HP DATA SYSTEMS

[redacted]

RELIABILITY

HEWLETT PACKARD

RELIABILITY MANUAL

HEWLETT-PACKARD DATA SYSTEMS DIVISION

NOTICE

5950-3735

? ? WHAT DOES RELIABILITY MEAN TO YOU ? ?

"FLEXING SMOOTHLY, GIANT WING SPAR
STRENGTH BEYOND THE STRESS BY FAR
UP ABOVE THE WORLD SO HIGH
FLYING SAFELY THROUGH THE SKY"

Anonymous

"THE MOST NERVE-WRACKING PART OF THIS SPACE FLIGHT IS THE FACT THAT MY LIFE DEPENDS ON THOUSANDS OF CRITICAL PARTS, EACH PRODUCED BY THE LOWEST BIDDER"

Quip By An Astronaut

RELIABILITY IS A DIFFICULT AND VEXATIOUS ART. IT CAN BE TAUGHT AND IT CAN BE NUTURED. PEOPLE CAN IMPROVE THEIR SKILLS WITH EXPERIENCE, BUT JUST AS IN ANY ART, IT CANNOT BE LEGISLATED, IT CANNOT BE CONTROLLED BY PROCEDURE, AND NO ULTIMATE DESIGN MANUAL CAN BE WRITTEN. RELIABILITY MUST BE LIVED AND BREATHED BY EVERYONE CONCERNED IF IT IS TO BE ACHIEVED.

Anonymous

KNOWING IS NOT ENOUGH; WE MUST APPLY.
WILLING IS NOT ENOUGH; WE MUST DO.

Goethe

HP DATA SYSTEMS RELIABILITY CREED

Optimum reliability and product value originates with design decisions, is maintained through application of controlled production processes, is critically dependent on reliability of components, and must be monitored constantly to assure continuing success.

Reliability oriented design practices are critical factors in maximizing reliability within the functional and cost objectives required to provide a commercial product with maximum value to our customers.

The intrinsic reliability of a good design can be seriously reduced through failure to follow design documentation and/or to maintain controlled production processes.

Continuing success for both design and production reliability contribution depends on recognizing that many factors are involved, with each subject to potential change at any time. These changes may not be corrected in a timely manner unless there is a feedback system capable of providing information to promote prompt definition of abnormal conditions. Feedback must cover all factors involved including vendor reliability, production processes, and most important, field performance in our customers' applications.

As an HP Data Systems Team Member, I understand our reliability objectives together with the part I can play in achieving them. I am proud of the products shipped, and wish to contribute towards the continuing optimization of their reliability and value to our customers.

PREFACE

This manual provides Hewlett-Packard Data System Division with a document covering many of the reliability considerations associated with the development, marketing, production, and field support of products that provide a maximum value to HPDS Customers.

The Reliability Manual is designed to serve the following purposes:

- Develop an understanding of "Reliability" in terms of practical considerations and without the need for an extensive background in statistical mathematics.
- Assist HPDS personnel in relating the impact of their personal work activities on the reliability of HPDS Products, and to set their individual objectives accordingly.
- Promote the continuing development and improvement of Division Programs designed to enhance the reliability and value of HPDS Products.
- Provide information serving the needs of HPDS Customers wishing to acquire knowledge concerning HPDS Reliability Attitudes and Activities.

Jim Gillette,
Mgr. Quality & Reliability Engineering,
Hewlett-Packard Data Systems Division

May 1977

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1.0 PURPOSE

This manual will provide readers who are not working directly in the field of reliability engineering with a general understanding of the practical considerations associated with developing and maintaining product reliability, and will outline the program followed by HP Data Systems Division to provide guidance for setting and achieving objectives in this area.

This manual is available to employees and customers of HP Data Systems Division as well as others having an interest in understanding HP Data Systems approach to optimizing product value and reliability.

The manual is not designed to serve the interests of readers wishing to explore theoretical or statistical concepts associated with reliability. Appendix A provides a recommended reading list for those who wish to study the subject in greater depth.

2.0 ORGANIZATION OF THE MANUAL

This manual is arranged in three major sections and an appendix:

UNDERSTANDING RELIABILITY REQUIREMENTS (Section 3) is designed to promote a better understanding of the actions involved in achieving an optimum balance between product reliability, value, and cost.

Paragraph 3.2, titled Prerequisite For Product Reliability, is of special interest to management as it provides a comprehensive overview in outline form. Section 5 of the manual relates the subjects of paragraph 3.2 to corresponding actions taken as part of the Data Systems Reliability Program.

RELIABILITY FROM A CUSTOMERS' VIEWPOINT (Section 4) deals with considerations that will aid customers in objectively reviewing the potential reliability of products under consideration for their specific applications.

HP DATA SYSTEMS RELIABILITY PROGRAM (Section 5) is an outline of the reliability program followed by HP Data Systems Division to assure optimum product reliability and customer value.

The outline follows the sequence of subject matter covered in paragraph 3.2 titled Prerequisite for Product Reliability. Specific operating details associated with the subjects outlined are provided by separate documentation as required within each HPDS operating department.

APPENDIX: The appendix contains a list of Reliability Books and Articles together with a reading guide for individuals wishing to explore the subject of reliability in greater depth.

3.0 UNDERSTANDING RELIABILITY REQUIREMENTS

This section of the manual outlines some major factors that must be understood and planned for if optimum reliability levels are to be achieved.

3.1 Reliability Defined

Reliability is the probability of failure free operation within specified performance limits for a given period of time and under defined environmental operating conditions. Reliability is typically expressed as a decimal fraction or as a percentage.

3.2 Prerequisite For Product Reliability

The following list outlines those factors having maximum impact on a manufacturers' ability to achieve a continuing optimum level of product reliability. Section 5 of the manual outlines HP Data Systems' approach in each of these areas.

a. ***Active Vendor Reliability Program:*** Vendors who understand reliability requirements and implement them to assure delivery of components, materials, or process services that are uniformly reliable are considered to be "Reliable Vendors". Reliable component selection is synonomous with reliable vendor selection with few exceptions.

b. ***Use of Parts With Proven Reliability:*** Ultimately reliability depends on the part or component. A simple component from an unreliable vendor (or damaged by faulty manufacturing processes) installed in a key circuit will cause the largest system to fail.

c. ***Reliability Oriented Design Practices:*** This is where it starts; subsequent activities can only maintain or reduce the intrinsic reliability of the design.

d. ***Clear Design Specification Goals:*** This is the roadmap; without it the design may tend to ramble, and rambling designs are noted for potential unreliability.

e. ***Good Design Documentation:*** Yes, engineering can make one; however production's ability to make others depends on following the instructions of the designer. Without instructions, or with incomplete information, the many factors in production serve to redesign the product (intentionally or otherwise).

f. ***Comprehensive Qualification Testing:*** Without this disciplined test program, how do you know the design and subsequent production units will be capable of meeting all specifications claimed?

g. ***Accurate Sales Specifications:*** Specifications generate customer expectations. Products that meet expectations promote happy customers (and profits). Implied specifications are also critical. . . .Would you be happy with an automobile top speed of 50 miles per hour if the speedometer reads to 100?

h. ***Objective Selling:*** Sales efforts must match products to customer application requirements. No single product can cover the extremes of application requirements for that type of product.

i. ***Controlled Production Processes:*** Identify and promote the continuing use of production process methods that contribute effectively to maintaining the intrinsic reliability of the design. Building it to the print is also a good practice.

j. ***Effective Acceptance Testing:*** Do production acceptance tests fully verify that completed products meet all sales specifications? Is there a proper balance between the 100% and sample testing?

k. ***Protective Shipping Methods:*** If reliability efforts have been successful to this point, don't throw reliability away between the factory and customer's site.

l. ***Appropriate Customer Site Preparation Instructions:*** In some types of products, external site factors may be a significant factor in maintaining reliability (or performance) of the installed product. Know when this is applicable, and supply the correct information in a timely manner.

m. ***Clear Installation and Service Procedures:*** Help make the transition from a product in a box to an effective working installation, a happy experience for the customer. Service engineers who stumble through incomplete or inaccurate service data do not create the desired image in the eyes of the customer, nor do they feel inclined to bless the creator of the product and its support information.

n. ***Equitable Warranty Coverage:*** Warranty Coverage protects the customer in those instances where a product has not been delivered free of quality or reliability problems. The less effort directed towards delivering such a product, the longer the warranty period must be to assure customer protection. Long warranty periods result in high warranty costs; and warranty problems tend to lower customer satisfaction levels.

o. ***Appropriate Preventive Maintenance Recommendations:*** Proper preventive maintenance programs will deal with the replacement of those parts with established life characteristics. Replacement as recommended will reduce the risk of unscheduled down time do to preventable failures.

p. ***Trained Customer Service Engineers:*** In spite of all efforts, customers will see failures. Trained responsive service engineers minimize the impact of these failures.

q. ***Readily Available Spare Parts:*** The trained responsive service engineer who must explain "how long it will be before he can get the customer back on the air" has lost all his customer appeal. Reliability of the replacement part is also of vital importance. This is especially true where replacement is made at the assembly (Printed Circuit Board) level. Boards that have been awaited anxiously, and which fail on installation or shortly thereafter, do nothing to promote customer happiness.

r. ***Continuing Feedback On Performance In All Areas:*** Without feedback in terms of Field Warranty Information, Internal Production Failure Patterns, etc. there will be no means of detecting a smoldering problem, only those that burst into full flame. Feedback systems promote knowledge of normal conditions. This is a good reference point from which to depart if one looks for the smoldering problems; or wishes to reduce the cost of many fire fighters beating the bush for problems and devising means for smaller feedback loops. Everyone knows you need data before you can attack a problem.

s. ***Prompt Correction Of Problems:*** This is a nice thing to do. It reduces manufacturing costs and improves customer dispositions. Everyone should want to help with this.

3.3 Setting Reliability Objectives

Reliability Objectives are typically stated in terms of desired MTBF. Two fundamental approaches are applicable to setting reliability goals:

a. ***Establish Achievement of Stated MTBF as the Objective*** and apply the design and reliability engineering technology needed to achieve it. This approach sets MTBF as a primary factor and cost considerations as a secondary factor.

b. ***Establish Primary Objectives in Terms of Product Functions and Marketability Factors*** — approach reliability optimization by application of reliability oriented design, production, and serviceability practices throughout the product life cycle.

The approach outlined in (a) is seldom applied to a product developed for sale in a competitive commercial market. This approach is applicable to a limited number of military or space oriented applications, and some high volume consumer products.

The approach outlined in (b) is applicable to all products; and the successful application of it will result in products having a maximum value through an optimum balance between functional capabilities, initial cost, mean time between failure, and ease of service.

Ultimate success depends on taking advantage of all possible opportunities to improve reliability through design optimization and production process control as required to assure no reduction of the intrinsic reliability of the design. It follows, that those companies willing to understand and utilize these opportunities will be in the best position to maximize the value of their products.

MTBF Objectives Under Approach (b) can be established using demonstrated experience with equipment of similar functional complexity, or the preceeding generation of a product family. The natural evolution and improvement in component manufacturing technology will provide some degree of improvement in each new product; hopefully this will offset the higher risks associated with any new technology components introduced with the new design.

In Summary: Each new product should be expected to reflect an increase in MTBF over any functionally equivalent product in current production, and selling for a comparable price.

3.4 Reliability Relationships

From the definition of reliability in 3.1, it follows that MTBF and Reliability are not synonomous terms. Before exploring their relationship, it might be helpful to consider definitions for MTBF and Failure Rate.

a. ***MTBF:*** (Mean Time Between Failure) — is a statistical value that reflects the average * hours of operation between failures as measured on a sample group of units when operated for an extended period of time. For example: If 100 units were operated for 6 months with an average monthly use of 347 hours (16 hrs. per day; 5 days per week) and 50 failures were observed, the following MTBF computation could be made.

(100 units) × (347 hrs.) × (6 months) = (208,200 operating hrs.)
(208,200 operating hrs.) / (50 failures) = (4164 hrs. MTBF)

This does not imply that each unit failed every 4164 hours. It is highly probable that many of the units completed the full six months without failure; and others failed several times. The underlying reason for this is the chance distribution of a small percentage of parts that will fail. Consider 4000 parts per unit (400,000 total) and the 50 failures (.0125% of total parts); in the extremes, one of the 100 units could have received all 50 of the parts; or 50 of the units could have each received 1 of the parts. The actual distribution is governed by chance.

b. ***Failure Rate:*** (The Reciprocal of MTBF) — is also a statistical value. It is the average* fraction failing observed per hour of operation.

In the example, dividing the 50 failures observed by the 208,200 hours shows an average of .00024015 failures per hour (a very small number). For convenience this can be expressed in failures per 1000 hours, failures per million hours, etc. The most commonly used term is percent per 1000 hours (this is the same as failures per 100,000 hrs.).

Example:

.000240 failures per hour = .240000 failures per 1000 hours (failures per hr. × 1000); to convert to percent multiply by 100 giving 24.015% per 1000 hours.

---

*Average, as used in this text, is defined as the arithmetical mean unless otherwise noted.

Failure rate is convenient when combining the failure rates of components, assemblies, products, etc., to determine the total failure rate of the combination. If the failure rates per hour are known for each item they can be added to arrive at the total failure rate per hour. With the total failure rate per hour known, the reciprocal will be the MTBF of the combination in hours.

Example:

10 products, that make up a system, have a combined failure rate of .00125 Failures Per Hour (125% per 1000 Hours). The reciprocal (1/.00125) is 800 hours; or the MTBF is 800 hours for the system.

c. ***Reliability is related to MTBF by the following generally accepted formula.*** The formula assumes that the failure rate (or MTBF) is at a constant value. *The following terms are used:*

P_s = Probability of surviving (having no failures). It is typically left as the decimal fraction between 0 and 1, but may be converted to percentage by multiplying by 100 if desired.

e = Base of natural logrithms (e = 2.7182818. . .)

t = The period of operating time of interest. It is typically in hours, but may be in any time units (months, weeks, days, etc.) providing the same time unit is used for "m".

m = The MTBF of the product in the same time unit as (t).

$P_s = e^{-t/m}$ (× 100 if percent probability is desired).

Example:

How reliable will products having an MTBF of 4000 hours be in surviving 7 days of operation (168 hours)? In this example, it is assumed the products are accessible for service on a weekly basis.

$P_s = e^{-168/4000} = .95886$ (95.87% reliable).

In other words, the weekly service check will find products operating normally about 96 times out of every 100 weekly checks.

Suppose the same question were asked for a situation in which the service check must be made on a monthly basis (every 728 hours)?

$P_s = e^{-728/4000} = .8336$ (83.36% reliable).

What is the probability that products will survive a period of time equal to the MTBF?

$P_s = e^{-4000/4000} = .36787$ (36.79% will survive)

How reliable will they be in completing an 8 hour working day without failure?

$P_s = e^{-8/4000} = .99800$ (99.8% reliable)

d. ***Unreliability vs Reliability:*** Where reliability is involved there are two possible outcomes; success or failure. The sum of reliability and unreliability must always equal one.

P_s = Reliability (success)

P_f = Unreliability (failure)

$P_s = (1 - P_f) \times 100$ (if stated as a percentage)

$P_f = (1 - P_s) \times 100$ (if stated as a percentage)

e. ***Redundancy*** is a method of improving reliability by providing multiple (parallel) paths for success.

When working with redundant elements, there are two rules that will be of assistance. These involve the treatment of elements in series (failure of one results in total failure), and elements in parallel (failure of both are required to cause total failure).

Elements in Series: P_s for the total series is the product of the individual P_s for each element in the series.

$P_{sT} = P_{s1} \times P_{s2} \times P_{s3} \ldots$ etc.

Elements in Parallel: P_f for the total elements in parallel is the product of the P_f for each of the elements

$P_{fT} = P_{f1} \times P_{f2} \times P_{f3} \ldots$ etc.

With either P_f or P_s known, the other term may be found by subtracting the known term from 1.

Example: (See Figure 3.4A)

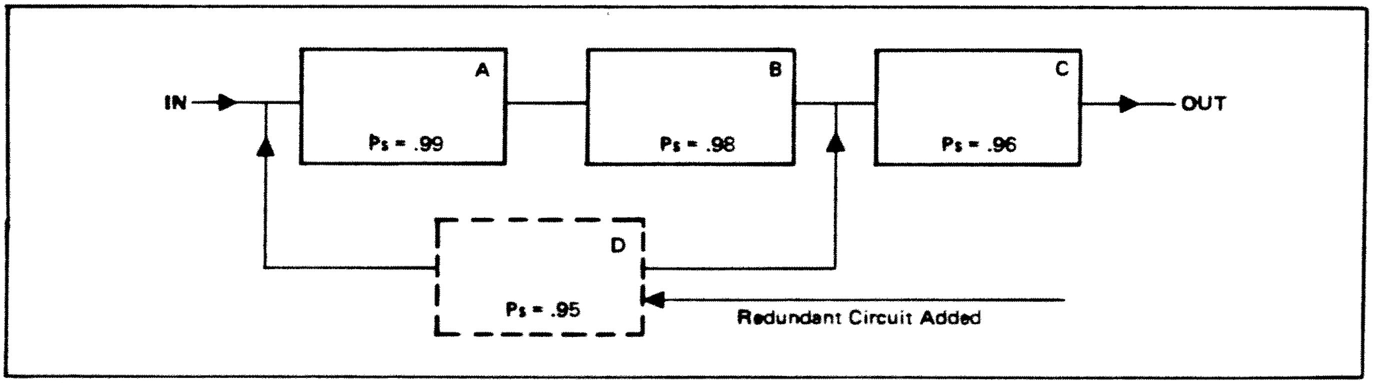
If elements in series will be paralleled; first step is to determine their combined P_s. Convert this to P_f and combine with the P_f of the element that will be in parallel. If this combination is then in series with another element, convert the parallel P_f to P_s and combine with the P_s of the additional series element. These steps are illustrated below in figure 3.4A.

In figure 3.4A, the P_s for elements A, B, C and D have been determined from their individual MTBFs and the reliability time (t) that is of interest.

$P_s = e^{-t/m}$

The time period (t) of interest is 24 hours and the MTBFs' of elements A, B, C and D are 2388, 1188, 588, and 468 hours, respectively.

Figure 3.4A. Reliability Improvement Through Redundancy



P_s for AB and C in Series = .99 × .98 × .96 = .9313 *(93.13%)*

Placing D as a redundant circuit in parallel with A and B requires the following expanded computation.

$$Ps_{(ABC+D)} = \underbrace{\underbrace{\left(1-\underbrace{\left(\underbrace{(1-.95)}_{(1)} \times \underbrace{(1-\underbrace{(.99 \times .98)}_{(2)})}_{(3)}\right)}_{(4)}\right)}_{(5)} \times (.96)}_{(6)} = .95856 \ (\underline{95.86\%})$$

Steps To Solve

1. Coopute P_f for D
2. Compute P_s for A and B in series
3. Compute P_f for A and B in series
4. Compute P_f for A and B in parallel with D
5. Compute P_s for A and B in parallel with D
6. Compute P_s for A, B and D in series with C = Answer

Note the 2.73% improvement in reliability generated over the initial A, B, C in series combination: *95.86%* vs *93.1%*

3.5 Mechanics of Failure

Mechanics of failure is a complex subject and dealing with it fully is beyond the scope of this manual. The following simplistic presentation will serve to promote a practical understanding of value to the reader in relating to other elements of the subject of reliability.

For our purposes, the mechanics of failure will be presented on the basis of stress versus strength relationships. *Stress factors* are those external forces that must be tolerated by the part or component throughout its life; this includes the shelf storage period prior to installation as well as subsequent periods of operating and non-operating time. Typical examples of stress factors include: heat, vibration, voltage application, humidity, shock, cold, condensation . . . etc. *Strength* is a characteristic of the part or component that permits it to resist a range of stress without degredation of any strength characteristic. The *strength characteristics of any given component type* will vary with each stress it must resist. There is no signal value of strength. As an example: consider the stresses that must be resisted by a typical integrated circuit. The external package must have strength to protect the internal elements against the penetration of moisture; the internal lead bonds must have strength to resist vibration and shock without separation; the internal circuit elements and metalization must have strengths to resist degradation by the normal voltage application and current flow to be encountered in the circuit. Within the component type, the *strength characteristics of any individual component* are determined by design, and by the quality levels of the materials, workmanship, and processes used in producing it.

Failures Occur When the applied stress exceeds the available strength to resist the stress. Example: the internal lead bond was imperfect; and the applied vibration in shipping the assembly caused the lead to separate. The external package of the IC was not moisture sealed to the normal degree; and operation under high humidity caused corrosion within the circuit, and early life failure. The degree of overlap (where stress exceeds strength) may be slight or great. If it is slight, the rate of degradation may be slow; and the result is a failure later in the life of the part. If the overlap is great (part was seriously defective), the failure may occur immediately following the application of normal circuit stress factors.

This subject will be discussed further under Infant Mortality and Reliability Screening (Paragraph 3.6).

There are three basic failure classifications of interest:

a. ***Degradation Failures:*** In this type of failure, the strength characteristic changes (degrades or weakens) with the application of stress over a period of time. Prior to point of failure, one of two things happens: the rate of diminishing strength accelerates and a catastrophic failure occurs; or the part characteristics change such that it will not support normal operation in the application.

b. ***Random Failures:*** In this type of failure, the strength characteristics do not degrade over a period of time. The actual failure will occur when a random set of circumstances develop; and the failure will be catastrophic in most cases. The application of various levels of stress will affect the probability of a failure; but short of failure, these stresses will not change or degrade any characteristic of the item.

c. ***Wearout Failures:*** In this type of failure, it has been pre-established that usage of the part will result in a gradual deterioration of the part strengths. Ultimately, this wear will result in the part becoming unsuitable for use; and as the part strengths deteriorate during use, there is increasing probability of random failure due to chance conditions.

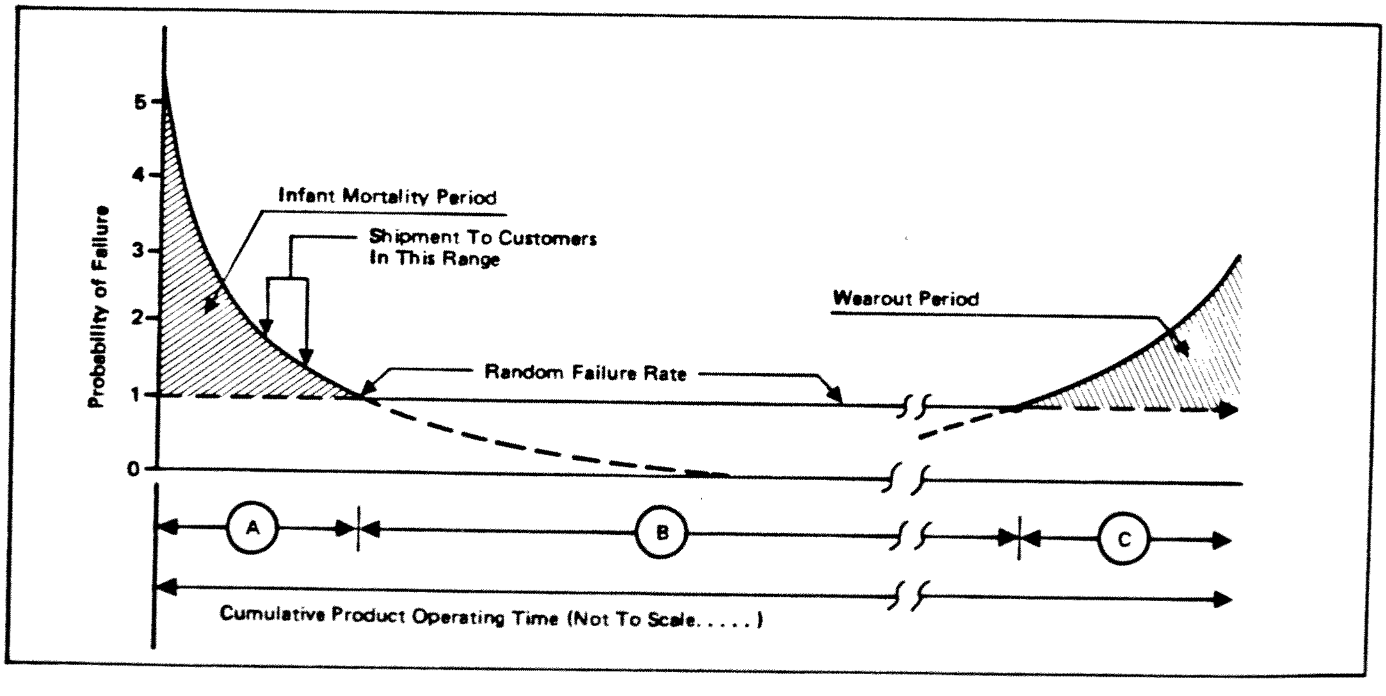
Parts susceptible to wearout are usually scheduled for regular inspection to determine wear, or are scheduled for replacement as part of the Preventive Maintenance Program for a product.

Failure Mechanisms vs Product Life Periods:

We are all intuitively familiar with three basic periods in the life of a product; and in fact these same periods are applicable to the life of each of us. To illustrate, we can consider ourselves as having just taken delivery of a new automobile; we intuitively feel that it would not be comfortable to immediately take off on a long journey. We would much prefer to accumulate a few hundred (or thousand) miles of troublefree performance before such a trip. Following this "Infant Mortality" period, we feel quite sure there are no major problems, and proceed to enjoy many thousands of miles of driving even though there is some chance of a "Random Failure". Following years of use we again become apprehensive, in terms of reliability on a long trip, as we anticipate that wear has taken a toll and failure is just around the corner ("Wearout Failure").

The following diagram is often referred to as the "Bathtub Curve". It depicts the risk of failure on the vertical axis, and time on the horizontal. Three "Product Life Periods" have been defined and will be discussed with respect to the predominating type of failure.

Figure 3.5A. Typical Bathtub Curve



The first type of failure to be considered is the Random Failure. This is basic to all parts and components, and is common to all three periods (A-B-C) of 3.5A. It is presumed to be constant throughout the time periods, and may be considered as the area below the dotted line in A and C, and under the solid line in B. The period "B" is defined as the Useful Life of the product and typically is many tens of thousands of hours in length for electronic products. For all practical purposes it will extend well beyond the period of time by which the product will have been replaced for reasons of obsolescence.

When the failure rate per unit of time is constant, the terms Failure Rate and MTBF are applicable; and the discussions in Sections 3.4 are valid in terms of the MTBF vs Reliability Relationships.

The second type of failure is depicted by the shaded area in period (A) of the curve. This is defined as the "Infant Mortality Period", and is typically very short when compared to the useful life period (B). As indicated, products are delivered to customers with some degree of residual infant mortality. The start of (A) begins when the product has been assembled and operates properly for the very first time under factory test conditions. Any operation in the factory or by the customer then becomes part of (A).

During this period, the failures caused by the residual imperfections in parts or components used will occur. The normal stress levels of the product will tend to exceed the available strengths of the imperfect parts; and as time is accumulated, there will be a few additional failures. As the failed items are replaced with good parts the product risk of failure approaches the constant value per unit of time as shown in period (B).

Use of the term "Failure Rate" when considering period (A) is improper. When the failure rate is not a constant value, the risk of failure is referred to as the "Hazard Rate". If the shape of the curve is known (this is possible using reliability test data) it is possible to establish the number of expected failures by integration of the curve between two selected points in time. Having integrated the period for number of failures, and having established the length of the period as the difference between the two time points on the Hazard Rate Curve, it becomes possible to arrive at an average MTBF value by dividing the time period by number of failures. Having done this, and confining considerations to relatively short time periods, it is possible to use the principles of Section 3.4, recognizing that the average MTBF established is equivalent to the MTBF of a product having a constant failure rate over this period of time.

The third type of failure is depicted by the shaded area in period (C). Period (C) is the end of life, or wearout period. Note that the constant failure rate level of period (B) still exists for the majority of parts or components in the product; however, some portion of the parts or components may have physical wear (in case of moving mechanical parts), or limited life (such as indicator lamps, etc.). As this end of life period approaches, these parts must either be replaced following inspection for wear limits, or replaced on a specific time interval basis, in order to maintain the constant failure rate level for extended periods of time. When handled properly, these limited life items will be well identified, and scheduled for inspection and replacement as part of the Preventive Maintenance Program for the product.

Since wearout failures are preventable by maintenance; they must not be treated as having an MTBF value based on normal wearout characteristics. In addition to normal wearout characteristics, there is the potential for infant mortality degradation failures, and also the probability of chance type failures (random failures). When establishing the overall MTBF of a product, the MTBFs of these parts are treated on the basis of the Random Failure Rate, and not wearout. As an example: the brushes on an electric motor may have a useful life of 2000 hours. The same brush may have a random failure rate that is equivalent to an MTBF of 500,000 hours and would be treated as a 500,000 hour part in establishing the basic MTBF of the product.

3.6 Infant Mortality And Reliability Screening

Infant mortality is a fact of life; it exists because of abnormal weakness in the strength values of a part or component characteristic. The result is some small percentage of the parts have strength characteristics falling below the normal range of variation for the part. When these parts see the normal application stresses, which will exceed the available strength to varying degrees, the result is a failure.

The time required to bring about failure is unknown, and depends on the degree of overlap between stress and strength. If the overlap is large enough, the failure will probably occur during factory testing. If it is only slight, the failure may require several hundred hours of operation.

Infant Mortality is the result of process variability, or poor process control, on the part of component manufacturers. If each raw material used contained no impurities, if each step of the production process is precisely controlled at all times, if testing and handling of the items assured no abnormal stress, etc., there would be no reason for infant mortality.

The basic strength characteristics would distribute about the normal mean value with a very small variation. This is an idealistic view; and we must accept and deal with the real world.

Methods used to reduce the impact of product Infant Mortality include the following:

a. Basic testing by the manufacturer of a product, followed by a period of operation intended to precipitate infant mortality failures, and a final performance test prior to shipment.

   The operating period used to reduce infant mortality is difficult to determine. If operation is at normal room temperature it may take several hundred hours to reduce infant mortality to a negligible value.

b. Same principle as (a) except for acceleration of time by operation at elevated temperature. The allowable temperature for a product will be considerably below the value required for effective component screening. For example: typical Integrated Circuit reliability screening dictates operation of the IC at 125°C for a period of 168 hours. With typical components the product "upper operating temperature limit" may be as low as 55°C. Using the temperature acceleration factors for TTL and DTL ICs, as listed in MIL-HDBK-217B, it would require 12 hours at 55°C for every hour at 125°C for purposes of causing the same probability of failure.

c. Procurement and use of Pre-Screened parts. These are available at an added cost, and are typically produced under strict process control including several specific reliability screening processes.

d. Some product manufacturers elect to pre-screen parts at the component level, or to route the parts to firms specializing in component reliability screening.

   A good general compromise is to identify the critical few components that contribute the majority of failures. In general, less than 10% of the component types will contribute from 50% to 80% of the total failures. These parts are very good candidates for either procurement of high rel parts, or for pre-screening processes.

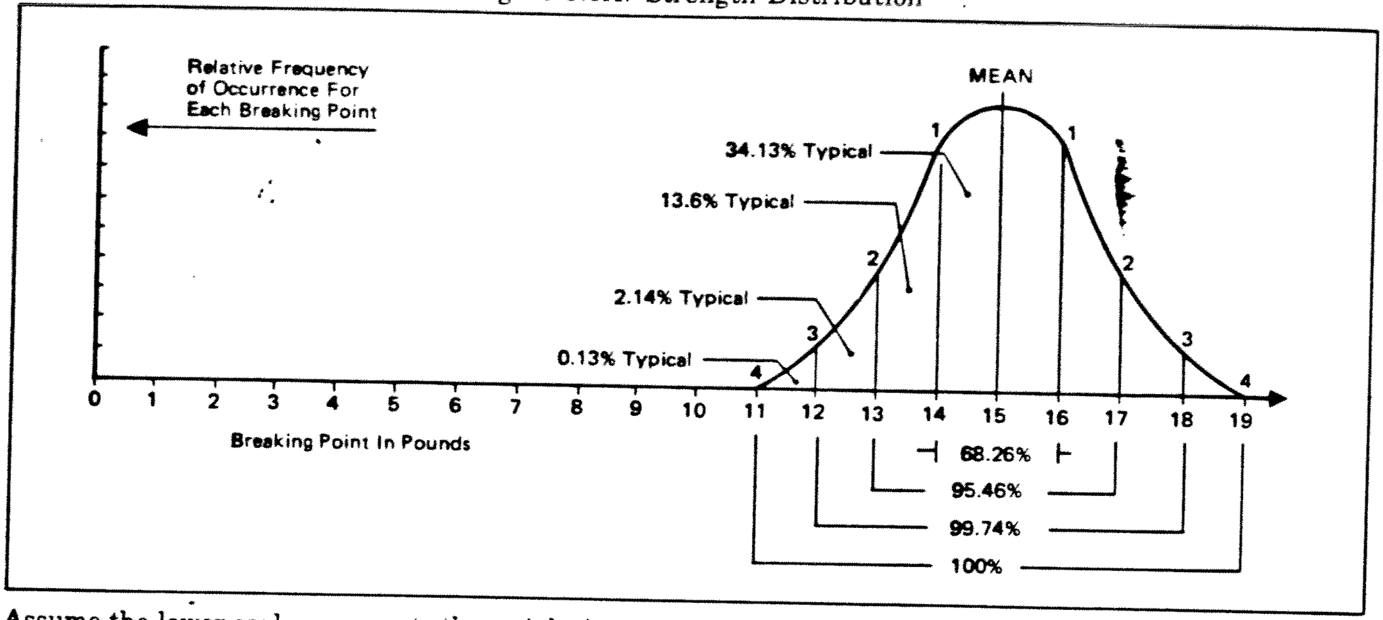
e. By default, time alone will take care of the problem. There are a limited number of infant mortality prone parts distributed by chance among the thousands of parts used. The probability of any given product having one is relatively small. If the manufacturer follows good testing programs, and includes a significant number of hours of operation as part of the production process, it may be better to risk a few warranty repairs in place of processing 100% of the products through a screening program. The added cost of screening must be reflected in the selling price of the product.

Reliability Screening Of Components

Prior to preceding with this subject, an understanding of the meaning of the terms Distribution of Strengths, Distribution of Stress, and the concept of an overlap between them is essential.

Strength Distribution can be illustrated by a simple example. In this example, we will test the breaking point of a population of rubber bands. The test setup consists of an anchor point for one end of the band, and a means of adding weight in small increments until the band breaks. Following each breaking of a band, we will record the weight required to break it. The greater the number of bands broken, the more confidence we will have that we know the mean strength level for the band population, and the variation in it (the percentage of the population that is above and below this value), as well as the range of values associated with these percentages. Presume we have tested several thousand bands and have processed the data to arrive at the "normal distribution" for this population. This can be represented by Figure 3.6A.

Figure 3.6A. Strength Distribution



Assume the lower scale represents the weight in pounds required to break the band. The vertical scale is not important but it represents the relative number of times the breaking point (strength limit) occurred at that value. The vertical lines bracketing the percentage values represent the standard deviation intervals (1) through (4) starting from the mean and going in each direction.

The percentage numbers show the percent of the band population having strengths within the deviation interval. This interval shows both plus and minus variation; one half of the percentage will be above and below as shown.

From this observation we can predict that rubber bands chosen from this population will safely support loads from 1 to 10 pounds (if the production process used remains constant). If we apply the bands to a situation that requires them to support weights above 10 pounds, there will be some problems. If the weights go as high as 14 pounds, we can expect some band failures. The number can be computed if we know the distribution curves for the stress (range of weights to be supported) and the strengths (per curve shown). The stress curve would have a similar shape and can be visualized as the same curve moved horizontally to the left along the same scale. If our stress distribution curve started with a lower value of 16 pounds, it would be obvious that rubber bands from this population are not suited for the intended application.

Control must be based on statistical samples. If we were to test all rubber bands made, we would have a final and true distribution of the population, but would have none left to use for any practical purpose. We must recognize the importance of controlling production processes, even for rubber bands, so that when we choose to test a sample from the population it has a high probability of reflecting the characteristics of the population.

Suppose the producer of rubber bands does not have good process control. The end result will be a wider variance range and possibly a shift in the mean value. If we were to test several thousand bands it would not be improbable that some very small number would break at lower values (2 to 11 pounds for instance) while the vast majority would still fall in the distribution shown.

What we now have is an example of infant mortality (bands breaking in range of 2 to 10 pounds); and we can introduce the concept of *Reliability Screening*. We face some *fundamental considerations* as follows:

a. We can use the bands as received and let the weak ones break as they will. . .normal infant mortality.

b. We can apply a known stress level (weight) that will break the weak bands without damaging the good bands. In this case we might choose a weight of 13 pounds recognizing that it will break some small percentage (approx. 2.27%) of normal bands in addition to the weak ones. Presuming the upper limit of distribution of weights to be supported is 12 pounds, placing the reliability screen above this value will assure a small safety margin.

c. The reliability screen used must be compatible with the type of weakness to be removed. For instance we might decide to screen the bands by placing them in moisture for a period of time. . .possibly the use of vibration. . .heat runs. . .etc. The importance of matching the screening stress to the predominant mode of failure cannot be over emphasized.

A more practical illustration of this applies to integrated circuits where the outer case may not be sealed against humidity within normal distribution limits. If we decide to screen these parts by placing them in a high temperature oven, we would not accelerate the failure mode; in fact, we would temporarily stop any progressing-deterioration by driving the moisture out of the part with heat.

Once an appropriate reliability screen is selected, it must be applied to 100 percent of the components (never use on a sample basis). In some instances, components may require screening for several modes of failure. This is a complex process, and should be undertaken only when full control of the process is possible. The following summary outlines essential elements:

Reliability Screening Consideration Summary

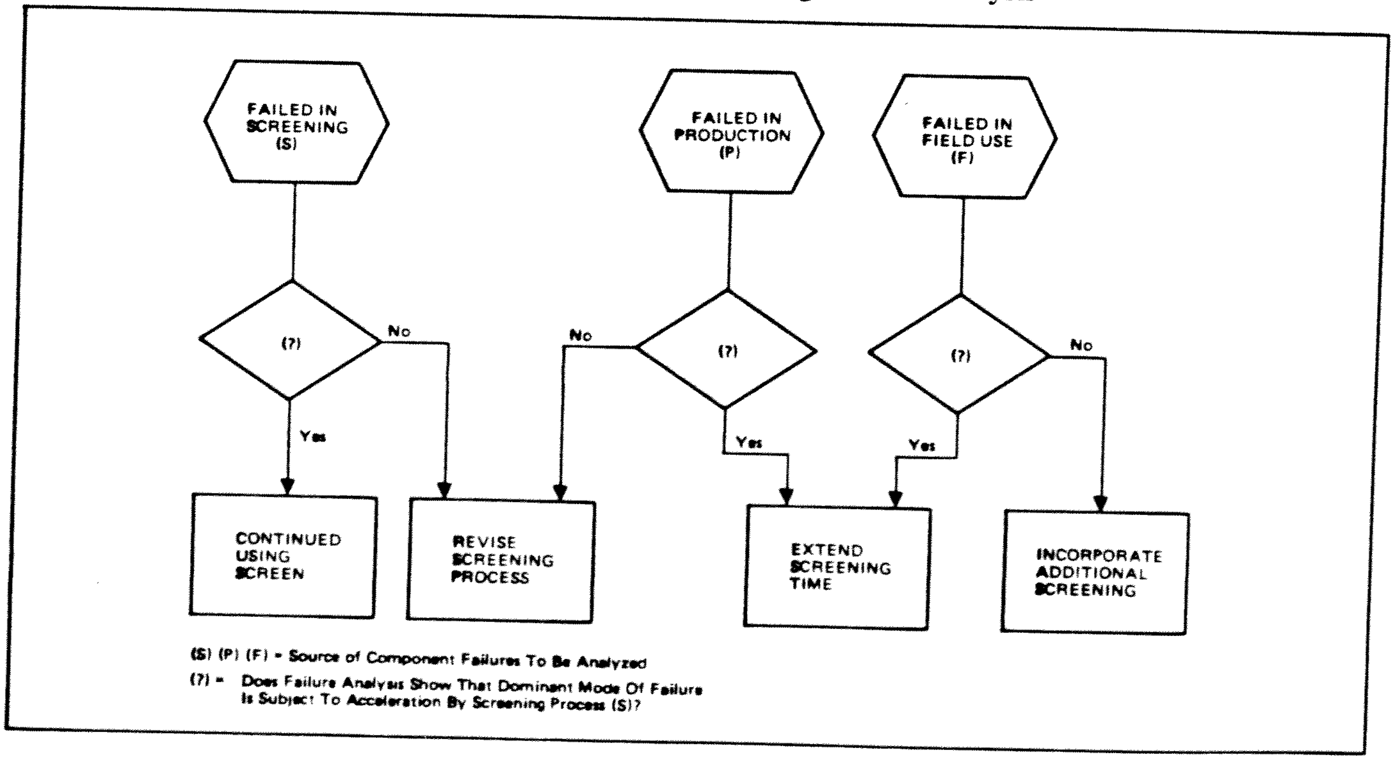
a. Normal distribution of strengths for the characteristics involved in the predominant modes of failure must be known.

b. Screening stresses selected for use must work to accelerate the predominant mode of failure, and must be of such degree as to not overstress the normal population strengths.

c. Screening cannot continue without feedback, and be effective. Adjustment in time spent screening and types of screening may be necessary. The following example illustrates the need for this feedback. See Figure 3.6B.

A reliability screening operation is integrated into a routine manufacturing process. Components failing during the screen, during production test, and during field use of the product are available for failure analysis. The "*Question*" asked in the diagram is "*Is the predominant mode of failure accelerated by the stress used in reliability screening?*"

Figure 3.6B. Reliability Screening Process Analysis



3.7 Reliability Versus Application Stress Level

Whenever an overlap exists between applied stress and the strength of a part or component characteristic, two possible conditions will exist with respect to the probability of failure.

a. The applied stress will exceed the energy level required to activate a degradation process associated with the characteristic under stress. The degree by which the stress exceeds the strength will determine the elapsed time required to bring the part to a point of failure.

b. The applied stress interacts with the available strength to set up conditions where there is a distinct probability of failure due to random conditions within the part or component; however, short of chance failure, there is no gradual degradation such as exists per (a).

For simplicity, we have related the preceeding statements to a single implied characteristic of a part or component. Under actual stress conditions, there are several characteristics under simultaneous different types of stress (heat, voltage, power, etc.) with each stress acting as discussed.

Whenever the stress level is applied to the part, the conditions outlined in (a) and (b) will exist. During the Infant Mortality period the majority of the failures are due to condition (a).

Condition (b) is predominant during the useful life period of the product, and results in a relatively constant failure rate during this period. The actual rate being a function of the type and degree of stress applied to the part or component.

Optimizing Stress Levels During Design is vital to the overall reliability of the product. It is very important for the design engineer to be fully aware of the critical stresses for each component used and how they affect the failure rate.

The three critical stresses are: Operating Ambient Temperature, Internal Power Dissipation, and Voltage Stress Level. While it is not possible to provide comprehensive design data in this manual, Figures 3.7A, B, and C from MIL-HDBK-217B serve to illustrate the relative effect of these parameters on the base failure rate factor. Paragraph 3.8, under Mathematical Models for Reliability Calculation, discusses how the several factors are combined to arrive at an overall failure rate for a given set of conditions. Stress Level, as illustrated, is just one of the factors used.

Sources of Stress Level Effect Data include RADC Notebook II and MIL-HDBK 217B.

Component Quality Level Impact on Reliability, together with the interaction of design stress decisions, is illustrated by Figure 3.7D.

Component strength distributions are shown for three quality situations. High Reliability components, (HR) in 3.7D, have a narrower dispersion of strength due to the fact that a majority of the weaker components have been screened out of the lots, and also due to the very tight controls under which the components are produced. Commercial quality, with normal content of infant mortality prone items, is illustrated by the (CN) distribution curve. Here we have a significantly greater number of the weaker parts. From time to time, the vendor supplying commercial quality components may permit a larger than normal number of weak components to become part of the items sold. This is indicated by the lower distribution (CB), indicating an occasional "Bad Lot" of parts.

The scale used (0 to over 100%) is applicable to both the strength and stress distributions. The 100% point signifies the value chosen, by the component supplier, as the maximum rated stress allowable. Notice that the majority of the distribution falls well above this value. The upper limit, for strength distributions, is determined by the design and manufacturing technology used to produce the item.

Figure 3.7A. Fail Rate vs Stress
Fixed Film Resisters

MIL-R-22684 & MIL-R-39017 RESISTORS, FIXED, FILM, (INSULATED)
BASE FAILURE RATES, λ_b

T	RATIO OF OPERATING TO RATED WATTAGE									
(°C.)	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0011	.0013	.0014	.0016	.0017	.0019	.0021	.0023	.0026	.0029
5	.0012	.0013	.0015	.0016	.0018	.0020	.0022	.0024	.0027	.0030
10	.0012	.0014	.0015	.0017	.0019	.0021	.0023	.0026	.0028	.0032
15	.0013	.0014	.0016	.0017	.0019	.0022	.0024	.0027	.0030	.0033
20	.0013	.0015	.0016	.0018	.0020	.0023	.0025	.0028	.0031	.0035
25	.0013	.0015	.0017	.0019	.0021	.0024	.0026	.0029	.0033	.0037
30	.0014	.0016	.0018	.0020	.0022	.0025	.0028	.0031	.0035	.0039
35	.0015	.0016	.0018	.0021	.0023	.0026	.0029	.0033	.0037	.0041
40	.0015	.0017	.0019	.0021	.0024	.0027	.0031	.0034	.0038	.0043
45	.0016	.0018	.0020	.0022	.0025	.0029	.0032	.0036	.0041	.0046
50	.0016	.0018	.0021	.0024	.0027	.0030	.0034	.0038	.0043	.0048
55	.0017	.0019	.0022	.0025	.0028	.0032	.0036	.0040	.0045	.0051
60	.0018	.0020	.0023	.0026	.0029	.0033	.0038	.0043	.0048	.0054
65	.0019	.0021	.0024	.0027	.0031	.0035	.0040	.0045	.0051	.0058
70	.0020	.0022	.0025	.0029	.0033	.0037	.0042	.0048	.0054	.0062
75	.0020	.0023	.0027	.0030	.0034	.0039	.0045	.0051	.0058	
80	.0022	.0025	.0028	.0032	.0036	.0041	.0047	.0054	.0061	
85	.0023	.0026	.0030	.0034	.0039	.0044	.0050	.0057		
90	.0024	.0027	.0031	.0036	.0041	.0047	.0053			
95	.0025	.0029	.0033	.0038	.0043	.0050	.0057			
100	.0026	.0030	.0035	.0040	.0046	.0053				
105	.0028	.0032	.0037	.0043	.0049	.0056				
110	.0030	.0034	.0039	.0045	.0052					
115	.0031	.0036	.0042	.0048						
120	.0033	.0039	.0045	.0052						
125	.0035	.0041	.0048							
130	.0038	.0044	.0051							
135	.0040	.0047								
140	.0043	.0050								
145	.0046									

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Figure 3.7B. Fail Rate vs Stress
Silicon NPN Transistors

MIL-S-19500 TRANSISTORS, GROUP I, SILICON, NPN
BASE FAILURE RATE, λ_b, IN FAILURES PER 10^6 HOURS

T	$S = \frac{\text{Operating Power (mw)}}{\text{Maximum Rated Power (mw)}}$									
(°C)	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0034	.0041	.0048	.0057	.0067	.0079	.0095	.011	.014	.018
10	.0038	.0046	.0054	.0064	.0075	.0089	.010	.013	.017	.023
20	.0043	.0051	.0060	.0071	.0084	.010	.012	.015	.020	.029
25	.0046	.0054	.0064	.0075	.0089	.010	.013	.017	.023	.033
30	.0048	.0057	.0067	.0079	.0095	.011	.014	.018	.025	
40	.0054	.0064	.0075	.0089	.010	.013	.017	.023	.033	
50	.0060	.0071	.0084	.010	.012	.015	.020	.029		
55	.0064	.0075	.0089	.010	.013	.017	.023	.033		
60	.0067	.0079	.0095	.011	.014	.018	.025			
65	.0071	.0084	.010	.012	.015	.020	.029			
70	.0075	.0089	.010	.013	.017	.023	.033			
75	.0079	.0095	.011	.014	.018	.025				
80	.0084	.010	.012	.015	.020	.029				
85	.0089	.010	.013	.017	.023	.033				
90	.0095	.011	.014	.018	.025					
95	.010	.012	.015	.020	.029					
100	.010	.013	.017	.023	.033					
105	.011	.014	.018	.025						
110	.012	.015	.020	.029						
115	.013	.017	.023	.033						
120	.014	.018	.025							
125	.015	.020	.029							
130	.017	.023	.033							
135	.018	.025								
140	.020	.029								
145	.023	.033								
150	.025									
155	.029									
160	.033									

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Figure 3.7C. Fail Rate vs Stress Tantalum Capacitors

MIL-C-3965 & MIL-C-39006 Capacitors, Tantalum,
Non-Solid, Base Failure Rate λ_b

	S, RATIO OF OPERATING TO RATED VOLTAGE									
T(°C.)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	.0042	.0047	.0059	.008	.012	.018	.026	.037	.051	.069
5	.0043	.0047	.0060	.008	.012	.018	.027	.038	.052	.070
10	.0044	.0048	.0061	.009	.013	.019	.027	.039	.053	.071
15	.0044	.0049	.0062	.009	.013	.019	.028	.039	.054	.073
20	.0046	.0050	.0064	.009	.013	.020	.028	.040	.056	.074
25	.0047	.0052	.0065	.009	.014	.020	.029	.041	.057	.077
30	.0048	.0053	.0068	.009	.014	.021	.030	.043	.059	.079
35	.0050	.0055	.0070	.010	.015	.022	.031	.044	.061	.082
40	.0052	.0058	.0073	.010	.015	.022	.033	.046	.063	.085
45	.0054	.0060	.0076	.011	.016	.023	.034	.048	.066	.089
50	.0057	.0064	.0080	.011	.017	.025	.036	.051	.070	.094
55	.0061	.0067	.0085	.012	.018	.026	.038	.054	.074	.100
60	.0065	.0072	.0091	.013	.019	.028	.041	.058	.079	.106
65	.0070	.0078	.0098	.014	.020	.030	.044	.062	.085	.115
70	.0076	.0084	.0107	.015	.022	.033	.048	.068	.093	.125
75	.0084	.0093	.0117	.016	.024	.036	.052	.074	.102	.137
80	.0093	.0103	.0130	.018	.027	.040	.058	.083	.114	.152
85	.0105	.0116	.0147	.021	.031	.045	.066	.093	.128	.172
90	.0120	.0133	.0168	.024	.035	.052	.075	.106	.146	
95	.0139	.0154	.0195	.027	.040	.060	.087	.123	.170	
100	.0164	.0182	.0230	.032	.048	.071	.103	.145	.200	
105	.0197	.0218	.0276	.039	.057	.085	.123	.175		
110	.0242	.0268	.0339	.048	.070	.104	.152	.214		
115	.0304	.0336	.0425	.060	.088	.131	.190			
120	.0391	.0433	.0547	.077	.114	.168	.245			
125	.0517	.0572	.0723	.102	.150	.223				

Establishing Component Failure Rates is the most difficult part of MTBF calculations. For each type of component there is a basic failure rate as a function of operating temperature. This rate is further adjusted by multipliers for such things as circuit application stresses, product environmental stress, and general quality levels achieved by component suppliers. The last factor is the largest, and also is constantly fluctuating due to vendor process and quality assurance variations.

Testing to Establish Failure Rates is not practicable for the majority of commercial production operations. Many components have normal MTBF values of 1,000,000 hours (0.1% per 1000 hrs.) and it would require millions of hours of test time to establish the true failure rate with any reasonable degree of confidence.

In lieu of this type of direct testing, testing is often done at two elevated temperatures (one test at 150°C and one at 125°C for example) using parts from the same population. Processing of the failure and test data generated can expose the activation energy levels which in turn can be used to extrapolate the failure rates at other operating temperatures. Testing of this type has contributed greatly to the development of mathematical models which permit good approximation of component failure rates.

Mathematical models provide one of the better methods of setting component failure rates. These are based on a combination of empirically fitting math models to observed failure data in combination with engineering judgments and known laws of science.

Two of the more accepted sources of this type of information are RADC* Notebook II, and MIL-HDBK-217A (217B has recently been released). Both of these documents were developed to support Military Requirements for this type of information.

An Example of how the general principles are used is illustrated by the following computation of failure rate for a digital microcircuit having a dual expander function. The factors used in the example are taken from RADC Notebook II.

(F) = [(B) × (C) × (P) × (E) × (Q)] = Total Fail Rate in % Per 1000 Hours

(B) = Base failure rate in % per 1000 hours. This value is a function of temperature. For the example: the following formula establishes (B).

$(B) = 0.981\ e^{-2298/T}$ e = Base of Natural Logrithms 2.7182818
T = Absolute Junction Temperature

(C) = Complexity Adjustment Factor. For the example, the factor for a dual expander = (2)

(P) = Package Type Factor = (2) for this example.

(E) = Environmental Use Factor = 2 for ground fixed operation, = 5 for ground portable, = 10 for missile. Ground fixed is presumed for the example and the factor is (2).

(Q) = Vendor Achieved Quality Level = 1 for optimum screened parts, = 2 for upper grade quality, = 15 for average grade and up to 30 for lower grade. Upper grade is presumed for the example and the factor is (2).

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Computation of Failure Rate

Case temperature in operation is presumed to be 40°C; and a 10°C rise is assumed for a junction temperature (T) of 50°C. This is 323° absolute (273°C × 50°C = 323°K).

$$(B) = 0.981\ e^{-2298\ 323} = .0007977\%\ \text{per 1000 hours}$$

$$\begin{array}{cccccccccccc}
(F) & = & (.0007977) & \times & (2) & \times & (2) & \times & (2) & \times & (2) & = .012763\%\ \text{per 1000 hrs.} \\
 & & \uparrow & & \uparrow & & \uparrow & & \uparrow & & \uparrow & \\
 & & (B) & \times & (C) & \times & (P) & \times & (E) & \times & (Q) &
\end{array}$$

Conversion to MTBF = $1 \times 10^5/.012763$ = 7,835,148 hours MTBF

This may seem high; however, if we presume the use of 1000 such parts in a product, the failure rate would be multiplied by 1000, and would be 12.763% per 1000 hours. Converting this to a product MTBF yields a value of 7,835 hours.

MTBF Calculations are Intended to Apply to the constant failure rate portion of the product life period. During the infant mortality period discussed in paragraph 3.6, the actual hazard rate is varying as it rapidly diminishes during the very early life of a product. The rate at which it diminishes decreases with time, and extends the tail of the infant mortality period out to several thousand hours. This is not significant, as the major decrease in failure rate will occur within the first few hundred hours; and most of that will be during the test periods preceding shipment to customers.

3.9 Reliability Testing, Poisson Failure Distribution

Several types of testing programs can be considered as forms of reliability testing. Some of the more significant tests include:

a. Testing at the *component level* to establish the *failure rates* and failure modes of electronic components.

b. *Life testing* of mechanical parts to establish the wearout characteristics and relate the data to a *preventive maintenance* program.

c. Product level *reliability qualification testing* may be conducted for the primary purpose of *gathering failure rate data* and detecting major pattern type failures. Qualification testing may also be for the purpose of *assuring a minimum MTBF value* for the product; the majority of the tests included in MIL-STD-781B are designed for this purpose. The variety of test plans covered is necessary for the purpose of balancing the test time considerations with the consumer and producer risk factors. In a test of this type, there is a producer's risk that the test will reject equipment which in fact meets or exceeds the specified MTBF value. There is a similar risk for the consumer that the test may result in acceptance of a product that does not meet the minimum MTBF value. In the test plans the relationship between the minimum value and specified value is called the discrimination ratio.

Preliminary Test Considerations must address the following areas as part of the test planning:

a. What is the *purpose of the test*?. . .To gather general failure rate information?. . .To qualify the product for a minimum MTBF?. . .etc.

b. Under what *environmental conditions* will the test be conducted? Normal ambient temperature, elevated temperature, with power on and off periods, with vibration intervals,. . .etc? MIL-STD 781B provides a well accepted outline of possible conditions under the heading of Test Levels.

c. One of the major considerations is the actual *operating mode to be used* during the test; if at all possible, it should approximate normal operation; short of this, the test should result in operation of as much of the product as possible. Most tests will require both a routine operating mode, and a periodic *complete performance test routine* to detect any failures that would not be found by observation of the routine operating mode.

Definition of Reliability Failures should be well established prior to start of test. The failures to be included will depend on the primary function of the test program. In any case, test plans should include means for recording any type of abnormal behavior. The following are among the types of failures which may occur.

a. *Design Failures* are typically corrected by a change in product design, and will not recur in the remainder of the test period. Design failures are not included as reliability failures when establishing product failure rates.

b. *Pattern Failures* are either synonomous with design failure, or are attributable to a gross problem with the specific part or component involved. This, in turn, translates to a design problem within the part or component, or possibly a production quality problem with the item. If the cause can be positively established as transitory in nature, these failures may be excluded in determining failure rates.

It should be noted that wearout may be the cause of failure; and the solution may be replacement of the item as part of preventive maintenance. When this decision is made, and replacement is scheduled on the basis of elapsed time, operations, or by inspection; the failure may also be excluded.

c. *Infant Mortality Failures* are the most difficult to deal with during the test. In general, the purpose of the test will be to uncover basic problems and to establish the "product failure rate". If the test does not include special burn-in periods, to eliminate infant mortality failures, the MTBF (computed on the basis of test hours divided by Failures) will be misleading if interpreted directly as the normal failure rate.

Infant mortality failures will not be separable from normal random failures unless extensive failure analysis techniques are employed along with considerable judgment.

If care is taken to establish accurate time to failure (hours of operation prior to failure) for each failure, the resulting data can be processed to yield early life hazard rate curves for the product (or component) as a function of cumulative operating time.

d. *Random Reliability Failures* are failures occurring from chance causes, and not identifiable in any other way. These are always reliability failures regardless of the test objectives.

e. *Production Quality Failures* can be identified when failure analysis shows the cause to be improper production workmanship quality (in terms of building or adjusting the product). These failures must be considered in the infant mortality category as they will all be one-time failures that, when corrected, will not contribute to an ongoing failure potential. There are some exceptions; and considerable judgment is indicated.

f. *Detection of Pattern Failures*, and *Design Stress Failures*, depends primarily on how field failure data is handled and analyzed. Detection of these failures during reliability test periods will depend on the seriousness of any design error, or the inferior quality of a pattern failure component. Tables 3.9A and 3.9B illustrate the general considerations.

Table 3.9A illustrates the wide range of failure rates (and the corresponding MTBF values) that can exist within a complex product. Some of these values may belong at a lower failure rate; but due to abnormal design stress, or component pattern weaknesses, they act as high failure rate items. The problem is to detect and eliminate these situations.

It is not practical to conduct extensive failure analysis on every failure during production testing. We must set some practical criteria for triggering an investigation.

Table 3.9A. Normal Failure Rate and MTBF Values for Components

FAILURE RATE %/1000 HRS	EQUIVALENT MTBF IN HOURS
0.001	100 000 000
0.01	10 000 000
0.1	1 000 000
0.5	200 000
1.0	100 000
5.0	20 000
10.0	10 000
100	1 000
1000	100
10 000	10
100 000	1

TYPE OF COMPONENTS AND CONDITIONS INVOLVED

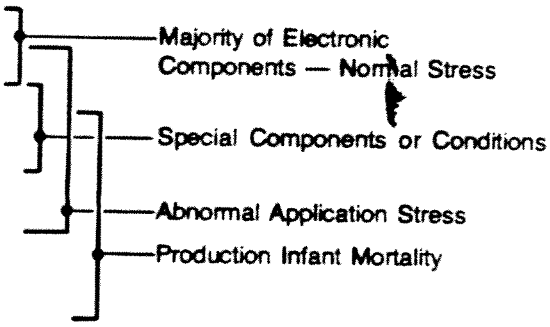


Table 3.9B. Percent Probability of Seeing (N) or More Failures Vs Test Time and Component MTBF Value

TEST HOURS	(N)	COMPONENT MTBF IN HOURS 100 000	10 000	1 000	500	SOURCE OF TEST HOURS
140	1	0%	1%	13%	24%	Environmental Test (1 unit)
420	1	0	4%	34%	57%	Environmental Test (3 units)
2 500	2	0	3%	71%	46%	First Production (25)
19 000	2	2%	57%	100%		Reliability Testing
24 000	2	2%	69%	100%		+ Second Production (50)
29 000	2	3%	79%	100%		+ Third Production (50)
32 500	2	4%	84%	100%		+ 3 Mos Warranty Data *
147 600	2	43%	100%			+ 6 Mos Warranty Data *
277 800	2	77%	100%			+ 9 Mos Warranty Data *
408 000	2	91%	100%			+ 12 Mos Warranty Data *

Cumulative Test Hours

* Allowance for 2 Month Delay in Receiving and Processing Data is Included.

ASSUMED CONDITIONS FOR ABOVE TABLE

- Poisson Failure Distribution
- 25 Units in First Production — Constant 50 Units Per Month Thereafter
- 16,500 Test Hours Generated by Reliability Qualification Testing
- 100 Hours Test Time on Each Unit Produced
- Customer Operation Averages 347 Hrs Per Month

Table 3.9B illustrates the probability of seeing (N) number of failures as a function of the MTBF of the component and the number of cumulative operating hours of use. During the environmental test period, (N) is set at N=1 since every failure will be analyzed. Starting with the reliability test, and following into production, (N) is set at N=2. During this period, analysis takes place if there have been 2 or more identical failures. The table covers MTBFs of 500, 1000, 10,000, and 100,000 hours.

Note the necessity for following the products into field warranty in order to accumulate the operating hours needed to expose pattern type failures.

NOTE

> Table 3.9B is applicable only to failures resulting from a population of parts having a constant failure rate per unit of time (Poisson Distribution); it is not applicable to early life hazard rate failure distributions.

Conducting Reliability Tests requires the following:

a. Test plans well in advance of the test: Plans must include number of units, type of test, purpose, environmental conditions, operating mode, performance test routine, and definition of failures to be included.

b. Logging forms on which to record the operating history of each item in the test: Data includes hours of operation, periods of interruption, time of failure, failure report number, etc.

c. Documentation for recording and analyzing each failure: This should be readily traceable to the equipment log for the unit in which the failure occurred.

d. Provisions for repairing failures: This must include careful removal and identification of the component or part failing.

e. Provisions for analysis of the failed part, as well as a review of the circuitry or other application in which the part or component failed. Without this analysis, there is a significant reduction in the benefits derived from the test program.

Total Test Time is generally one of the more significant elements in planning. When specialized test programs are involved for proving minimum MTBF values (as covered by MIL-STD-781B), the probable time required to reach decisions can be estimated by the Operating Characteristic Curve for the test plan. These curves relate the probable test time to the ratio between the Specified MTBF for the test and the true (but unknown) MTBF of the population under test.

Where the test is for the purpose of gathering information on failure rates, the planned test time should be related to the expected MTBF (typically determined by calculation) after considering the following:

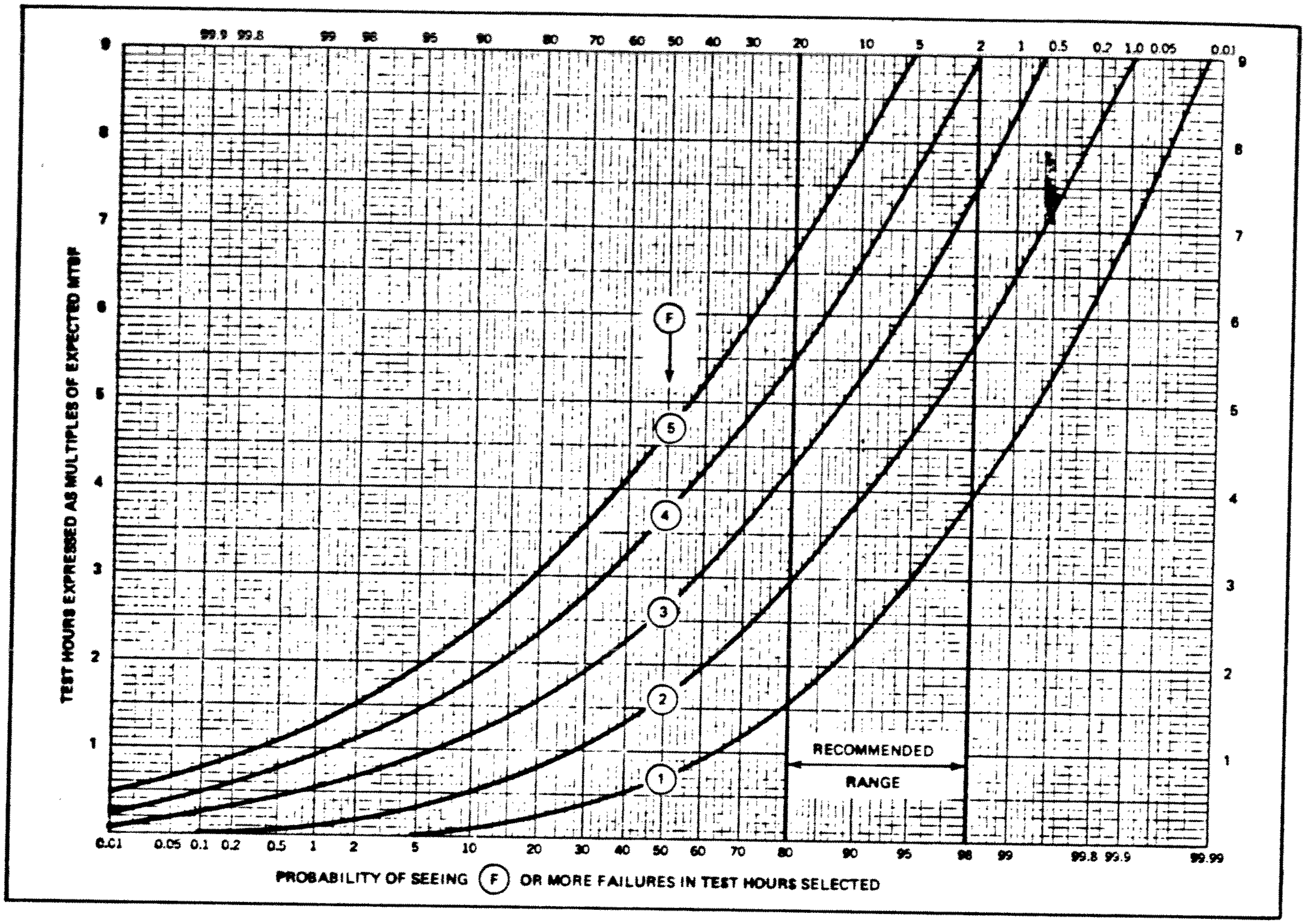
a. If the failure rate is a constant value (Poisson Distribution), Figure 3.9C shows the probability of seeing (F) or more failures based on the relationship of test time to the true (but unknown) MTBF of the population under test. To assure seeing at least one failure, a test period equal to three times the expected MTBF is recommended. This assures a 95% probability of seeing one or more failures and an 80% probability of seeing 2 or more.

Figure 3.9C is applicable only if the products to be tested are through their infant mortality period, as defined in Paragraph 3.6, and exhibit a constant failure rate.

Confidence Intervals may be computed for the results of reliability tests. The intervals are bounded by an upper and lower MTBF value established by the desired degree of confidence. The degree of confidence stated is the probability that the true MTBF of the population, from which the test sample was drawn, falls within this interval. The width of the interval is a function of the degree of confidence desired and the number of failures from which the test MTBF was computed.

Intuitively, we can accept this if we consider the following example: MTBF testing of one unit for 1000 hours has resulted in 1 failure. The test has been terminated, and the MTBF computed; 1000 hrs/1 failure = 1000 hrs MTBF. How confident are we that the true MTBF of the entire population falls within the bounds of "998 hours and 1002 hours"? The confidence we can associate with this is very close to 0%. If we revise the bounds of the interval to "0" and "Infinite" Hours, we are 100% confident that the true MTBF falls within this range.

Figure 3.9C. Failure Probability as a Function of Test Time



The effect of a large number of failures can also be judged. Assume completion of a test with 10,000,000 test hours of operation and 10,000 failures. The MTBF observed is still 1000 hours; however we can increase the confidence level associated with the 998 hour to 1002 hour interval to something better than zero (although it may still be small for such a narrow interval.)

The mathematics associated with calculation of confidence intervals will not be discussed; however Table 3.9D provides some factors (derived from chi squared tables) which are commonly used for computing upper and lower limits for confidence intervals. The table applies when testing from a population having an exponential failure distribution.

Tabulated values assume the test is terminated when the last test failure occurred. If this is not the case, and the test is terminated on the basis of time, an additional failure is to be assumed. In some cases (where there have been few failures) it may be better to assume the test is terminated at the last failure and exclude the additional test hours accumulated beyond this point.

To Use The Table, compute the observed MTBF (Test Hours/Failures). Multiply this value by the Upper and Lower factors selected from the table on the basis of desired confidence level and number of test failures.

Some examples illustrate usage of the table for different test conditions:

Test Stopped on Failure: (Normal Use of Table)

Total Test Hours = 17,485 with 15 failures. *Observed MTBF is* 17,485/15 = *1165.7 hours.*

We wish to establish, with 80% confidence, an interval containing the true MTBF of the population.

Table 3.9D. Two Sided Confidence Limit Factors for MTBF

NUMBER OF TEST FAILURES	UPPER AND LOWER CONFIDENCE LIMIT MULTIPLIERS BY (CONFIDENCE INTERVAL)									
	(99 PERCENT)		(95 PERCENT)		(90 PERCENT)		(80 PERCENT)		(50 PERCENT)	
	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
1	200	0.189	39.22	0.271	19.42	0.334	9.479	0.434	[illegible].478	0.721
2	19.32	0.269	8.264	0.359	5.626	0.422	3.759	0.514	[illegible].086	0.743
3	8.876	0.323	4.850	0.415	3.670	0.476	2.722	0.564	[illegible].737	0.765
4	5.952	0.364	3.670	0.456	2.927	0.516	2.292	0.599	[illegible].578	0.783
5	4.638	0.397	3.080	0.488	2.538	0.546	2.055	0.626	1.484	0.797
6	3.904	0.424	2.725	0.514	2.296	0.571	1.904	0.647	1.422	0.808
7	3.436	0.447	2.487	0.536	2.131	0.591	1.797	0.665	1.377	0.818
8	3.112	0.467	2.316	0.555	2.010	0.608	1.718	0.680	1.343	0.826
9	2.873	0.484	2.187	0.571	1.917	0.624	1.657	0.693	1.316	0.833
10	2.690	0.500	2.085	0.585	1.843	0.637	1.607	0.704	1.294	0.839
11	2.545	0.514	2.003	0.598	1.783	0.649	1.567	0.714	1.276	0.845
12	2.428	0.527	1.935	0.610	1.733	0.659	1.533	0.723	1.261	0.850
13	2.330	0.538	1.878	0.620	1.691	0.669	1.504	0.731	1.247	0.854
14	2.247	0.549	1.829	0.630	1.654	0.677	1.478	0.738	1.236	0.858
15	2.176	0.559	1.787	0.639	1.622	0.685	1.456	0.745	1.226	0.862
16	2.115	0.568	1.750	0.647	1.594	0.693	1.437	0.751	1.217	0.865
17	2.061	0.577	1.717	0.654	1.570	0.700	1.420	0.757	1.208	0.869
18	2.013	0.585	1.688	0.661	1.547	0.706	1.404	0.763	1.201	0.872
19	1.970	0.592	1.661	0.668	1.527	0.712	1.390	0.767	1.194	0.874
20	1.932	0.599	1.637	0.674	1.509	0.717	1.377	0.772	1.188	0.877
25	1.786	0.629	1.545	0.700	1.438	0.741	1.327	0.792	1.164	0.888
30	1.686	0.653	1.482	0.720	1.389	0.759	1.291	0.806	1.147	0.896
40	1.563	0.688	1.400	0.750	1.325	0.785	1.245	0.828	1.124	0.908
50	1.485	0.713	1.347	0.772	1.283	0.804	1.214	0.844	1.109	0.916
75	1.375	0.756	1.271	0.807	1.223	0.835	1.169	0.869	1.087	0.930
100	1.314	0.783	1.229	0.830	1.189	0.855	1.144	0.885	1.074	0.939

From the table, the upper limit factor for 80% and 15 failures is 1.456. 1.456 × the observed MTBF of 1165.7 hours gives an *upper limit of 1697 hours*. The lower limit multiplier is 0.745 and gives *a lower limit value of 868 hours*. We now feel 80% confident that the true MTBF will fall between 868 hours and 1697 hours. This does not mean we are 80% sure the true MTBF is either of these values, only that the interval contains the true value. The best estimate of the MTBF at any point in time is the observed value from a test, or the cumulative hours and failures from a number of tests from the same population.

Test Stopped on Basis of Time: (Compared With Stop on Failure)

Total Test Hours = 17,485 with 3 failures observed. When the 3rd failure occurred, the total test hours were 16,248. We now calculate two sets of limits for the 80% interval. One will adjust test to stop at 3rd failure; the other will add the 4th failure and use total test time.

Stop on 3rd Failure: *Observed MTBF* = 16248/3 = 5416 hrs. The *upper* 80% limit = 2.722 × 5416 = *14,742* hrs. and the *lower* 80% limit = .546 × 5416 = 2957 hrs.

Stop on Time: *Observed MTBF* = 17485/4 = 4371 hrs. The *upper* limit = 2.292 × 4371 = *10,018* hrs. and the lower limit = .599 × 4371 or 2618 hrs.

Since assuming the 4th failure results in a less desirable interval, it would be preferable to use the results at time of 3rd failure.

If the time beyond the last failure is considerably in excess of the "observed MTBF", as computed on the basis of total time at time of last failure, it will be advantageous to assume the additional failure.

Confidence intervals should be calculated and used only with an understanding of their limitations. The most significant limitation is the fact that most reliability testing, especially when electronic components are involved, is done with the components operating in the early life period of the population where the failure rate is not constant, and where analysis of reliability should be done on the basis of the Hazard Rate Behavior.

3.10 Reliability Testing to Develop Hazard Rate Curves

Development of Product Hazard Rate Curves from Reliability Qualification Test Data involves the following steps.

a. Knowledge of total operating time for every item in the test, including any item placed in the test as replacement for an item failing. In this discussion, the term item is applicable to individual components or complete units of product depending on the test.

b. Knowledge of total operating hours at time of failure of any item in the test. Time error should be as small as possible and typically not greater than ± 12 hours. This requires test monitoring at least once during each 24 hour period throughout the test.

c. Ordering of the test data and computation of the cumulative hazard value for each failure.

d. Trial fitting of cumulative hazard values to hazard paper for an assumed distribution. . . .Determine the distribution function for the best straight line fit of data.

e. Convert distribution parameters to a Hazard Rate Curve for the Test Data.

f. Determine working formulas that are convenient for the curve, and which will match it, within appropriate limits, over the time period of primary interest. These formulas will permit the curve to be drawn, and integration for failures over selected periods of time. Figure 3.11A illustrates such a curve. The typical period of interest is from 20 hours to 10,000 hours.

Planning for Reliability Testing in contemplation of developing Hazard Rate Curves requires the following primary considerations.

a. Knowledge of all failure details following the point in time where the product was made to operate properly for the first time (defective parts were replaced, and production errors corrected).

b. Accumulation of as many failures as possible. The more failures the better when computing and plotting the cumulative hazard value.

c. Some relatively small number of failures (2 or more) occurring as far out in time as the test will permit (typically at operating times in excess of 1600 test hours).

Considering these requirements, general planning for a test program will include operation of a minimum of three products or 50% of the units to be tested (whichever is greater) for a minimum period of 10 weeks. The time duration beyond 10 weeks is determined by the 2nd failure occurring after 1600 hours of operation. For a general guide, the total test time for all units should not be less than three times the calculated MTBF for the product. If additional units of product are required they may be placed in test at any time and in any quantity. No unit should remain in the test for less than 168 hours if its failure data is to be included in the test program.

Practical Use of Hazard Rate Curves is illustrated in paragraphs 11 and 12 covering warranty cost prediction, and failure rate under warranty conditions.

The curves have value as a tool to permit better understanding of the observed behavior associated with the "bathtub curve" discussed in Paragraph 3.5. Their ultimate value is evaluated on the basis of how well they track with experience over a period of time.

3.11 Warranty Cost Consideration and Predictions

Warranty costs can be significant when compared with the profits from a product. The production plan must include appropriate steps to minimize these costs which must otherwise be reflected in the selling price of the product or subtracted from profits. In addition to minimizing costs, the customer must be provided with equitable protection covering errors in basic design, production workmanship, and the infant mortality failure content of the components used in the product.

There is no logical requirement for warranty protection covering the true random failure rate for the product (based on the useful life portion of the "bathtub curve" discussed in Section 3.5); however it is not possible to separately identify the individual warranty failures (as to infant mortality or random); and the manufacturer must accept both as part of the warranty expense.

Hazard Rate Curves can be developed from Reliability Qualification Test Data. While such curves cannot be precise, and will typically apply only to the operating environment associated with the test conditions; they do provide the manufacturer with a tool for use in evaluating the potential warranty costs to be expected. In general their use by a customer is for general information only. Typical customers will not acquire a sufficient quantity of the product to measure the overall statistical behavior of the components as reflected by the hazard rate curve. The exception would be O.E.M. Customers purchasing several hundred units and observing failure data as the units are operated over 12 to 15 months. Integration of the Hazard Rate Curve between two points in time will provide the number of failures to be expected. This data (Failures versus operating time) can then be processed in terms of Average MTBF (T2 — T1)/Failures = MTBF; and this in turn will convert to the average failure rate during the period.

Figure 3.11A is an illustration of such a curve, and shows the relative failure rate averages for three periods: (1) is the first 1000 hours of use (possibly the initial 3 month warranty period), (2) is for the next 4000 hours (possibly the first year under a maintenance contract), and (3) is a composite of the first 15 months, including the 3 month warranty and 12 month maintenance periods.

Using the formulas, the following computations can be made for the periods ( ) indicated:

(1) Average MTBF is 1518 Hours = 65.89% Per 1000 Hr. Fail Rate

(2) Average MTBF is 4663 Hours = 21.44% Per 1000 Hr. Fail Rate

(3) Average MTBF is 3297 Hours = 30.33% Per 1000 Hr. Fail Rate

CAUTION

While the formulas are the same for all products; the constants C, M, A, and B are unique for each product.

The curve is derived from data taken during a reliability qualification test (see Paragraph 3.10). The following formulas are used to explore various periods of time on the curve·

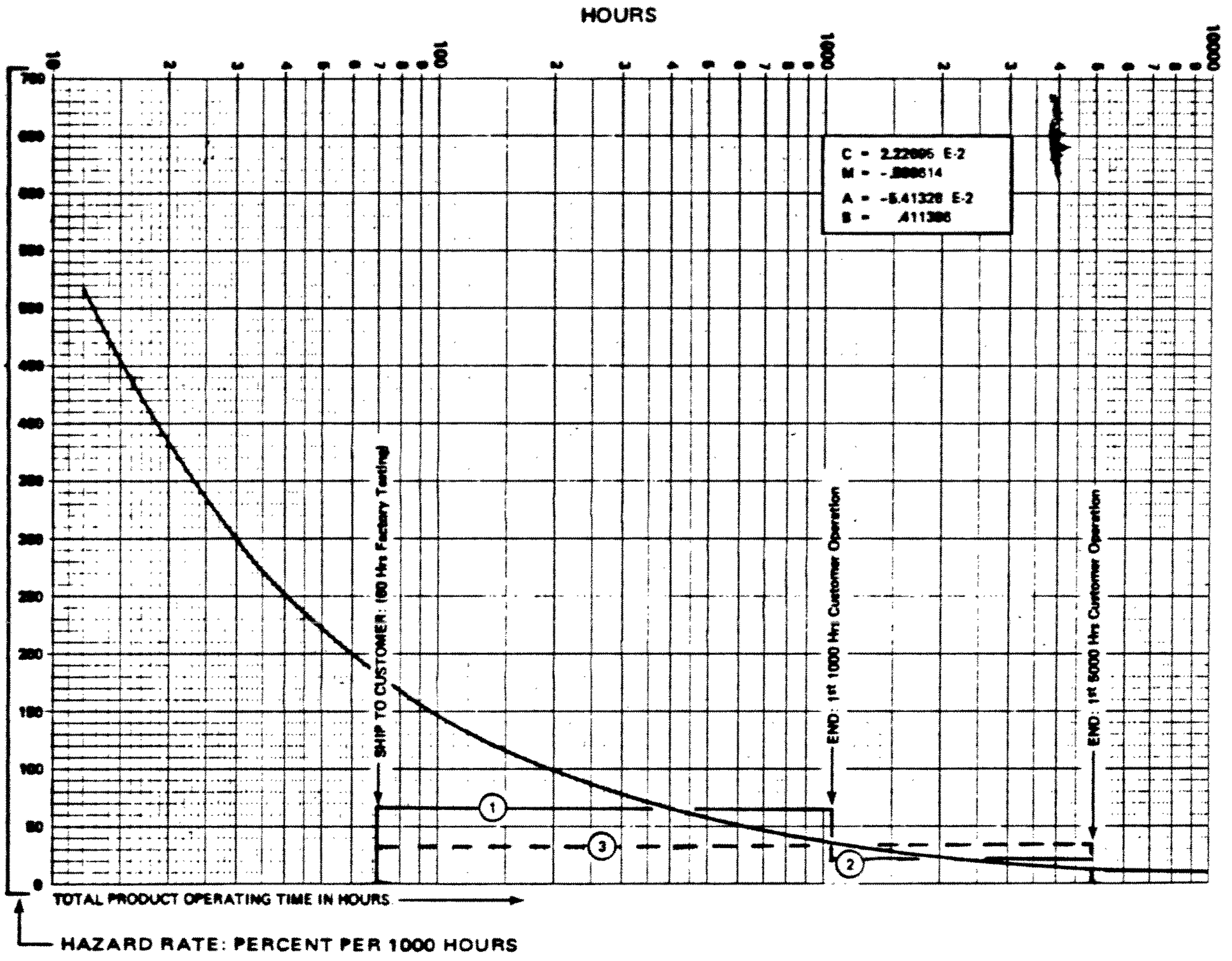
Formula For Curve: $H = C(T^M) \times 10^5$

H = Hazard Rate in % per 1000 hrs. at time (T).
C & M are constants as shown on curve.

Formula For Failures between time T_1 and T_2 on curve.

$F = A(T_1^B - T_2^B)$ where F = number of failures per unit.

Figure 3.11A. Typical Hazard Rate Curve



Formula For MTBF (average MTBF during period T_1 to T_2) in hours.

$$MTBF = (T_2 - T_1)/F$$

Formula For Average Failure Rate (λ) in % per 1000 Hours.

$$\lambda = (1/MTBF) \times 10^5$$

The Probable Warranty Costs Per Product can be predicted, within reasonable limits, by using the Hazard Rate Curve. The steps for this are as follows, using the curve from Figure 3.11A:

a. ***Determine the average number of product operating hours per month:*** *In this case we are using 333 hours.*

b. ***Determine the average cost of repairing a failure:*** *$400* will be used in the example.

c. ***Determine average MTBF for warranty period:*** *1518 hours* was established from the hazard rate curve and warranty period (as per (1) in Figure 3.11A).

d. ***Determine MTBF during useful life period:*** While the hazard rate curve shows a continuing reduction of hazard rate as operating time is accumulated; a constant value will be assumed which is based on the *Average MTBF for the 4000 hour period starting at 1000 hours and ending at 5000 hours* on the curve. This is per (2) in Figure 3.11A. Useful life MTBF is *4663 hrs.*

e. ***Establish the length of the warranty period in hours:*** In this case it will be 3 months warranty at usage rate of 333+ hrs. per month. Warranty Period = *1000 hrs.*

f. ***Determine total operating hours for 100 units of product*** as the base for computing warranty failures: This is chosen as a minimum number for which we could expect reasonable correlation; but more to the point, it also enables us to simultaneously express "failures per 100 units" and "percent of units failing" as the same numerical value. *Total hours per 100 units in warranty = 100,000 hours.*

g. ***Establish the point on the curve at which the product is shipped to the customer:*** *60 hours* will be used.

h. ***Total failures during warranty*** (for 100 units) are computed:

(f)/(c) = 100,000/1518 = 65.88 failures = (66).

i. ***Normal failures included*** in the total are computed:

(f)/(d) = 100,000/4663 = 21.44 normal failures (21).

j. ***Infant mortality failures*** are computed:

(h) − (i) = (66) − (21) = (45) infant mortality failures.

k. ***Warranty cost per 100 units*** is computed:

(b) × (h) = $400 × 66 = *$26,400 total* ($264 per unit.)

l. ***Cost can be broken down*** in terms of Normal Failure and Infant Failure Costs:

Normal Failures = (21) × $400 = $ 8,400 Per 100 = $ 84 Per Unit
Infant Failures = (45) × $400 = $18,000 Per 100 = $180 Per Unit

Impact of Additional Operating Time on Warranty Cost is easily evaluated: The formulas shown with Figure 3.11A are used to compute average MTBF for the same operating periods starting at a new shipping point. To illustrate the effect, let's move the ship point from 60 hours out to 300 hours; this would be equivalent to an additional 10 days of operation at 24 hours per day. The recomputed values are as follows:

(1) MTBF (Avg.) = 2135 hrs. for first 1000 hrs. (Use for Total Failures)

(2) MTBF (Avg.) = 4943 hrs. for next 4000 hrs. (Use for Normal Failures)

(3) MTBF (Avg.) = 3913 hrs. for first 5000 hrs. (Reference Only)

Following computations can now be made: (Failures Per 100 Units)

Total Failures = 100,000/2135 = (47) × $400 = $18,800

Normal Failures = 100,000/4943 = (20) × 400 = $ 8,000

Infant Failures = (47) − (20) = (27) × 400 = $10,800

Gross Warranty Cost Saved (per 100 Units) is now computed:

FAILURE CATEGORY		FAIL COST @ 60 HRS.		FAIL COST @ 300 HRS.	
Normal Failures		$ 8,400		8,000	(−$ 400)
Infant Failures		18,000		10,800	(−$7,200)
Total Failures		$26,400		$18,800	(−$7,600)
Gross Savings	=	($26,400 — $18,800)	=	$7,600	= ($76 Per Unit)

Is the Additional Time and Incremental Cost Justified?

There is no fixed answer to this question. Up to the break-even point (in this case spending $76 per unit) the manufacturer has an obligation to provide maximum MTBF to the customer; beyond this point, the relative value of absorbing costs out of profits to promote short term reliability improvements, or alternatively to pass the extra cost on to the customer in terms of price increase, must be determined by judgment for each product analyzed.

What Incremental Costs Must Be Considered?

Some of the more significant cost items associated with additional factory operation prior to shipment include:

- Cost of carrying 10 days (for this example) of normal production permanently in inventory.
- Space and occupancy costs for 10 days of production volume held.
- Labor and overhead for conducting test.
- Cost of labor and materials for repairing failures.
- Cost of capital equipment investment involved in program.

What About Time Acceleration Using High Temperature?

This requires assurance that the dominant cause of failure is accelerated by higher temperatures. If so, and if costs for heating facilities are suitable, there may be a more optimum cost using heat for accelerating time on the hazard rate curve. This is seldom the case; and time acceleration with high temperature is more effective when applied to screening of individual components rather than at the product level.

3.12 Warranty Failure Rate Considerations

Warranty Failure Rates are generally considered to be a management tool for use in evaluating the probable degree of customer satisfaction, or warranty problem level, with the product.

Computations are typically based on the number of products under warranty (during the time period of interest) and the number of Warranty Failures reported. Reported Failures/Units in Warranty × 100 = Percent Failure Rate. Prior to computation, non-reliability related failure items are screened out.

Does this method actually reflect the reliability level of the product? The answer to this depends on the general stability of other factors that will influence the computed value under typical conditions. This paragraph will cover these factors and illustrate their impact on typical calculations.

The examples will always assume the products under warranty are behaving as depicted by the hazard rate curve of Figure 3.11A. In Paragraph 3.11, it was easy to picture a group of 100 units used throughout a 3 month (1000 hour) warranty period, and to proceed with warranty cost computations. From reading Paragraph 3.11, we now recognize there is an hour by hour variation in failure rate (properly called hazard rate when it varies); and the number of failures per 100 units during any given time period (T1 to T2) will be different depending on where this time period is located on the hazard rate curve. In 3.11 we were only interested in total failures for the 1000 hour (3 month) period. We will now concern ourselves with month by month failure rates in order to understand the composite effect, on failure rates, of the following typical shipping and warranty conditions:

a. ***Product shipment levels are not uniform month to month.***

b. ***There may be several types of warranty coverage including periods greater than 3 months.***

c. ***If customers change, the average usage per month may change.*** Addition of a new OEM contract (for example) might introduce a high volume shipment simultaneously with the new OEM (Original Equipment Manufacturer) operating the products a maximum number of hours per month (728 hrs.); other customers might average a normal 40 hour week (174 hours per month).

Having recognized the variability of shipping levels, and usage, we must also recognize the monthly total of failures (generated by units under a three month warranty) is the sum of the failures in units in the first, second, and third month of operation. There may not be the same number of units operating in each month; and each month has a different failure rate (failures per 100 units).

Figure 3.12A illustrates the "Failures Per 100 Units", or Percent Failing, for the first 6 months of customer use starting at a 60 hour ship point. Values are given for customer usage at the rate of 174 hours per month, and also for maximum usage of 728 hours per month. Months 4 through 6 are shown to illustrate that diminishing rates will continue; however 4 through 6 values will not be used in the examples to follow. The numbers shown above the hazard rate curve indicate the T1 and T2 times used for computations associated with 174 and 728 hours per month operation.

Figure 3.12A. Failures Per 100 Units by Month (1 through 6)

Hrs/Month	(1)	(2)	(3)	(4)	(5)	(6)	Normal Rate (*) (Random Failures)
174	21.89	13.12	10.10	8.44	7.36	6.59	3.73%/174 Hrs
728	54.98	25.99	19.28	15.85	13.70	12.19	15.62%/728 Hrs

Infant Mortality Contribution may be calculated by subtracting the Normal Rate (*) from each monthly value. Stay within corresponding Hrs. Per Month Usage.

NOTE

> Values in this table are applied to the number of units falling within each month's group to compute the failures and failure rates in Tables 3.12B through F.

(*) Failure rates for periods other than 1000 hours are computed by dividing the failure rate per 1000 hrs. by 1000, giving the failure rate per hour. Failure rate per hour is then multiplied by the number of hours of interest, in this case by 174 and by 728. The normal failure rate is 21.46% per 1000 hours based on the MTBF value of 4663 hours which is the integrated average for the 4000 hrs. explained in Paragraph 3.11d.

Failure Rate Prediction based on the data from Figure 3.12A can now proceed. If desired, the predictions can be separated into Normal Failure Rate content, and Infant Mortality Content. This will be illustrated only for the total rates, but can be evaluated on a month by month basis if desired. Steps in predicting the Total Failure Rate are as follows:

a. ***Determine the average hours usage per month:*** We will use both 174 and 728 hr. values from 3.12A to illustrate the impact of this variable.

b. ***Determine Warranty Period covered by prediction:*** We will use a 3 month period. For comparison, we will also use a 15 month period.

c. ***Since the failure rate varies as a function of the month in which a group of units is operating; we must determine the number of units in each month's operating period covered by the warranty:*** For example; all units covered by a 3 month warranty must be operating in the first, second, or third month; while units covered by a 15 month warranty will be operating in the first to fifteenth month. To make our example simple, we will assume operation of 100 units in each month's group unless otherwise indicated.

d. ***Compute the number of failures generated by each month's group*** based on units in that month, and failures per 100 units for that month.

e. ***Compute total failures for the reporting period*** by summing the failures from each month's group. (Rounded numbers will be used in examples.)

f. ***Compute total units in warranty*** by summing the number of units in each month's group.

g. ***Compute the failure rate:*** Total Failures divided by Total Units In Warranty × 100 equals the Failure Rate in Percent.

Example Using Average Operating Time of 174 Hours and 3 Mos. Warranty

a. = 174 hrs.
b. = 3 months Warranty Coverage
c. = 100 units in first, second, and 3rd month (300 total)
d. = (from 3.12A) 1st month = 21.89, 2nd month = 13.12, 3rd = 10.10
e. = 45 failures (21.89 + 13.12 + 10.10 = 45.11 rounded to 45)
f. = 300 units in warranty (100 in each of the 3 months)
g. *Failure Rate = 15%* (45/300 × 100 = 15%)

Example Using Average Operating Time of 728 Hours and 3 Mos. Warranty

a. = 728 hrs.
b. = 3 months Warranty Coverage
. = 100 units in each month
d. = (From 3.12A) 1st Mo. = 54.98, 2nd Mo. = 25.99, 3rd Mo. = 19.28
e. = 100 failures (54.98 + 25.99 + 19.28 = 100.25 rounded to 100)
f. = 300 units in warranty (100 in each of the 3 months)
g. *Failure Rate = 33.3%* (100/300 × 100 = 33.3%)

Effects of Extending Warranty Period Coverage will be illustrated in the next two examples. With extended warranty periods, many of the units will be operating in the normal failure rate period which we have defined in Paragraph 3.11 as the average failure rate for the 4000 hour period starting at 1000 hours and ending at 5000 hours. When the hazard rate curve value drops below the normal failure rate, the normal failure rate value will be used for the remaining months groups included under warranty for the reporting period.

Example Using Average Operating Time of 174 Hours and 15 Mos. Warranty

a. = 174 hrs.
b. = 15 Months Warranty
c. = 100 Units in 1st through 15th month (1500 units total in warranty). (Since the hazard rate does not drop below the normal rate until the 16th month of use at 174 hrs. per month, the total period of 60 hrs. to 2670 hrs. was integrated using formulas in Figure 3.11A. This is only permissible in place of summing the individual months because there are the same number of units in each month. Answer
d. = 109.8 rounded to 110.)
e. = 110 failures (from Step c and d combined)
f. = 1500 (15 months with 100 units in each month of warranty)
. *Failure Rate* = 7.3% (110/1500 × 100 = 7.3%)

Example Using Average Operating Time of 728 Hours and 15 Mos. Warranty

a. = 728 hrs.
b. = 15 Months Warranty
c. = 100 units in 1st through 15th month of warranty
d. = (From 3.12A) 1st 3 months = 100.25, next 12 months × normal Rate of 15.62 per month = 187.44
e. = 288 failures (100.25 + 187.44 = 287.69 rounded to 288)
f. = 1500 units in warranty (100 in each of the 15 months)
g. *Failure Rate = 19.2%* (288/1500 × 100 = 19.2%)

Comparison of Normal and Infant Mortality Content in Examples is accomplished by computing the difference between total failures and the normal failures. *Total Normal Failures* can be computed for each usage rate by multiplying the normal rate by the period of warranty covered. In the following tabulation, normal failures are also expressed as a percentage of the total failures. Obviously the Infant Mortality Failures are the difference between this and 100%.

HOURS USAGE PER MONTH	WARRANTY PERIOD	NUMBER OF FAILURES		PERCENT OF FAILURES	
		TOTAL	NORMAL	INFANT	NORMAL
174 Hrs.	3 Mos.	45	11	75.6%	24.4%
728 Hrs.	3 Mos.	100	47	53.0%	47.0%
174 Hrs.	15 Mos.	110	56	49.1%	50.9%
728 Hrs.	15 Mos.	288	234	18.7%	81.3%

Comparison of combinations of the preceeding examples is shown in Tables 3.12B, and 3.12C, (with the addition of MTBF data). Since we know the total operating hours and number of failures average MTBF is easily computed.

Table 3.12B. Typical Month Warranty Information

AVG. USAGE	NO. FAIL (% FAIL)	AVG. MTBF	NO. FAIL (% FAIL)	AVG. MTBF
PER MONTH	3 MOS. GROUP — 300 UNITS		15 MOS. GROUP — 1500 UNITS	
174 Hrs.	45 (15.0%)	1160 Hrs.	110 (7.3%)	2372 Hrs.
728 Hrs.	100 (33.3%)	2184 Hrs.	288 (19.5%)	3792 Hrs.
	3 MOS. GROUP — 600 UNITS		15 MOS. GROUP — 3000 UNITS	
Combined Hrs.	145 (24.2%)	1866 Hrs.	398 (13.3%)	3399 Hrs.
	COMBINED 3 & 15 WARRANTY GROUPS — 1800 UNITS IN WTY.			
174 Hrs.	155 (8.6%)	2021 Hrs.		
728 Hrs.	388 (21.6%)	3377 Hrs.		
	COMBINED ALL GROUPS WTY. & HRS. MIXED — 3600 UNITS			
Combined Hrs.	543 (15.1%)	2990 Hrs.		

Table 3.12C. Possible Failure Rates From 3.12B

PERCENT FAILED	AVERAGE MTBF HRS.	UNITS IN WARRANTY	WARRANTY GROUPS & USAGE HRS. INCLUDED			
			3 MOS.	15 MOS.	174 HRS.	728 HRS.
7.3%	2372	1500		X	X	
8.6%	2021	1800	X	X	X	
13.3%	3399	3000		X	X	X
15.0%	1160	300	X		X	
15.1%	2990	3600	X	X	X	X
19.2%	3792	1500		X		X
21.6%	3377	1800	X	X		X
24.6%	1866	600	X		X	X
33.3%	2184	300	X			X

In Summarizing, it can be shown that conditions other than "Quality and Infant Mortality" have an affect on product Warranty Failure Rates. As the reader may have considered by now, the same factors will cause a related fluctuation in Warranty Cost percentages as reported on a monthly basis. This is not tabulated, but data is here, and can be used to illustrate the effect if the reader is so inclined. Use the number of failures, total failure cost, and the total product sales value for the number of units in warranty.

Tables 3.12D, E, and F illustrate the effect of another variable on Warranty Failure Rate. This is non-uniformity of monthly shipments and the resulting variation in number of units in the individual months of the 3 month warranty. This effect combines with the variations of warranty period and hours per month usage.

Table 3.12D shows a reference condition for a 3 month warranty period with 100 units in each month of the period. Usage is set at 174 hours per month so that values from Table 3.12A can be used.

Table 3.12D. Reference for Tables 3.12E and 3.12F

WARRANTY MONTH	1	2	3	TOTALS
Units in Warranty	100	100	100	300
Fail By Month	21.89	13.12	10.10	45
Computed Failure Rate				*15.0%*

Table 3.12E. (Shipments Have Increased by 40/Mo. for Past 2 Mos.)

Units in Warranty	180	140	100	420
Fail by Month	39.40	18.37	10.10	68
Computed Failure Rate				*16.2%*

Table 3.12F. (Shipments Have Decreased 40/Mo. for Past 2 Mos.)

Units in Warranty	20	60	100	180
Fail by Month	4.37	7.87	10.10	22
Computed Failure Rate				*12.2%*

Similar Computations Using the 728 Hrs. Per Month Usage Table show the following:

Reference: 100 Failures/300 In Warranty = 33.3% Failure Rate
Increase Shipments: 155 Fail/420 Wty. = 36.9% Failure Rate
Decrease Shipments: 46 Fail/180 Wty. = 25.6% Failure Rate

The Message From Paragraph 3.12 is "Use Warranty Failure Rate Values only when all of the factors behind them are known and taken in proper perspective."

3.13 MTBF SPECIFICATIONS (Specifications "NO") (Information "YES")

MTBF is a statistical characteristic measurable only over a large number of units, and an extended period of time. Individual units may, or may not, contain infant mortality weaknesses. There will be instances where a product contains more than one infant mortality problem.

MTBF information should be provided to customers (such as OEM's) who must deal with failures in a large number of units. The data should be provided as information only (not a specification), and should clearly define the time factors involved. Examples of how this might be stated include:

a. Calculated MTBF is 2619 Hours. The Average Field MTBF will exceed this value if measured over the first 5000 hours of operation.

b. Calculated MTBF is 2619 Hours. The Average Field MTBF expected is as follows:

1138 Hours (averaged over first 500 hours of use — 0 to 500 hours.)
2609 Hours (averaged over next 1000 hours of use — 500 to 1500 hours.)
5226 Hours (averaged over next 4000 hours of use — 1500 to 5500 hours.)

Field Experience information is useful as long as the sources of variation are understood (Paragraph 3.12 covers this). Generally, the number of operating hours per month is an unknown factor; however an operating month is a unit of time, and when warranty failure rates are known (example 6.9% per month), we can establish the operating months between failure: 6.9% per month = .069 failures per month; 1/.069 = number of months between failure = 14.49 months. If we believe the average operating time is 174 hours per month, we can multiply by this and estimate an average field MTBF of 174 × 14.49 = 2521 hours. This should not be done unless there is a high level of confidence in the hours per month value used.

Mean Time to Repair information is also useful to customers and should be made available. It is highly useful to separate the diagnostic time from the repair time, although this is typically not possible. Under no circumstances should the value include any time spent in travel, nor time spent in acquiring the necessary repair parts or assemblies.

4.0 RELIABILITY FROM A CUSTOMER VIEWPOINT

This section covers subjects which must be considered by a customer in order to achieve an optimum reliability relationship between the purchased product and the application in which it is to be used.

4.1 Maximum Value Concept

The concept of maximum value involves consideration of total cost of ownership. This includes consideration of initial purchase and installation costs, continuing cost for routine operation, incremental costs associated with down time for failure repair, (also for preventive maintenance), direct preventive maintenance costs, and direct repair costs for failure. Some of these costs may be weighted to better reflect their importance in the specific application. Each product considered is evaluated in a similar manner; and the product providing the minimum cost per hour of use offers the maximum value. There are some instances where other considerations may override the use of maximum value as the primary method for selection of a product.

Computing Maximum Product Value Factor

The following formula, and definitions, may be of value in computing a maximum value factor for a product or system. The principle is to establish the best possible estimate of average cost per hour of use, and equate this in terms a Value Factor.

V_f = $1/C_h$ = "Value Factor"

C_h = Average Cost ($) per hour of normal operational use.

L_u = Life (Hrs.) = (Hrs. Use Per Year) X (Life In Years)

$C_h = A + C + F + P + N$

A = Acquisition Cost: = (Purchase & Installation Costs) / L_u

C = Capital Cost: = (Cost of Invested Capital for L_u Period) / L_u

F = Failure Cost: = $D_c + R_c$

D_c = (MTTR X Hourly Down-Time Costs) / MTBF

R_c = (Avg. Repair Cost For Labor & Material) / MTBF

P = Preventive Maintenance Costs = (Average PM Cost/PM Period in Hours) + (Total PM Down Time Cost/PM Period in Hours)

N = Normal operating costs per hour of use: include space costs, power costs, operating supplies, operating labor, etc. The total is adjusted to an average cost per hour of use.

MTBF = Mean Time Between Failures (Based on Best Estimate of Normal Failure Rate)

MTTR = Mean Time to Repair Failures

PM Period = Specified time interval, in hours, between maintenance operations.

PM Down Time = Time required to complete PM work. It should reflect only that time which prevents or materially reduces the availability of the product for normal use.

4.2 Critical Application Considerations

Products selected from commercial manufacturers can be expected to perform in accordance with published specifications. They can also be expected to include some inherent problems. These will vary to some degree depending on the maturity of the product and the design and production maturity of the supplier. The following types of problems can be expected.

a. ***Newly Introduced Products:*** During the first six to twelve months of initial shipments there is a relatively high probability of encountering *minor* (and in some cases major) *design problems*. Some of these may affect all applications, and others may cause difficulty only under unique circumstances. As the supplier becomes aware of the problems and takes corrective action, the risk will diminish. The risk should be relatively minor in products having at least one year of shipments and total shipments of several hundred products.

User Documentation Problems are also probable with new products. Typically, the problem will be with user operating instructions failing to cover some applications, or not being clear on others. Technical errors may also appear in the service support information. These problems should be minimal following the first year of field sales.

b. ***Mature Products:*** Throughout the production life of all commercial products there will be varying levels of Infant Mortality and Product Workmanship Quality. The problems associated with production workmanship will be minimal in products from suppliers with well established, and disciplined, production programs. The infant mortality problems vary, and depend to a large extent on the degree of vendor control exercised by the supplier of the product.

Customers having critical applications must consider the risks involved in selecting a product, and take actions to minimize the impact of their selection on any critical considerations.

Examples of critical applications might include:

a. Any application where failure would jeopardize life.

b. Applications where failure down time would result in major costs (process control in large volume production for example).

c. Applications where service can be accomplished only at scheduled intervals, or with unusual cost factors.

Actions to minimize risks include the following, and should be considered prior to selecting a product.

a. Conduct a formal survey of potential suppliers. The survey team should include personnel well qualified to evaluate suppliers in the following areas:

  - Financial Responsibility
  - Production Capability
  - Design Concepts Used In Product
  - Maturity of Technology Used in Product
  - Provisions for Product Serviceability
  - Design Documentation
  - Configuration Management Concepts
  - Reliability Assurance Programs
  - Supplier Quality & Reliability Surveillance (Component, Parts, and Materials Suppliers)
  - Product Qualification & Reliability Testing Programs
  - Production Process Documentation and Quality Control Methods
  - Warranty Policy
  - Field Service Support Capability
  - Approach to Problem Identification and Correction (Both Factory and Field Failure Problems)
  - Knowledge of Field MTBF and MTTR Performance of Products

b. Consider steps required to minimize the impact of infant mortality failures.

  - Can supplier provide test information showing how the infant mortality hazard rate varies with time?
  - Will normal system testing time at customers site provide sufficient reduction in hazard rate?
  - Can arrangements be made with supplier to conduct special burn-in of product? Can this be done with less cost by supplier or by customer?

4.3 Service Support Considerations

Assuming a minimum five year (60 month) product life, and a three month warranty period, it can be shown that 95% of the product life is not covered by warranty. During this period, failure recovery costs become part of customer operating and ownership expense. Every consideration should be given to minimizing this expense. Prior to making a final selection of product and supplier, careful consideration should be given to the following service support factors:

a. Serviceability of the product: how rapidly can a problem be diagnosed and a defective item replaced?
b. Maintenance contract availability at a competitive price.
c. Training of service personnel.
d. Availability of service personnel.
e. Availability of spare parts.
f. Relative cost factors associated with the above.

All of the above factors (except cost) determine the Mean Time to Repair a failure (MTTR).

4.4 System Availability and Redundancy Considerations

Many applications encounter high costs during periods when a system is inoperable due to failure. On the basis of statistical averages, there will be a failure at MTBF intervals. The total available time must be allocated to either operating the product normally, or repairing it as rapidly as possible. The statistical average of the time taken to return the product to normal operation, following the failure, is defined as the Mean Time To Repair (MTTR). This is determined by Service Support Capability.

System Availability is computed by dividing the MTBF value by the sum of MTBF and MTTR, and multiplying by 100 to express the availability as a percentage.

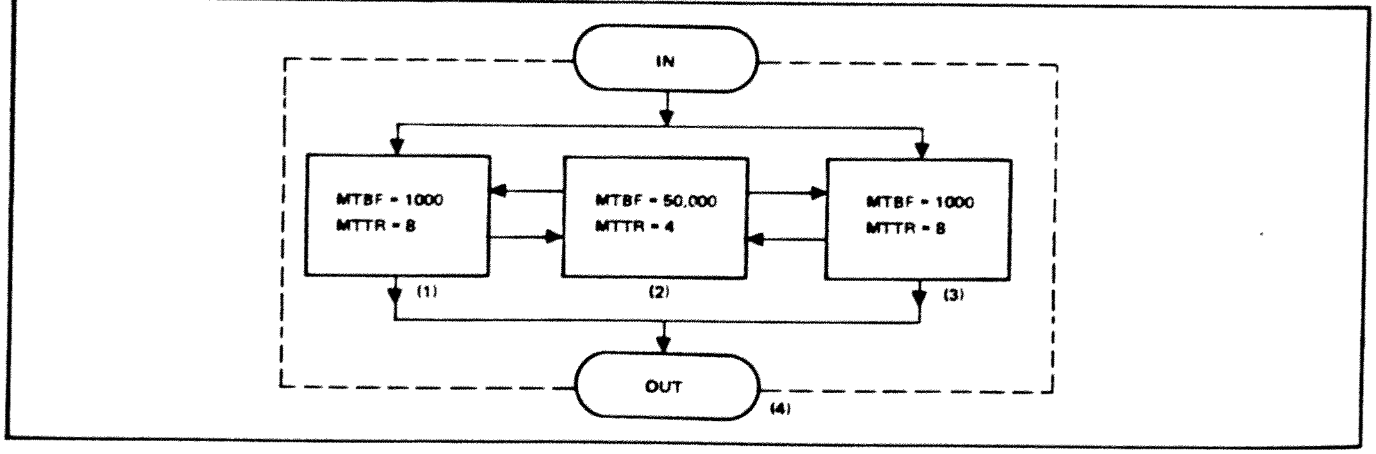
Example:

Assume a system MTBF of 1000 hours and an average MTTR of 8 hours. What is the percent availability?

System % Availability = 1000/(1000+ 8) = .99206 x 100 = 99.21%

System Redundancy should be considered if continuous operation is a critical factor. Figure 4.4A illustrates the use of two identical systems, (1) and (3), together with a switching unit (2) that will transfer operation to the operating system in the event of system (1) or (3) failure. The three elements now comprise a total system, which will be available as long as the switching unit and one or the other of the basic systems have not failed. Redundancy affect on total system availability can be evaluated using the same principles described in Paragraph 3.4.e. Figure 4.4A also shows the MTBF and MTTR values in hours for each element.

Figure 4.4A. Redundant System Diagram



The first order of business is to compute Availability (A), and Unavailability (U); where (A) + (U) = 1

Since systems (1) and (3) are identical, their availability (A) is 1000/1008 = .992063 (x 100 if you want it in percent).

Unavailability (U) is 1 − .992063 = 7.9365 x 10^{-3}

Unavailability of both (1 and 3) is the product of their individual (U)s = $(7.9365 \text{ x } 10^{-3})^2$ since they are both the same. (U) for (1 and 3) = 6.2988 x 10^{-5}.

Availability of (1 or 3) = 1 − (U) for (1 and 3) or 1 − (6.2988 x 10^{-5}); (A) for (1 or 3) = .9999370.

Since total system (4) operation depends on the availability of (1 or 3) and also (2), we must multiply their (As') together for the final availability of (4).

(A) for (2) = 50,000/50,004 = .9999200

(A) for (1 or 3) and (2) = .9999370 x .9999200 = .999857

Results of this redundancy are: System Availability has been increased from 99.206% for a single unit (1) to 99.986% (for (4)) by the addition of a redundant unit (3) and the required switching unit (2). Obviously this is a very expensive method for increasing availability, and would only be used under justifiable conditions.

4.5 Reliability/MTBF Specification Considerations

Reliability Specifications for commercial products have little practical value. Reliability and MTBF are not synonomous terms. MTBF is a statistical parameter associated with hardware; and Reliability is a means of expressing the probability of operating without failure for a predetermined period of time. This relationship is discussed in 3.4. The same can be said for MTBF Specifications in terms of incorporating them in formal procurement specifications. In lieu of such specifications, it is not unreasonable to incorporate a general requirement for supplier to make available to customer any normal information concerning reliability of products included within the procurement specification. This should include information as to calculated MTBF, results of reliability qualification tests, and information concerning field failure rates during the warranty period.

Why Not Include MTBF Specifications?

First, it is not practicable for a supplier to conduct sufficient testing to know the true MTBF of a population of products to be produced.

Second, the majority of customers cannot maintain sufficient documentation of operating hours and failure detail to support compliance or non-compliance with a specification.

Third, due to normal distribution of MTBF values generated by multiple tests from a total population, there is a very good chance that any single observation of MTBF would result in a value distributed on the low side of the true mean value for the population. As discussed in Paragraph 3.9, a confidence interval can be chosen; and a lower value stated, such that the desired percentage of random test results will fall above this value. This lower value has no practical use other than as a means of protecting the supplier, (when the value is stated as a Minimum MTBF) or, when two sided intervals are used, to bracket the unknown value of the true mean with a stated degree of confidence.

Fourth, reputable suppliers provide their customers with appropriate protection against hidden design defects. In many cases this protection is extended beyond normal warranty periods (if the deficiency would cause a problem when the customer up-grades the product or system as allowed by design). These suppliers will also maintain a regular program of surveillance of failures to assure detection of subtle problem areas. In general, any attempt to include MTBF Specifications provides no customer protection in terms of reliability.

Calculated MTBF Values should be requested as part of the specification, and will provide useful information as long as both the supplier and customer are knowledgeable concerning the assumptions made and basis of the calculations. In general calculations based on RADC Notebook II, and MIL-STD-217, are accepted. Paragraph 3.8 covers this in more detail.

4.6 Cosmetic Appearance of Design Modifications

Products having complex logic functions, which may be utilized by customers in almost infinite combinations, (typical computer/software operating systems) are difficult to evaluate with 100% assurance of finding and fixing all possible design or software bugs prior to initial shipments. There is no final test that is more effective in locating these final few problems than multiple customer use. See paragraph 6.1 on Software Evaluation.

As a result of this reality, the first year of field use will involve situations where design changes are a must. These bring questions relating to maintaining the image of quality concurrent with maintaining maximum product value, for example:

a. Should Printed Circuit Board Assemblies that require jumper installations for the design fix be scrapped out to avoid the image of poor quality produced by the jumpers?

b. If the answer to (a) is no, should there be restrictions on the number of jumpers installed?

c. Should components used for the fix be mounted in other than the normal manner (i.e., affixed to the leads of another component in lieu of arranging for normal independent mounting to the Printed Circuit Board or other type of assembly)?

Customers planning to purchase newly released products should question the manufacturer regarding this subject. Manufacturers who adhere strictly to scrapping major assemblies that require visible modification work (jumpers for example) must recover the expense of this action in the price of the product. It may also result in delay of shipments, since time is required to revise the design and procure new assemblies. Manufacturers who subscribe to the following guideline for revising assemblies can provide continuing product value.

> All proposed fixes (factory or field) are reviewed to assure proposed rework will in no way affect performance, life, or reliability of the product. The cosmetic appearance of the fix is a secondary consideration subject to the judgment of Production and Quality Engineering. Where the visability of the fix is during service operations only, a considerable degree of cosmetic quality departure can be tolerated. Where the fix is visable to the user during normal operation there can be little tolerance for other than normal standards of visual quality.

4.7 WARRANTY COVERAGE (see Paragraphs 3.11 and 3.12)

Equitable warranty coverage should be offered by the manufacturer. The primary value of warranty is to permit supplier to ship products without need to include (and pass on to customer) the expense of 100% reliability screening of all products in order to locate, and eliminate, the few components that may cause infant mortality failures. It is often less expensive to repair these failures under warranty than to add the cost of screening all products. See Paragraph 3.6. Customers should explore this thoroughly with the supplier. In almost all cases, a 90 day warranty will more than cover the infant mortality failures. Customers can assure this by operating the products for the maximum time possible during the warranty period.

The suppliers warranty policy should also include coverage of any basic design errors. This is not to imply that supplier should automatically retrofit all units previously shipped; only that appropriate corrective action should be taken if design errors cause problems for the customer. There are many instances where a subtle design problem causes problems for only a fractional percentage of the customers.

4.8 Recommended Operating Methods

The question often arises concerning the merit of full time power-on operation versus turning power off during periods of non usage. In addition to energy conservation, the following factors should be considered:

a. Products which are primarily electronic will not reach the end of their useful life due to wearout from 100% power on operation. They will typically be replaced due to obsolescence.

b. Products having mechanical motion will wear to the extent of requiring scheduled replacement of parts subject to wear. This is normally covered as part of the preventive maintenance program.

c. Maximizing Reliability involves stabilizing the stress strength relationship of all components in the product. Leaving power applied 100% of the time is probably the best approach for electronic products as it will minimize any thermo-mechanical stresses due to heating and cooling, and will also minimize any moisture absorption due to breathing during cooling.

Electronic Products should be operated with continuous power-on for maximum reliability.

Electro-Mechanical Products must be individually evaluated in terms of wearout or preventive maintenance cycle costs versus full time operational advantages to the electronic components. If power on-off operation is indicated, there will be some incremental increase in electronic failures until the components susceptible to thermo-dynamic stress and moisture absorption have failed. When these are replaced (Infant Mortality Items), the on-off cycling will have a minimal impact on reliability.

5.0 HEWLETT-PACKARD DATA SYSTEMS DIVISION RELIABILITY PROGRAM

This section provides an outline of HPDS activities directed towards providing reliable products with maximum value.

The illustrations in Paragraph 5.0 relate to the program; and the remaining paragraphs deal with each of the prerequisites for product reliability as discussed in Paragraph 3.2.

The details associated with each element of the HPDS Reliability Program are covered separately within the HPDS departments having direct responsibility for their implementation.

Each employee of HPDS is encouraged to evaluate his or her specific responsibilities as they relate to HPDS Product Reliability; and also, to be aware of any activities (regardless of the area in which they occur) which may impact adversely on the HPDS Reliability Program. These activities are brought to the attention of Production Engineering, and Reliability Engineering, to assure investigation and corrective action.

Customers having specific interest in HPDS Reliability Activities are encouraged to arrange for a factory visit, and thereby avail themselves of an opportunity to discuss their interests directly with the factory personnel involved.

List of Illustrations (Paragraph 5.0 Only)

5.0A. ***Quality Reliability Standards:*** (Covers the major elements of the program as these elements impact on HPDS customers.)

5.0B. ***Reliability Program Outline:*** (Relates the actions associated with components, assemblies, hardware products, and systems.)

5.0C. ***Basic Development Program Outline:*** (Shows the major activities and checkpoints associated with development and release of a new product.)

5.0D. ***HPDS Manufacturing Program Flow Chart:*** (Illustrates the basic sequence of production, including the points at which failure and defect information is acquired as part of the Production Failure Information System.)

5.0E. ***Environmental Test Outline:*** (Flow charts the environmental test program to which new products are exposed during the development cycle).

5.0F. ***Product Assurance Functional Organization:*** (Outlines the basic areas of responsibility in the Product Assurance Department.)

Figure 5.0A. Quality Reliability Standards

PRODUCT VALUE — All products authorized for shipment shall be fully suitable for the purpose for which they were designed, and shall provide a maximum of overall value to the customer.

PERFORMANCE — Products accepted for shipment shall meet or exceed all published specification limits and/or all Production Acceptance Test limits in affect at time of shipment.

RELIABILITY — Product Design and Production Activities are directed towards maximizing the intrinsic, and continuing, reliability of each product (consistent with providing maximum product value to the customer).

DESIGN DOCUMENTATION AND WORKMANSHIP — Products accepted for shipment shall be in conformance to design documentation and Hewlett-Packard Data Systems Workmanship Standards applicable at time of shipment.

PRODUCT IDENTIFICATION — The Product Model and Option Identification System shall permit customers to obtain suitable replacement parts for any product. The system shall provide for a unique identification of each product configuration.

PACKAGING FOR SHIPMENT — Packaging and Shipping Procedures shall assure delivery of the product without degradation of quality or reliability. Provisions shall be made to provide customers with proper guidance for unpacking (and repacking) the product to assure continuing protection when needed.

SPARE PARTS — All products authorized for shipment shall be supportable in terms of readily available spare parts stocked in appropriate Hewlett-Packard Service Locations.

OPERATING AND SERVICE INFORMATION — All products authorized for shipment shall be supportable in terms of the availability of all necessary operating and service information. Operating information shall be appropriate for the normal skills of personnel expected to operate the product. Service information shall be of sufficient scope and detail as required for service personnel of the skill levels normally employed by HP Service Locations throughout the world.

SERVICE SUPPORT — Factory Service Engineering Support shall be available to assure back-up for O.E.M. Customer Service and Hewlett-Packard Service Organizations. This support will include direct technical assistance in resolving major problems, general service information in the form of service notes, and the availability of service training programs.

Figure 5.0B. Reliability Program Outline

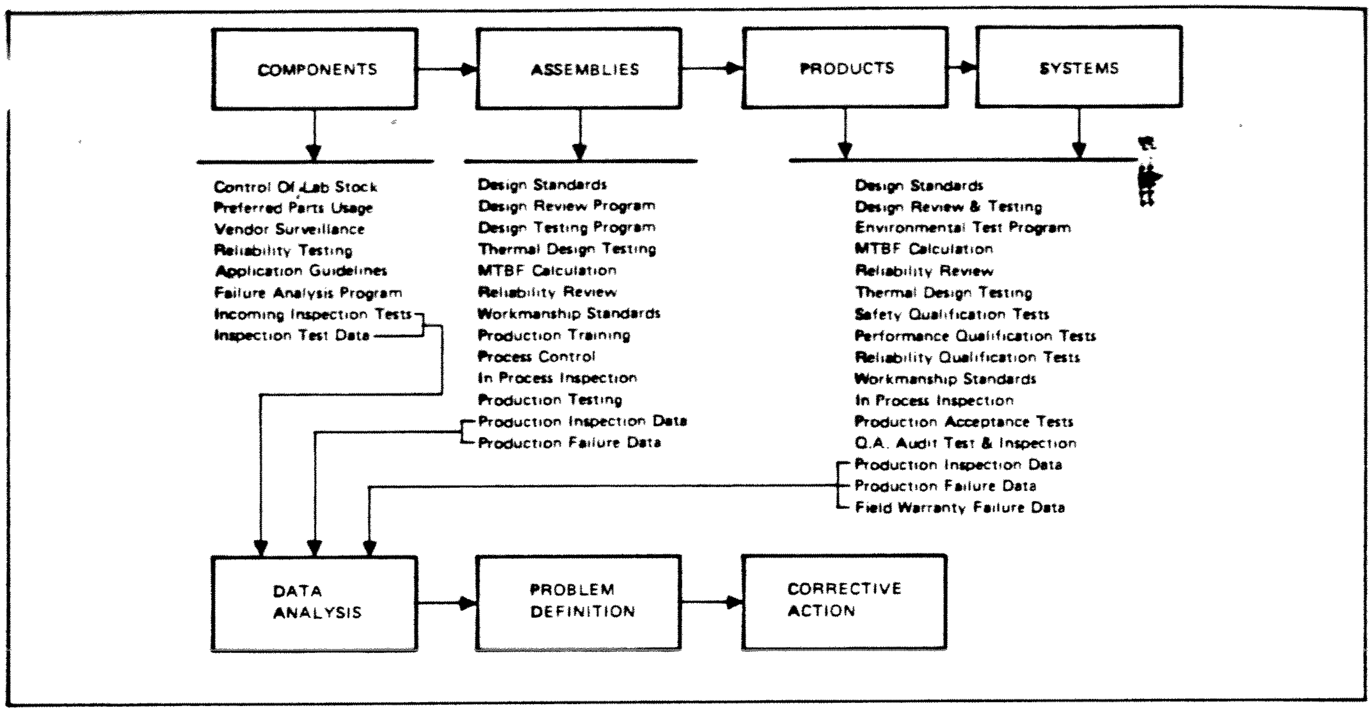


Figure 5.0C. Basic Development Program Outline

Development Status	Evaluation	Pre Production			Released
Product Status	Breadboard Model	Lab Prototype	Production Prototype	Pilot Run	Production Released
Component Reliability	X	X	X	X	X
Design (ERS) Specifications		(Preliminary)	(Final)		(Sales Spec)
Design Review Activities	X	X	X	X	(On Request)
Design Testing	X	X	X	X	(Changes Only)
Qualification Testing			X	X	(Audits)
Environmental Test Program	(On Request)	(Optional)	X	X	(Audits)
MTBF Calculation & Reliability Review		(Preliminary)	X	(Final) X	(Continuous)
Reliability Qualification Testing				X	X
Design Responsibility	X	Engineering		X	(Manufacturing)
Management Control Points And Shipment Status	X X	X No Shipments	X	X X	(Shipments)

Figure 5.0D. HP Data Systems Manufacturing Program Flow Chart
(Including Production Failure Information Flow)

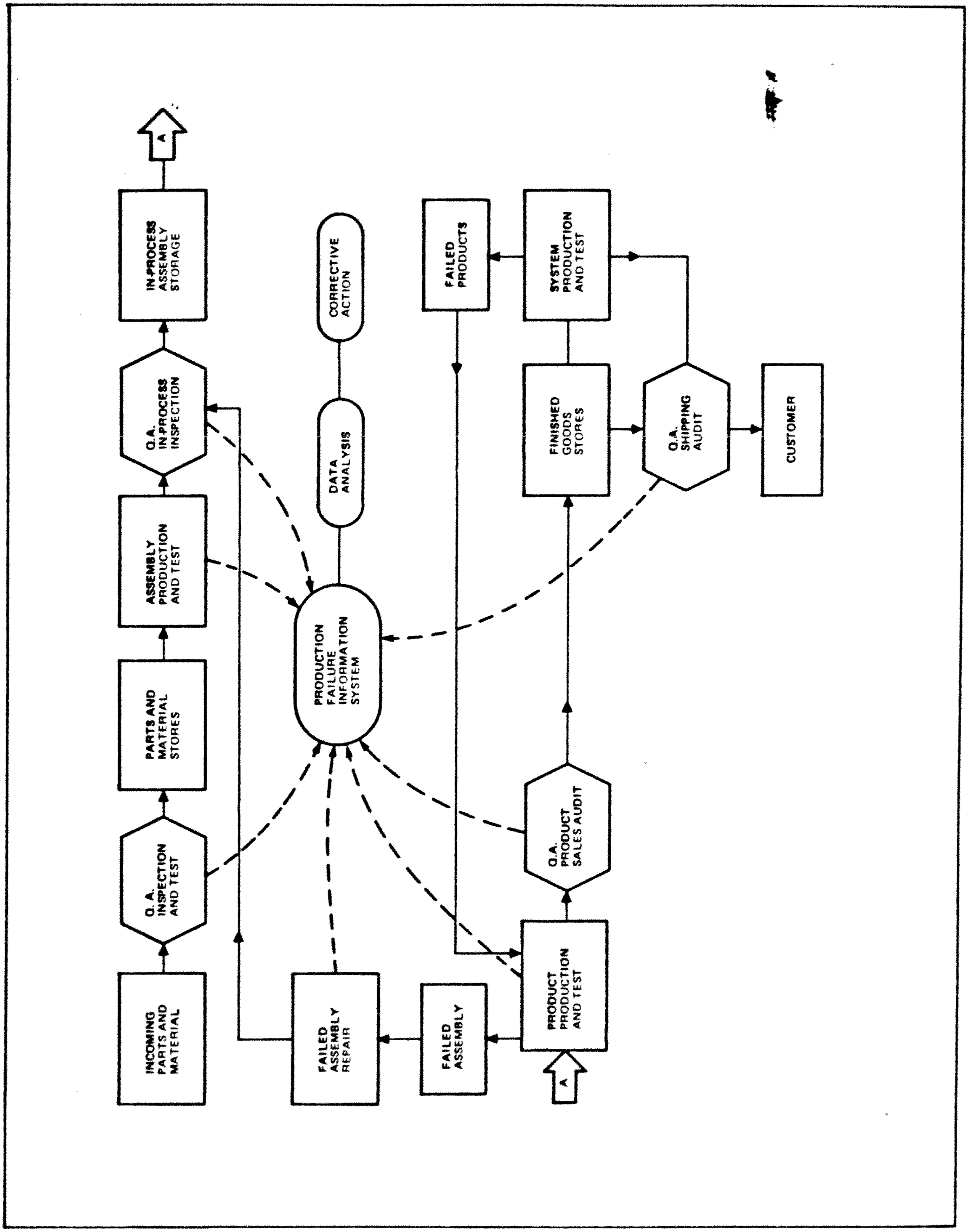


Figure 5.0E. Environmental Test Outline

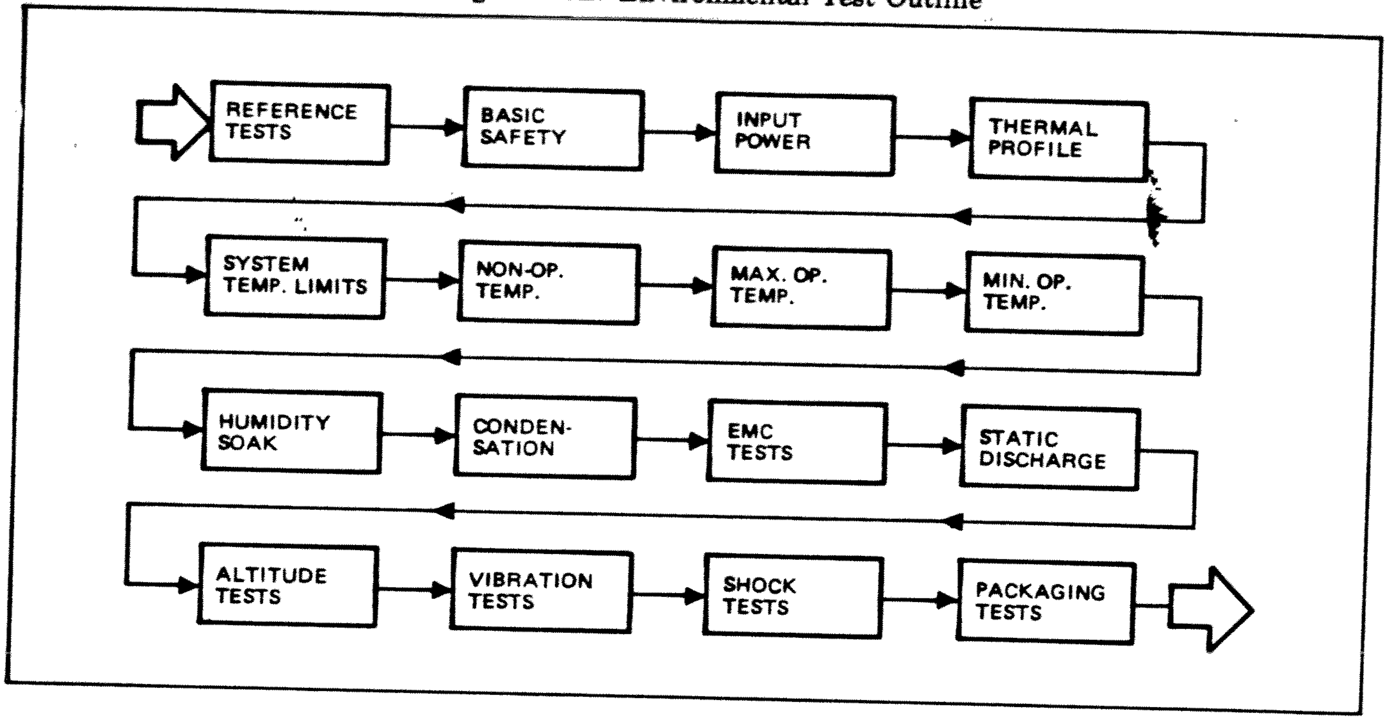
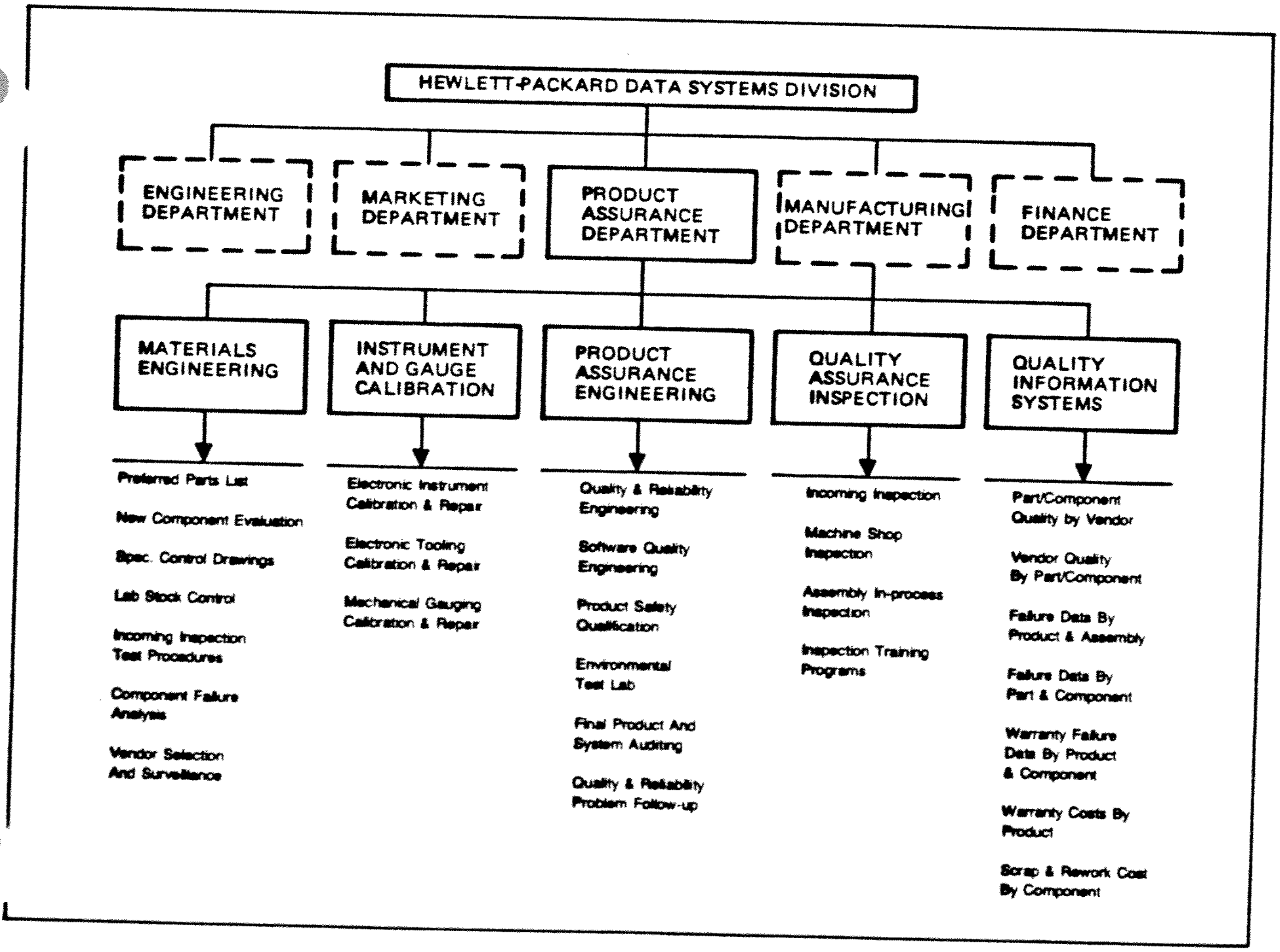


Figure 5.0F. Product Assurance Functional Organization



5.1 Vendor Reliability

Vendor Reliability is synonomous with component, part, or material reliability. Responsibility for selection and surveillance of Hewlett-Packard vendors rests with the Materials Engineering Sections in the various divisions. These sections work closely to provide comprehensive coverage of HP vendors throughout the world.

a. *Selection and Control Over Parts, Components, and Materials* to be used under a specific HP Stock Number is accomplished through controlling documentation that includes the name of each approved vendor, vendors authorized stock number, basic description of the item, and requirements for incoming inspection if applicable. Regardless of inspection requirements, all items must comply with the controlling documentation prior to stockroom acceptance.

   Items purchased under "specification control drawing" control also have the specification control drawing number and revision letter shown on the controlling documentation.

   No parts, components, or materials are purchased for production use unless such items are specifically described by the applicable controlling documentation.

   Only Materials Engineering personnel are authorized to add, delete, or otherwise modify information on the controlling documentation.

b. *Qualification of a Specific Vendor Part* listed on the controlling document is based on the following general actions:.

   - Results of Vendor Survey: Survey may or may not have been conducted by HPDS as the results of a survey made by the Materials Engineering Section of another HP Division, together with current good experience with the vendor, may be used.
   - Materials Engineering may selectively test a sample lot of parts from the vendor. Tests will include parametric measurements (to assure vendor is meeting his own published specifications), accelerated life tests to expose failure modes, and application testing under laboratory or controlled production test conditions.

c. *Vendor Survey Considerations* are determined according to the type of component or part to be supplied. Survey teams include members capable of evaluating the following general areas:

   - Financial Responsibility
   - Production Capability
   - Technology utilized and degree of expertise demonstrated
   - Production Process Control Methods
   - Quality and Reliability Program Implementation
   - Special considerations depending on type of part, component, material, or process supplied by vendor. Individual guidelines and checklists are available.

d. *Continuing Vendor Surveillance* is accomplished by Materials Engineering utilizing the following:

   - Results of Incoming Inspection: Reject rates by part and vendor permit performance comparisons between vendors; and reject rates by vendor and part permit evaluation of vendors performance on each part supplied by the vendor.
   - Monitoring of reliability performance in production and field environments. See Paragraph 5.18 on reliability feedback information.

- Random auditing of vendor's facility, and review of any significant changes in vendor's processes.
- Results of Lot Sample Testing (destructive tests, on vendors components, conducted to detect changes in basic failure modes and strengths at point of failure).

5.2 Preferred Parts Program

Product reliability is ultimately determined by the reliability of parts and components used. Every effort is made to encourage the use of components with a history of reliable performance.

The focal point for this encouragement is the HPDS Lab Stock Catalog and Lab Stock Area. Materials Engineering has control over the contents of the "Lab Stock Area" from which the design teams obtain parts and components used in development work.

Prior to listing an item in the preferred parts list, or including it in the available lab stock area, the following criteria must be met on a selective basis as deemed necessary by Materials Engineering.

a. *New Parts or Components* (Lab Stock Only)

- There is no reasonable alternate item on the preferred list.
- Component is supplied by a reliable vendor.
- Materials Engineering tests show item meets all published specification limits.
- Where deemed necessary, by the risk involved in the application, Materials Engineering accelerated life tests have been completed and show no primary failure modes indicative of vendor processes problems; and the extrapolated MTBF for the component is reasonable for the type of component.

Each Material List is reviewed to assure maximum adherence to the use of preferred parts. It is the objective of the design team to maximize usage of preferred parts in all new designs.

b. *Preferred Parts* (Catalog and Lab Stock)

- Produced by a reliable supplier using mature technology.
- Materials Engineering tests have shown component to fully meet all published specifications.
- Production Failure History shows no abnormal early life failure patterns during the normal production test processes.
- Component has been in field use within HP for a period of at least one year with no indication of abnormal field failure activity.

5.3 Reliability Oriented Design Practice

This is the heart of Product Reliability. Subsequent activities can only degrade the intrinsic reliability of a design.

Today's products are complex and cover a wide scope of technology. Design specialists are required to assure maximum achievement within a technology and for the total development program. Reliability oriented design practices vary with the technology and are covered in specialized reference information in the form of Reliability Design Handbooks, etc. Assurance that all possible actions have been taken to maximize reliability requires use of a Design Review Checklist as a memory jogger for the designer.

The following paragraphs outline some of the HPDS Reliability Oriented Design Considerations.

a. *Minimize Parts Count* required to perform functions.

b. *Maximize Usage of Preferred Parts* with a target of 80% of the parts in a new design being parts with factory and field proven reliability.

c. *Minimize Design Stress Levels* as much as possible.

d. *Environmental Effects Are Considered* to be sure part is not stressed excessively by the expected usage environment, or part is protected from the environment.

e. *Concentrating on Thermal Design* provides for reliability improvement. Reduction of failure rates by 16% can be achieved (for the general mix of components used by HPDS) for each 10°C reduction in temperature within the range of 0°C and 75°C. This reduction is most effective during the infant mortality period.

f. *Thermal Profile Evaluation* of each assembly, and product, to assure detection of hot spots and appropriate design action.

g. *Consideration of How the Product Will Fail* exposes means of minimizing the damage from failure, and in many instances a means of preventing the failure.

h. *Failure Repairability* is considered to assure minimum down time when a failure occurs.

i. *Self Test and Troubleshooting* features are incorporated in complex circuitry to minimize time required for diagnosis of a problem, and in many instances to make it possible for the user to define a malfunction prior to calling the service engineer.

j. *Calculation of MTBF and Failure Rate* for each assembly permits identification of those components having significant impact on assembly failure rates. Calculations are made by Reliability Engineering using the principles of RADC Notebook II, and MIL-STD-217. Calculations are based on Ground Fixed Environment, 50% Circuit Stress Levels, 40°C Component Operating Ambient, and use of Upper Grade Quality Components. See Paragraph 3.8.

k. *Product Qualification Testing* is conducted, prior to major design checkpoints, to verify that the design meets all External Reference Specification (ERS) objectives. This includes performance and features.

l. *Software Evaluation and Qualification* continues throughout the design period, and includes evaluation of diagnostics as well as operating system software.

m. *Environmental Evaluation and Qualification Testing* is an integral part of the design cycle. Tests are done in accordance with "HP Data Systems Lab Manual for Environmental Evaluation and Qualification Testing."

n. *Product Sales Specifications* are carefully evaluated to assure no claims are made that have not been fully substantiated by the design and qualification testing program.

o. *Production Test Procedures at the major assembly level* function to minimize the problems associated with product level testing; and every effort is made to achieve an assembly level test that will certify the assembly as a functioning spare part item. Where this cannot be achieved with a high degree of confidence, items scheduled for spare parts usage are also subjected to product level testing before shipment.

p. *Complete Manufacturing Documentation* is provided to guide production of products in accordance with design conditions that have been evaluated and qualified to specifications. The following items are among those provided.

- Parts Fabrication and Machining Drawings.
- Shop Process Documentation for Special Parts.
- Specification Control Drawings on Special Purchased Parts.
- Assembly Drawings, Process Sheets, and Samples As Applicable
- Critical Assembly and Adjustment Process Instructions.
- Complete Electrical and Mechanical Adjustment Procedures.
- Production Acceptance Test Procedure.
- Assembly and Product Material Lists.
- Process Definition and Control Documentation for any new general processes introduced with the New Product.

q. *Reliability Qualification Testing* is conducted on new products with calculated MTBF values of 10,000 hours or less, or when deemed appropriate due to introduction of new technology (or high power and temperature considerations). The test is planned for two major purposes.

- Assurance that any major pattern problems will be found prior to any volume shipment to customers.
- Acquisition of failure data permitting development of product hazard rate curves and Average MTBF versus operating period data.

r. *Reliability Enhancement* of the product is considered as part of the production cycle. Steps taken selectively include the following actions as appropriate to the product.

- Procurement of Pre-screened Components.
- In-House Reliability Screening of Selected Components.
- Sub-Contracted Reliability Screening of Components.
- Periods of operation at upper and lower temperature limits of product specifications.
- Extended periods of operation under standard conditions of 25°C temperature. This is typically adjusted on the basis of hazard rate curve data (see Paragraphs 3.11 and 3.12).

s. *Use of Reliability Oriented Design Guidelines* is vital to the overall success of the product reliability program. Following is a partial list of information used as a supplemental part of this program.

- Reliability Design Handbook (Available from RADC — Catalog Number RDH 376)
- Reliability Prediction of Electronic Equipment (MIL-HDBK-217B)
- HPDS Lab Stock Catalog of Preferred Parts
- HPDS Design Review Checklists (A-5950-3660 -1 through -5)
- HPDS Lab Manual for Environmental Evaluation and Qualification Testing (5951-9148)
- HPDS Standards for Preparation and Content of Test Procedures (A-5951-3086-1)

- HPDS Product Safety Design Guidelines (Interprets HP Corporate Series 500 Product Safety Standards for HPDS Products)
- HP Corporate Design Standards — Mechanical Design and Manufacture
- HP Corporate Manufacturing Documentation Manual

5.4 Product Design Specification

HPDS development of a new product is governed technically by the External Reference Specification (ERS). This document is prepared early in the development cycle, and must be available on completion of the Lab Prototype Phase of development.

The document is maintained throughout the development period, and serves as a reference for all product evaluation and qualification testing.

Prior to Manufacturing Release of the product, appropriate sections of the ERS are transferred to documents that will support the product throughout it's life cycle. The product Sales Data Sheet (Specification Section) becomes the official specification document; and the ERS is no longer maintained.

5.5 Design Documentation and Configuration Management

Design Manufacturing Documentation and Configuration Management Standards serve to assure production capability in duplicating product units in compliance with the design, and as changes occur, to assure support of the product in an orderly manner (in terms of spare parts availability and assembly interchangeability requirements).

Paragraph 5.3 p. outlines some of the critical design documentation required. Full details are covered in the Manufacturing Documentation Standards Manual.

HPDS Configuration Management is based on the following principles:

a. *Each product configuration,* including model and option numbers, is covered by a specific material list showing all parts and assemblies required for the specific configuration.

b. *Each basic assembly* of the product carries a unique assembly number as well as a configuration code. The assembly number will be revised if there is any change made that would create a non-interchangeable situation between assemblies carrying the same number. The configuration code, which consists of four digits showing year and week of last change, is revised if there is any change that would affect the material list or service support documentation.

c. *Each serialized product* includes a configuration code as the prefix portion of the serial number. The code is identical in principle to the code used for assemblies (year and week of last change). The principle of updating this code is the same as for the assembly. If there is any change code update on an assembly installed in the product, the product code must be updated to the same date code. If the product change involves a portion of the product not covered by assembly change code, the product code is updated with the effectivity of the change, and may be a later code than would appear on any of the assemblies.

5.6 Product Qualification Testing (Hardware/Software/Systems)

HPDS products fall into three categories: Individual *Hardware Product Units* which may be sold to customers for incorporation in larger systems, HPDS *Systems* comprised of several Hardware Products plus Software, and products consisting of *Operating System Software* only.

Each of these "product types" is subjected to rigorous qualification testing activities prior to acceptance for routine production and shipment. The following paragraphs outline these activities by product type.

a. ***Hardware Product Qualification Testing*** starts in the design area, and continues throughout the development cycle. Good designs will include allowance for incremental changes in performance resulting from the gradual drift in component characteristics as a function of time or environmental operating conditions. Verification of these margins requires special testing which may not be required as an ongoing element of the production acceptance tests. The following general areas are covered by Hardware Qualification Tests.

- Verification of all technical ERS requirements.
- Verification of design margins under extremes of environmental operating conditions.
- Verification of specified performance levels under extremes of environmental conditions. Tests are outlined in "HPDS Lab Manual for Environmental Evaluation and Qualification Testing."
- Final Product Qualification Testing is done using Pilot Production Units. All requirements must be met, and must be compatible with published sales specifications, prior to release for production and shipment.

b. ***System Qualification Testing*** parallels the principles of hardware qualification tests, but includes the software products to be used with system hardware. The total system is covered by an ERS which is the primary basis for the system certification test plan. This plan becomes the basis for action taken to qualify the system as a combination of hardware and software. Prior to release for production, the system must meet all ERS requirements, and there must be a System Verification Test Program which is useable by Field Service engineers as the final test following installation or servicing of the system.

c. ***Software Qualification or Evaluation*** involving products consisting of operating software includes a detailed review of the code, and operational qualification in the systems in which the software is supported.

5.7 Product Sales Specifications

Product Sales Specifications exist only as published in the Sales Data Sheet for the specific product item. Specification sections of operating and service manuals also include the same data; however, the sales data sheet is the controlling document. Prior to release for manufacturing and shipment, the Lab Project Manager and Marketing Product Manager take steps to assure all claims made in the sales data sheet have been verified by the qualification test program.

Following release for production, the Production Engineer and Marketing Product Manager continue to assure accuracy of the Sales Data Sheet throughout the life cycle of the product.

ustomer Service Engineering and Technical Publications are responsible for assuring accuracy of similar nformation in the operating and service manuals for the product.

5.8 Sales Reliability Considerations

Commercial Products are designed to serve a majority of the market application requirements for which the product was designed. In any market there are fringe applications where a given product may not be the best choice for the customer.

Sales Personnel make every effort to assure each sale of an HPDS product is appropriate for the application, and will assist the customer in evaluating his reliability considerations along the lines outlined in Section 4 of this manual.

5.9 Production Process Reliability

Application of Reliability Oriented Design Practices (5.3) and Extensive Qualification Testing (5.6) together with comprehensive documentation for production (5.5) provides manufacturing with the foundation on which to maintain the intrinsic reliability of the design, throughout the life cycle of the product. It is well recognized, that production does not improve reliability (exclusive of detecting and correcting design oversites), but can at best maintain the intrinsic reliability of the design.

The following paragraphs outline the major elements of the production operation together with actions taken to maintain production process reliability.

a. *Buyers* purchase parts and components only in accordance with the controlled list of approved vendors, and vendor part numbers. Purchase orders reflect Specification Control Drawings when called for by the controlling documentation.

b. *Incoming Inspection* receives and inspects items when inspection is designated. Inspection is accomplished using inspection plans, defect classifications, and specific procedures as supplied by Materials Engineering, Production Engineering, and Quality Reliability Engineering.

c. *Materials Handling* personnel are trained in handling the various types of material as it is moved and stored. Every effort is made to assure no damage from this source.

d. *Stockroom Acceptance* personnel check each lot of material received to assure that it has been accepted by Incoming Inspection (if inspection is required); or if no inspection is required, that the material complies with the vendor and stock number authorized by the Controlling Document.

e. *Shop Machining Operations* are controlled by individual process sheets for each operation. The process sheets include routing through in-process inspection operations as called for by the production plan for the part. Preparation of the production plan may involve the Lab Project Engineer, Production Engineer, Tooling Engineer, and Quality Engineer, depending on the nature of the part.

f. *General Process Control,* in either the shop or assembly areas, is exercised by the shop supervisor with the guidance of a Process Engineer. Activities include definition and documentation of the process, recognition of the points in the process where auditing will provide a maximum sensitivity to changes in the process, also development and implementation of continuing process auditing to assure maintenance of process control. In many cases, the auditing action is carried out by Product Assurance Personnel assigned to the area.

g. *Product/Part Sensitive Processes* are controlled by the operation process sheets incorporated in the production plan for the item involved. Auditing and control over these becomes part of the inspection program included in the plan.

h. *Production Assembly Processes* are controlled by several methods. The method selected will best fit the complexity of the assembly and the area in which it will be produced. Every assembly will (as a minimum) be covered by a complete material list showing every component or part used and information showing the location of the item in the assembly. When more complex assemblies are involved, an assembly drawing may be added, and may include process control sheets covering any critical steps in the assembly. In other cases, a complete sample assembly may be used. In all cases, information on basic workmanship standards is available, and will not be duplicated in a routine manner on the drawings.

Product Assurance Personnel maintain surveillance of the assembly areas, and conduct in-process inspection of items produced. No major assemblies may be accepted for stock except through the Product Assurance Inspection function.

i. *Assembly Testing* is one of the normal operations for all major assemblies. Controlled test procedures are used; and all failures are reported within a Production Failure Information System. The majority of the testing is accomplished under automatic or semi-automatic test conditions. Troubleshooting methods are built into the test equipment wherever possible. Tested assemblies are stamped for process control purposes. All production test equipment, including standard commercial instruments and special HPDS designed equipment, is covered by test and calibration procedures within a controlled system that assures use of currently calibrated test equipment.

j. *Assembly and Product Inspection* involves a mixture of 100% and Sample Inspection. The 100% routine inspection operations incorporated in the production plan are conducted by Production Personnel. The sample inspection operations are covered by Product Assurance Personnel (who may also audit the operation of all inspection operations within their area of responsibility). All inspection operations (Production and Product Assurance) enter defect information within the Production Failure Information System. The Production Failure Information System is covered in Paragraph 5.18.

k. *Product Level Assembly and Testing Processes* are similar. Each product has (as a minimum) a complete material list and a production test procedure. As product complexity increases, additional assembly drawings and detailed process sheets will be added. Each product has a specific production plan which includes the required in-process inspection operations as well as preliminary and final acceptance tests as applicable. Results of product inspection and test are entered in the Production Failure Information System.

l. *Reliability Enhancement* at the product level may be included in the production plan if complex products are involved. The fundamental sequence includes completion of the product to point of full performance verification, and additional operation for the period of time desired for reliability enhancement (operation may be at factory ambient, or at elevated temperature). Following this is a test and repair cycle, and the Final Production Acceptance Test.

5.10 Production Acceptance Testing

Production acceptance testing is done in accordance with test procedures developed concurrently with the product. The design team provides the basic procedure covering the product. Production Engineering adapts it to the production plan and special electronic tooling developed for production test. The adapted procedure is verified, and approved by the design function and the Reliability Engineer assigned to the product.

Production Acceptance Tests are conducted by manufacturing on 100% of all products shipped.

Product Assurance receives the tested products from production, and will conduct an additional test as well as an inspection. The tests are adjusted between sampling and 100% depending on the Q.A. Plan for the product, and current defect or failure levels.

No products are accepted for inventory or shipment without the authorization of Product Assurance. Each product carries an identification card showing Product Assurance Inspection and Test (or the equivalent authorization if accepted on a sample basis).

Test procedures used by Product Assurance parallel those used by Production, but are not restrictive. A continuing effort is made to assure use of the best possible test procedure at the earliest possible point in the production plan.

5.11 Product Shipping Protection

Product shipping protection is assured as an integral part of the development cycle. During the environmental test period, the product is subjected to transportation testing while in the package designed to protect it. Requirements for these tests are covered in "HPDS Lab Manual for Environmental Evaluation and Qualification Testing."

5.12 Customer Site Preparation

Operation and Service Manuals for individual products provide the necessary instructions for unpacking and installing the product. This will include any special considerations for the customer's site.

Where large systems are involved, a Site Preparation Manual is specially written. It provides detailed requirements which must be met by the customer's site in order to assure reliable operation of the product.

5.13 Installation and Service

Hewlett-Packard Sales and Service Facilities are located throughout the world, and can provide Installation, Warranty Service, Failure Repairs, and Maintenance Contract coverage for the majority of HPDS Customers requiring these services. A complete list of sales and service offices, and their respective capabilities is available.

5.14 Warranty Protection

Basic warranty protection is granted by HPDS to assure customers a minimum of expense due to any residual infant mortality failures that may be present in the products received, or any errors in production workmanship.

The specific coverage is stipulated by individual sales agreements reached between the customer and HPDS Sales. The various warranty available is covered by the HP Data Systems Marketing Policy.

5.15 Preventive Maintenance

The more complex electro-mechanical products, and some electronic products, require periodic inspection and replacement of parts subject to limited life or mechanical wear. These items are listed in the operating and service manuals for the product, and must be taken care of as specified in order to realize the intrinsic reliability of the product.

5.16 Service Training

Hewlett-Packard provides training, for HP Field Service Engineers, on each new product. The training program must be in operation; and trained service support personnel must be available, prior to shipment of the first product of a new type.

This training is also available to O.E.M. Customer Service Engineers charged with servicing HPDS products in OEM Systems.

5.17 Spare Parts

Spare parts are essential to any field service activity. Prior to Shipment Authorization for a new product, the spare parts orders for HP Service Centers must be ready for concurrent shipment, or must have been previously shipped.

HPDS also provides each field service office with Spare Parts Kits for each new product type. These kits must be available (by date of first shipments) for concurrent shipment to the regional sales and service office that will support the product.

5.18 Reliability Information Feedback

There are two primary sources of Reliability Information available for use as feedback. The most directly controllable source is from Production Failure Information; and the second source is from Field Warranty Failure Information. HP Data Systems utilizes both of these sources extensively.

Production Failure Information is derived from many sources within the production operation. Illustration (D) in Paragraph 5.0 shows, via the dotted lines, the input sources. Data is processed and analyzed as required to identify problem areas. Primary emphasis is on identification of component problems which may be due to infant mortality, a specific pattern problem with a vendor, design application problems, and problems introduced by the test used. The chance of random failure problems during production is relatively small.

The HPDS Production Failure Information System provides the following failure information for the product structure levels indicated:

. *Product Level Failures*

- How many produced during report period (typically 3 months average).
- How many assemblies failed and overall failure rate.
- Point in Product Test Cycle where failure occurred.

b. *Assembly Level Failures*

The critical few assembly types which comprise the major portion of total assembly failures are identified by ranking them in order of production failure repair costs. Each failure is priced per a standard labor rate, and standard part cost of the part failing. The following information is available for each assembly number.

- How many produced during report period.
- How many failures during assembly level tests.
- How many failures during product level tests.
- Specific components that failed in this assembly during the period.
- Quantity of each component used for total assemblies produced.
- Failure rate for each component.

c. *Component Level Failures*

The critical few component types are identified, again by costing the production failure repair charges for each type, and ranking in terms of diminishing failure cost. The following data is available for each component stock number.

- Quantity used in all assemblies (during reporting period).
- Failure rate in areas of: Incoming Inspection Test, Assembly Test, and Product Test.
- Failure details within each assembly in which it is used: Circuit location, component vendor, fail code, and point in production process where failure occurred (Assembly Test, Product Test, Heat or Cold Cycle, Reliability Enhancement, Final Acceptance, etc.).
- Comparison of failure rates, of stock number, in different assemblies with overall failure rate.

d. *Workmanship Defects*

With the type of information available from the system, it is possible to identify the following.

- Specific workmanship problems within each assembly.
- Most significant general type of workmanship problem.
- Where, in the production process, the defect was found.

Field Warranty Failure Information is derived from a combination of HPDS Field Warranty Repair Data, and data acquired when the failed assemblies are repaired. The majority of major products are serviced by field exchange of the failing assembly. This assembly is then returned to the HP Board Repair Facility for repair, and reused as an exchange assembly. Data acquired permits the following information to be developed for each product:

- Product Level Failure rate under warranty conditions.
- Number of assemblies, of each type, that have failed during period.
- Within each assembly type, the specific parts failing, and quantity associated with each circuit position.

Informal Reliability Feedback information is provided by Production Test personnel as they observe abnormal conditions, and by customers, or HPDS Field Service personnel, as they observe abnormal conditions or pattern problem areas. These inputs will serve to identify any major problem area that develops suddenly; however, they do not identify the more subtle, and often costly, failure patterns detected by the methodical processing of Production Test and Field Warranty Failure data.

5.19 Problem Correction

Problem correcting action is initiated on identification of any specific problem area. Personnel or organizational functions involved will depend on the nature of the problem. The Manufacturing Production Engineer is primarily responsible for directing the course of the action, with assistance from Materials Engineering, Customer Engineering, and Quality Reliability Engineering. The Engineering Department may assign personnel if the problem becomes technically difficult to resolve.

6.0 SOFTWARE RELIABILITY CONSIDERATIONS

This section of the manual explores considerations involved in evaluating software reliability, and outlines the actions taken by HP Data Systems to gain assurance that the majority of system software/hardware problems have been identified, and corrected, prior to releasing the system design for production and customer shipments.

6.1 General Considerations

Software, or Firmware, can be classified within three general types. Firmware is functionally identical to software, with the exception that firmware logic is permanently resident in a ROM (Read Only Memory) component. The three types are as follows:

a. *Diagnostic Software* is used as a test tool to evaluate the performance of hardware, or combinations of hardware and software.

b. *Operating System Software* is the software, supplied as an integral part of a system level product, which must be operational in the system in order for the system user to develop and utilize Application Software Programs.

c. *Application Software* includes all operating software programs developed by the user to perform specific tasks having value to the user. This is the software that actually creates value from ownership of the total system.

"Bugs" in Software/Hardware combinations are defined as residual deficiencies in software logic, or hardware operation, that prevent the proper completion of a logical task using appliction software programs.

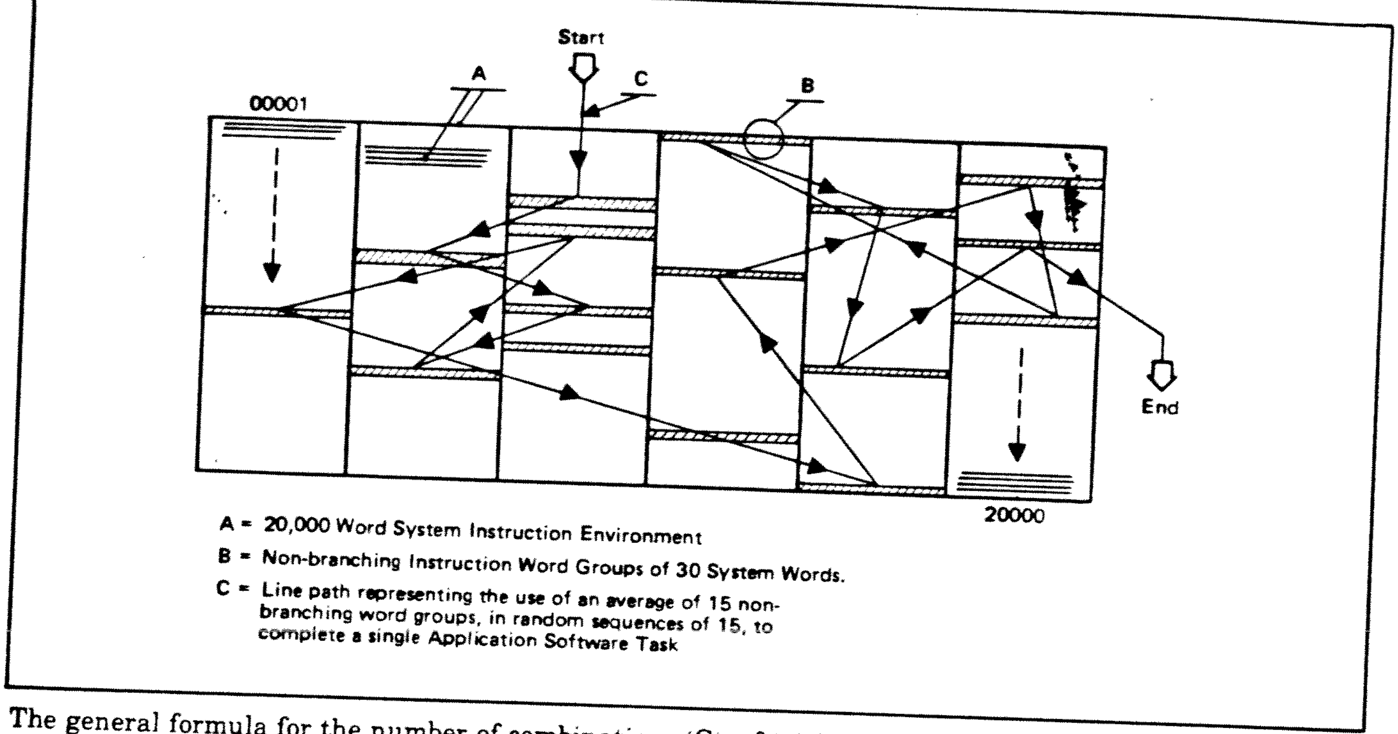
The theoretical number of logical tasks that could be created is an astronomical number. Fortunately the normal number of tasks in general use is infinitely smaller.

The Potential Magnitude of Software Evaluation Effort can be visualized with the aid of Figure 6.1A which represents the software environment of a relatively small system. In the example, the system consists of 20,000 *Words* (A) which are arranged in sequential order as required to set up a number of non-branching *Instruction Word Groups*. These groups will vary in length, with an average content of 30 words. In Figure 6.1A, these groups are represented by (B). If all 20,000 words are used, it would be possible to generate 667 of these 30 word groups.

Execution of a logical *Task* requires the use of various combinations of instruction groups. For this example, the average number of groups required per task is 15. In Figure 6.1A, the line path (C) represents a typical path for a task using 15 instruction word groups. The sequence in which they are used is a function of the application software requirements (as programmed by the user).

Estimation of the total number of logical software tasks that might be subjected to evaluation can be estimated by asking the question "How many tasks can be generated using a total of 667 instruction word groups, in randomly selected sequences of 15 groups?"

Figure 6.1A. Small System Software Environment



A = 20,000 Word System Instruction Environment

B = Non-branching Instruction Word Groups of 30 System Words.

C = Line path representing the use of an average of 15 non-branching word groups, in random sequences of 15, to complete a single Application Software Task

The general formula for the number of combinations (C), of (n) items, taken in groups of (a), is as follows:

$$n^{c}a = \frac{n!}{a!\ (n-a)!}$$

In this example, (n) = 667, (a) = 15, and (n− a) = 652

or

$$667^{c}15 = \frac{667!}{15! \times 652!}$$

C = Approx. 1.5 x 10^{30} Combinations

1.5 x 10^{30} represents all possible tasks that can be generated from 667 sets of instruction word groups used in random sequences of 15.

NOTE

Direct solution of this problem is beyond the capacity of most large computer systems. The answer is derived by use of the Stirling Approximation for each factorial term.

This approximation is: $n! = n^{n} \times e^{-n} \sqrt{2 \pi n}$

For those of you not familiar with factorial terms (n!): The direct answer for 667! = (667 x 666 x 665 x 664 . . . etc. x 3 x 2 x 1).

To appreciate the magnitude of this number, visualize a line 1 inch long as representing 1 million of the tasks. Continue visualizing the extension of this line (at the same rate of 1 million tasks per inch) out into space until all tasks are represented by a single line. Now, if you could travel at the speed of light, it would require 4 million years to travel the length of the line (Speed of Light = 186,000 Miles Per Second).

Since we wish to consider testing each task, we first need to establish the probable rate at which testing can take place. We will assume that a computer can execute each word of an instruction group in 1 millionth of a second (1 microsecond). Each task consists of 450 words (15 instruction groups at 30 words per group) and will require 450 microseconds to test. This will correspond to *testing tasks at the rate of 2,222.22 per second or 8 million per hour.*

We recognize that many of the possible combinations of tasks will have no useful function, so we will *estimate the time to test only 1 billionth of the total.*

$\frac{1.5 \times 10^{30}}{10^{9}} = 1.5 \times 10^{21}$ Tasks to test at rate of 8×10^{6} per hour.

$\frac{1.5 \times 10^{21}}{8 \times 10^{6}} = 6.25 \times 10^{13}$ Hours to test 1 Billionth of Tasks

$\frac{6.25 \times 10^{13}}{8760^{*}} = 7.13 \times 10^{9}$ = **(7) Billion Years to Test only one Billionth of the tasks.**

*Hours Per Year

You should now be convinced that software qualification testing cannot be accomplished using the logical approach of testing all possible operating sequences to assure they work. This is similar to product hardware testing where it is also not possible to conduct actual testing on all combinations of part and component tolerances that may exist during the life of the product. In both cases (software and hardware) there is a major dependence on the judgment used in design and development, together with a certain degree of risk that some problems will not be discovered other than through customer application and use of the product.

Let's proceed by viewing the scope of evaluation that might be accomplished by a reasonable software evaluation effort on a system of this size. It is not realistic to assume full time effort throughout the evaluation period; so let's establish some realistic times as follows:

a. *Basic Time Factors Are*

- 1 year = 24 hrs. x 365 days or 8,760 hours maximum.
- Normal Hours = 8 hrs. x 5 days x 52 weeks = 2080.
- We will allow approximately 10% for extra time for a total of 2200 hours per man year. Dividing this by 12 gives approximately 183 hours per man month.

b. *Qualification Test Program Efforts Might Include*

- Engineers to develop and conduct the testing required during the time period for the evaluation program. It is estimated that 50% of the engineer's time is spent planning tests, and the other 50% in evaluation of results, and pursuit of corrective action. A program of this size could involve as many as 8 engineers on a full time basis.
- 6 calendar months allowed for the program.
- 2 computer systems available for test use. We assume they would be utilized directly for actual testing about 80% of the normal 183 hours per month. For the 2 computers, and a 6 month period, this would generate approximately 1757 test hours.

- From the preceding paragraphs, we established that we can test 8 million tasks per compute operating hour.
- Total tests conducted in 6 months = 8 million per hour × 1757 test hours = approx. 14.1 billion tests.
- This is only 93.7×10^{-18} percent of the 1.5×10^{30} possible tasks, . . a very insignificant scope of tes coverage for a relatively large effort over a long period of time.

Practicable Software Evaluation Programs can, at best, evaluate only a very minute percentage of the potential operating tasks available for customer application software. Fortunately the majority of the customer applications involve only a few tasks; and the combined efforts of factory evaluation testing and early life customer use will quickly eliminate the vast majority of any residual bugs in the hardware and software.

Detection and removal of software bugs can be viewed as similar to the detection and removal of design errors during the early life period of a hardware product. Every effort is made to assure that performance is within specified limits; however, there may be areas of implied performance that are reasonable, but which were not specifically covered (by either specifications or by direct testing) during the qualification test period. Residual problems will not exist in the more obvious and commonly used areas of performance, but will be found only when a chance condition exists that involves secondary areas.

At the present time, there does not seem to be any widely accepted definitions covering the statistical distribution of software bugs. It seems logical to assume that, for any given system, there are a descrete but unknown number of bugs that exist; and as each one is discovered and removed, there is a diminishing probability of encountering the next bug. If we accept this, it implies that as software is used it becomes increasingly more reliable. As a counter argument to this logic, we can assume that correction of a bug has the possibility of creating one or more additional bugs that may be found in the future. It is obviously not possible to completely re-evaluate all software tasks following the fix of a detected bug. If we subscribe to this school of thought, we can argue that a software system will reach a point of constant reliability (where we average the creation of a new bug for each one we fix); or we can argue that it diminishes in reliability (we average slightly more than one new bug for each one fixed).

These considerations apply to a composite view of the software and system as it involves all customers. From a practical point of view, individual customers will probably confine the use of a system to a limited variety of application software. Once the bugs (if any) are removed, this software becomes infinitely reliable until such time as new application software programs are developed.

6.2 HP Data Systems Approach

This paragraph briefly outlines the principles followed by HP Data Systems for the purpose of minimizing the risk of leaving undetected "bugs" in software at the time of system release for production and customer shipments.

Software Functions (Instruction Word Groups) are defined for the system in the External Reference Specification (ERS) for the system software. The ERS for software parallels the purposes served by the ERS for hardware as discussed in Paragraph 5.4.

During the development phase, every effort is made to verify each function (instruction) as it is developed.

System Software Evaluation and Qualification, prior to release for production and customer shipment, is accomplished by a separate group within the Product Assurance Department.

The Software Quality Engineers assigned to the system will prepare a Qualification Test Plan encompassing the following activities.

a. *Functional Verification* of all instructions and functions defined in the Software ERS. This will involve the use of special application software designed to test both the standard and unique functions of the system.

b. *Response To User Operating Error:* How gracefully does the system respond to, or recover from, incorrect or random action by the user?

c. *System Limits Testing* to assure proper operation under minimum and maximum loads and configurations. For example: How well does the system operate with a single terminal user? How well with a maximum terminal mix?

d. *Performance Testing* (speed and accuracy as applicable). These tests are typically in combination with maximum limit testing conditions.

e. *Compatibility Tests* to evaluate compliance with any applicable industry (or other) software standards.

APPENDIX

This appendix consists of a selected bibliography of books and articles on the subject of reliability, and also reading guide based on the readers area of interest.

Selected Bibliography

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24. Reliability in The Electronics Manufacturing Phase, C. Jowett, Microelectronics and Reliability, Vol. 15, pp 595-600, Pergamon Press, 1976

25. Hazard Plotting for Incomplete Failure Data, W. Nelson (General Electric), Journal of Quality Technology, Vol. 1, No. 1, January 1969

Reading Guide by Area of General Interest

Management: 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 19, 23, and 24

Reliability Technology: 1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25

Production Quality and Reliability: 5, 6, 7, 8, 9, 18, 19, 22, 23, and 24

Quality and Reliability Programs: 5, 6, 8, 9, 10, and 19