirements and Constraints

A product's requirements and constraints are defined in terms of customer demands and the company's core competencies, culture, and goals. If the product is for direct sale to end users, marketing usually takes the lead in defining the product's requirements and constraints through interaction with the customer's marketplace, examination of the current product sales figures, and analysis of the competition. Alternatively, if the product is a subsystem that fits within a larger product, the requirements and constraints are determined by the product into which the subsystem fits. The results of capturing product requirements and constraints allow the design team to choose product parts that conform to product-specific and company objectives.

The definition process begins with the identification of an initial set of requirements and constraints defined by either the marketing activity (or in some cases by a specific customer), or by the product into which the subsystem fits. The initial requirements are formulated into a requirements document, where they are prioritized. The requirements document needs to be approved by several groups of people, ranging

from engineers to management to customers (the specific people involved in the approval will vary with the organization and the product). Once the requirements are approved, the engineering team prepares a preliminary specification indicating the exact set of requirements that are practical to implement. Disconnects between the requirements document and the preliminary specification become the topic of trade-off analyses (usually cost/performance trade-offs), and if, after analyses and negotiation, all the requirements cannot be implemented, the requirements document may be modified. When the requirements document and the preliminary specifications are agreed upon, a final specification is prepared and the design begins.

## 22.3 The Product Life Cycle Environment

The product life cycle environment goes hand in hand with the product requirements. The life cycle environment affects product design and development decisions, qualification and specification processes, parts selection and management, quality assurance, product safety, warranty and support commitments, and regulatory conformance.

The product life cycle environment describes the assembly, storage, handling, and scenario for the use of the product, as well as the expected severity and duration of these environments, and thus contains the necessary load input information for failure assessment and the development of design guidelines, assembly guidelines, screens, and tests. Specific load conditions may include steady-state temperatures, temperature ranges, temperature cycles, temperature gradients, humidity levels, pressure levels, pressure gradients, vibrational or shock loads and transfer functions, chemically aggressive or inert environments, acoustic levels, sand, dust, and electromagnetic radiation levels. In electrical systems, stresses caused by power, current, and voltage should also be considered. These conditions may influence the reliability of the product either individually or in combination with each other. Since the performance of a product over time is often highly dependent on the magnitude of the stress cycle, the rate of change of the stress, and the variation of the stress with time and space, the interaction between the application profile and the internal conditions must be specified in the design.

The product life cycle environment can be divided into three parts: the application and life profile conditions, the external conditions under which the product must operate, and the internal product-generated stress conditions. The application and life profile conditions include the application length, the number of applications in the expected life of the product, the product use or non-use profile (storage, testing, transportation), the deployment operations, and the maintenance concept or plan. This information is used to group usage platforms (whether the product will be installed in a car, boat, airplane, satellite, or underground), to develop duty cycles (on-off cycles, storage cycles, transportation cycles, modes of operation, and repair cycles), to determine design criteria, to develop screens and test guidelines, and to develop support requirements to sustain attainment of reliability and maintainability objectives.

The external operational conditions include the anticipated environment(s) and the associated stresses that the product will be required to survive. These conditions are usually determined through experimentation and through the use of numerical simulation techniques. Experiments are performed by creating environmental parameter monitoring systems consisting of sensors placed near and within the product that are capable of monitoring the loads that the product experiences. A sensor's function is to convert a physical variable input into, in most cases, an electrical output that is directly related to the physical variable. Signals can be transmitted to either local or remote output devices, enabling data to be collected in a safe and secure manner. Numerical simulation techniques combine material properties, geometry, and product architecture information with environmental data to determine the life cycle environment based on external stresses. Whenever credible data are not available, the worst-case design load must be estimated. A common cause of failure is the use of design factors related to average loads, without adequate consideration being given to the extreme conditions that may occur during the product's life cycle.[2]

The internal operational conditions are associated with product-generated stresses, such as power consumption and dissipation, internal radiation, and release or outgassing of potential contaminants.

If the product is connected to other products or subsystems in a system, the stresses associated with the interfaces (i.e., external power consumption, voltage transients, voltage spikes, electronic noise, and heat dissipation) must also be included.

Life cycle stresses can cause strength degradation in materials, for example, combined stresses can accelerate damage and reduce the fatigue limit. In such cases, protective measures must be taken to mitigate the life cycle environment by the use of packaging, provision of warning labels and instructions, and protective treatment of surfaces. The measures to be taken must be identified as appropriate to assembly, storage, transportation, handling, operation, and maintenance. Protection against extreme loads may not always be possible, but should be considered whenever practicable. When overload protection is provided, a reliability analysis should be performed on the basis of the maximum anticipated load, keeping the tolerances of the protection system in mind.[2] If complete protection is not possible, the design team must specify appropriate maintenance procedures for inspection, cleaning, and replacement.

An example of the scenario for use of a product is a flight application, which can involve engine warm-up, taxi, climb, cruising, maneuvers, rapid descent, and emergency landing. Each part of the application will be associated with a set of load conditions, such as time, cycles, acceleration, velocity, vibration, shocks, temperature, humidity, and electrical power cycles. Together, these loads comprise a load history of the product.

## 22.4 Characterization of Materials, Parts, and Manufacturing Processes

Design is intrinsically linked to the materials, parts, interfaces, and manufacturing processes used to establish and maintain the functional and structural integrity of the product. It is unrealistic and potentially dangerous to assume defect-free and perfect-tolerance materials, parts, and structures. Materials often have naturally occurring defects, and manufacturing processes can introduce additional defects in the materials, parts, and structures. The design team must also recognize that the production lots or vendor sources for parts that comprise the design are subject to change, and variability in parts characteristics is likely to occur during the fielded life of a product.

Design decisions involve the selection of parts, materials, and controllable process techniques using processes appropriate to the scheduled production quantity. Any new parts, materials, and processes must be assessed and tested before being put into practice, so that training for production personnel can be planned, quality control safeguards can be set up, and alternative second sources can be located. Often, the goal is to maximize part and configuration standardization, to increase package modularity for ease in fabrication, assembly, and modification, to increase flexibility of design adaptation to alternate uses, and to utilize common fabrication processes. Design decisions also involve choosing the best material interfaces and the best geometric configurations, given the product requirements and constraints.

## 22.5 Parts Selection and Management

Product differentiation, which determines market share gain and loss, often motivates a company to adopt new technologies and insert them into their mainstream products. However, while technological advances continue to fuel product development, two factors, management decisions regarding when and how a new technology will be used, and accurately assessing risks associated with a technology, differentiate the winners from the losers. Few companies have failed because the right technology was not available; far more have failed when a technology was not effectively managed.

The methodology, shown in Figure 22.1, provides an "eyes-on, hands-off" approach to parts selection and management, which enables organizations to:

- Employ risk assessment and mitigation techniques to address technology insertion;
- Organize and conduct fact-finding processes to select parts with improved quality, integrity, application-specific reliability, and cost-effectiveness;

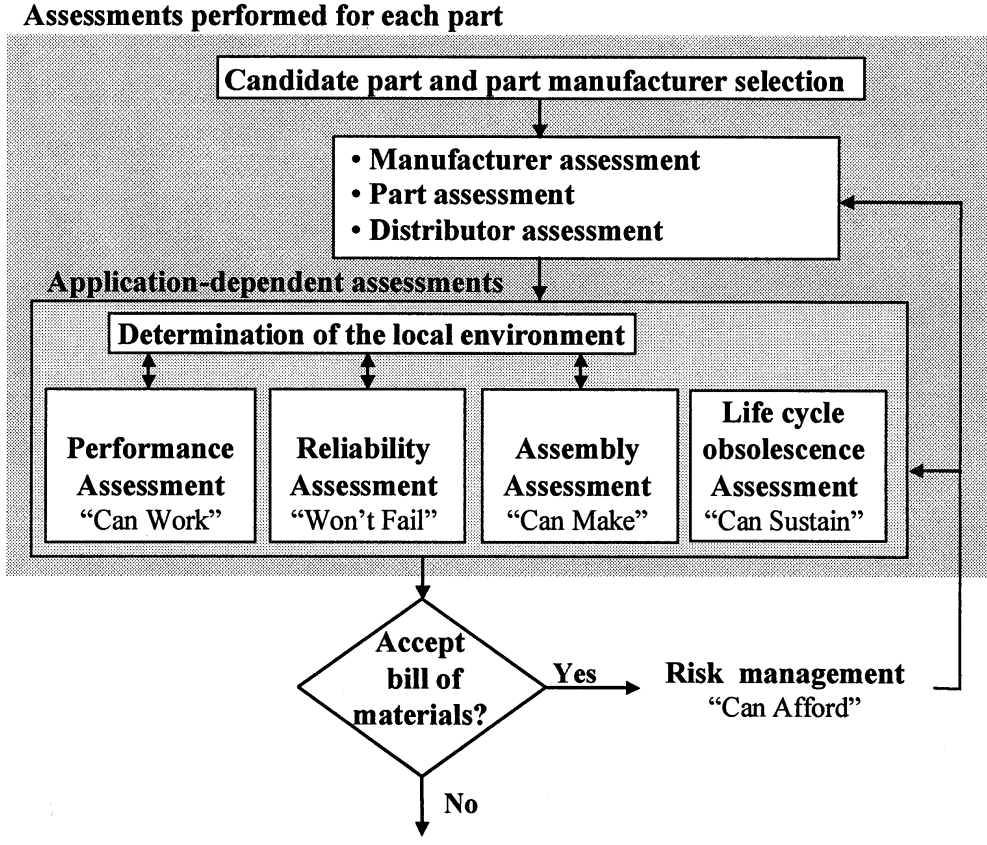


**FIGURE 22.1** Parts selection and management methodology.

- Make an informed organization-wide decision about parts selection and management, based upon organization resources, policies, culture, goals, and customer demands;
- Understand and evaluate the local environment the part sees within a product's life cycle, and thereby choose the most appropriate technique to fit the part to its intended environmental requirements;
- Maximize product supportability by preparing for and meeting the challenge of parts becoming obsolete during product life; and
- Improve supply-chain interactions and communications with regulatory agencies to minimize time to profit.

### 22.5.1 Candidate Part and Part Manufacturer Selection

A candidate part is one that conforms to the functional, electrical, and mechanical requirements of the product, considering product requirements, technology direction, and development. In addition, a candidate part must conform to availability and cost constraints. Availability of an electronic part is a measure of the ease with which the part can be procured. Availability is assessed by determining the amount of inventory at hand, the number of parts required for units in production and forecasted, the economic order quantity for the part(s), the lead time(s) between placing an order for the part(s) and receiving the part(s), production schedules and deadlines, and part discontinuation plans. The cost of the part is assessed relative to the product's budget during candidate part selection. In many cases, a part similar to the required one will have already been designed and tested. This "preferred part" is typically mature,

in the sense that the variabilities in manufacturing, assembly, and field operation that could cause problems will have already been identified and corrected. Many design groups maintain a list of preferred parts of proven performance, cost, availability, and reliability.

### 22.5.2 Manufacturer, Part, and Distributor Assessment

In the manufacturer assessment, the part manufacturer's ability to produce parts with consistent quality is evaluated, and in the part assessment, the candidate part's quality and integrity is gauged. The distributor assessment evaluates the distributor's ability to provide parts without affecting the initial quality and integrity, and to provide certain specific services, such as part problem and change notifications. The equipment supplier's parts selection and management team defines the minimum acceptability criteria for this assessment, based on the equipment supplier's requirements. If the part satisfies the minimum acceptability criteria, the candidate part then moves to "application-dependent assessments."

If the part is found unacceptable due to nonconformance with the minimum acceptability criteria, some form of equipment supplier intervention may be considered.[3,4] If equipment supplier intervention is not feasible due to economic or schedule considerations, the candidate part may be rejected. If, however, equipment supplier intervention is considered necessary, then the intervention action items should be identified, and their cost and schedule implications should be analyzed through the "risk management" process step.

### 22.5.3 Performance Assessment

The goal of performance assessment is to evaluate the ability of the part to meet the functional, mechanical, and electrical performance requirements. In order to increase performance, products often incorporate features that tend to make them less reliable than proven, lower-performance products. Increasing the number of parts, although improving performance, also increases product complexity, and may lead to lower reliability unless compensating measures are taken.[5] In such situations, product reliability can be maintained only if part reliability is increased or part redundancy is built into the product. Each of these alternatives, in turn, must be assessed against the incurred cost. The trade-off between performance, reliability, and cost is a subtle issue, involving loads, functionality, system complexity, and the use of new materials and concepts.

In general, there are no distinct stress boundaries for parameters such as voltage, current, temperature, and power dissipation, above which immediate failure will occur and below which a part will operate indefinitely.[6] However, there is often a minimum and a maximum stress limit beyond which the part will not function properly, or at which the increased complexity required will not offer an advantage in cost-effectiveness. Part manufacturers' ratings or users' procurement ratings are generally used to determine these limiting values. Equipment manufacturers who integrate such parts into their products need to adapt their design so that the parts do not experience conditions beyond their absolute maximum ratings, even under the worst possible operating conditions (e.g., supply voltage variations, load variations, and signal variations).[7] It is the responsibility of the parts selection and management team to establish that the electrical, mechanical, and functional performance of the part is suitable for the operating conditions of the particular product. If a product must be operated outside the manufacturer-specified operating conditions, then uprating* may have to be considered.

Part manufacturers need to assess the capability of a part over its entire intended life cycle environment, based on the local environment that is determined. If the parametric and functional requirements of the system cannot be met within the required local environment, then the local environment may have to be modified, or a different part may have to be used.

*The term *uprating* was coined by Michael Pecht to distinguish it from *upscreening*, which is a term used to describe the practice of attempting to create a part equivalent to a higher quality by additional screening of a part (e.g., screening a JANTXV part to JANS requirements).

### 22.5.4 Reliability Assessment

Reliability assessment results provide information about the ability of a part to meet the required performance specifications in its life cycle application environment for a specified period of time. Reliability assessment is conducted through the use of integrity test data, virtual qualification results, or accelerated test results. The reliability assessment process is shown in Figure 22.2.

Integrity is a measure of the appropriateness of the tests conducted by the manufacturer and of the part's ability to survive those tests. Integrity monitoring tests are conducted by the part manufacturer to monitor part/process changes and the ongoing material or process changes specific to the part. Integrity test data (often available from the part manufacturer) is examined in light of the application life cycle stresses and the applicable failure modes and mechanisms. If the magnitude and duration of the application life cycle loads are less severe than those of the integrity tests, and if the test sample size and results are acceptable, then the part reliability is acceptable. However, if the magnitude and duration of the application life cycle loads are more severe than those encountered during the integrity tests, then integrity test data cannot be used to validate part reliability in the application, and virtual qualification should be considered.

Virtual qualification is a simulation-based methodology used to identify the dominant failure mechanisms associated with the part under the life cycle loads, to determine the acceleration factor for a given set of accelerated test parameters, and to determine the time-to-failures corresponding to the identified failure mechanisms. Virtual qualification allows the operator to optimize the part parameters (e.g., dimensions, materials) so that the minimum time-to-failure of any part is greater than the expected product life.

If virtual qualification proves insufficient to validate part reliability, accelerated testing should be performed. Once the appropriate test procedures, conditions, and sample sizes are determined, accelerated testing can be conducted by either the part manufacturer, the equipment supplier, or third-party test facilities. Accelerated testing results are used to predict the life of a product in its field application by computing an acceleration factor that correlates the accelerated test conditions and the actual field conditions. Whether integrity test data, virtual qualification results, accelerated test results, or a combination thereof are used, each applicable failure mechanism to which the part is susceptible must be addressed.

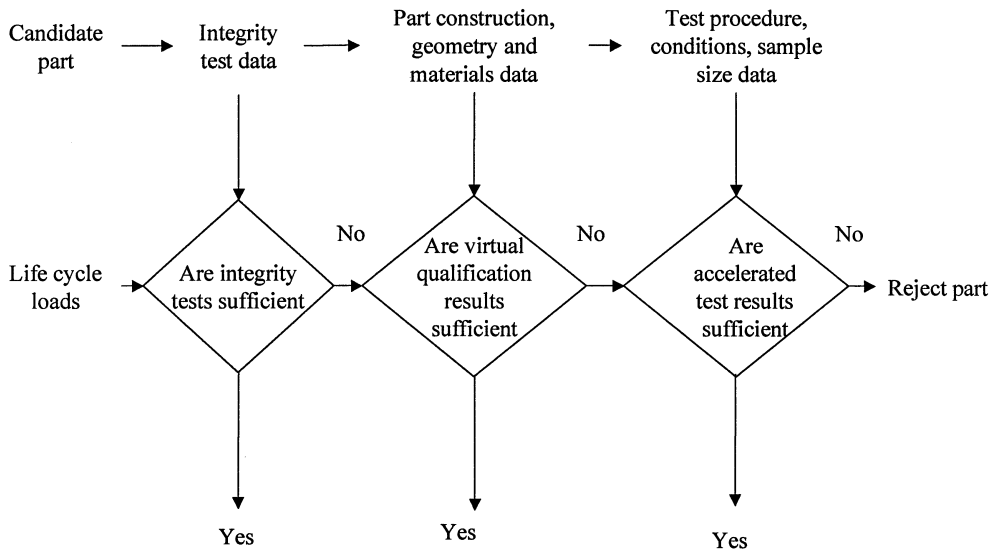


**FIGURE 22.2** Reliability assessment process.

If part reliability is not ensured through the reliability assessment process, the equipment supplier must consider an alternate part or product redesign. If redesign is not considered a viable option, the part should be rejected, and an alternate part must be selected. If the part must be used in the application, redesign options may include thermal management techniques, vibration damping, and modification of assembly parameters. If product design changes are made, part reliability must be reassessed.

## 22.5.5 Assembly Issues

A part may be unacceptable from an assembly viewpoint if (1) it is incompatible with the assembly equipment or process; (2) it is impossible or impractical to wire the part into the product (routing compatibility), or (3) it cannot be acceptably tested or reworked. Assembly compatibility addresses whether a product that contains the part can be manufactured (assembled). Routing compatibility assesses if the candidate part can be routed within a specific application on the selected board. Test and rework acceptability assess whether the candidate part can be adequately and economically tested and reworked during assembly and maintenance.

### 22.5.5.1 Assembly Compatibility

Parts must conform to a range of constraints associated with their assembly into products. There are three categories of assembly constraints that must be considered when designing a product:

- Assembly process compatibility — Assembly process compatibility involves comparing the part's size, shape, and mounting method to the process that will be used to assemble the boards containing the part.
- Proximity to other structures — Proximity checking involves checking the location of the component relative to other parts assembled on the board and the edge of the board. Proximity checking includes evaluating the orientation (rotation) of the part.
- Artwork verification — Artwork verification involves checking the board layout for the correct orientation and location of fiducials (alignment marks), alignment holes, and other structures necessary to facilitate assembly.

There are three possible outcomes from assembly compatibility and proximity checking: cannot be assembled, can be assembled with a corresponding cost and yield penalty, and can be assembled with no cost or yield penalties. Artwork verification is decoupled from parts selection.

### 22.5.5.2 Routing Compatibility

Routing compatibility pertains to the layout and routing of an application. If the selection of a particular part causes significant layout or routing problems within the board, the part may be rejected. Rejection of a part is usually based on its use of routing resources within the board. Two routing issues must be considered:

- How much board area is required to wire the part to the rest of the product?
- How many layers of the board are required to "escape route" the part?

Escape routing is only applicable if the part has an area array format connection to the board, for example, a flip chip or ball grid array package. A component is virtually always "routable," given a sufficient number of board layers. If the rest of the parts on the board are known, routing estimation techniques can be used to determine the effective routing limited footprint of a part under the constraints posed by the board design rules (lines, spaces, via/hole capture pad diameter) and layer count. If a candidate part exceeds the fraction of board wiring resources budgeted to it based on board growth and cost constraints, it may be rejected.

A limiting requirement for some parts is escape routing. If a part's I/Os are in an area array format (as opposed to a peripheral format), the part cannot be wired into the product until all of its I/Os are routed out from under the part. The process of liberating I/Os from an array is called escape routing.

#### 22.5.5.3 Test and Rework Acceptability

Test and rework costs are important criteria in determining whether a part is acceptable or not. The cost of testing the part (to a specified quality level) prior to assembly and the cost of replacing the part if it needs to be repaired after it is assembled must be considered.

The cost of testing a part is related to the level of testing performed by the part manufacturer, whether the part is in a package or bare, the function that the part performs, the number of gates or bits in the part, and the test equipment. If the part does not come from the manufacturer fully tested (e.g., a bare die), then test costs may need to be assessed. Test costs include the cost of creating the test patterns (or obtaining them from the manufacturer) and the cost of applying the test to the part. Predicting testing costs is of little value unless the corresponding test coverage (fraction of defects detected by the test) is also predicted.

Another key assembly-related cost is the cost of replacing a part that has been identified as defective during the assembly process. The cost of removing a defective part is a function of how the part is mounted to the board, the size of the part, and its proximity to other parts.

### 22.5.6 Life Cycle Mismatch Assessment

Lengthy design, qualification, and production processes inherent in electronic industries often cause parts to become obsolete before the first product is produced.[8] Furthermore, to cater to market demands and remain competitive, part manufacturers often introduce new parts and discontinue older parts. In general, electronic products go through six phases during their life cycle: design, manufacturing, growth, maturity, decline, and discontinuance. A life cycle mismatch occurs between a product and its constituent parts if the parts are not available to support the product throughout its life cycle. When factors such as lead time, risk of part obsolescence, or estimation of the product market are ignored or improperly judged during the design phase, the consequences can be costly. The obsolete part can inhibit the functioning of the product, idle the assembly line, lead to dissatisfied customers, and cause a loss of reputation to the company. The net outcome can be a financial loss for the company.

A successful life cycle mismatch assessment process is one that prevents, if possible, the selection of parts that are already obsolete or soon to be discontinued. This strategy reduces the risk associated with a life cycle mismatch between a product and its parts. The part selection depends on the degree of mismatch and the flexibility to adopt an obsolescence management strategy (e.g., redesign, lifetime buy, buy from aftermarket sources, part substitution). The strategy is intended to mitigate obsolescence risks associated with using the part at some future point in the life cycle of the product. If the equipment supplier finds the life cycle mismatch between part and product unacceptable, the part is unsuitable and should be rejected.

### 22.5.7 Risk Management

After a part is accepted, resources must be applied to managing the life cycle of the part, including supply chain management, obsolescence assessment, manufacturing and assembly feedback, manufacturer warranties management, and field failure and root-cause analysis. It is important to consider the process of managing the part and all the risks associated with the long-term use of the part throughout its life cycle during the part selection process. The risk management process is characterized using the risks identified in the parts selection process to determine the resources needed to support a part throughout its application life cycle, thus minimizing the probability of a failure. The key metric used to determine whether risks should be managed or not is resources, which include time, data, opportunity, and money.

The risks associated with including a part in the product fall into two categories:

- Managed risks: risks that the product development team chooses to proactively manage by creating a management plan and performing a prescribed regimen of monitoring the part's field performance, manufacturer, and manufacturability; and
- Unmanaged risks: risks that the product development team chooses not to proactively manage.

If risk management is considered necessary, a plan should be prepared. The plan should contain details about how the part is monitored (data collection), and how the results of the monitoring feed back into various parts selection and management processes. The feasibility, effort, and cost involved in management processes prior to the final decision to select the part must be considered.

Feedback regarding the part's assembly performance, field performance, and sales history may be essential to ascertain the validity of the predictions made during the part selection process. If the feedback calls for changes in selection criteria, they should be incorporated into the part selection process. Prospective parts should be judged based on the altered part selection criteria. Part monitoring data may also be needed to make changes in parts that are already in use. For example, part monitoring field data might indicate that a change in operating conditions is required for the part to perform satisfactorily.

## 22.6 Failure Modes and Mechanisms

Failure mechanisms are the physical processes by which stresses can damage the materials used to build the product. Investigation of the possible failure modes and mechanisms of the product aids in developing failure-free and reliable designs. The design team must be aware of all possible failure mechanisms if they are to design hardware capable of withstanding loads without failing. Failure mechanisms and their related models are also important for planning tests and screens to audit the nominal design and manufacturing specifications, as well as the level of defects introduced by excessive variability in manufacturing and material parameters. Numerous studies focusing on material failure mechanisms and physics-of-failure-based damage models and their role in obtaining reliable electronic products have been illustrated in a series of tutorials comprising all relevant wearout and overstress failures.[9-23]

Catastrophic failures due to a single occurrence of a stress event when the intrinsic strength of the material is exceeded are termed overstress failures. Failure mechanisms due to monotonic accumulation of incremental damage beyond the endurance of the material are termed wearout mechanisms.[24] When the damage exceeds the endurance limit of the component, failure will occur. Unanticipated large stress events can either cause an overstress (catastrophic) failure, or shorten life by causing the accumulation of wearout damage. Examples of such stresses are accidental abuse and acts of God. On the other hand, in well-designed and high-quality hardware, stresses should cause only uniform accumulation of wearout damage; the threshold of damage required to cause eventual failure should not occur within the usage life of the product.

Electrical performance failures can be caused by individual components with improper electrical parameters, such as resistance, impedance, capacitance, or dielectric properties, or by inadequate shielding from electromagnetic interference (EMI) or particle radiation. Failure modes can manifest as reversible drifts in transient and steady-state responses, such as delay time, rise time, attenuation, signal-to-noise ratio, and crosstalk. Electrical failures common in electonic hardware include overstress mechanisms due to electrical overstress (EOS) and electrostatic discharge (ESD), such as dielectric breakdown, junction breakdown, hot electron injection, surface and bulk trapping, and surface breakdown, and wearout mechanisms such as electromigration and stress-driven diffusive voiding.

Thermal performance failures can arise due to incorrect design of thermal paths in an electronic assembly. This includes incorrect conductivity and surface emissivity of individual components, as well as incorrect convective and conductive paths for heat transfer. Thermal overstress failures are a result of heating a component beyond critical temperatures such as the glass-transition temperature, melting point, fictile point, or flash point. Some examples of thermal wearout failures are aging due to depolymerization, intermetallic growth, and interdiffusion. Failures due to inadequate thermal design may be manifested as components running too hot or too cold and causing operational parameters to drift beyond specifications, although the degradation is often reversible upon cooling. Such failures can be caused either by direct thermal loads or by electrical resistive loads, which in turn generate excessive localized thermal stresses. Adequate design checks require proper analysis for thermal stress, and should include conductive, convective, and radiative heat paths.

Mechanical performance failures include those that may compromise the product performance without necessarily causing any irreversible material damage, such as abnormal elastic deformation in response

to mechanical static loads, abnormal transient response (such as natural frequency or damping) to dynamic loads, and abnormal time-dependent reversible (anelastic) response, as well as failures that cause material damage, such as buckling, brittle and/or ductile fracture, interfacial separation, fatigue crack initiation and propagation, creep, and creep rupture. To take one example, excessive elastic deformations in slender structures in electronic packages can sometimes constitute functional failure due to overstress loads such as excessive flexing of interconnection wires, package lids, or flex circuits in electronic devices, causing shorting and/or excessive crosstalk. However, when the load is removed, the deformations (and consequent functional abnormalities) disappear completely without any permanent damage.

Radiation failures are principally caused by uranium and thorium contaminants, and secondary cosmic rays. Radiation can cause wearout, aging, embrittlement of materials, and overstress soft errors in electronic hardware, such as logic chips. Chemical failures occur in adverse chemical environments that result in corrosion, oxidation, or ionic surface dendritic growth. There may also be interactions between different types of stresses. For example, metal migration may be accelerated in the presence of chemical contaminants and composition gradients, and thermal loads can accelerate a failure mechanism due to a thermal expansion mismatch.

Failure modes and effects analysis (FMEA) is an evaluation process for analyzing and assessing the potential failures in a product. Its objectives are to:

1. Identify the causes and effects of each failure mode in every part in the product;
2. Ascertain the effects of each failure mode on product operation and personnel safety;
3. Assess each potential failure according to the effects on other portions of the systems; and
4. Provide a recommendation to eliminate the causes of the failure modes or compensate for their effects.

Failure effects may be considered at subsystem and at overall system levels.

There are two approaches to FMEA: functional and hardware. The functional approach, which should be used when the product definition has been identified, begins with the initial product indenture level, and proceeds downwards through lower levels. The top level shows the gross operational requirements of the product, while the lower levels represent progressive expansions of the individual functions of the preceding level. This documentation is prepared down to the level necessary to establish the hardware, software, facilities, and personnel and data requirements of the system.

The hardware approach to FMEA should be used when the design team has access to schematics, drawings, and other engineering and design data normally available once the system has matured beyond the functional design stage. This approach begins with obtaining all the information available on the design, including specifications, requirements, constraints, intended applications, drawings, stress data, test results, and so on, to the extent they are available at that time. The approach then proceeds in a part level-up fashion.

Once the approach for the analysis is selected, the product is defined in terms of a functional block diagram and a reliability block diagram. If the product operates in more than one mode in which different functional relationships or part operating modes exist, then these must be considered in the design. FMEA should involve an analysis of possible sneak circuits in the product, that is, an unexpected path or logic flow that can initiate an undesired function or inhibit a desired function. Effects of redundancy must also be considered by evaluating the effects of the failure modes assuming that the redundant system or subsystem is or is not available. The FMEA is then performed using a worksheet, and working to the part or subsystem level considered appropriate, keeping the design data available in mind. A fish-bone diagram of the product, showing all the possible ways in which the product can be expected to fail, is often used in the process. The analysis should take all the failure modes of every part into account, especially when the effects of a failure are serious (e.g., high warranty costs, reliability reputation, safety). FMEA should be started as soon as initial design information is available, and should be performed iteratively as the design evolves, so that the analysis can be used to improve the design and to provide documentation of the eventually completed design.

## 22.7 Design Guidelines and Techniques

Generally, products are replaced with other products, and the replaced product can be used as a baseline for comparisons with products to be introduced. Lessons learned from the baseline comparison product can be used to establish new product parameters, to identify areas of focus in new product designs, and to avoid the mistakes of the past.

Once the parts, materials, processes, and stress conditions are identified, the objective is to design a product using parts and materials that have been sufficiently characterized in terms of how they perform over time when subjected to the manufacturing and application profile conditions. Only through a methodical design approach using physics-of-failure and root-cause analysis can a reliable and cost-effective product be designed. A physics-of-failure-based reliability assessment tool must exhibit a diverse array of capabilities:

1. It should be able to predict the reliability of components under a wide range of environmental conditions;
2. It should be able to predict the time-to-failure for fundamental failure mechanisms; and
3. It should consider the effect of different manufacturing processes on reliability.

All of these can be accomplished by the use of tools such as virtual qualification and accelerated testing. Design guidelines that are based on physics-of-failure models can also be used to develop tests, screens, and derating factors. Tests based on physics-of-failure models can be designed to measure specific quantities, to detect the presence of unexpected flaws, and to detect manufacturing or maintenance problems. Screens can be designed to precipitate failures in the weak population while not cutting into the design life of the normal population. Derating or safety factors can be determined to lower the stresses for the dominant failure mechanisms.

In using design guidelines, there may not be a unique path to follow. Instead, there is a general flow in the design process. Multiple branches may exist, depending on the input design constraints. The design team should explore an adequate number of these branches to gain confidence that the final design is the best for the prescribed input information. The design team should also assess the use of guidelines for the complete design, and not those limited to specific aspects of an existing design. This does not imply that guidelines cannot be used to address only a specific aspect of an existing design, but the design team may have to trace through the implications that a given guideline suggests.

### 22.7.1 Protective Architectures

In designs where safety is an issue, it is generally desirable to design in some means for preventing a part, structure, or interconnection from failing, or from causing further damage when it fails. Fuses and circuit breakers are examples of elements used in electronic products to sense excessive current drain and to disconnect power from the concerned part. Fuses within circuits safeguard parts against voltage transients or excessive power dissipation, and protect power supplies from shorted parts. As another example, thermostats can be used to sense critical temperature limiting conditions, and to shut down the product or a part of the system until the temperature returns to normal. In some products, self-checking circuitry can also be incorporated to sense abnormal conditions and make adjustments to restore normal conditions, or to activate switching means to compensate for the malfunction.[6]

In some instances, it may be desirable to permit partial operation of the product after a part failure in preference to total product failure. By the same reasoning, degraded performance of a product after failure of a part is often preferable to complete stoppage. An example is the shutting down of a failed circuit whose function is to provide precise trimming adjustment within a deadband* of another control

*When the input in a control system changes direction, an initial change in the input has no effect on the output. This amount of side-to-side play in the system for which there is no change in the output is referred to as the deadband. The deadband is centered about the output.

product; acceptable performance may thus be achieved, perhaps under emergency conditions, with the deadband control product alone.[6]

Sometimes, the physical removal of a part from a product can harm or cause failure in another part by removing either load, drive, bias, or control. In such cases, the first part should be equipped with some form of interlock mechanism to shut down or otherwise protect the second part. The ultimate design, in addition to its ability to act after a failure, should be capable of sensing and adjusting for parametric drifts to avert failures.

In the use of protective techniques, the basic procedure is to take some form of action, after an initial failure or malfunction, to prevent additional or secondary failures. By reducing the number of failures, techniques such as enhancing product reliability can be considered, although they also affect availability and product effectiveness. Equally important considerations are the impacts of maintenance, repair, and part replacement. For example, if a fuse protecting a circuit is replaced, the following questions need to be answered: What is the impact when the product is re-energized? What protective architectures are appropriate for postrepair operations? What maintenance guidance must be documented and followed when fail-safe protective architectures have or have not been included?

### 22.7.2 Stress Margins

A properly designed product should be capable of operating satisfactorily with parts that drift or change with variables such as time, temperature, humidity, pressure, altitude, etc. as long as the interconnects and the other parameters of the parts are within their rated tolerances. To guard against out-of-tolerance failures, the design team must consider the combined effects of tolerances on parts to be used in manufacture, of subsequent changes due to the range of expected environmental conditions, of drifts due to aging over the period of time specified in the reliability requirement, and of tolerances in parts used in future repair or maintenance functions. Parts and structures should be designed to operate satisfactorily at the extremes of the parameter ranges, and allowable ranges must be included in the procurement or reprocurement specifications.

Statistical analysis and worst-case analysis are methods of dealing with part and structural parameter variations. In statistical analysis, a functional relationship is established between the output characteristics of the structure and the parameters of one or more of its parts. In worst-case analysis, the effect that a part has on product output is evaluated on the basis of end-of-life performance values or out-of-specification replacement parts.

### 22.7.3 Derating

Derating is a technique by which either the operational stresses acting on a device or structure are reduced relative to the rated strength, or the strength is increased relative to the allocated operating stress levels. Reducing the stress is achieved by specifying upper limits on the operating loads below the rated capacity of the hardware. For example, manufacturers of electronic hardware often specify limits for supply voltage, output current, power dissipation, junction temperature, and frequency. The equipment design team may decide to select an alternative component or make a design change that ensures that the operational condition for a particular parameter, such as temperature, is always below the rated level. The component is then said to have been derated for thermal stress.

The derating factor, typically defined as the ratio of the rated level of a given stress parameter to its actual operating level, is actually a margin of safety or margin of ignorance, determined by the criticality of any possible failures and by the amount of uncertainty inherent in the reliability model and its inputs. Ideally, this margin should be kept to a minimum to maintain the cost-effectiveness of the design. This puts the responsibility on the reliability engineer to identify the rated strength, the relevant operating stresses, and the reliability as unambiguously as possible.

To be effective, derating criteria must target the right stress parameter to address modeling of the relevant failure mechanisms. Field measurements may also be necessary, in conjunction with modeling

simulations, to identify the actual operating stresses at the failure site. Once the failure models have been quantified, the impact of derating on the effective reliability of the component for a given load can be determined. Quantitative correlations between derating and reliability enable design teams and users to effectively tailor the margin of safety to the level of criticality of the component, leading to better and more cost-effective use of the functional capacity of the component.

### 22.7.4 Redundancy

Redundancy permits a product to operate even though certain parts and interconnections have failed, thus increasing its reliability and availability. Redundant configurations can be classified as either active or standby. Elements in active redundancy operate simultaneously in performing the same function. Elements in standby redundancy are designed so that an inactive one will, or can, be switched into service when an active element fails. The reliability of the associated function increases with the number of standby elements (optimistically assuming that the sensing and switching devices of the redundant configuration are working perfectly, and that the failed redundant components are replaced before their companion components fail).

A design team may often find that redundancy is

- The quickest way to improve product reliability if there is insufficient time to explore alternatives, or if the part is already designed;
- The cheapest solution, if the cost of redundancy is economical in comparison with the cost of redesign; and/or
- The only solution, if the reliability requirement is beyond the state of the art.

On the other hand, in weighing its disadvantages, the design team may find that redundancy will:

- Prove too expensive, if the parts, redundant sensors, and switching devices are costly;
- Exceed the limitations on size and weight;
- Exceed the power limitations, particularly in active redundancy;
- Attenuate the input signal, requiring additional amplifiers (which increase complexity); and/or
- Require sensing and switching circuitry so complex as to offset the reliability advantage of redundancy.

## 22.8 Qualification and Accelerated Testing

Qualification includes all activities that ensure that the nominal design and manufacturing specifications will meet or exceed the desired reliability targets. Qualification validates the ability of the nominal design and manufacturing specifications of the product to meet the customer's expectations, and assesses the probability of survival of the product over its complete life cycle. The purpose of qualification is to define the acceptable range of variabilities for all critical product parameters affected by design and manufacturing, such as geometric dimensions, material properties, and operating environmental limits. Product attributes that are outside the acceptable ranges are termed defects, since they have the potential to compromise product reliability.[25]

Qualification tests should be performed only during initial product development, and immediately after any design or manufacturing changes in an existing product. Once the product is qualified, routine lot-to-lot requalification is redundant and an unnecessary cost item. A well-designed qualification procedure provides economic savings and quick turnaround during development of new products or mature products subject to manufacturing and process changes.

Investigating failure mechanisms and assessing the reliability of products where longevity is required may be a challenge, since a very long test period under the actual operating conditions is necessary to obtain sufficient data to determine actual failure characteristics. One approach to the problem of obtaining meaningful qualification data for high-reliability devices in shorter time periods is using methods such as virtual qualification and accelerated testing to achieve test-time compression. However, when

qualifying the reliability of a product for overstress mechanisms, a single cycle of the expected overstress load may be adequate, and acceleration of test parameters may not be necessary. This is sometimes called proof-stress testing.

### 22.8.1 Virtual Qualification

Virtual qualification is a process that requires significantly less time and money than accelerated testing to qualify a part for its life cycle environment. This simulation-based methodology is used to identify and rank the dominant failure mechanisms associated with the part under life cycle loads, to determine the acceleration factor for a given set of accelerated test parameters, and to determine the time-to-failure corresponding to the identified failure mechanisms. Each failure model comprises a stress analysis model and a damage assessment model. The output is a ranking of different failure mechanisms, based on the time-to-failure. The stress model captures the product architecture, while the damage model depends on a material's response to the applied stress. This process is therefore applicable to existing as well as new products. The objective of virtual qualification is to optimize the product design in such a way that the minimum time-to-failure of any part of the product is greater than its desired life. Although the data obtained from virtual qualification cannot fully replace those obtained from physical tests, it can increase the efficiency of physical tests by indicating the potential failure modes and mechanisms that the operator can expect to encounter.

Ideally, a virtual qualification process will involve identification of quality suppliers, computer-aided physics-of-failure qualification, and a risk assessment and mitigation program. The process allows qualification to be readily incorporated into the design phase of product development, since it allows design, test, and redesign to be conducted promptly and cost-effectively. It also allows consumers to qualify off-the-shelf components for use in specific environments without extensive physical tests. Since virtual qualification reduces emphasis on examining a physical sample, it is imperative that the manufacturing technology and quality assurance capability of the manufacturer be taken into account. The manufacturer's design, production, test, and measurement procedures must be evaluated and certified. If the data on which the virtual qualification is performed are inaccurate or unreliable, all results are suspect. In addition, if a reduced quantity of physical tests is performed in the interest of simply verifying virtual results, the operator needs to be confident that the group of parts selected is sufficient to represent the product. Further, it should be remembered that the accuracy of the results using virtual qualification depends on the accuracy of the inputs to the process, i.e., the accuracy of the life cycle loads, the choice of the failure models used, the choice of the analysis domain (for example, 2D, pseudo-3D, full 3D), the constants in the failure model, the material properties, and so on. Hence, to obtain a reliable prediction, the variabilities in the inputs should be specified using distribution functions, and the validity of the failure models should be tested by conducting accelerated tests.

### 22.8.2 Accelerated Testing

Accelerated testing involves measuring the performance of the test product at loads or stresses that are more severe than would normally be encountered, to enhance the damage accumulation rate within a reduced time period. The goal of such testing is to accelerate time-dependent failure mechanisms and the damage accumulation rate to reduce the time to failure. The failure mechanisms and modes in the accelerated environment must be the same as (or quantitatively correlated with) those observed under actual usage conditions, and it must be possible to quantitatively extrapolate from the accelerated environment to the usage environment with some reasonable degree of assurance.

Accelerated testing begins by identifying all the possible overstress and wearout failure mechanisms. The load parameter that directly causes the time-dependent failure is selected as the acceleration parameter, and is commonly called the accelerated load. Common accelerated loads include thermal loads, such as temperature, temperature cycling, and rates of temperature change; chemical loads, such as humidity, corrosives, acid, and salt; electrical loads, such as voltage, or power; and mechanical loads, such as vibration, mechanical load cycles, strain cycles, and shock/impulses. The accelerated environment may

include a combination of these loads. Interpretation of results for combined loads requires a quantitative understanding of their relative interactions and the contribution of each load to the overall damage.

Failure due to a particular mechanism can be induced by several acceleration parameters. For example, corrosion can be accelerated by both temperature and humidity; and creep can be accelerated by both mechanical stress and temperature. Furthermore, a single accelerated stress can induce failure by several wearout mechanisms simultaneously. For example, temperature can accelerate wearout damage accumulation not only by electromigration, but also by corrosion, creep, and so on. Failure mechanisms that dominate under usual operating conditions may lose their dominance as the stress is elevated. Conversely, failure mechanisms that are dormant under normal use conditions may contribute to device failure under accelerated conditions. Thus, accelerated tests require careful planning if they are to represent the actual usage environments and operating conditions without introducing extraneous failure mechanisms or nonrepresentative physical or material behavior. The degree of stress acceleration is usually controlled by an acceleration factor, defined as the ratio of the life of the product under normal use conditions to that under the accelerated condition. The acceleration factor should be tailored to the hardware in question, and can be estimated from an acceleration transform (that is, a functional relationship between the accelerated stress and the life cycle stress), in terms of all the hardware parameters.

Once the failure mechanisms are identified, it is necessary to select the appropriate acceleration load; to determine the test procedures and the stress levels; to determine the test method, such as constant stress acceleration or step-stress acceleration; to perform the tests; and to interpret the test data, which includes extrapolating the accelerated test results to normal operating conditions. The test results provide failure information for improving the hardware through design and/or process changes. Accelerated testing includes:

- Accelerated test planning and development: Accelerated test planning and development is used to develop a test program that focuses on the potential failure mechanisms and modes that were identified during virtual qualification as the weak links under life cycle loads. The various issues addressed in this phase include designing the test matrix and test loads, analysis, design and preparation of the test device, setting up the test facilities (e.g., test platforms, stress monitoring schemes, failure monitoring and data acquisition schemes), fixture design, effective sensor placement, and data collection and post-processing schemes.
- Test device characterization: Test device characterization is used to identify the contribution of the environment on the test device in the accelerated life tests.
- Accelerated life testing: Accelerated life testing evaluates the vulnerability of the product to the applied life cycle due to wearout failure mechanisms. This step yields a meaningful assessment of life cycle durability only if it is preceded by the steps discussed above. Without these steps, accelerated life testing can only provide comparisons between alternate designs if the same failure mechanism is precipitated.
- Life assessment: Life assessment is used to provide a scientific and rational method to understand and extrapolate accelerated life testing failure data to estimate the life of the product in the field environment.

Detailed failure analysis of failed samples is a crucial step in the qualification and validation program. Without such analyses and feedback to the design team for corrective action, the purpose of the qualification program is defeated. In other words, it is not adequate to simply collect failure data. The key is to use the test results to provide insights into, and consequent control over, relevant failure mechanisms and to prevent them, cost-effectively.

## 22.9 Manufacturing Issues

Manufacturing and assembly processes can significantly impact the quality and reliability of hardware. Improper assembly and manufacturing techniques can introduce defects, flaws, and residual stresses that act as potential failure sites or stress raisers later in the life of the product. If these defects and stresses

can be identified, the design analyst can proactively account for them during the design and development phase.

Auditing the merits of the manufacturing process involves two crucial steps. First, qualification procedures are required, as in design qualification, to ensure that manufacturing specifications do not compromise the long-term reliability of the hardware. Second, lot-to-lot screening is required to ensure that the variabilities of all manufacturing-related parameters are within specified tolerances.[25,26] In other words, screening ensures the quality of the product by precipitating latent defects before they reach the field.

### 22.9.1 Process Qualification

Like design qualification, process qualification should be conducted at the prototype development phase. The intent at this step is to ensure that the nominal manufacturing specifications and tolerances produce acceptable reliability in the product. The process needs requalification when process parameters, materials, manufacturing specifications, or human factors change.

Process qualification tests can be the same set of accelerated wearout tests used in design qualification. As in design qualification, overstress tests may be used to qualify a product for anticipated field overstress loads. Overstress tests may also be exploited to ensure that manufacturing processes do not degrade the intrinsic material strength of hardware beyond a specified limit. However, such tests should supplement, not replace, the accelerated wearout test program, unless explicit physics-based correlations are available between overstress test results and wearout field-failure data.

### 22.9.2 Manufacturability

The control and rectification of manufacturing defects has typically been the concern of production and process-control engineers, but not of the design team. In the spirit and context of concurrent product development, however, hardware design teams must understand material limits, available processes, and manufacturing process capabilities to select materials and construct architectures that promote producibility and reduce the occurrence of defects, increasing yield and quality. Therefore, no specification is complete without a clear discussion of manufacturing defects and acceptability limits. The reliability engineer must have clear definitions of the threshold for acceptable quality, and of what constitutes nonconformance. Nonconformance that compromises hardware performance and reliability is considered a defect. Failure mechanism models provide a convenient vehicle for developing such criteria. It is important for the reliability analyst to understand which deviations from specifications can compromise performance or reliability, and which deviations are benign and can be accepted.

A defect is any outcome of a process (manufacturing or assembly) that impairs or has the potential to impair the functionality of the product at any time. The defect may arise during a single process or may be the result of a sequence of processes. The yield of a process is the fraction of products that are acceptable for use in a subsequent manufacturing sequence or product life cycle. The cumulative yield of the process is approximately determined by multiplying the individual yields of each of the individual process steps. The source of defects is not always apparent, because defects resulting from a process can go undetected until the product reaches some downstream point in the process sequence, especially if screening is not employed.

It is often possible to simplify the manufacturing and assembly processes to reduce the probability of workmanship defects. As processes become more sophisticated, however, process monitoring and control are necessary to ensure a defect-free product. The bounds that specify whether the process is within tolerance limits, often referred to as the process window, are defined in terms of the independent variables to be controlled within the process and the effects of the process on the product or the dependent product variables. The goal is to understand the effect of each process variable on each product parameter to formulate control limits for the process, that is, the points on the variable scale where the defect rate begins to possess a potential for causing failure. In defining the process window, the upper and lower

limits of each process variable beyond which it will produce defects must be determined. Manufacturing processes must be contained in the process window by defect testing, analysis of the causes of defects, and elimination of defects by process control, such as by closed-loop corrective action systems. The establishment of an effective feedback path to report process-related defect data is critical. Once this is done and the process window is determined, the process window itself becomes a feedback system for the process operator.

Several process parameters may interact to produce a different defect than would have resulted from an individual parameter acting independently. This complex case may require that the interaction of various process parameters be evaluated in a matrix of experiments. In some cases, a defect cannot be detected until late in the process sequence. Thus, a defect can cause rejection, rework, or failure of the product after considerable value has been added to it. These cost items due to defects can return on investments by adding to hidden factory costs. All critical processes require special attention for defect elimination by process control.

### 22.9.3 Process Verification Testing

Process verification testing is often called screening. Screening involves 100% auditing of all manufactured products to detect or precipitate defects. The aim of this step is to preempt potential quality problems before they reach the field. In principle, screening should not be required for a well-controlled process. When uncertainties are likely in process controls, however, screening is often used as a safety net.

Some products exhibit a multimodal probability density function for failures, with a secondary peak during the early period of their service life due to the use of faulty materials, poorly controlled manufacturing and assembly technologies, or mishandling. This type of early-life failure is often called infant mortality. Properly applied screening techniques can successfully detect or precipitate these failures, eliminating or reducing their occurrence in field use. Screening should only be considered for use during the early stages of production, if at all, and only when products are expected to exhibit infant mortality field failures. Screening will be ineffective and costly if there is only one main peak in the failure probability density function. Further, failures arising due to unanticipated events such as acts of God (lightning, earthquakes) may be impossible to screen cost-effectively.

Since screening is done on a 100% basis, it is important to develop screens that do not harm good components. The best screens, therefore, are nondestructive evaluation techniques, such as microscopic visual exams, X-rays, acoustic scans, nuclear magnetic resonance (NMR), electronic paramagnetic resonance (EPR), and so on. Stress screening involves the application of stresses, possibly above the rated operational limits. If stress screens are unavoidable, overstress tests are preferred to accelerated wearout tests, since the latter are more likely to consume some useful life of good components. If damage to good components is unavoidable during stress screening, then quantitative estimates of the screening damage, based on failure mechanism models must be developed to allow the design team to account for this loss of usable life. The appropriate stress levels for screening must be tailored to the specific hardware. As in qualification testing, quantitative models of failure mechanisms can aid in determining screen parameters.

A stress screen need not necessarily simulate the field environment, or even utilize the same failure mechanism as the one likely to be triggered by this defect in field conditions. Instead, a screen should exploit the most convenient and effective failure mechanism to stimulate the defects that can show up in the field as infant mortality. Obviously, this requires an awareness of the possible defects that may occur in the hardware and extensive familiarity with the associated failure mechanisms.

Unlike qualification testing, the effectiveness of screens is maximized when screens are conducted immediately after the operation believed to be responsible for introducing the defect. Qualification testing is preferably conducted on the finished product or as close to the final operation as possible; on the other hand, screening only at the final stage, when all operations have been completed, is less effective, since failure analysis, defect diagnostics, and troubleshooting are difficult and impair corrective actions. Further, if a defect is introduced early in the manufacturing process, subsequent value added through new materials and processes is wasted, which additionally burdens operating costs and reduces productivity.

Admittedly, there are also several disadvantages to such an approach. The cost of screening at every manufacturing station may be prohibitive, especially for small batch jobs. Further, components will experience repeated screening loads as they pass through several manufacturing steps, which increases the risk of accumulating wearout damage in good components due to screening stresses. To arrive at a screening matrix that addresses as many defects and failure mechanisms as feasible with each screen test, an optimum situation must be sought through analysis of cost-effectiveness, risk, and the criticality of the defects. All defects must be traced back to the root cause of the variability.

Any commitment to stress screening must include the necessary funding and staff to determine the root cause and appropriate corrective actions for all failed units. The type of stress screening chosen should be derived from the design, manufacturing, and quality teams. Although a stress screen may be necessary during the early stages of production, stress screening carries substantial penalties in capital, operating expense, and cycle time, and its benefits diminish as a product approaches maturity. If almost all of the products fail in a properly designed screen test, the design is probably incorrect. If many products fail, a revision of the manufacturing process is required. If the number of failures in a screen is small, the processes are likely to be within tolerances and the observed faults may be beyond the resources of the design and production process.

## 22.10 Summary

Reliability is not a matter of chance or good fortune; rather, it is a rational consequence of conscious, systematic, rigorous efforts at every stage of design, development, and manufacture. High product reliability can only be assured through robust product designs, capable processes that are known to be within tolerances, and qualified components and materials from vendors whose processes are also capable and within tolerances. Quantitative understanding and modeling of all relevant failure mechanisms provide a convenient vehicle for formulating effective design, process, and test specifications and tolerances.

The physics-of-failure approach is not only a tool to provide better and more effective designs, but it also helps develop cost-effective approaches for improving the entire approach to building electronic products. Proactive improvements can be implemented for defining more realistic performance requirements and environmental conditions, identifying and characterizing key material properties, developing new product architectures and technologies, developing more realistic and effective accelerated stress tests to audit reliability and quality, enhancing manufacturing-for-reliability through mechanistic process modeling and characterization to allow pro-active process optimization, increasing first-pass yields, and reducing hidden factory costs associated with inspection, rework, and scrap.

When utilized early in the concept stage of a product's development, reliability serves as an aid to determine feasibility and risk. In the design stage of product development, reliability analysis involves methods to enhance performance over time through the selection of materials, design of structures, choice of design tolerance, manufacturing processes and tolerances, assembly techniques, shipping and handling methods, and maintenance and maintainability guidelines. Engineering concepts such as strength, fatigue, fracture, creep, tolerances, corrosion, and aging play a role in these design analyses. The use of physics-of-failure concepts coupled with mechanistic and probabilistic techniques are often required to understand the potential problems and trade-offs, and to take corrective actions. The use of factors of safety and worst-case studies as part of the analysis is useful in determining stress screening and burn-in procedures, reliability growth, maintenance modifications, field testing procedures, and various logistics requirements.

### Defining Terms

**Accelerated testing:** Tests conducted at stress levels that are more severe than the normal operating levels, in order to enhance the damage accumulation rate within a reduced time period.

**Damage:** The extent of a product's degradation or deviation from a defect-free state.

**Derating:** Practice of subjecting parts to lower electrical or mechanical stresses than they can withstand to increase the life expectancy of the part.

**Failure mechanism:** A process (such as creep, fatigue, or wear) through which a defect nucleates and grows as a function of stresses (such as thermal, mechanical, electromagnetic, or chemical loadings) ultimately resulting in the degradation or failure of a product.

**Failure mode:** Any physically observable change caused by a failure mechanism.

**Integrity:** A measure of the appropriateness of the tests conducted by the manufacturer and the part's ability to survive those tests.

**Overstress failures:** Catastrophic sudden failures due to a single occurrence of a stress event that exceeds the intrinsic strength of a material.

**Product performance:** The ability of a product to perform as required according to specifications.

**Qualification:** All activities that ensure that the nominal design and manufacturing specifications will meet or exceed the reliability goals.

**Quality:** A measure of a part's ability to meet the workmanship criteria of the manufacturer.

**Reliability:** The ability of a product to perform as intended (i.e., without failure and within specified performance limits) for a specified time, in its life cycle application environment.

**Wearout failures:** Failures due to accumulation of incremental damage, occurring when the accumulated damage exceeds the material endurance limit.

## References


1. Pecht, M., *Integrated Circuit, Hybrid, and Multichip Module Package Design Guidelines—A Focus on Reliability*, John Wiley & Sons, New York, 1994.
2. O'Connor, P., *Practical Reliability Engineering,* John Wiley & Sons, New York, 1991.
3. Jackson, M., Mathur, A., Pecht, M., and Kendall, R., Part Manufacturer Assessment Process, *Qual. Reliab. Eng. Int.,* 15, 457, 1999.
4. Jackson, M., Sandborn, P., Pecht, M., Hemens-Davis, C., and Audette, P., A Risk-Informed Methodology for Parts Selection and Management, *Qual. and Reliab. Eng. Int.,* 15, 261, 1999.
5. Lewis, E.E., *Introduction to Reliability Engineering*, John Wiley & Sons, New York, 1996.
6. Sage, A.P. and Rouse, W.B., *Handbook of Systems Engineering and Management,* John Wiley & Sons, New York, 1999.
7. IEC Standard 60134, Rating systems for electronic tubes and valves and analogous semiconductor devices, (Last reviewed in July 1994 by the IEC Technical Committee 39 on Semiconductors), 1961.
8. Stogdill, R. C., Dealing with obsolete parts. *IEEE Des. Test Comput.,* 16(2), 17, 1999.
9. Dasgupta, A. and Pecht, M., Failure mechanisms and damage models, *IEEE Trans. Reliab.,* 40(5), 531, 1991.
10. Dasgupta, A. and Hu, J.M., Failure mechanism models for brittle fracture, *IEEE Trans. Reliab.,* 41(3), 328, 1992.
11. Dasgupta, A. and Hu, J.M., Failure mechanism models for ductile fracture, *IEEE Trans. Reliab.,* 41(4), 489, 1992.
12. Dasgupta, A. and Hu, J.M., Failure mechanism models for excessive elastic deformation, *IEEE Trans. Reliab.,* 41(1), 149, 1992.
13. Dasgupta, A. and Hu, J.M., Failure mechanism models for plastic deformation, *IEEE Trans. Reliab.,* 41(2), 168, 1992.
14. Dasgupta, A. and Haslach, H.W., Jr., Mechanical design failure models for buckling, *IEEE Trans. Reliab.,* 42(1), 9, 1993.
15. Engel, P.A., Failure models for mechanical wear modes and mechanisms, *IEEE Trans. Reliab.,* 42(2), 262, 1993.
16. Li, J. and Dasgupta, A., Failure mechanism models for material aging due to interdiffusion, *IEEE Trans. Reliab.,* 43(1), 2, 1994.

17. Li, J. and Dasgupta, A., Failure-mechanism models for creep and creep rupture, *IEEE Trans. Reliab.,* 42(3), 339, 1994.
18. Dasgupta, A., Failure mechanism models for cyclic fatigue, *IEEE Trans. Reliab.,* 42(4), 548, 1993.
19. Young, D. and Christou, A., Failure mechanism models for electromigration, *IEEE Trans. Reliab.,* 43(2), 186, 1994.
20. Rudra, B. and Jennings, D., Failure mechanism models for conductive-filament formation, *IEEE Trans. Reliab.,* 43(3), 354, 1994.
21. Al-Sheikhly, M. and Christou, A., How radiation affects polymeric materials, *IEEE Trans. Reliab.,* 43(4), 551, 1994.
22. Diaz, C., Kang, S.M., and Duvvury, C., Electrical overstress and electrostatic discharge, *IEEE Trans. Reliab.,* 44(1), 2, 1995.
23. Tullmin, M. and Roberge, P.R., Corrosion of metallic materials, *IEEE Trans. Reliab.,* 44(2), 271, 1995.
24. Upadhyayula, K. and Dasgupta, A., Guidelines for physics-of-failure based accelerated stress testing, Annu. Reliab. Maintainability Symp. 1998 Proc., Int. Symp. Prod. Qual. Integrity, 345, 1998.
25. Pecht, M., Dasgupta, A., Evans, J. W., and Evans, J. Y., *Quality Conformance and Qualification of Microelectronic Packages and Interconnects*, John Wiley & Sons, New York, 1994.
26. Kraus, A., Hannemann, R., Pecht, M., *Semiconductor Packaging: A Multidisciplinary Approach,* John Wiley & Sons, New York, 1994.

## Further Information

Microelectronics Reliability: http://www.elsevier.com/locate/microrel
IEEE Transactions on Reliability: http://www.ewh.ieee.org/soc/rs/transactions.htm