Reliability Analysis Center

Blueprints for Product Reliability

Defining Reliability Programs

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RAC is a DoD Information Analysis Center sponsored by the Defense Technical Information Center dedicated to the reliability improvement of military and commercial products and systems

About the RAC Blueprints

The RAC "Blueprints for Product Reliability" are a series of documents published by the Reliability Analysis Center (RAC) to provide insight into, and guidance in applying, sound reliability practices. The RAC is the Information Analysis Center chartered to be a centralized source of data, information and expertise in the subjects of reliability, maintainability and quality. While sponsored by the US Department of Defense (DoD), RAC's charter addresses both military and commercial communities with the requirement to disseminate guidance information in these subjects. The Blueprints serve to provide information on those approaches to planning and implementing effective reliability programs based on experience, lessons learned, and state-of-the-art techniques. To make the Blueprints as useful as possible, the approaches and procedures are based on the best practices used by commercial industry and on the concepts documented in many of the now-rescinded military standards. The tree shown in Figure 1 depicts the Blueprints that make up the series (the section numbers below each second tier document indicate the corresponding sections of this Blueprint).

In the government sector, and in particular the DoD, significant changes have been made regarding the acquisition of new products. Previously, by imposing standards and specifications, a DoD customer would require contractors to use certain analytical tools and methods, perform specific tests in a prescribed manner, use components from an approved list, and so forth. Current policy emphasizes the use of commercial technology as well as specifying "performance-based" requirements only, with suppliers left to determine how to best achieve them.

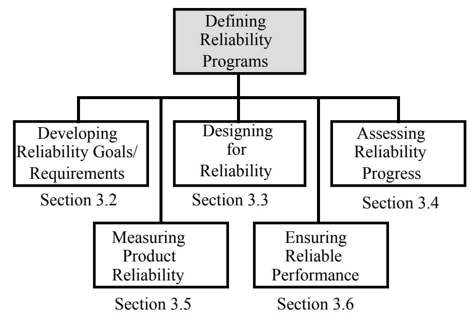

Figure 1. RAC Blueprints for Product Reliability

Users of the RAC Blueprints

The Blueprints are designed for use in both the government and private sectors. They address products ranging from completely new commercial consumer products to highly specialized military systems. The documents are written in a style that is easy to understand and implement whether the reader is a manager, design engineer or reliability specialist. In keeping with the new philosophy of the DoD, which is now similar to that of the private sector, the Blueprints do not provide a cookbook of reliability tasks that should be applied in every situation. Instead, some general principles are cited as the underpinnings of a sound reliability program. Then, many of the tasks and activities that support each principle are highlighted in detail sufficient for the user to determine if a task or activity is appropriate to his or her situation.

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SECTION ONE - INTRODUCTION

The purpose of this Blueprint, *Defining Reliability Programs*, is to provide guidance in identifying appropriate activities to be used to develop and ensure reliable products and systems. It is specifically intended to help a product manager tailor activities such that they become cost effective and timely parts of his program. The tailored set of chosen tasks and their timing, whether they are few or many, constitutes the reliability program for that product or system. In order to optimize the practical use of this Blueprint, the sections are presented in the logical order with which the manager faces various reliability issues. In this format *the content is grouped by purpose rather than by type of task*. For example, several purposes are served by the various types of testing. Therefore, it is appropriate to discuss testing in several sections rather than in one section exclusively on testing. Reliability topics are discussed in the context of their:

- *Purposes* (what)
- *Benefits* (why)
- *Timing* (when)
- *Application guidelines* (how)

SECTION TWO - BASIC RELIABILITY CONCEPTS

This section discusses the concept of reliability and its importance as a product characteristic.

2.1 <u>The Definition of Reliability</u>

Succinctly put, *reliability* is a performance attribute that is concerned with the probability of success and frequency of failures and is defined as:

The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.

2.2 <u>The Importance of Reliability</u>

Reliability is a measure of a product's performance that affects both product function and operating and repair costs. Too often performance is thought of only in terms of speed, capacity, range, and other "normal" measures. However, if a product fails so often that it's seldom available for use, its speed, range, and capacity are not relevant. Reliability is critical to safety and liability as well.

> ***Insight***
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> *Reliability is usually measured in terms of time between failures for repairable products, time to failure for non-repairable products, and probability of success for one-shot devices.*

The reliability of a product is a primary factor in determining operating and repair costs, which are partially a function of the number of repairs needed over time, the number of spare parts required, and the number of maintenance personnel necessary. Other factors such as the repair policy (or maintenance concept) affect these costs, but reliability is a significant, and often the principal, factor.

Reliability determines whether or not a product is *available* to perform its function. A product with perfect reliability (i.e., no failures during the life of the product) would always be available for use. But perfect reliability is difficult to achieve. So, even when a "good" level of reliability is achieved, some failures are to be expected. The effects of failures on availability (and cost) can be minimized with a "good" level of *maintainability* (a measure of how quickly the product can be repaired). Consequently, product reliability and maintainability (R&M) are said to be complementary

> ***Insight***
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> *Product status when operation is required includes the combined effects of product reliability and maintainability, but excludes operating time.*

characteristics, and can be combined to measure the percentage of time that the product is available for use. If the product never failed, the reliability would be infinite and the availability would be 100%. Or, the product never needed to be repaired, its maintainability would be zero and, again, availability would be 100%.

2.3 Key Reliability Issues

Notes for Parts Suppliers

The issues faced by part suppliers, who strive to maximize manufacturing yields, typically require more emphasis on materials and process controls. Reliability programs for part suppliers would require different tailoring than those for product suppliers.

For any product or system, the key reliability issues from any *customer's* perspective are:

- What *measures of reliability are important* to me?
- What *levels of reliability are necessary* to meet my needs?
- How will I *determine if the required levels of reliability have been achieved*?

From a *supplier's* perspective, the issues are:

- What *reliability activities are the most effective* for the product or system, such that the reliability program objective is achieved?
- What *reliability design goals are appropriate* to ensure that customers' needs are met?
- What *design approaches will be most effective* in achieving the required reliability in the expected environmental and usage profiles?
- What tasks can be effectively used to *assess progress towards reliability goals and requirements?*
- What are the most appropriate means to *determine if the reliability objective has been achieved*?
- How can the designed-in reliability be retained during manufacturing and operational use, thereby *ensuring reliable performance*?

In the commercial world, the average consumer is not usually concerned with the second set of issues - they are left to the supplier to confront. If a supplier does a poor job, the customer will go elsewhere for the product. Thus, competition in the marketplace provides a strong incentive to meet the customer's needs. In the defense world, the degree of competition is often less than in the commercial world. If dictated by the nature of the product (e.g., used only by the military), the risks (e.g., very high with unproven technologies being used), and the type of acquisition (e.g., new development), it may be beneficial for the government customer to take an active role in addressing the supplier's issues. Some industrial customers may also benefit from being involved with some of these issues, especially those dealing with measuring progress and determining the achieved level of reliability.

Insight

Managers and engineers must first focus on the primary objective of a reliability program. Only then should attention be given to selecting those value-added tasks that, for a given product and situation, best allow the objective to be achieved.

2.4 The Basics of a Reliability Program

The objective of any set of reliability tasks is to design and manufacture a reliable product in a cost effective manner. In order to effectively achieve that result:

- The *customer's reliability expectations and needs should be fully understood*.
- All levels of *supplier management should be actively committed* to meeting the reliability objective through an appropriate allocation of resources.

- The *attributes of design and manufacturing that impact reliability should be considered as an integral part of the system engineering process*.
- The *product should be designed for the intended use environment* and the consequences of failure understood.
- The *reliability of the design should be verified* to ensure that goals and requirements have been achieved.

Customer's Reliability Expectations and Needs Should be Fully Understood. Adequate levels of reliability are essential to the overall performance of the product. These levels may be expressed by the customer (in which case, they are part of the customer's specification) or determined by the supplier as necessary to compete satisfactorily and to minimize liability. In either case, it is the customer's needs that must be understood and satisfied.

Supplier Management Should be Actively Committed. The ability to successfully achieve the reliability objective is dependent on the demonstrated level of commitment by management, particularly at the upper levels. This commitment can be reinforced by making sure that this objective is an integral part of the corporate technological and business strategy. Demonstrated and emphatic management commitment will help reinforce any "culture change" that may be necessary to implement those actions necessary to achieve the program objective.

Reliability Attributes of Design and Manufacturing Should Be an Integral Part of the System Engineering Process. By making the reliability aspects of design and manufacturing an integral part of the system engineering process, reliability requirements will be addressed concurrently with other performance requirements. In this way, reliability activities will be integrated with other engineering and design tasks, thereby avoiding duplicative effort and making the best use of output information and results. In planning a reliability program, the integration of design, analysis, and other tasks to minimize costs and maximize the use of task results should be explicitly addressed.

Product Should be Designed for the Intended Use Environment. To be reliable, the product should be designed for the environment in which it will be used, and the design should be thoroughly understood. Characterizing the environment is a top priority. The use environment includes all the stresses experienced by a product during packaging, shipping, and handling; storage; operation; and repair/maintenance. It addresses the types of users and product duty cycles. Understanding the strengths and weaknesses of a design requires that critical failures be analyzed to determine their root cause and product-level effects, and to change the design to eliminate or minimize the effects of the failure modes.

Reliability of the Design Should be Verified. Verifying that the reliability objective has been met can be accomplished through testing or analysis. Through testing, the product's design (and the tools used to create that design) can be validated. Testing may uncover unexpected design weaknesses or unsatisfactory performance, and serves as a development tool that provides the feedback needed by engineers to refine their design and revise their analyses. Extensive testing may become prohibitive due to the nature of the product (very simple or based on prior, proven technology; or because it is too expensive). In such cases, analytical means can be used to determine if requirements have been met. Many times, both testing and analysis are used.

Insight

- *Customer needs can be determined through market surveys or quality function deployment (QFD)*
- *The reliability program objective should be an integral part of the business strategy, with strong and consistent organizational commitment*
- *An effective concurrent engineering process can result in lower cost, more highly competitive products that reach the market faster*
- *Robust products are insensitive to environmental effects. A thorough understanding of the intended environment helps to eliminate overdesign*
- *Use a cost effective balance between analysis and testing to measure design reliability, considering safety, liability and competitive market factors.*

> *Insight*
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> *Achieved reliability depends on inherent design, manufacturing processes, and operating conditions that dictate how a product is used, maintained and repaired. Attention to process control and continuous improvement through integrated process development efforts can minimize the degradation of inherent reliability.*

The objective of a sound reliability program should be similar to that for other design characteristics, since *reliability is an inherent design characteristic*. Attempts to improve the inherent reliability of a product after the design is "frozen" are usually expensive and inefficient. In addition, reliability depends on other factors, most notably how the product or system is actually used and repaired if failures occur. These factors can easily compromise the performance of a "good" design. For example, poorly trained repair personnel can cause product reliability to suffer due to induced failures. So, although suppliers may concentrate on achieving reliability through sound engineering, design, test, and manufacturing, it must be remembered that many "post" manufacturing activities should be planned early. These range from strategizing repair policies to establishing failure data tracking systems in order to capitalize on the inherent reliability characteristics of the product.

2.5 Reliability Oriented Tasks

The remaining sections of this Blueprint provide insight into the reliability tasks that may be appropriate for different product development situations. To set the stage for those discussions, the tasks that are common to the reliability discipline must be introduced. Table 1 (on page 6) includes those tasks that have become common practice over the years. They represent an extensive set of activities grouped by the *technical nature of the activity*. Because the Blueprint format is oriented towards the performance of tasks that *serve a reliability purpose*, the tasks in the table identified are *cross-referenced to the purposes they can address* in a reliability program. In the later sections that address each purpose, those referenced tasks will be discussed in greater detail. The intent is to *emphasize the purposes that the tasks serve*, rather than the task itself.

2.6 Product Program Phases

Each product, from the simplest to the most complex, passes through a sequence of phases during its life cycle. The definitions of the phases vary among commercial companies, and within the military. Table 2 describes the sequence of general phases that will be used in this document to describe a product's life.

Table 2: Product Life Cycle Phases

Concept/ Planning	Design/ Development	Production/ Manufacturing	Operation/ Repair	Wearout/ Disposal
• Formulate ideas, estimate resources and financial needs • Identify risks & requirements • Program objective	• Identify and allocate needs and requirements • Propose alternate approaches • Design and test the product • Develop manufacturing, operating, and repair/maintenance tasks	• Refine and implement manufacturing procedures • Finalize production equipment • Establish quality processes • Build & distribute the product	• Implement operating, installation and training procedures • Provide repair and maintenance service • Repair warranty items • Provide for performance feedback	• Implement refurbishment and disposal tasks • Resolve potential wearout issues

> *Insight*
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> *Emphasis should be placed on "finalizing" the inherent reliability of the product as early as possible during its life cycle. Poor timing typically results in expensive redesign or inefficient use of resources.*

What sometimes distinguishes one phase from the next is a decision milestone, sometimes referred to as a "gate." It represents a point in time where the program can go forward or stop. For many products, the phases may be abbreviated or combined. For example, the Concept/Planning and Design/Development phases may be combined under a compressed schedule for a new product that is simply an update or slightly modified version of an older, proven product. Reliability tasks for this type of program would concentrate only on the differences between the old and the modified product. As a result, the number of engineering tasks would be reduced. It is important to

Table 1: Reliability Tasks

Type of Activity	Tasks and Description	Relevant to Issues: Define Program 3.1	Determine Requmts. 3.2	Design Rel. 3.3	Assess Progress 3.4	Measure Rel. 3.5	Ensure Rel. 3.6
DESIGN	**<u>Critical Item Control</u>**. Monitoring in-house and suppliers' activities to reduce the risk to product reliability from items identified as critical. Can include hardware and software.	X			X		X
	<u>Critical Item Identification</u>. Cataloging items that have relatively high impact in determining product reliability. Can include hardware and software.			X			
	<u>Derating</u>. Limiting the maximum allowable stresses on a part to a designated value below its rated maximum stress in order to improve its reliability.			X			
	<u>Design Reviews</u>. Formal or informal independent evaluation and critique of a design to identify and correct hardware or software deficiencies.	X		X	X		
	<u>Environmental Characterization</u>. Determination of the operational stresses the product can be expected to experience.		X	X			X
	<u>Fault Tolerance</u>. Designing alternate means to continue operation when components of a product fail.		X	X			
	<u>Parts Application</u>. Using parts under design rules intended to assure that they will operate reliably under the expected operational stresses.			X			
	<u>Parts Selection</u>. Choosing parts that will be effective and reliable in the planned application and which should be available at reasonable cost during the product's life.			X			
	<u>Supplier Control</u>. Monitoring suppliers' activities to assure that purchased hardware and software will have adequate reliability.	X			X		X
	<u>Thermal Design</u>. Consideration of heat generation and dissipation in the product in order to prevent reliability problems caused by the effects of temperature.			X			
ANALYSIS	**<u>Allocations</u>**. Translation of product reliability goals into reliability goals for the components making up the product.		X	X			
	<u>Design of Experiments (DOE)</u>. Systematically determining the impact of process and environmental factors on a desired product parameter, in order to reduce product variability by controlling the factors.			X	X		X
	<u>Dormancy Analysis</u>. Determination of the effects of expected periods of storage or other non-operating conditions on the reliability of the product.		X	X	X		
	<u>Durability Assessment</u>. Determination of whether or not the mechanical strength of a product will remain adequate for its expected life.		X	X	X	X	
	<u>Failure Modes, Effects & Criticality Analysis (FMECA)</u>. Systematically determining the effects of part or software failures on the product's ability to perform its function. This task includes FMEA.			X	X	X	X
	<u>Failure Reporting Analysis & Corrective Action System (FRACAS)</u>. A closed-loop system of data collection, analysis and dissemination to identify and correct failures of a product or process.			X	X	X	X
	<u>Fault Tree Analysis (FTA)</u>. Using inductive logic to determine the possible causes of a defined undesired operational result.			X	X	X	
	<u>Finite Element Analysis (FEA)</u>. Determining the mechanical stresses present in products through simulation by decomposing the product into simple elements.			X	X		
	<u>Life Cycle Planning</u>. Determining reliability (and other) requirements by considering the impact over the expected useful life of the product.	X	X	X	X	X	X

Table 1: Reliability Tasks (Cont'd)

Type of Activity	Tasks and Description	Relevant to Issues: Define Program 3.1	Determine Requmts. 3.2	Design Rel. 3.3	Assess Progress 3.4	Measure Rel. 3.5	Ensure Rel. 3.6
ANALYSIS (CONT'D)	**Modeling & Simulation**. Creation of a representation, usually graphical or mathematical, for the expected reliability of a product, and validating the selected model through simulation.		X	X			
	Parts Obsolescence. Analysis of the likelihood that changes in technology will make the use of a currently available part undesirable.	X		X	X		X
	Predictions. Estimation of reliability from available design, analysis or test data, or data from similar products.		X	X	X	X	
	Repair Strategies. Determination of the most appropriate or cost effective procedures for restoring operation after a product fails.	X		X			X
	Sneak Circuit Analysis (SCA). Investigation to discover the existence of unintended signal paths in a product.			X	X	X	
	Thermal Analysis. Analysis of the heat dissipations, transfer paths and cooling sources to determine if part/product temperatures are consistent with reliability needs.		X		X		
	Translations. Determine product design goals (i.e., product reliability) from the user's operational requirements.		X				
	Worst Case Circuit Analysis (WCCA). Analysis of the effects of variability in the components of a product on the product's performance.			X	X	X	
TEST	**Accelerated Life Test**. Testing at high stress levels over compressed time periods to draw conclusions about the reliability of a product under expected operating conditions, based on formulated correlation factors.			X	X	X	
	Environmental Stress Screening (ESS). Operating a product under high stress to identify defects (by causing them to become failures) in order to eliminate them before a product is shipped to its user.						X
	Production Reliability Acceptance Test (PRAT). Testing a product during production to assure that its reliability has not degraded.					X	X
	Reliability Demonstration Test (RDT)/Reliability Qualification Test (RQT). Testing a product to demonstrate whether its reliability requirement has been achieved.					X	
	Reliability Growth Test (RGT)/Test Analyze and Fix (TAAF). Testing a product to identify reliability deficiencies in order to eliminate their causes.				X	X	
	Test Strategy. Determination of the most cost effective mix of tests for a product.	X		X	X	X	X
OTHER	**Benchmarking**. Comparison of a supplier's performance attributes to its competitors' and to the best performance achieved by any supplier in a comparable activity.	X	X				
	Statistical Process Control (SPC). Comparing the variability in a product against statistical expectations, to identify any need for adjustment of the production process.	X					X
	Quality Function Development (QFD). Capturing the desires of the customer and translating these to tasks needed in the product development program.	X	X				
	Market Survey. Determining the needs and wants of potential customers, their probable reaction to potential products, and their level of satisfaction with existing products	X	X				X
	Inspection. Comparing a product to its specifications, as a quality check.	X					X

understand that *tasks performed in one phase are often the result of the analysis, trade-offs and planning performed in an earlier phase*. For example, trade-offs addressing approaches to manufacturing printed circuit boards would be performed during Design/Development, with the implementation of the process decision to follow during the Production/Manufacturing phase.

SECTION THREE - RELIABILITY PROGRAM ISSUES

This Blueprint discusses reliability tasks in the framework of six issues to be addressed in building reliable products. It highlights those tasks that can be used effectively to resolve each of the relevant issues to meet the reliability program objective. The process of addressing these issues forms the basis of a tailored reliability program:

- Defining a reliability program (3.1)
- Developing reliability goals and requirements (3.2)
- Designing for reliability (3.3)
- Assessing reliability progress (3.4)
- Measuring product reliability (3.5)
- Ensuring reliable performance (3.6)

It is important that the supplier select only those tasks that are best suited to achieve the desired results given current market conditions; the competitive environment; the phase of product development; and associated technical and strategic risks. An effective reliability program will require the performance of one or more tasks that will add value as a means of satisfying the reliability objective. For example, a manufacturer of safety-critical medical equipment may consider that the primary objective of its reliability program (other than the obvious safety issues) is a high level of reliability such that the product has a discriminated market position against its competitors. For the "assess reliability progress" issue, a detailed reliability prediction (high reliability), coupled with a failure modes and effects analysis (safety-critical) and worst case circuit analysis (robust design) may be necessary to achieve the goal. A manufacturer of low-cost "throwaway" calculators may rely only on data from warranty returns from a previous version of the product to assess its reliability. It should also be remembered that a specific task can be used for different purposes. For example, a development test has an inherent purpose to create reliability growth (improve design reliability) but it can also be used to "prove" the level of achieved reliability (measure product reliability), if necessary.

Figure 2 provides a graphical representation of the relationships among the issues that need to be addressed to meet the reliability program objective, the tasks that can be performed to resolve each, and the basics of reliability success.

3.1 <u>**Defining a Reliability Program**</u>

3.1.1 **Purpose**. The reliability program exists to plan, define and implement those reliability tasks that are considered necessary by the supplier to meet the overall reliability objective for the product. The scope of the objective drives the number and type of tasks required, and the level of detail necessary in performing each task. Successful implementation of the reliability program ensures that product reliability issues are addressed as part of the overall engineering and manufacturing effort, and provides a high degree of confidence that the objective of the reliability program will be met. Table 3 provides an overview of the tasks that may be considered relevant in the definition of the reliability program.

Lessons Learned

Defining a reliability program early in the development of a product provides direction and focus for subsequent activities.

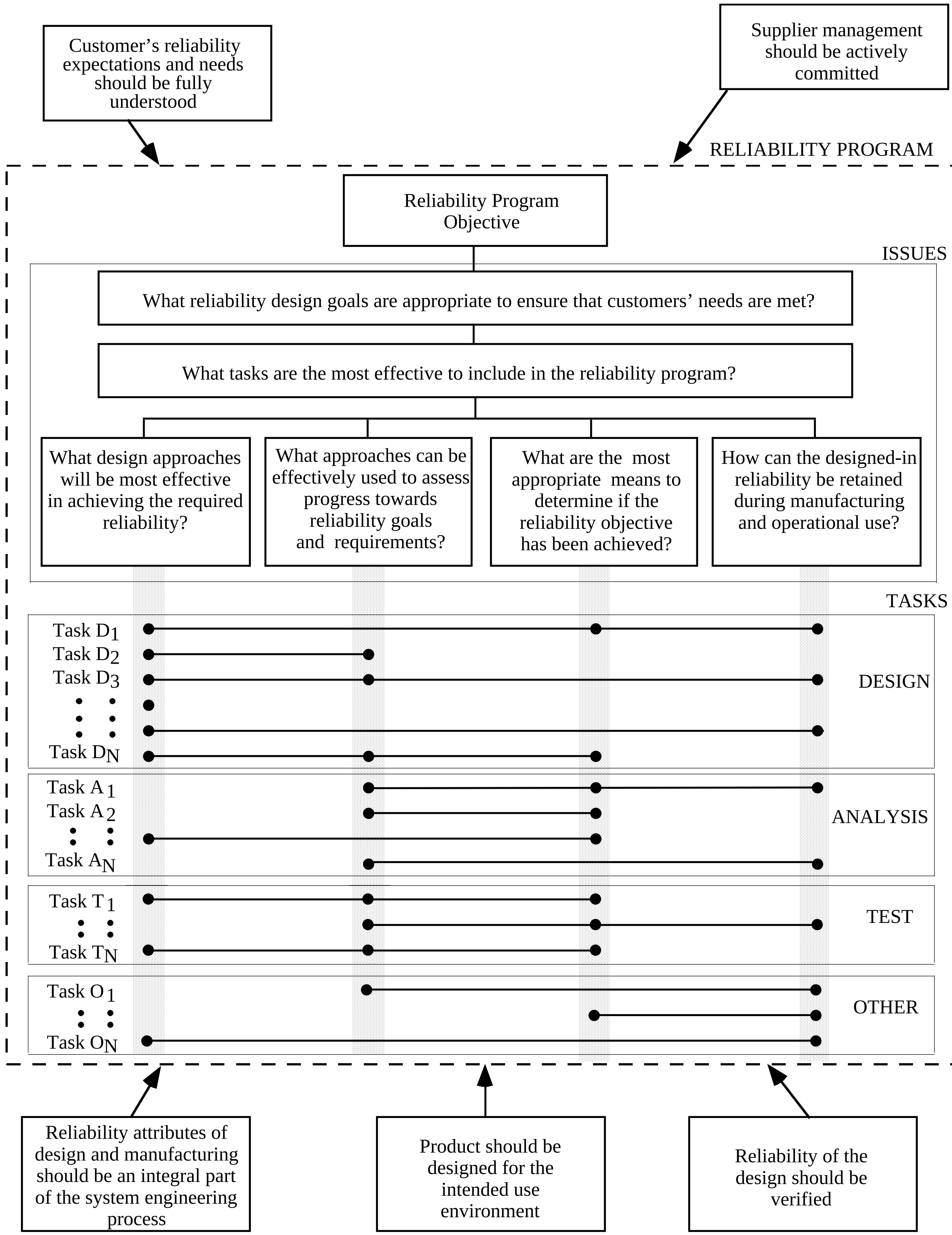

Figure 2: Reliability Program Concept

Table 3: Tasks Relevant to Include in Defining a Reliability Program

Tasks	Purpose
Benchmarking	Benchmark "world-class" competitors' or industry leaders' practices to adapt the best relevant features to the product being developed, including technical, manufacturing or administrative processes.
Critical Item Control	Establish appropriate definitions and limits for hardware and software critical item identification and control, based on reliability, cost, availability and/or safety criteria.
Design Reviews	Define the frequency and level of detail for hardware and software reviews to assess reliability progress. Tailor formality to product complexity and criticality.
Inspection	Define the plans and identify the processes for which inspection should be used. Inspection should be considered for processes that explicitly or implicitly affect the ability of the product to meet customer needs.
Life Cycle Planning	Define the methodology for establishing, assessing and ensuring that the product meets the customer's useful life (end-of-life) expectations.
Market Survey	Obtain an overview of customer needs and expectations regarding elements of product reliability performance. Customer needs and expectations may be solicited as either quantitative or qualitative inputs.
Parts Obsolescence	Establish the groundrules which delineate how parts obsolescence issues will be addressed (lifetime buys, substitute parts, new technology).
Quality Function Development (QFD)	Define how "customer needs" data will be obtained and analyzed to populate the QFD matrix, and the process by which engineering solutions to meet those needs will be identified.
Repair Strategy	Define repair strategies to identify who will repair/maintain the product (customer or supplier), the level of detail required in operating and repair procedures, skill levels required by those performing the repair and the level of spare parts supply needed to support the product.
Statistical Process Control (SPC)	Establish groundrules under which critical design, manufacturing or administrative processes will be identified, and how statistical process control will be used to identify and control variability in these processes.
Supplier Control	Establish the groundrules under which parts or software will be selected, purchased and applied. Define criteria for selection, qualification and control of vendors or subcontractors. Establish procedures for defining supplier-vendor relationships.
Test Strategy	Define test strategies to identify the appropriate tests which should be performed on both hardware and software, and the required test levels and durations, to efficiently meet the design, assessment and measurement goals established for the product, and to ensure that inherent reliable performance is retained during customer use.

Insight

Choosing tailored tasks suitable to the reliability program objective, and timing them to be effective, is more important than the degree of documentation in a formal plan. The key is that the appropriate tasks are chosen, communicated, and understood by all personnel within the organization.

Notes for Parts Suppliers

A reliability program should emphasize those tasks that can improve yield. Tasks may include materials supplier control and in-house statistical process control to approach near-zero defect manufacturing. A test strategy may emphasize design of experiments (DOE).

3.1.2 **Benefits**. By evaluating the nature of the product to be developed and the marketplace in which it is to be sold, and then defining an appropriately tailored reliability program, the supplier has the best chance of designing and manufacturing a reliable product that meets customers needs, and is delivered on-time and within budget. This should be the most basic objective of the reliability program. The ability to achieve this benefit occurs most often when the supplier is successful in integrating reliability tasks into a systems engineering process. The business factors which should be considered in tailoring these tasks, and the potential benefits derived, are included in Table 4.

Table 4: Business Factors Affecting Reliability Program Tailoring

Business Factor	Benefits
Market Conditions	The conditions of the marketplace (size, number of competitors, etc.) and the primary factors that influence the market (price/cost, level of competition, performance, customer needs) form the basis for formulating the business strategy. Understanding the marketplace allows a business strategy to be developed that incorporates the perceived and desired objectives of the supplier into a realistic and achievable plan. The scope of the reliability program should reflect the type of product being offered, and the conditions under which it will be sold, in order to meet both the reliability and business objectives.

Table 4: Business Factors Affecting Reliability Program Tailoring (Cont'd)

Business Factor	Benefits
Business Strategy	When the reliability program objective is compatible with and integrated into the supplier's core business strategy, there is generally corporate "buy-in" into making sure that all product objectives are met. The reliability program should be tailored to meet the composite business objective, which may be driven by cost, schedule, performance, or customer needs. Management and worker commitment to the strategy objectives will increase the likelihood that they will be met.
Life Cycle Cost	A properly tailored reliability program, integrated into the overall business strategy, should provide an optimum balance between the costs to plan and implement the tasks associated with the program, and the "cost of ownership" associated with product warranties, repairs, replacements, etc., during customer use of the product. Minimizing the total life cycle cost of the product is a major factor in improving the supplier's long-term market position.
Competitive Advantage	Suppliers compete on factors such as price, performance, reliability, quality, warranty coverage, etc. The ability to discriminate products in one or more of these areas can provide a competitive advantage to build or retain market share. Tailoring of the reliability program to include only value-added tasks for the customer can help control the cost of doing business, as well as allow the supplier to focus on those elements of business strategy having the most benefit in achieving a competitive advantage.
Risk Strategy	The business strategy defined by the supplier, and the market conditions under which the business strategy will be executed, inherently introduce risks to the business in terms of technical, financial, or administrative challenges. The scope of the reliability program can be tailored to help mitigate the relevant risk categories by planning tasks that will provide confidence that the reliability objective will be met within schedule and budget constraints.

Lessons Learned

Reliability tasks should be integrated into the design of the product and the manufacturing processes. The emphasis should not be on the accounting aspects of reliability (predictions, reports, etc.).

Benefits accrue from integrating reliability into the overall systems engineering process because reliability is closely related to other product characteristics, such as maintainability and safety. Tasks that may appear to be performed specifically for reliability are actually beneficial to other product characteristics and provide inputs to many tasks performed during a product or system development program. For example, a failure modes and effects analysis (FMEA), usually done under the auspices of a reliability program, has much to contribute to an analysis of product safety. It would not make sense to perform a safety analysis without the benefit of the FMEA. As another example, a thermal analysis performed to select blowers and other heat transfer components is also a necessary input for reliability failure rate calculations. The following are product characteristics which are related to reliability tasks.

- Availability
- Customer Satisfaction
- Facilities
- Human Factors
- Liability
- Life Cycle Cost
- Operating Procedures
- Producibility
- Product Performance
- Production Cost
- Manufacturability
- Safety
- Service and Repair
- Service Life
- Size, Weight and Other Physical Attributes
- Spares
- Storage, Packaging and Handling Consideration
- Test Equipment
- Training

3.1.3 **Timing**. Defining the objective of the reliability program, and planning the tasks that will be needed to support that objective, should begin at the initial stages of the product Concept/Planning phase. Once this has been accomplished, the supplier can choose to document the overall plan in a formal Reliability Program Plan, or in less formal and more general program documentation.

The tasks to be applied during the reliability program are executed at the appropriate points in the product life cycle, i.e., parts control tasks and planning for manufacturing process tolerances should be performed during the earliest stages of Design/Development, while tasks such as statistical process control cannot be implemented until processes that need to be controlled are initiated. In all cases, the timing of tasks depends upon how the program is tailored, and what tools are considered appropriate to address the reliability program issues. Implementation of tasks in particular phases typically requires planning, analyses and trade-offs in earlier phases. For example, failure to perform analyses, trade-offs and planning for manufacturing processes during the Concept/Planning and Design/Development phases could result in excessive material scrap and rework during the Production/Manufacturing phase. The same can be said for a failure to recognize the impact of repair strategies as part of the design process. The Concept/Planning and Design/ Development phases should have a broader scope than the product design itself in order for the product to be totally "successful."

3.1.4 **Application Guidelines**. The reliability program should be consistent with the technology, complexity and expected use of the product, and should reflect the factors that comprise the business strategy. When products are considered relatively complex, or perform critical functions, an approach of functional specialization (design engineering, manufacturing engineering, reliability engineering, etc.), that often results in inefficient and ineffective communication between specialized experts, may not result in a successful product. For simpler products, this "stovepiping" may be acceptable, or not relevant (one person has total responsibility for the design, analysis, test, and manufacture of a product).

Insight

The scope of the reliability program is typically increased based on:

- *Challenge to state-of-the-art*
- *Criticality of use (safety and/or liability)*
- *Use of new technology*
- *Severity of operating environments*
- *Extended operational life*
- *Inability to repair in a cost effective manner*
- *Extent of warranty provisions*

Concurrent engineering, an implementation of the systems engineering approach, replaces the stovepipes with multi-disciplined design teams. These teams have all the needed specialists represented, and the members of the team work together to try to optimize the product, rather than a specific feature, subsystem or component. One member of the team has primary responsibility for the reliability characteristics of the product, but "good" reliability is a team goal.

It is important to note that the customer for a reliability program may be external or internal to the supplier. In the latter case, for example, upper management (the customer) may be assessing the practicality of the reliability program as part of its effort to judge the risks of a new product development effort. The following are examples of different reliability program situations:

Example 1: *Commercial Off-The-Shelf Design*. A customer has decided to buy an off-the-shelf commercially available product. The customer has determined that the product's performance in actual use has been sufficient to meet his requirements. Because there is no need to modify the product there may be limited benefit from a reliability program (there is no design activity, but planning a repair strategy and control of suppliers may still be required). In the situation where a number of suppliers are being considered to provide the product, the customer might use his knowledge of each supplier's attention to reliability in his design and manufacturing processes, as well as the level of reliability he's experienced, as criteria in choosing the supplier to be used. Therefore, it is to each supplier's advantage to provide this information to the customer.

Example 2: New Product Development for Open Market. A supplier plans the development of a new product for the open marketplace. He has no specific customer defined requirements. This example is broad in the sense that the supplier has to decide what his goals will be for product reliability, as well as how to best achieve them. He should use customer expectations and needs (expressed by market surveys, Quality Function Deployment, etc.), competitive market position (degree to which he desires his product to be discriminated on the basis of reliability) and reliability levels of past and current products as factors in setting realistic reliability goals. The means to achieve the goals should stress "up front" techniques to design-in reliability, with tasks tailored based on the challenges associated with meeting the reliability goals. Some critical factors that may warrant an increase in the scope of the reliability tasks include (1) product complexity, (2) use of new or unproven technologies, (3) severity of the operating environment, (4) criticality of use and safety issues, (5) the ability to cost effectively repair the product and (6) warranty provisions.

Insight

The three basic elements that form part of a sound reliability program are:

- ***Understanding** - are the customer's needs and the importance of reliability understood*
- ***Approach** - is a sound, cost effective approach for designing and manufacturing a reliable product identified*
- *Demonstrate **Compliance** with internal and/or external customer needs*

Example 3: New Product Development for Competitive Procurement. A customer is planning a new, competitive procurement to develop and acquire a new product. Under the customer's policies, only "performance-based" reliability requirements (numerical reliability specified, but not how to achieve it) have been specified. As in Example 2, the supplier must define a reliability program that accomplishes the required objective in a cost effective manner in order to be considered competitive. Because the customer will assign a risk to each supplier's proposal, it is critical that the supplier clearly show an *understanding* of the reliability challenges of the development, a sound cost effective *approach* to achieving a reliable product and an indication that he will *comply* with the performance-based requirements.

Example 4: Modified Commercial Design. The government is planning to competitively acquire a commercial product with specific changes to adapt the product to a military operating environment. Each competing supplier should provide the information stated in Example 1 on his existing design and explain how reliability will be addressed in the design changes to be made, as well as their effect on the product's reliability. This example is a hybrid of Examples 1 and 3.

Each of the four examples requires a different tailored approach to be successful. Table 5 highlights the four scenarios.

Notes for Nondevelopmental Items

In general, a reliability program for a nondevelopmental item is limited to a description of how the supplier designs and validates reliability for his products. It should also cover integration of the item into the overall system.

Table 5: Example Reliability Programs Summary

Example	Customer Requirements	Design Flexibility	Reliability Program
1: Commercial Off-The-Shelf Design	Performance based requirements for off-the-shelf purchase. External customer.	No need to alter design.	Limited or none. Part of supplier competitive advantage could be the program previously used to develop the product and the achieved success.
2: New Product Development for Open Market	None. Supplier has to define own goals to achieve product success. Internal customer.	Complete design flexibility.	Freedom to tailor activities appropriate to challenges of meeting reliability goals.
3: New Product Development for Competitive Procurement	Performance based requirements for new product development. External customer.	Design is flexible as long as requirements can be achieved.	Program tailored to meet requirements. To effectively compete, reliability program must be "packaged" in the proposal as a risk mitigation approach.
4: Modified Commercial Design	Performance based requirements for modified commercial products. External customer.	Flexibility limited to modified portions of design.	Example is a hybrid of examples 1 and 3.

3.2 Developing Reliability Goals and Requirements

3.2.1 **Purpose**. The purposes of developing reliability goals and requirements are to:

- Establish product-level reliability specifications that, if met, will ensure that the reliability performance of the product will meet the customer's functional needs and be consistent with other product constraints.
- Allocate the product-level reliability requirements down to the level needed (i.e., subsystem, equipment or assembly level) to be meaningful to the design and manufacturing process engineers.

Insight

Reliability performance requirements should be stated in terms most meaningful to the customer's needs. Design requirements should be stated in terms most responsive to the customer's needs. These terms can include mean time between failure (for repairable products), the mean time to failure, and service life (or useful life).

A number of reliability approaches and tasks are relevant to the goal/requirement development process. Table 6 lists those commonly applied tasks that should be considered for application to address this issue.

Table 6: Tasks Relevant to Developing Reliability Goals/Requirement

Tasks	Relevance To Purpose
Allocations	Used to establish lower assembly level requirements from product level requirements based on complexity, parts counts, etc. Provide an effective means to check reliability requirements for realism.
Benchmarking	Can be used to establish competitive position with respect to reliability. Identifies goals necessary to develop discriminated product on reliability basis.
Dormancy Analysis	Accounts for periods of non-operating or stand-by conditions which the product will experience throughout its useful life, in order to establish and understand special design needs and their impacts on the product.
Durability Assessment	Used to define life limiting aspects of product. An effective means to strategize for repair policy and plan for upgrading products.
Environmental Characterization	A process to identify the scope and magnitude of the end-use environments to which the product will be exposed throughout its useful life. Used to establish performance-based reliability requirements.
Fault Tolerance	Consideration of this failure masking technique allows the establishment of higher level reliability product goals, but lowers series reliability potential.
Life Cycle Planning	A process to set goals for all portions of life cycle. Considers levels of reliability at each stage and plans for end-of-life. Impacted significantly by repair policies and product durability.
Market Survey	A basic means to identify customer needs and expectations as an input to developing supplier product goals.
Modeling & Simulation	An approach to establish meaningful reliability requirements that can be allocated to lower assembly levels. Provides a means to determine degree of appropriate fault tolerance. Provides understanding of impact of unit failure on product.
Predictions	A means to estimate realism of potential hardware and software reliability goals and requirements. Can indicate scope of fault tolerance appropriate for challenging requirement levels.
Quality Function Deployment QFD)	A technique for understanding customer needs that provides a means of defining quantitative reliability goals and tasks to effectively satisfy them.
Thermal Analysis	An analysis to determine the relationship between the intended design reliability and the thermal use environment to establish performance-based reliability requirements.
Translations	Models that will translate customer or user performance based requirements into product design reliability goals or requirements.

Insight

Requirements should be realistic and achievable within budget and schedule constraints. Also, the principle of diminishing returns should be applied. Achieving an extra 5 or 10% of performance may cost more than the benefits gained. Requirements that are too lenient, on the other hand, can lead to customer dissatisfaction and loss of sales.

3.2.2 **Benefits**. Without understanding what the customer needs or wants, one or both of two undesirable results may occur: the customer will not be satisfied with the product, or resources will be wasted through overdesign. If defining the reliability program gives direction to subsequent efforts, then developing the reliability goals and requirements scopes the magnitude of those efforts.

3.2.3 **Timing**. The customer or the supplier should define the reliability goals and requirements prior to the beginning of the development cycle. In the initial phases of a totally new design, the requirements may be stated as "goals" with firm requirements not defined until later. Based on the results of early studies in the Concept/Planning phase, the initial requirements may have to be adjusted, but a valid starting point is essential. The goals and requirements may be based on customer expressed performance based requirements or on internally developed strategies to "position" new products in the open marketplace. Allocation of requirements down to a given level should be done after a product reliability model has been developed and before design efforts at that level begin.

Insight

If neither the customer or the supplier tracks the product performance parameters, the level of achieved product reliability cannot be determined. Only important product performance parameters should be measured and tracked.

3.2.4 **Application Guidelines**. Customer reliability performance needs and expectations may be specifically expressed, implicitly expressed or not expressed at all. They may have to be hypothesized by the supplier based on other desired customer requirements. Table 7 summarizes typical situations. No matter what method or methods are used, the primary goal is to "thoroughly understand what the customer needs and expects."

Notes for Parts Suppliers

Yield rates and outgoing part quality levels are important considerations for suppliers of parts.

Table 7: Customer Reliability Requirement Scenarios

Customer Requirements	Description of Scenario	Application Guidance
Expressed Explicitly	Customer specification includes requirements for reliability performance as a quantitative measure (i.e., percent reliability, mean-time-between-failure, etc.)	The specified value may need to be adjusted to account for factors that may cause failure that are beyond supplier control, i.e., translation of user requirements to design goals.
Expressed Implicitly	Specification includes product characteristics that necessitate certain levels of reliability in order to satisfy them (i.e., life cycle cost, support cost, maintenance manpower, warranty provisions).	The level of reliability necessary to meet other explicitly stated product characteristics should be derived. This process is based on known or hypothesized relationships among characteristics and often involves trade-offs.
Not Expressed	Often the case for commercial products. Supplier must "anticipate" needs and/or position his product in the marketplace. Supplier may or may not have data on similar or competitive products.	Market surveys, Quality Function Deployment, benchmarking, etc., are among approaches that can be used. Data on existing products can help the supplier "position" his reliability objective. Often, this can be a competitive advantage.

<u>Product Reliability and Series Reliability</u>. A customer may specify, or a supplier define, reliability requirements in different contexts. One, which represents the reliability with which the product will perform its characteristic function, is referred to as *product reliability*. It may also be referred to as system, mission, or functional reliability. These requirements take into account design approaches such as redundancy or other forms of fault tolerance. When reliability is discussed in terms of its effect on operating and repair/maintenance costs, it is typically referred to as *series*, basic or logistics reliability. This measure does not reflect the product's ability to perform its overall function.

Instead, it reflects the ability of the entire design to be free from failure. For simple products where redundancy and other forms of fault tolerance are not necessary, the product reliability and the series reliability are the same. Table 8 explains the differences between these two types of reliability.

Table 8: Product (Mission) Reliability and Series (Basic) Reliability Characteristics

Product (Mission) Reliability	**Series (Basic) Reliability**
Measure of product's ability to perform and complete its function	Measure of product's ability to operate without repair or adjustment
Considers only failures that cause loss of product characteristic function	Recognizes effects of all occurrences that demand repair without regard to effect on function or mission
Improved by redundancy	Degraded by redundancy
Usually higher than series reliability	Can be equal to, but is usually lower than, product reliability

Performance Reliability and Design Reliability. Commercial and military customers measure the *reliability performance* of products in their own ways, to suit their own needs. These measures may or may not include factors outside the control of the product or system supplier. The way in which a customer measures the reliability of a product in use may not be directly meaningful as a *design reliability* goal or requirement. While some factors are not under the supplier's control, they should be accounted for in establishing the level of design reliability necessary to meet the customer's needs or expectations. Usually, the supplier can anticipate that while many failures affecting reliability performance will be caused by the design, other classes of induced failures will occur during use (including repair and manufacturing). This hierarchy of failure causes can be visualized as segments of a pyramid as shown in Figure 3.

Insight

- *Performance reliability reflects the quality of the design and the impact of poor maintenance (e.g., maintenance-induced failures) and other factors such as operating constraints. Design reliability reflects only inherent design characteristics such as safety margins, part selection, defect detection, etc.*

- *The military usually defines its measure of reliability performance as operational reliability. A car owner may be most concerned with low cost of operation and infrequent visits to the repair shop. An airline may be most concerned with schedule reliability.*

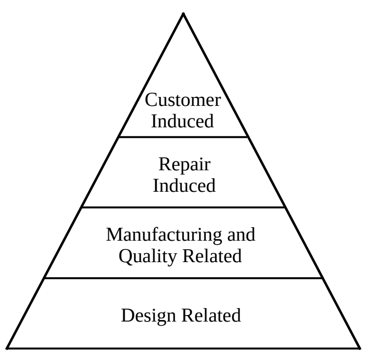

Figure 3: Product Performance Failures

The shape of the "pyramid" can vary with time because each segment is a function of time. It is critical to account for all known failure causes in establishing product design reliability goals. The process of establishing *design requirements/goals* from *needed performance measures* is sometimes referred to as "translating" customer (performance) reliability to supplier (design) reliability. Table 9 shows how performance reliability and design reliability differ.

Table 9: Performance Reliability and Design Reliability Characteristics

Comparison	Design Reliability	Performance Reliability
Used to:	Define, measure and evaluate inherent capabilities of the product	Describe performance when operated in planned environment
Derived from:	Performance reliability requirement/ goals.	Usage profiles, benchmarking, etc.
Selected such that:	Achieving them allows projected satisfaction of reliability performance needs	Customer is satisfied
Accounts for:	Failure events subject to supplier control	All failures, regardless of cause
Includes:	Only effects of design	Combined effects of design, quality, installation environment, customer influence, repair, delays, etc.

Design Goal Realism. The initial design goals/requirements that are derived from customer needs have to be considered preliminary. They must be evaluated for realism. Questions that have to be answered include: are the requirements compatible with the available technology and do they unnecessarily conflict with product constraints such as price, weight and power. Answering these questions usually involves a review of previous studies and data for similar or comparative products (if any exist). The requirements may need to be adjusted to account for improvement of technology, different operating environments, different duty cycles, and so forth.

Insight

Product requirements should be allocated to a useful level of indenture. Allocations should consider complexity, level of design flexibility, and safety concerns.

Allocation of Reliability to Lower Levels. Product-level requirements are not usually sufficient to scope the design effort. For example, a requirement that a truck have an MTBF of 1000 hours doesn't help the designers of the transmission, engine, and other components. Consequently, the requirement process for "complex" products usually involves allocating the product reliability requirements to lower levels. When a product contains "few" parts, the allocation of product requirements may not be necessary or cost effective. Functional complexity, parts counts, and challenge to the state-of-the-art are some considerations in a typical allocation process. In some cases, the process is iterative, requiring several attempts to satisfy all requirements. In cases where the requirements can't be satisfied (components are needed with unattainable levels of reliability), trade-off discussions with the customer may be necessary.

Notes for Nondevelopmental Items

The supplier would typically use the level of achieved reliability performance on previous, similar products. Ensuring that the item will integrate into the required environment is critical.

Product Life Cycle. Another important aspect of determining reliability goals is recognizing the various phases of a product life cycle. For example, some products or systems are continually operational while others are operated only a limited number of hours per day. Some products may be in storage for years before they are put into operational use. The design life is also a factor. Should the product last 5 years, 10 years or 20 years? Will it wear out before it's obsolete? These are all factors to be considered in establishing product goals and requirements over its life cycle.

3.3 Designing for Reliability

3.3.1 **Purpose**. The purpose is to choose an effective set of tasks to design products that meet customer needs (failure free) and are insensitive to failure or environmental extremes (fault-tolerant, robust) to the extent that is economically and technically feasible and necessary to meet the reliability program objective. Tasks that have relevance in terms of addressing and solving design issues are listed in Table 10.

Table 10: Tasks Relevant to Reliability Design

Tasks	Purpose
Accelerated Life Test	As a design tool, accelerated testing ensures that components and assemblies are robust enough for the design. It enables alternative choices early in the design while change is still cost effective.
Allocations	Design goals are established for lower levels of assembly by allocation. By iterating the reliability model the scope of the designers' efforts can be determined and coordinated for overall product success.
Critical Item Identification	Reliability can be severely limited by critical (weak link) parts or software. These items need to be identified and controlled to effectively achieve reliability goals. Control approaches may include tests, special procedures, safety-margins or fault tolerance.
Derating	Limiting stresses on parts to levels below vendor ratings is a proven approach to improved reliability by preventing or lessening the impact of particular failure mechanisms.
Design of Experiments (DOE)	Cost effective examination of design alternatives is a key to design optimization for reliability. DOE is a process that can assess the impact of variables on the design prior to finalization.
Design Reviews	The complexity of designs usually necessitates that the product be subjected to periodic reviews. This activity is timed to enable design changes and reallocation of resources while the penalty for change is not prohibitive.
Dormancy Analysis	Nonoperating conditions often result in failure mechanisms different than operating ones. Products with significant periods of dormant exposure should be subjected to a special review of this class of mechanisms.
Durability Assessment	Early wearout can be as bad as or worse than poor reliability during useful life. Durability incorporates those features that will optimize useful product life.
Environmental Characterization	Knowing the environmental stresses to be withstood is critical to design success. Measures can be taken to inhibit their detrimental effects only if they are known.
Failure Modes, Effects & Criticality Analysis (FMECA)	A reliable product is one where the consequence of failure is understood and controlled. The FMECA process also serves as a key technique in the software and diagnostics design of the product.
Failure Reporting, Analysis & Corrective Action (FRACAS)	Effective tracking of failure data, and the identification and correction of causes is necessary to improve the designed in reliability. It's a critical process in overcoming problems that may not have been foreseen.
Fault Tolerance	Achievement of high levels of reliability can usually only be achieved through some form of fault tolerance (redundancy, graceful degradation, etc.). Fault tolerance typically has a penalty in terms of lower series reliability.
Fault Tree Analysis (FTA)	This top down failure consequence assessment tool is especially important to safety considerations. What could cause a potential catastrophic event is an important design input.
Finite Element Analysis (FEA)	Simulation approaches are effective checks of the mechanical and thermal robustness of designs prior to hardware availability. They enable effective trade-offs of design alternatives in a rapid manner.
Life Cycle Planning	Basic constraints on design practices are design life and operational and environmental profiles. How long should it be in service or in storage, and how it will be shipped and handled all need to be addressed to ensure that the design is reliable.
Modeling & Simulation	The relationships of elements of the design are critical to reliability. Modeling provides a mathematical and graphical understanding of how components, assemblies, units and software are related to the overall product performance. Simulation allows validation of the assumed model.
Parts Application	Application issues such as tolerances and susceptibility to environmental stresses are important to reliability. Component packaging is a critical consideration for harsh environments.
Parts Obsolescence	Use of parts that will become obsolete or have diminishing sources can severely limit the product's long term availability. This aspect of parts selection cannot be neglected in design.

Insight

Models that are relevant to the design of reliable software include:

- *Waterfall - emphasizes completion of each phase of software development before proceeding to the next phase. Primarily suited for small system developments, or system upgrades/improvements of existing software.*
- *Spiral - accommodates incremental development and prototyping of software, making it better suited to large software projects.*

Table 10: Tasks Relevant to Reliability Design (Cont'd)

Tasks	Purpose
Parts Selection	Choosing reliable parts is a basic ingredient in a reliable product design. Other considerations are multiple sources, diminishing sources and component testing.
Predictions	Design alternatives need to be traded-off before they are implemented. Predictions often form the basis for informal hardware and software design decisions. They allow the "what if" design optimization process to take place.
Repair Strategies	How, when and by whom repairs will be performed is a vital input to the design process. Fault detection and isolation methods are based on these policies, as are spares, personnel training and test equipment decisions.
Sneak Circuit Analysis (SCA)	Complex systems where reliability is critical have to be free from the threat of hidden circuit paths and unanticipated functions. This analysis provides this type of design assurance.
Test Strategy	Should include part, module, or assembly level tests and software tests that address trade-off decisions having an impact on design decisions. Tests should precipitate design flaws before the product is finalized and begins its Production/Manufacturing phase.
Thermal Design	One of the most critical stresses impacting reliability is temperature. An effective thermal design uses appropriate thermal transfer mechanisms to limit temperature and improve reliability.
Worst Case Circuit Analysis (WCCA)	An important design characteristic is being free from susceptibility to part parameter tolerances and drift. The WCCA provides a design tool to make circuits less susceptible to these reliability limitations.

3.3.2 **Benefits**. The only way to deliver a reliable product is by designing it to be reliable. Reliability cannot be tested or inspected into a product. The major benefits of improving designed-in, or inherent, reliability can include:

- Lower product costs (less scrap and rework "fixing" the design during manufacturing)
- A focus on meeting the reliability needs of the customer
- A reduced need for testing or screening at high levels of assembly
- Lower field service and warranty repair costs
- Minimized product safety and liability issues

These benefits can translate into higher profits and greater customer satisfaction which, in turn, can lead to a competitive advantage and an increase in the supplier's market share resulting from "best-in-class" or "world class" reliability performance.

3.3.3 **Timing**. Reliability should be a part of all design decisions, trade-offs and activities, beginning with the Concept/Planning phase, where the supplier will determine which tasks will add value to the product design for the customer, while meeting the reliability program objective. As the product evolves into the Design/Development and Production/Manufacturing phases, consideration should be given to the processes that will be used during manufacturing. Waiting until the Production/Manufacturing phase is too late to be efficient or cost effective. As a groundrule, each design task performed for reliability should be timed to minimize the cost and schedule impact associated with implementing or modifying the product design.

3.3.4 **Application Guidelines**. Although reliability can be considered a true design characteristic, the achieved value in actual field use can be influenced by other factors. A concerted effort must be made to design the product to minimize the influence of these external factors, which will allow the achieved reliability to approach the inherent level determined by the customer needs.

Design for reliability is supported by a number of reliability tasks. Table 11 lists the most relevant tasks, and how they can be used to design reliability into the product. Some of the techniques which have proven to be more successful because they emphasize proactive rather than reactive impact on the design include:

- Environmental characterization (tailoring of design requirements to expected operating conditions)
- Parts selection and control (includes parts, components, assemblies and software)
- Parts application (i.e., derating, thermal and mechanical design management)
- Thermal and mechanical analysis (reducing failure accelerating temperature/vibration conditions)
- Critical item identification and control (risk reduction)
- Modeling and simulation (design trade-off techniques)

It is important to emphasize, however, that designing for reliability should address not only the product, but also the processes used to develop and manufacture the product. Inadequate or deficient manufacturing processes, for example, may introduce defects that can lead to failures after delivery to the customer. The same is true for quality processes and repair strategies. In designing the processes that will be used to manufacture the product, consideration should be given to the defects that may result and the potential ways to eliminate them. Similarly, how the product will be operated and repaired is a major consideration in the design process.

Lessons Learned

Optimistic values should not used for thermal, mechanical, and electrical ratings.

Environmental and operating stresses should be accurately characterized.

The consequences of single point failures in some products may not be serious. In those cases, redundancy and other design approaches intended to eliminate single-point failures are probably not warranted.

In some cases, it is the mechanical components and parts that determine the product's inherent reliability.

Table 11: Design For Reliability - Application Guidance

Task	Application Guidance
Accelerated Life Test	To develop reliable designs, accelerated life testing can be applied to parts or assemblies that are being considered for use in the design. These tests can be performed directly by the supplier, by the supplier's vendor(s) or by a third-party test house. The results of these tests should be used to influence the selection/application of parts/assemblies for the design.
Allocations	Allocation of high-level hardware and software reliability requirements down to lower levels provides a means of establishing reliability design goals that are consistent with the overall design objective. It also provides a means of providing design goals to subcontractors which can be established as contractual requirements.
Critical Item Identification	The identification of reliability and safety critical items is typically determined by the technology used, its failure history, design constraints, cost/availability and output results of the FMECA. Critical items based on cost or availability criteria can typically be controlled through effective management of parts control tasks.
Derating	Limiting electrical, thermal or mechanical stresses on parts to levels below maximum ratings can increase part reliability/life, but may result in additional product complexity (potentially lower series reliability) overall. Derating postpones or avoids activation of life-limiting failure mechanisms.

Table 11: Design For Reliability - Application Guidance (Cont'd)

Task	Application Guidance
Design of Experiments (DOE)	The efficiency of tests is achieved through better collection and use of the data, thereby minimizing total test time and cost. DOE can be applied to design of both products and processes. Once the physical product properties are known, and their interactions understood, those factors affecting product reliability can be systematically and scientifically addressed in the product design.
Design Reviews	Can be formal or informal, depending on product complexity and strategic considerations. Design reviews for reliability may be separate, or part of an overall product design review. Design reviews are appropriate before each "major" product decision point. Use of independent experts adds value.
Dormancy Analysis	Understanding how parts and materials respond under exposure to those environments typical of storage or long periods of non-operation can help the supplier design to avoid or minimize problems.
Durability Assessment	Applies traditionally to mechanical systems, but can also include electronics. Parts or materials that exhibit potential problems related to wearout phenomena can be designed differently to reflect the desired useful life goals of the product (either longer or shorter, depending on the customers needs).
Environmental Characterization	The ability to accurately identify the environmental and customer use characteristics increases the probability that the customer will experience reliability that approaches designed-in levels. It also enables design practices to be better tailored to produce a "robust" design.
Failure Modes, Effects and Criticality Analysis (FMECA)	Analysis during the earliest stages of design will help identify critical safety or critical functional problems which can be eliminated or minimized through alternate design approaches. Criticality analysis will assist the supplier in ranking the severity of a failure, and the probability of its occurrence.
Failure Reporting Analysis and Corrective Action (FRACAS)	Can be used to collect information on hardware and software failures resulting from product development testing, or at lower levels of assembly. Root failure causes and corrective actions should be identified, confirmed and corrected in the design, reported in the failure system, and communicated to the appropriate personnel to correct problems in similar products, circuits or assemblies. It should be closed-loop to be effective.
Fault Tolerance	The use of redundancy (hardware design) and block masking (for computer memory) are two techniques for making product performance more tolerant to the failure of one or more of its parts.
Fault Tree Analysis (FTA)	Similar to an FMECA, an FTA will help to conceptualize the major failure modes of the product by identifying all of the lower level failures which an contribute to each product failure mode. The product design can then be improved by eliminating or minimizing the effect of those failures.
Finite Element Analysis (FEA)	Items to be analyzed should be carefully selected due to the cost of the task. Selection criteria may include items with little or no prior experience base, state-of-the-art design or packaging concepts, extreme environmental exposure, or critical thermal/mechanical performance or behavior constraints.
Life Cycle Planning	In designing for reliability, life planning activities could include the selection and analysis of materials, parts components and software which will impact the overall useful life (durability) of the product. Attention would be given to identification of life-limiting failure mechanisms which would suggest the need for alternative design approaches.
Modeling and Simulation	If based on accurate data and done correctly, product reliability models can identify shortfalls in meeting customer requirements. Modeling redundancy into the product design, or developing other product models, can mitigate this risk. A model is generally needed before reliability goals can be determined or analyses performed. Simulation will help prove whether the model assumptions are valid.
Part Application	Parts should be applied consistent with their design ratings for performance limits and environmental constraints. Applying parts at less than 100% of their ratings (derating) can increase part reliability/life.
Parts Obsolescence	Parts that are approaching the end of their technological life cycle may not be suitable for new product designs due to potential obsolescence issues. Using these types of parts in a product design may necessitate the use of lifetime buys to sustain the product over its design, manufacturing and customer usage life.

Table 11: Design For Reliability - Application Guidance (Cont'd)

Task	Application Guidance
Part Selection	Parts should be selected that have known characteristics, and that are readily available from reputable and, preferably, multiple suppliers. Deviation from these criteria may increase technical and financial risks.
Predictions	Prediction techniques can be used to impact the design by identifying areas of high technical risk resulting from elevated temperatures (change board layout) or high electrical stress (select part with higher parameter ratings). They can also be used to trade-off design configurations, or to identify reliability-critical items.
Repair Strategy	Product hardware and software should be designed for ease of troubleshooting, maintenance and repair. Modular design and use (or re-use) of proven hardware/software can reduce maintenance and repair costs.
Sneak Circuit Analysis (SCA)	Identification of sneak circuits allows the designer to eliminate hidden flaws which could result from highly complex electronic circuits or functional interfaces, or inadequate understanding of the product design.
Test Strategy	An overall test strategy in designing for reliability may include accelerated life stress testing (as part of durability analysis), or design of experiments (to evaluate alternative design or process approaches). Growth testing, when judiciously applied, can also be used to identify and correct hardware or software design problems, although potentially at a point in the design that will be more costly to correct.
Thermal Design	Product performance susceptibility to temperature extremes and thermal shock may be achieved through supplemental cooling, derating practices, optimal placement of parts/components, or thermal packaging design.
Worst Case Circuit Analysis (WCCA)	This analysis is one of the more successful techniques in designing for robustness (fault tolerance) in electronic circuit/product design. It should be performed on any circuit that is safety critical, or has major life cycle cost impact. The circuit design can then be refined to incorporate redundancy, or use improved parts (less parameter drift) to improve product robustness.

A reliability model, often in the form of a block diagram, is needed before reliability goals can be determined or analyses performed. The model shows the functional relationships between components and assemblies within the product. The model is iterative in nature, and its validity can be assessed through a variety of simulation techniques. Comparison of the model to product reliability goals provides focus to potential design improvements.

Reliability analysis techniques can serve a useful purpose beyond the simple assessment of progress in the design of the product. Analyses can also be effectively applied as a means of trading off design options and characterizing the impact of design decisions. Used in this manner, the supplier can have greater confidence in manufacturing a product that will operate failure-free and be tolerant of faults to the extent that the basic reliability objective can be achieved within the required business constraints.

Testing also plays an important role in the design process. While often viewed as a "reactive" means of measuring reliability, certain types of testing may also be vital to successful product design. Incremental testing of critical parts, assemblies and functional performance of the design may be beneficial to understanding and making decisions about the product and process design. Design of experiments is an effective test process for optimizing product or process design characteristics in a cost effective manner. The use of test data for design improvement can be extended to more formalized test-analyze-and-fix (TAAF) or reliability growth test (RGT) programs. They can prove useful in identifying necessary design changes in products that have a high degree of functional and/or physical complexity.

Insight

Reliability Growth Testing is sometimes misinterpreted as a substitute for good up-front design. In practice, "test-analyze-and-fix" testing can be misapplied as a trial and error approach to fixing a bad design.

Notes for Nondevelopmental Items

Since the product is already designed and in production, tasks associated with designing in reliability are not applicable.

3.4 Assessing Reliability Progress

3.4.1 **Purpose**. Reliability assessments are performed to:

- Determine progress in meeting the reliability performance goals and requirements
- Evaluate the impact of design decisions on reliability, such as the approach to cooling, types and ratings of proposed parts, fault tolerances, etc.
- Understand how a design can fail, the causes of these failures, and how to reduce their probability and consequence.

Because all of these purposes are closely coupled with design, it could be argued that the assessment methods discussed in this section are merely extensions of tasks initially performed during the design of the product. While this may be true, the concept of separately addressing the primary issues faced in structuring an effective program warrants this separate section. Table 12 includes those reliability activities that should be performed during the earliest stages of product design, but can be iterated to assess reliability progress.

Table 12: Tasks Relevant to Assessing Reliability Progress

Tasks	Purpose
Accelerated Life Test	Assesses the effects of changes on part or assembly design on product life, or to identify predominant failure mechanisms under accelerated conditions in order to define ESS environmental parameters.
Critical Item Control	Retains continuous control over items that have been designated as critical to the reliability, performance or cost of the design. Items are added or deleted from the Critical Item list as conditions warrant.
Design of Experiments (DOE)	Evaluates the effects of changes in design on reducing the sensitivity of the product to design and manufacturing process variations (changes in processing temperatures, durations, etc.).
Design Reviews	Provides a formalized review of product hardware and software reliability progress using system engineering team consensus and checklists to assure design is on track.
Dormancy Analysis	Assesses the effects of changes in environmental storage parameters on product characteristics (performance, sensitivity to corrosion, etc.).
Durability Assessment	Assesses the product design for materials stress/strength properties to ensure that customer needs related to product life are met.
Failure Modes, Effects and Criticality Analysis (FMECA)	Assesses progress in identifying, quantifying, eliminating or reducing the effects of single-point or critical hardware/software failures in the product based on changes in the design.
Failure Reporting Analysis and Corrective Action (FRACAS)	Accumulates failures and corrective action information to measure progress in eliminating hardware and software failure modes and mechanisms and documenting the effectiveness of corrective actions.
Fault Tree Analysis (FTA)	Assesses progress in identifying the cause and effects of single-point or critical hardware/software failures in the product resulting from design modifications or enhancements.
Finite Element Analysis (FEA)	Assesses the ability of the design to withstand thermal and mechanical stresses using simulation techniques.
Life Cycle Planning	Assesses the useful life characteristics of the product based on changes in or modifications to materials, parts, processes or software.
Parts Obsolescence	Identifies and implements alternative courses of action in response to imminent unavailability of parts, through lifetime buys, substitute parts, or investment in new technology.
Predictions	Assesses progress in (1) meeting design goals, (2) meeting derating requirements, (3) identifying environmental design precautions, and (4) identifying reliability critical items as the design matures.

Table 12: Tasks Relevant to Assessing Reliability Progress (Cont'd)

Tasks	Purpose
Reliability Growth Test (RGT)/Test Analyze and Fix (TAAF)	Monitors the growth in product reliability resulting from the identification and elimination of failure modes, and confirmation of corrective action effectiveness.
Sneak Circuit Analysis (SCA)	Assesses progress in identifying, eliminating or reducing the effects of sneak circuit paths that may unexpectedly occur during normal product operation.
Supplier Control	Continually compares the status of parts and assembly selection (quality, availability), and application (derating practices) to the reliability program objective to ensure customer needs continue to be met. Supplier control includes monitoring of vendor practices in terms of quality and performance.
Test Strategy	Judiciously applies value-added and cost effective tests to quantitatively and/or qualitatively assess the impact of design decisions and changes on long-term product reliability.
Thermal Analysis	Determines the adequacy of the thermal design (temperature control) as the design is developed.
Worst Case Circuit Analysis (WCCA)	Assesses progress in desensitizing the product to extremes or changes in environmental conditions, or changes in part parameters as the design matures.

3.4.2 **Benefits**. Assessment is a broad term that includes all tasks used to determine the extent of design progress. It can be accomplished by analysis, test, or review. Thorough analysis is the key to getting the product as "right" as possible the first time, before testing begins. Analysis of the design is a "paper" process. It is relatively inexpensive, compared to building and testing models or prototypes. Analyses can also provide an effective tool for decision making. For example, should reliability goals be reallocated, is additional cooling required, is redundancy necessary, and is one supplier's power supply more reliable than another's, are all questions which can be answered by effective analyses. Testing, while much more costly, can provide more realistic results because fewer assumptions are necessary and reasonably representative environmental stresses and operational profiles can be used.

3.4.3 **Timing**. Assessments should be thought of as tools to aid in the decision making process, not ends in themselves. Their timing should be such that they have an impact on the design, and should make use of the best available information at that time. While limited assessment occurs in the Concept/Planning phase, it is in the Design/Development phase where resources spent on assessment have the most positive, cost effective impact on the product design. Updates to these initial assessments should be made as additional data become available, prior to key decision points in the development process, and as required to monitor progress towards the reliability goal.

3.4.4 **Application Guidelines**

Reliability Predictions. Reliability predictions are a means of determining the feasibility of requirements, assessing progress toward achieving those requirements and comparing the reliability impact of design alternatives. Predictions can be made through any appropriate combination of reliability models, historical data, test data, and engineering judgment. The choice of which prediction method to use depends on the availability of information, which in turn is a function of the point of the product life cycle at which the prediction is performed. Considerations in performing predictions are that correct environmental stresses are used, the reliability model is correct, the correct part qualities are assumed and that all operational and dormancy modes are reflected.

Insight

No one prediction method is suitable for all product development phases. The method used should be based on available data and the level at which the prediction is made. It should address product- and operating-specific characteristics such as dormancy, type of technology, etc. Predictions should not be the sole basis for programmatic decisions when other relevant data exists.

Testing. Assessment through testing provides a realism not available through analysis. At a premium cost, the impact of such factors as temperature extremes and electromagnetic noise exposure can be determined. The integrity of interfaces between "black boxes" and the impact of human interaction and software integration can be assessed. These types of tests, when applied as part of the design process, can achieve savings many times their cost compared with "after-the-fact" reliability qualification forms of testing.

Design Reviews. One of the more important ways of assessing reliability design progress is through design reviews. Even the best trained, well intentioned hardware, software and systems design engineers may overlook some details in complex designs. An independent set of reviewers can be a valuable asset in taking a separate look at the design characteristics. Armed with the knowledge of what are critical reliability influences, they can identify problems in time for them to be cost effectively corrected.

Lessons Learned

Ground rules and assumptions for an analysis should be realistic and thoroughly understood.

Data sources should be described, appropriate, and up to date.

Analyses should be performed early enough to influence design decisions.

Analyses results should be shared and combined with results from related analyses.

Proven methods should be used with justification for use stated.

Assumptions, approaches, factors, and data should not be chosen to artificially present best case (optimistic).

Other Types of Analyses. The customer's reliability needs are met through sound design practice, proper application of parts, and good manufacturing processes. Other techniques are also available for ensuring that reliability continues to be an integral consideration in design decisions and approaches as the product development effort matures. Table 13 lists some common techniques that can be used for assessing progress, and guidance for their use. While most of these tasks may not result in a numerical value that is representative of the product reliability at a point in time, they provide a valuable means of better understanding the design's strengths and weaknesses so that it can be changed accordingly.

Table 13: Assessing Reliability Progress - Application Guidance

Tasks	Application Guidance
Accelerated Life Testing	Effective on parts, components or assemblies to identify failure mechanisms and life limiting critical components.
Critical Item Control	Apply when safety margins, process procedures and new technology present risk to the production of the product.
Design of Experiments (DOE)	Use when process physical properties are known and parameter interactions are understood. Usually done in early design phases, it can assess the progress made in improving product or process reliability.
Design Reviews	Continuing evaluation process to ensure details are not overlooked. Should include hardware and software.
Dormancy Analysis	Use for products that have "extended" periods of non-operating time or unusual non-operating environmental conditions or high cycle on and off periods.
Durability Analysis	Use to determine cycles to failure or determine wearout characteristics. Especially important for mechanical products.
Failure Modes, Effects and Criticality Analysis (FMECA)	Applicable to equipment performing critical functions (e.g., control systems) when the need to know consequences of lower level failures is important.
Failure Reporting Analysis and Corrective Action (FRACAS)	Use when iterative tests or demonstrations are conducted on breadboard, or prototype products to identify mechanisms and trends for corrective action.
Fault Tree Analysis (FTA)	Use for complex systems evaluation of safety and system reliability. Apply when the need to know what caused a hypothesized catastrophic event is important.
Finite Element Analysis (FEA)	Use for designs that are unproven with little prior experience/test data, that use advanced/unique packaging/design concepts, or will encounter severe environmental loads.
Life Cycle Planning	Use if life limiting materials, parts or components are identified and not controlled.

Table 13: Assessing Reliability Progress - Application Guidance (Cont'd)

Tasks	Application Guidance
Parts Obsolescence	Use to determine need and risks of application of parts and lifetime buys.
Prediction	Use as a general means to develop goals, choose design approaches, select components, and evaluate stresses.
Reliability Growth Test (RGT)/Test Analyze and Fix (TAAF)	Use when technology or risk of failure is critical to the success of the product. These tests are costly in comparison to alternative analytical techniques.
Sneak Circuit Analysis (SCA)	Apply to operating and safety critical functions. Important for space systems and others of extreme complexity. May be costly to apply.
Supplier Control	Apply when high volume or new technologies for parts, materials or components are expected
Test Strategy	Use when critical technologies result in high risks of failure.
Thermal Analysis	Use for products with high power dissipation, or thermally sensitive aspects of design. Typical for modern electronics, especially of densely packaged products.
Worst Case Circuit Analysis (WCCA)	Use when the need exists to determine critical component parameters variation and environmental effects on circuit performance.

The assessment methods chosen should be appropriate for the product and require only a reasonable level of investment when compared to the value of the results. The failure of some components, for example, may have little impact on either the product function, or on its operating and repair costs. A relatively costly analysis may not be justified. For some products, a thermal analysis may not be needed, given the nature of the product and its operating environment. In other cases, the consequences of failure may be so catastrophic that every possible effort should be made to make the product fail-safe or fault tolerant.

Notes for Nondevelopmental Items

Tasks in this area should be performed only to confirm suitability of the product for the intended application.

3.5 **Measuring Product Reliability**

3.5.1 **Purpose**. The purpose of measuring product reliability is to determine if goals/requirements have been achieved for the "final" product configuration. In so doing, reliability shortcomings may still be uncovered that need correcting. Preferably, testing and analysis tasks performed earlier in the product development life cycle will have served that purpose prior to any task intended specifically for measuring product reliability. Table 14 identifies reliability tasks/approaches that are considered relevant to measuring product reliability.

Table 14: Tasks Relevant to Measuring Product Reliability

Tasks	Purpose
Accelerated Life Test	Used to measure reliability in shortened test time based on assumed acceleration functions. Care must be taken that failure mechanisms are realistic for true operational environments.
Durability Assessment	Can be used as a paper analysis to confirm a design life for a product. It is more effectively applied earlier in development to ensure that design life is adequate.
Failure Modes, Effects and Criticality Analysis (FMECA)	Used ideally as a design and assessment tool to understand and alleviate failure consequences, it can also be an independently applied tool to check that certain failure consequences are avoided. A qualitative measurement.
Failure Reporting Analysis and Corrective Action (FRACAS)	A process used to inherently improve reliability but analysis of data can measure a reliability level. Has many shortcomings for this purpose, including accuracy of operating hours and realism of environmental stresses.
Fault Tree Analysis (FTA)	Used ideally as a design and assessment tool to understand and alleviate failure consequences, it can also be an independently applied tool to check that certain failure consequences are avoided. A qualitative measurement.

Table 14: Tasks Relevant to Measuring Product Reliability (Cont'd)

Tasks	Purpose
Life Cycle Planning	Includes a strategic combination of testing and analysis tasks to provide a realistic and cost effective measurement of product reliability, specifically in meeting useful life requirements.
Production Reliability Acceptance Test (PRAT)	Used as a measurement of product reliability as one of the last tasks before the product is shipped to the customer. It is typically performed on a sample basis.
Predictions	Calculates a reliability level based on parts, stresses, etc. under expected usage. Its paper analysis nature limits accuracy due to potential interface problems and environmental assumption inaccuracies.
Reliability Demonstration Test (RDT)/Reliability Qualification Test (RQT)	A formalized test of hypothesis under controlled conditions where an accept/reject decision is reached. Provides greatest assurance that goals have been achieved.
Reliability Growth Test (RGT))/Test Analyze and Fix (TAAF)	Used inherently to uncover design problems, but can result in a measured reliability value if necessary. TAAF is a less formal process than RGT.
Sneak Circuit Analysis (SCA)	Used ideally as a design and assessment tool to discover unintended paths and functions, it can also be an independently applied tool to check that certain failure consequences are avoided. A qualitative measurement.
Test Strategy	The test strategy will identify which tests are appropriate, and at what level, to reflect a realistic measurement of the reliability of the product. Tests may measure instantaneous reliability, or project estimates of the useful life of the product.
Worst Case Circuit Analysis (WCCA)	A tool used to effectively assess design tolerance to parameter variation, it can also be used as an independent check of the susceptibility to variation. A qualitative measurement.

The three basic methods used for determining whether product requirements have been met are inspection, analysis, and test. Inspection is best suited to the physical characteristics of a product (such as finish, form and other quality attributes) and is not useful in measuring the reliability of a product. Analytical methods can be quite useful and, in the case of high cost, highly complex products, the only affordable method for measuring the reliability of the design. For example, one-of-a-kind satellites often cannot be thoroughly tested at the product level, leaving analysis as the most reasonable measurement method. Many of the analytical methods used are the same ones applied during the design of the product. Testing, however, is generally considered to be the most definitive method of measurement.

3.5.2 **Benefits**. The basic benefit of measuring the product reliability is to establish a high level of confidence that the customer needs have been met. This provides assurance to external and internal customers that a further commitment to initiate production or accept delivery can be made. Another benefit is that if the measurement is unacceptable, a decision to produce or accept the product can be deferred until corrective action can be taken. This is an inefficient means of achieving a reliable product, but it may be preferred over accepting an undesired level of reliability.

3.5.3 **Timing**. Measurement of the reliability of the product should occur after the design is complete. Iterative types of analysis and testing, where applicable, should have already occurred in reaching a mature final design. The measurement is often a precursor to a decision to commit to production or to accept the product. However, the pressures to build and deliver products according to schedule constraints often force a short-sighted decision to proceed, even though the reliability measurement is less than desired. If this is the case, the resources spent in measurement would have been more effectively spent on RGT earlier in the program. In almost any scenario, resources are more effectively spent in designing in reliability, rather than in any form of measuring it.

3.5.4 **Application Guidelines**. Analytical methods that can be used for reliability measurement can include reliability predictions, FMEAs, and FTAs. Testing, however, is the most effective means to determine whether the customer (or self-imposed) quantitative reliability requirements have been achieved. Table 15 provides guidance on analysis and testing methods that can be applied to measure reliability.

Table 15: Measuring Product Reliability - Application Guidance

Test Type	Application Guidance
Accelerated Life Test	Can be applied at the part, assembly, or product level. Accelerated tests provide an effective means of measuring reliability in a shortened test time, but accelerating factors and representative failure mechanisms should be thoroughly understood in order for the measured reliability to be relevant.
Durability Assessment	Perform as a measurement task only if required by the nature of the product, and only if durability analysis was not applied earlier in the development of the product.
Failure Modes, Effects & Criticality Analysis (FMECA)	Measures are qualitative, in that they allow a "measurement" of the consequences and criticality of potential product failures.
Failure Reporting, Analysis & Corrective Action System (FRACAS)	Not a preferred method for measuring product reliability, but a thorough data collection system can capture data to analytically assess in-process and end-use reliability. Useful when formal testing is impractical.
Fault Tree Analysis (FTA)	Measures are qualitative, in that they allow a "measurement" of the consequences and criticality of potential product failures.
Life Cycle Planning	Effective planning of the product life cycle should include the measurement of product useful life at strategic points. Measurements should begin, as appropriate, during the part selection process to achieve high confidence in critical items. Measurements at higher levels of assembly, or of software, should be economically balanced between analysis and test tasks.
Predictions	When properly applied, predictions can be effective in noncritical products, or when testing is impractical (cost/schedule). Risk is involved, since the product does not explicitly experience environmental stresses.
Product Reliability Assessment Test (PRAT)	Use only when justified by the number of units to be produced. Use test environments, stresses and stress levels that simulate the expected operational environment. A modified RQT for production purposes, typically on a sample basis, may be used to measure the reliability of products being shipped. An expensive measurement technique.
Reliability Demonstration Test (RDT)/Reliability Qualification Test (RQT)	Use on designs that represent the approved production configuration, prior to a decision to start production. Use test environments and stress levels that simulate the end-use environment. Test is appropriate when there is a challenge to the state-of-the-art, when the use environment is severe, or when product operation is critical and production volume is high. Test plans should be consistent with program constraints. A costly, but high confidence test.
Reliability Growth Test (RGT)/Test Analyze and Fix (TAAF)	Perform on prototype equipment or software before any designs have been finalized. Time and funding should be available to correct design deficiencies. Use for measurement purposes only when growth is important and RQT can't be run separately. Measurement of reliability is contrary to inherent purpose of RGT.
Sneak Circuit Analysis (SCA)	Represents only a qualitative measurement and, therefore, is of limited value as a measurement tool. Proper application of SCA as a design and assessment tool should minimize its impact as an appropriate measurement technique.

> *Insight*
>
> *Effective test planning and implementation requires that:*
>
> - *The physical configuration of the product should be known.*
> - *The product should be representative of the design (development test) or the production version (demonstration test).*
> - *The test environment and stresses should be realistic.*
> - *The test set-up should not affect product performance.*
> - *Procedures, set-up, conditions, results, etc., should be documented so that measurements can be verified, failures reproduced, test conditions recreated, and corrective actions confirmed.*

> *Notes for Nondevelopmental Items*
>
> *In general, tasks within this area are not applicable, although previous test data or other evidence of measured reliability could be made available. Inspection can be used to assess the product quality. Qualification tests can be used to validate the ability of the product to operate in a different environment.*

Table 15: Measuring Product Reliability - Application Guidance (Cont'd)

Test Type	Application Guidance
Test Strategy	Develop the test strategy to suit the characteristics of the product and the market. For simple low cost products, testing may not be appropriate. For highly complex, safety-critical items, testing may be the only high confidence measurement that is appropriate.
Worst Case Circuit Analysis (WCCA)	Represents only a qualitative measurement and, therefore, is of limited value as a measurement tool. It can be effective in measuring the degree of product "robustness".

Selecting and designing specific test plans are the essence of tailoring as applied to testing. RQT tailoring involves selecting a test plan with the appropriate confidence for the intended results: the higher the confidence, the longer the test and the higher the cost. In all cases, *failure* should be precisely defined before testing begins. The definition should be appropriate for the product. For example, failures of a product with built-in-test capabilities might include false failure indications that would have resulted in loss of function or an unnecessary maintenance action.

While not as effective as testing for reliability measurement purposes, analyses are often the only practical way to determine if design goals/requirements are met. Sometimes the only measurement is from initial feedback from customer operational use or warranty returns. Obviously, an approach like this risks customer dissatisfaction and potential costly recalls. Like testing, the analyses that can be used to measure reliability can vary significantly in type and scope. For example, typical measurements address a numerical value of reliability such as MTBF, but the results of an FMEA or FTA showing that the impact of potential failures is not a safety concern, may be equally important. Not all reliability measurements are quantitative in nature.

3.6 Ensuring Reliable Performance

3.6.1 **Purpose**. The purpose is to plan and implement actions that will, over the entire product life cycle, ensure that the product approaches its inherent design reliability, and that the reliability of the product does not degrade. Table 16 describes those tasks considered most relevant in ensuring reliable performance.

Table 16: Tasks Relevant to Ensuring Reliable Performance

Tasks	Purpose
Critical Item Control	Allows the supplier to track individual items that, due to high cost, limited availability, or low reliability, are critical to the success of the product. Control factors can include identification of new or additional vendors, development of alternative technologies, or product modifications to eliminate the critical items.
Design of Experiments (DOE)	Provides a mechanism for evaluating corrective action alternatives resulting from unacceptable manufacturing process variability, or unexpected failures during product use. DOE results can restore process control or identify necessary product modifications.
Environmental Characterization	Should only be necessary if the conditions of the intended use environment change, including customer usage profiles. Changes may occur as the product penetrates new markets, and may require some product redesign to retain original inherent reliability.
Environmental Stress Screening (ESS)	Precipitates failures resulting from design flaws or workmanship defects at the level of assembly applied (module, board, assembly, equipment, etc.) before the product is delivered to the customer.

Table 16: Tasks Relevant to Ensuring Reliable Performance

Tasks	Purpose
Failure Modes, Effects and Criticality (FMECA)	Results can be used as an aid to troubleshooting failures and identifying necessary repairs and/or corrective actions.
Failure Reporting Analysis and Corrective Action (FRACAS)	Repository for in-process and customer usage failure information which can be used to identify root failure causes. Feedback allows correction of problems with current product or preliminary planning for next generation products.
Inspection	Ensures, through physical examination, that no physical defects exist which would make the product unsatisfactory for the customer (loose/missing hardware, scratches, broken pieces, etc.), or increase safety/liability risk. Inspection defects may not immediately affect reliable performance, but could after the customer receives/uses it.
Life Cycle Planning	Based on customer usage failure data, it should allow for replacement or modification of appropriate parts/assemblies to restore or extend the life of the product.
Market Survey	Provides feedback from the customer regarding levels of satisfaction, areas for improvement, etc., which can be used to ensure that performance reliability meets customer needs and approaches the inherent reliability.
Parts Obsolescence	Allows the supplier to identify and react to obsolete or diminishing supply parts by locating suitable replacements, exercising lifetime buys, or investing in new technology.
Production Reliability Acceptance Test (PRAT)	Ensures that products being delivered to customers demonstrate the ability to achieve the inherent reliability during normal customer use. Applied to 100% of delivered products or on a sample basis.
Repair Strategy	Accounts for the amount of detail required in operating and repair procedures, who will perform the repair (customer or supplier) and the skill level or proficiency of personnel performing the repair.
Statistical Process Control (SPC)	Identifies whether manufacturing process variability is in control, or out of control, and whether failures are random or special cause (correctable).
Supplier Control	Ensures that the supplier is receiving quality parts from vendors that retain the level of reliability inherent in the original product design. It should also allow the supplier to retain an adequate number of vendors for each part supplied.
Test Strategy	Defines and plans for tests that should be performed at the appropriate points in the product life cycle to ensure that failures introduced as a result of workmanship defects, manufacturing process flaws, or handling are eliminated before the product is delivered to the customer.

3.6.2 **Benefits**. The primary benefit of these tasks is a greater degree of confidence that the expected level of product reliability can be maintained once the product is introduced into the marketplace. This benefit can translate into a higher degree of customer satisfaction, which can result in larger market share, particularly when the inherent reliability of the product represents "best in product class" performance. Suppliers can leverage this higher level of confidence into several potential competitive/strategic advantages, including longer warranty periods, lower repair facility costs, and a lower cost of ownership for the customer.

3.6.3 **Timing**. Tasks that ensure reliable product performance must be planned well in advance of their implementation in order to be effective. Planning of product warranties, test and repair strategies, and a comprehensive failure reporting system, and their effects on life cycle cost, should be addressed as an integral part of the Concept/Planning phase of the product. In addition, ensuring reliable product performance is based on the definition and understanding of a product's intended environmental and usage profiles, which should be initiated during this phase. Manufacturing processes, and the means to control them, should begin to be defined as part of a concurrent engineering effort in the product Design/Development phase. Also, during this phase, the failure reporting system should be introduced and used by the design/manufacturing team to capture and correct relevant product and process problems. The failure reporting system is an important tool throughout the remaining phases of the product life cycle. During the Production/Manufacturing phase, techniques such as design of experiments (DOE) and statistical process control (SPC) can be applied to control and improve manufacturing processes by reducing process variability. The warranty program, if one is used, is implemented prior to initial shipment of the product, requiring that all activities associated with the supplier's repair strategy be put into place during the Production/Manufacturing phase, before products begin to be built, in order to maximize repair efficiency. Activities associated with part obsolescence and diminishing resources cannot necessarily be anticipated, but must be considered beginning with the part selection/application process during Design/Development, and continuing through the Production/Manufacturing and Operation/Repair phases. As the product line approaches Wearout/Disposal, the supplier may want to consider modifications to the product, using new available technologies, that will potentially improve the performance of the existing product (i.e., product replacement), or extend its useful life beyond what was originally designed in.

3.6.4 **Application Guidelines**. Ensuring that a product will achieve reliability performance that approaches its inherent reliability begins with an accurate assessment and understanding of its end-use environment and the way in which the product will be used by customers. Once understood, the task elements that will accomplish this can be planned and implemented. The primary tasks that may be considered include those listed in Table 17. It should be noted, however, that the depth to which a supplier chooses to apply any or all of these tasks should reflect the nature and complexity of the product, given the supplier's business strategy and competitive market conditions.

Notes for Part Suppliers

Focus should be on good failure reporting practices, DOE, SPC, and control of materials suppliers in order to maintain or improve process yield levels

Table 17: Ensuring Reliable Performance - Application Guidelines

Tasks	Application Guidance
Critical Item Control	As the product life cycle evolves, the supplier should monitor and adapt to potential changes in the list of critical items. Diminishing sources of parts/assemblies may require items to be added to the list. Improvements in reliability performance may allow items to be removed from the list.
Design of Experiments (DOE)	Use as part of the continuous process improvement effort to identify/solve "special cause" failures or pattern failures. DOE can also be used to identify process modifications which may allow the implementation of tighter process tolerance limits (narrower specifications).
Environmental Characterization	Design modifications should only be considered if the new application environment is more severe then the original. If necessary, supplemental cooling, conformal coating of PC boards, or adding vibration/shock isolation can restore the original inherent product reliability.
Environmental Stress Screening (ESS)	Stress screening should be applied, where cost effective, at each level of assembly susceptible to workmanship defects, process errors, or "induced" failures. The ESS levels should not precipitate failure mechanisms that are not expected during normal customer use, and they should not use up an excessive amount of the total product useful life.
Failure Modes, Effects and Criticality Analysis (FMECA)	The results of the FMECA can be used as a troubleshooting tool to efficiently identify failed parts/components during repair. This helps to eliminate or minimize incidents of incorrect repair or replacement, which can decrease the probability of additional failures being induced.
Failure Reporting, Analysis and Corrective Action System (FRACAS)	Use to determine whether product reliability is improving, remaining constant, or degrading based upon data collected during design, manufacturing, or actual consumer use (failure trend analysis). The system should also track the identification and implementation of corrective actions to eliminate the effect of failures on the inherent design reliability of the product.

Table 17: Ensuring Reliable Performance - Application Guidelines (Cont'd)

Tasks	Application Guidance
Inspection	Inspections to ensure reliability performance should look for loose or missing hardware, improper seating of connectors and printed circuit boards, signs of wear on mechanical parts, signs of wear or damage to seals/O-rings/etc., broken parts, or extraneous material (foreign objects, chemical residue, etc.).
Life Cycle Planning	Planning and implementation of warranties communicates to the customer the level of confidence that the supplier has in the reliability of its products. A strategy should be developed that encompasses planned action at the end of the product life cycle, such as product redesign, product replacement (next generation), or service life extension (prolong the useful life of the product).
Market Survey	Feedback from customers should be solicited as a means of measuring actual product performance in relation to meeting customer reliability needs. The survey should encompass both quantitative and qualitative levels of satisfaction. Deficiencies in product performance identified in the survey should be integrated into the failure reporting and corrective action system.
Parts Obsolescence	Obsolescence/diminishing resource issues can be a factor at any point in the product life cycle. Ensuring reliable performance implies the implementation of a strategy to counteract obsolescence issues including lifetime buys, investment in new parts or technology, tracking the availability of critical items, and/or demonstrating adequate control over vendors.
Production Reliability Acceptance Test (PRAT)	This test ensures that the quantified level of reliability for each product being shipped meets the required level of reliability for the product (i.e., meets the customer need). This is one of the most expensive and reactive methods for ensuring reliable performance, so is less desirable than the other tasks identified.
Repair Strategy	Should define the suppliers approach to having the product repaired (supplier vs. customer), including how, when, and where the repairs will be performed. The ability to maintain inherent design reliability depends on the amount and quality of data in repair procedures; the level and training of repair personnel; and the quality of replacement parts/assemblies.
Statistical Process Control (SPC)	Statistically-based control charts should be used to ensure that any process which could have a negative impact on inherent product reliability is in control, or whether "special cause" failures (or patterns of failure) exist which indicate the process is out of (or losing) control.
Supplier Control	Should maintain strong relationships with vendors, regardless of whether there is one, a few, or many vendors per item. Control of incoming parts quality may be left as the vendor's responsibility, or may be reinforced by inspection/testing at the supplier's facility, depending on vendor commitment to quality processes and continuous improvement.
Test Strategy	Tests should be selected based on their ability to ensure that process defects or errors are eliminated. Tests should not be performed which do not ultimately add value for the customer. There are no tests at the product level which will improve its' inherent reliability.

Warranties. While product warranties may not have a direct impact on ensuring reliable performance, their use communicates to the market the level of quality or performance for which the supplier is willing to accept liability. Although suppliers may (commercial) or may not (government) include the cost of the warranty in the product cost, the expressed or implied penalties for not meeting the warranty provisions can become quite severe in terms of costs, liability, or public relations. Since warranty periods are typically established based upon expected reliability performance which, in turn, should be based on the product design reliability, there should be a strong incentive for suppliers to strive to control their processes in order to ensure that product performance matches the customers needs (and the basis for the warranty). Suppliers should also recognize that warranties can be used as a means for obtaining or retaining a competitive advantage in the market by differentiating their products from their competitors. In order to successfully accomplish this, the supplier must be able to accurately quantify the expected performance of the product to position it within its associated niche in the market.

Notes for Nondevelopmental Items

Environmental stress screening may be used to eliminate potential latent defects. Short term warranties may be appropriate.

Lesson Learned

A cookbook approach can result in a program that is expensive and adds little value. Each product development effort must be considered individually, and then only those tasks that "fit" the effort should be made part of the reliability program.

SECTION FOUR - TAILORING A RELIABILITY PROGRAM

Defining a reliability program is a process that must be tailored to the customer's needs, product characteristics, and market conditions. Depending on many variables, a supplier may include or exclude any or all of the tasks mentioned in this Blueprint. To help the reader in this tailoring process, Table 18 includes suggestions of how some program tasks might be effectively tailored. The content is intended to be a headstart in the tailoring process, and should not be applied as a cookbook set of tasks to be used without thought. The table includes a classification of suppliers by product characteristics considering the technology, unit cost, safety implications, and production quantities of the product(s) they develop and manufacture. It relates the various supplier-product combinations to the five major issues confronted in the definition of a reliability program. For each classification and program objective, the applicable nature of the activity as it applies is briefly discussed, and some recommended solutions for meeting the purpose are identified.

SECTION FIVE - REFERENCES

The references in Table 19 provide additional information on the subjects discussed in this Blueprint. The relationship between the reference and sections within the Blueprint are indicated in the table for each source.

Table 18: Program Activity Characteristics and Guidelines for Supplier-Product Classifications

	Product Classification	Product Characteristics				Program Issue	Program Activity Characteristics/Guidelines
		Tech-nology	Unit Cost	Quan-tities	Safety Concerns		
GENERAL PUBLIC	Passive Items • Dry goods • Books • Handtools • Furniture	Low	Low	Large	None to Low	Reqmts	Customer doesn't specify requirements; suppliers determine quality goals through surveys, competitor benchmarking, warranty data, etc.
						Design	Reliability may not be addressed as a separate function but as part of product quality. High safety margins used.
						Assess	No separate reliability analyses usually apply. Warranty data and experience tracked.
						Measure	For products in which quality is driver, none. For others in which service life is a consideration, analysis, test, or both can be used.
						Ensure	Market dictates length of service. Overdesign typical.
	Consumer Products • Appliances • Power tools • Cameras • Computers • Electronics	Low to Mod.	Mod.	Mod. to Large	Low to Mod.	Reqmts	Supplier determines requirements based on customer needs. Tailors to warranty requirements and competitive comparable products.
						Design	Limited reliability practices (derating, etc.) used. Life testing often used.
						Assess	Predictions and modeling possibly beneficial.
						Measure	Some safety testing may be required by law. Some environmental testing may be appropriate. RQT usually not appropriate.
						Ensure	Short term warranty and ESS testing may be appropriate.
	Consumer Durables • Automobiles • Boats	Mod.	Mod. to High	Mod. to Large	Low to High	Reqmts	Reliability program recommended with allocated goals.
						Design	Product quality and price prime drivers. Small number of design teams with few members. Material selection and processes used are important. Life considerations important.
						Assess	Predictions and modeling should be used. FMEAs should be performed. DOE an effective tool and FEA used for mechanical integrity. Significant testing used to assess progress.
						Measure	More extensive environmental and some developmental testing usually appropriate. Growth and life testing selectively performed.
						Ensure	Warranty and service contracts applicable. Environmental stress screening may be beneficial.
INDUSTRIAL	Passive Items • Dry goods • Books • Handtools • Furniture	Low	Low	Large	None to Low	Reqmts	Customer doesn't specify requirements; suppliers determine quality goals through surveys, competitor benchmarking, warranty data, etc.
						Design	Reliability may not be addressed as a separate function but as part of product quality. High safety margins used.
						Assess	No separate reliability analyses usually apply. Warranty data and experience tracked.
						Measure	For products in which quality is driver, none. For others in which service life is a consideration, analysis, test, or both can be used.
						Ensure	Market dictates length of service. Overdesign typical.
	Light Equipment • Computers • Printers • Engines • Recorders	Low	Mod.	Large	Mod.	Reqmts	Customer may specify requirements for unique needs. Most goals internally developed for market.
						Design	Quality, service life, material selection, parts control and environment are typical concerns.
						Assess	Modeling usually done to scope design and understand interdependencies. Predictions possibly needed. Thermal analysis, FMEA, FTA should be considered.
						Measure	Development testing may be effective for high quantities and severe operations.
						Ensure	Statistical process control important to control variability.
	Heavy Equipment • Elevators • Escalators • Boilers • Transformers	Low to Mod.	Mod. to High	Mod.	Mod. to High	Reqmts	Translation of customer expressed needs to design specs needed. Surveys, QFD, & competitor benchmarking often beneficial. Government safety requirements common. Allocation of requirements usually required. Comprehensive reliability program recommended.
						Design	Although quality important, service life is a driver. Few to many design teams with many members. Consequences of failure must be controlled.
						Assess	Modeling is important and FMEA/FTA used to understand failure consequences. Safety, availability & operating costs very important. Customer may require specific analyses.
						Measure	Safety testing common. Customers may require formal demonstrations. Some simulation may be appropriate.
						Ensure	Warrantees apply; ability to repair is important; failure reporting is strongly recommended. ESS often used.

Table 18: Program Activity Characteristics and Guidelines for Supplier-Product Classifications (Cont'd)

	Product Classification	Product Characteristics: Tech-nology	Unit Cost	Quan-tities	Safety Concerns	Program Issue	Program Activity Characteristics/Guidelines
INDUSTRIAL	Industrial Systems • Aircraft • Railroad engines • Satellites • Medical equip.	High	High	Small to Mod.	High to Critical	Reqmts	Risks need identification, trade analysis may be needed. Allocation of requirements may be needed.
						Design	Derating, thermal control, shock and vibration isolation are important considerations. Safety and periods of failure free operation may be required.
						Assess	Dormancy and FEA analysis may be considered for extreme conditions.
						Measure	Qualification test may be considered. Growth and Life Test recommended.
						Ensure	Obsolete parts and wearout are a concern. Audits and inspections are useful. Consider ESS at lower assembly levels.
CONT'D	Structures Facilities • Bridges • Train tracks • Airports • Building power plants • Chemical plants	Low to High	High	Small	High	Reqmts	Requirements include tolerance to earthquakes & violent weather. Extremely long service life requirements.
						Design	Service life and safety essential. Reliability is important as it supports these requirements. Few to many design teams.
						Assess	FEA, DOE, and additional analyses can be beneficial. Materials selection critical.
						Measure	Only analysis of entire structure is feasible. Extensive model testing & simulation usually effective.
						Ensure	Periodic safety inspections or performance audits.
MILITARY	Passive Items • Uniforms • Food • Helmets • Desks • Dry goods	Low	Low	Large	None to Low	Reqmts	Customer doesn't specify requirements; suppliers determine quality goals through surveys, competitor benchmarking, warranty data, etc.
						Design	Reliability may not be addressed as a separate function but as part of product quality. High safety margins used.
						Assess	No separate reliability analyses usually apply. Warranty data and experience tracked.
						Measure	For products in which quality is driver, none. For others in which service life is a consideration, analysis, test, or both can be used.
						Ensure	Market dictates length of service. Overdesign typical.
	Small Weapon Systems • Rifles • Radios • Munitions	Low to High	Mod.	Large	Low to High	Reqmts	Customer usually specifies field reliability requirements in his terms, translation to design specifications needed. Allocation of requirements usually needed. Reliability program recommended.
						Design	Parts and material selection important. Many design teams with many members. Conservative safety margins used. DOE valuable.
						Assess	Predictions usually performed, and sometimes FMECAs. RGT effective in maturing design prior to large-scale production.
						Measure	Government-mandated formal demonstrations common. Sample testing may be effective in production.
						Ensure	Statistical process control valuable. FRACAS is a must and ESS should be considered.
	Critical Weapon Systems • Radars • Tanks • Aircraft engines • Smart munitions	High	High	Small to Mod.	High to Critical	Reqmts	Comprehensive program required. Customer specifications need to be translated and allocated. Requirements need to be flowed-down to subs.
						Design	System must be modeled. Part and material application critical to success. Thermal design important.
						Assess	Predictions and FMECAs necessary. Environment assumptions must be valid. FEAs and DOE usually performed.
						Measure	Developmental component, subsystem, and some product-level testing should be required. Model testing and simulation may be beneficial. Growth and life testing are recommended.
						Ensure	Warranties and part obsolescence should be considered. Repair and service strategy important. ESS should be used at various levels of assembly.
	Strategic Weapon Systems • Ships • Aircraft • Satellites • Submersibles	High	High	Small	High to Critical	Reqmts	Extensive allocation of requirements to subsystems and components required. Risks need identification. Trade analysis should be performed. Comprehensive program required.
						Design	Safety and periods of failure-free operation are big drivers. Parts control, derating and thermal design tasks apply. Modeling and predictions are necessary.
						Assess	Predictions and FMEAs usually performed. SCAs and WCCAs for especially complex designs in severe environments. Emphasis on safety. FEA effective also.
						Measure	Extensive and rigorous environmental and proof testing effective. Some form of RQT appropriate. PRAT test may be needed.
						Ensure	Periodic or continual audits and/or inspections may be beneficial. ESS at various levels of assembly is recommended. Lifetime extension often required.

Table 19: References for Product Reliability

References	Blueprint Sections					
	Program 3.1	Goals 3.2	Design 3.3	Assess 3.4	Measure 3.5	Ensure 3.6
Accelerated Testing, W. Nelson, John Wiley & Sons, 1990	X			X	X	X
Assurance Technologies: Principles and Practices, Dev G. Raheja, McGraw-Hill, 1991	X		X	X	X	X
Benchmarking Commercial Reliability Practices, Ned Criscimagna, RAC, 1995		X	X	X		
Business Process Reengineering or Quality Improvement, R. Wanner & J. Franceschi, RAC, 1995	X	X		X		
DoD Directive 4245.7: Transition From Development to Production, 1985	X		X		X	
Introduction to Concurrent Engineering, N. Fuqua, RAC, 1992	X	X	X			
Mechanical Reliability, A.D.S. Carter, John Wiley & Sons, 1986	X		X	X	X	X
MIL-HDBK-189: Reliability Growth Management, 1981	X			X	X	
MIL-HDBK-338: Electronic Reliability Design Handbook, 2 Vols., 1982		X	X	X	X	
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Parts Selection, Application and Control, N. Fuqua, W. Denson & J. Farrell, RAC, 1993			X		X	
Practical Reliability Engineering, P.D.T. O'Conner, John Wiley & Sons, 1985	X		X	X	X	X
Product Reliability, Maintainability, and Supportability Handbook, ed. by M. Pecht, CRC Press, 1995	X		X	X	X	
RAC Thermal Management Guidebook, P. MacDiarmid & R. Unkle, RAC, 1995		X	X	X		
Reliability Engineering for Electronic Design, N. Fuqua, Marcel Dekker, 1986	X		X	X	X	X
Reliability Engineering Handbook, D. Kececioglu, 2 Vols., Prentice-Hall, 1991	X			X	X	
Reliability Toolkit: Commercial Practices Edition, RAC, 1995	X	X	X	X	X	X
Reliability, Maintainability and Supportability Guidebook, SAE G-11 Committee, 1995	X	X	X	X	X	X
RL-TR-93-209: A Quality Process Approach to Electronic System Reliability, 2 Vols., Rome Lab, 1993		X	X	X		X
Service Life Extension Assessment, N. Criscimagna & R. Unkle, RAC, 1995				X		X
The New Weibull Handbook, R. Abernethy, Gulf Publ. Co., 2nd, ed., 1994			X	X	X	
Total Quality Management Toolkit, A. Coppola, RAC, 1993				X	X	
Tutorial Notes from Annual Reliability & Maintainability Symposium	X	X	X	X	X	X
Understanding Industrial Designed Experiments, 2nd Ed., S. Schmidt & R. Launsby, Air Academy Press, 1989	X					X