Reliability from Design Inception to Product Retirement

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SUMMARY & PURPOSE

In this presentation a product is followed from design inception to product retirement. An outline of a cohesive structure for reliability testing throughout a product's life cycle is presented. In this structure the design of each successive test is based on analysis, expert opinion, past data obtained from similar products in the field, and data from earlier tests. The appropriate location and use of (1) Over Stress Tests, (2) Design Reviews, (3) FMEA, (4) Reliability System Analysis, (5) Accelerated Life Tests, (6) Real Time Life Tests, (7) Reliability Growth Tests, (8) Burn-In, (9) Environmental Stress Screens and (10) Statistical Process Control are discussed. Finally, field failures and the steps necessary to insure that the resulting engineering change orders yield improved reliability are covered. This paper is based primarily on the observation and experience of the author which was gained during a 40-year career in reliability and quality.

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Dr. Dietrich has been director of consulting services for ReliaSoft for the last three years. During his 40+ year career he has served as a consultant to over 50 companies and government agencies both nationally and internationally. Some of his more notable clients have been the US Army, the US Navy, IBM, Cameron Oil, JPL, Guidant, Motorola, Raytheon, and Xerox. In addition, he has taught over 60 short courses for industry in the areas of Engineering Statistics, Statistical Process Control, Concepts of Reliability, Reliability Testing and Large Scale Reliability Systems Analysis.

He is a Professor Emeritus at the University of Arizona. During his 30 years on the faculty his teaching responsibilities were in the areas of statistical quality control, reliability, and engineering statistics. He was the first faculty member in the College of Engineering to have his courses televised. His courses were televised for 25 consecutive years to numerous government and industrial sites across the USA. He has received five teaching related awards, including the Tau Beta Pi Professor of the Year Award the first year it was given at the University of Arizona. He has published numerous papers and graduated 9 Ph.D. students.

Prior to entering graduate school he was employed for five years as a project engineer in environmental test and evaluation at the US Naval Missile Center, Point Mugu, California.

He was Charter Chairman of the Tucson Section of the American Society for Quality. He has served as Secretary and Vice Chairman of the Statistics Committee, and as Secretary of the Statistics Division of the American Society for Quality. He was also a guest co-editor for a special issue of the *IIE Transaction* devoted to reliability and quality. He served as an associate editor for the *IEEE Transactions on Reliability* for 12 years. He is presently on the RAMS Management Committee.

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1. *INTRODUCTORY CONCEPTS*

1.1 *Reliability is a Long Standing Bridge Between User and Product*

The Golden Gate Bridge across the San Francisco Bay area was so well constructed that since its opening 65 years ago, it has been used extensively and still carries unrestricted road traffic reliably. The great reliability of the bridge results from its relatively simple structure, good construction workers, and large safety factors. This is an example that shows how reliability is appreciated by the user of the product (or service).

2. *CUSTOMER REQUIREMENTS AND SPECIFICATIONS*

Few customers will specify traditional Reliability Requirements in terms of MTBF, Failure Rate or Probability of Occurrence. Even when they do, there are many misunderstandings. Designers, Analysts, Manufacturing and Sales often operate to a set of metrics that are not important to the customer. These are just a few of the reasons why it is paramount that the following steps be incorporated into the product design process:

(1) Reach a common understanding between buyer and supplier, of reliability expectations, early in the relationship.
(2) Make reliability a high priority requirement in each specification development.
(3) Establish an agreed on mission profile, mission time and operating environment.
(4) Insure that both buyer and supplier recognize the cost of poor reliability.
(5) Make sure that both consumers and producers understand that reliability is a long-term goal.
(6) Make sure that both consumers and producers are measuring reliability the same way. MTBF is the wrong specification metric. Money is the universal language.
(7) Unless there are real and measurable consequences for poor reliability, attention will always be weak.

3. *RELIABILITY DATA SYSTEM*

A Failure Reporting, Analysis and Corrective Action System (FRACAS) is one of the most important elements of a robust reliability program. A FRACAS system can be used to organize and address a company's reliability issues on a real-time basis.

The primary purposes of a FRACAS are to provide a closed-loop failure reporting system, procedures for analysis of failures to determine root-cause and documentation for recording corrective action. Failure data are powerful, but need to be managed properly to ensure accuracy and timeliness.

The design of a FRACAS depends greatly on the data collection and analysis needs of an organization, as well as the capability to collect and analyze the data. However, the main elements inherent to all FRACAS should be (1) the Failure Incident Report, (2) the Failure Analysis Report and (3) the Corrective Action Report. Other reports may be added to meet specific needs.

3.1 *Traceability*

In a well run reliability program it is absolutely required that individual components within a system be traceable. Data on how long a failed component was in actual operation is critical. To obtain this type of data, components must be bar-coded. With out bar-coding a company may end up paying for many failed components that are out of warrantee.

3.2 *Failure Incident Report*

A Failure Incidence Report should contain the following minimal information:

(1) ID number for the report
(2) Name of person writing the report
(3) Component part number and serial number
(4) Hours of component operation at time of incident
(5) Indication of whether a failure occurred or not
(6) Location of incident
(7) Date of incident
(8) Description of incident
(9) Date of repair
(10) Description of repair.

3.3 *Failure Analysis Report*

A Failure Analysis Report should contain the following minimal information:

(1) ID number for the report
(2) Name of person filling out the report
(3) Initial visual inspection
(4) List of fault codes/data downloaded from the component and or sub-system
(5) Initial work performed to determine root cause
(6) Detailed root cause analysis.

3.4 *Corrective Action Report*

A Corrective Action Report should contain the following minimal information:

(1) ID number for the report
(2) Owner and Priority
(3) Description of problem
(4) Short term corrective action
(5) Description of root cause
(6) Long term corrective action
(7) Preventive action

(8) Follow-up to ensure corrective/preventive actions are effective.

3.5 *Additional Failure Report Data*

Additional information can, and should, be captured to facilitate use by multiple groups within an organization. Additional Failure Report data that should be considered are:

(1) Was the failure covered under warranty?
(2) Was the failure due to a quality problem?
(3) Did the operator, or the way the product was installed, cause the failure?
(4) If a system is analyzed, was more than one component replaced to repair the system?
(5) Identification of the sub-component that caused the failure, to the level of detail known.
(6) Total time for repair (broken up into Logistics Time, Troubleshooting Time and Repair Time).

3.6 *Additional Corrective Action Data*

Additional Corrective Action Report data that should be considered are:

(1) The date of Corrective Action implementation.
(2) ID number of any Engineering Change Orders that were generated to correct the problem.
(3) Did the problem occur on the production line, in the field, during testing, or in more than one of these locations?

4. *DESIGN OF RELIABILITY TESTS*

The design of reliability and reliability related tests, whether or not they occur as part of product design, reliability evaluation or manufacturing process design is dependent on two types of operational data. These are a detailed mission profile and a detailed description of the operating environment. This same data should also be available to the product design team as the product must be designed to perform its intended mission with a specified reliability while in its operational environment.

4.1 *Mission Profile*

The more information provided in the mission profile and integrated into the design process, the more reliable the product. The following is a hypothetical example of a mission profile for a hydraulically actuated valve designed to control the flow of oil from a well head:

(1) The valve cycles (x) times per day on the average.
(2) The oil that flows through it is grit laden. Data on the amount and characteristic of grit per gallon of oil should be provided.
(3) The oil flows at 100 to 120 ft. per sec. Velocity profiles should be provided.
(4) The oil temperature is 300 to 350 deg. F. Temperature profiles should be provided.
(5) The relative oil pressure is 400 to 450 psi. Relative oil pressure profiles should be provided.
(6) During a valve's operation the relative hydraulic fluid pressure varies from 0 to 1000 psi.

Information like the above is best obtained by actual measurement, but this is not always possible. Hence, sources such as past history of similar products and expert opinion may have to be used. The more accurate the operational data, the more reliable the product will be.

4.2 *Operating Environment*

The operating environment is sometimes more important than the mission profile. In some situations the operating environment has a greater effect on device life then mission profile. This is often the case for electronics. The following hypothetical mission profile data incorporates some of the *worst* possible operating conditions for an electronic device. The device is a controller, mounted on a drilling and production platform, that is used to control all of the under ocean valves that are used to direct the oil flow from a well head. In operation, the controller actually controls the electric motors that run the hydraulic pumps that provide the hydraulic fluid to actuate the valves.

The controller operates in an environment where the temperature varies from -40 deg. F. to 120 deg. F. Actual real time data should be supplied on temperatures outside and internal to the device when in both an operating and stand-by mode.

The relative humidity can vary from 10% to 100 %. Actual relative humidity versus time profiles should be supplied.

The controller is subjected to an acoustically generated high G broadband random vibration environment. Actual vibration levels should be monitored on the controller or similar devices.

The controller operates in a salt spray environment. Concentrations of salt should be monitored.

Information similar to the above is best obtained by actual measurement. Data on the operating environment are usually easier to obtain than data on the mission profile.

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4.3 *Strength Stress Relationships*

Figure 1 is a simplistic depiction of the stress-strength relationships for a product. It shows that specified strength values may or may not include the maximum operational stress levels. Hence, a product designed to meet a specification may or may not be reliable. It also shows a design strength considerably larger then maximum operating stress, which is necessary for a product to be highly reliable. The difference between the design strength and maximum operational stress level is similar to a safety factor in structural design. The design strength is established a-prior based on past history of similar products, expert judgment and knowledge of the product's operating environment. It must be high enough to compensate for uncertainties in the operational environmental levels, irregularities in materials, inconsistencies in manufacturing and other various factors. It may need to be several times the measured maximum stress level if there is a large amount of uncertainty in the operating environment and product strength.

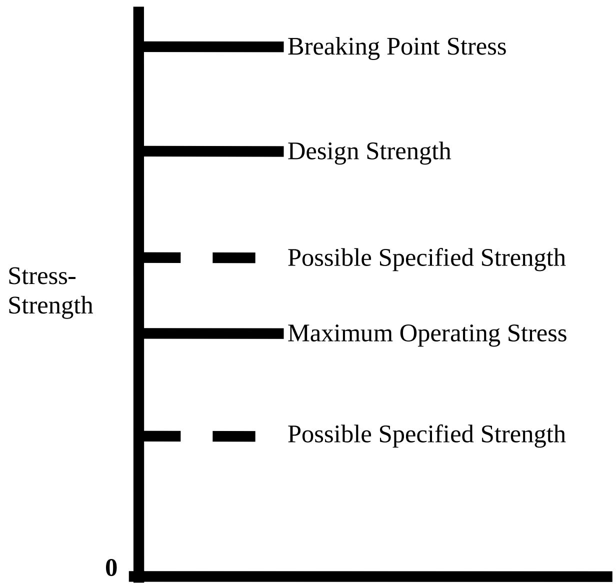

Figure 1, Hypothetical Stress-Strength Relationships

5. *RELIABILITY TESTS AND ANALYSES THAT OCCUR DURING PRODUCT DESIGN*

The primary purposes of reliability and reliability related tests, conducted during the product design phase, are to identify design changes necessary to insure that design strength is met and to identify the stress levels necessary to cause failure. This knowledge is critical when designing the reliability evaluation tests that come after design completion.

There are two primary types of reliability tests that occur during the design process. These are (1) component Over-Stress Tests and (2) subsystem and system Highly Accelerated Life Tests (HALTs). These tests are similar in concept, but are performed at different times in the product design and consequently have somewhat different objectives. The acronym HALT has different meanings to different people. Both of the above types of tests are qualitative, not quantitative in that they are meant to help improve the product design, not provide direct reliability estimates. It is the author's opinion that every reliability related test conducted during the product design process should be designed not only to help improve the product design, but to provide data to aid in the design of the more sophisticated quantitative reliability tests that occur later in the product's development and deployment cycle.

5.1 *Component Over-Stress Tests*

Component Over-Stress tests are a very important part of the design process. These tests are conducted early in the design cycle. Hence, they cost less than subsystem and system level tests and can be run relatively quickly. Ideally, all critical components should be Over-Stress tested and their strength improved to where it is considerably above the maximum operational stress level. With proper component Over-Stress testing, the only failures that should occur in the subsystem and system HALT are interface failures. By definition, component Over-Stress tests are designed to test the component in an environment that is significantly more extreme than its predicted operational environment. The author is a proponent of step-stress tests for component Over-Stress testing as these provide information on both the maximum stress levels where components will operate and the stress levels where they will fail. The maximum stress level where a component will operate should be above its design strength. After failure occurs, a failure mode analysis should be conducted and the product design should be improved to incorporate the changes dictated by the results of the Over-Stress tests and the subsequent failure mode analysis. The entire process should then be repeated until the product demonstrates that it meets or exceeds its design strength. Not all component level testing need be done in-house as there are many components available commercially that have been subjected to this type of testing. This is particularly true of electronic components. For these components it is only necessary to insure that the vendor's Over-Stress testing is consistent with the product's operational environment.

As a hypothetical example of a component level test procedure, consider the mission profile for the control valve previously described. During operation, the mission profile of this valve contains five stress factors. These are oil pressure, oil velocity, oil temperature, grit level and hydraulic fluid pressure. Engineering analysis concluded that there is also one critical operational environmental factor. Ocean currents cause flexing of the pipes that lead into and out of the valve. There are several questions that must be resolved by engineering analysis before a test is designed. For example:

(1) Can and should any of these factors be eliminated from consideration?
(2) Do any of these factors interact?
(3) Is it physically possible and economically feasible to perform tests that include all the factors not previously eliminated by engineering analysis?

Stress factors are eliminated from testing by engineering analysis and possible re-design. In this example, the stress factors to be considered are oil pressure, oil temperature, oil velocity, grit level, and inlet and outlet pipe flexing. Some of these might be eliminated from consideration as follows:

(1) The pipe flexing problem could be resolved by attaching the pipes to the frame, but this must be done

in a way that does not cause a compression/expansion problem due to external and internal temperature variation. If this temperature variation is small it may be ignored.

(2) Engineering analysis indicates that oil temperature is not a significant factor, hence can be excluded.

(3) Because the hydraulic actuators that operate the valves are external to the actual valve, the effects of this stress factor can possibly be evaluated by a separate less expensive test.

Hence, the only three factors that need to be considered in the Over-Stress test design are: (1) oil pressure, (2) oil temperature, and (3) grit level.

In the author's opinion, the following is a realistic hypothetical test design. Five components will be subjected to Over-Stress testing. Engineering analysis has concluded that test grit level can be kept constant, and a level is selected 20% above the measured maximum operating level. Since oil pressure and oil velocity are physically dependent factors, they will be ramped up at the same time. A mean test level, 10% above the maximum operating levels, is chosen as the starting point and the mean test level will be ramped up in steps of 30% of the maximum operating stress. Each ramp step is 24 hours in duration. During the test the oil pressure and velocity will be cycled about their mean levels consistent with the cycling that occurs in operation. Testing is continued until all components fail or a component fails below the design strength. If a component fails below the design strength, testing is stopped, a failure mode analysis is conducted and corrective action is taken. This corrective action must result in a product design change or a manufacturing process change. The test sequence will be repeated with five new components that incorporate the changes instituted during corrective action. If all additional failures occur above the design strength, testing is stopped and the design is frozen. If no failures have occurred and testing has reached levels of 200% of design strength, testing is also stopped and the design frozen. It should be emphasized that the design strength must be significantly above the estimated maximum operating stress level. If the design strength is set too low, the component will never be reliable. When establishing the design strength, all mission profile and operational environment factors must be considered. Also, factors such as material variation, manufacturing process variation and others specific to a particular product must be considered. Establishing the design strength is one of the most important parts in the design of a high reliability product.

5.2 *System and Subsystem HALT,*

HALTs are similar to component Over-Stress tests, but are conducted at the sub-system and systems levels. Because they occur further along in the product design process, they are more complex and cost more to conduct. If all components have been adequately Over-Stress tested, the HALT should identify only interface problems such as weak connectors, bad solder joints, incorrect tolerances and others. If frequent component failures occur during the HALT, the components have not been adequately over-stressed tested. In the author's opinion, HALT should use step-stress multi-environment tests, simultaneously incorporating all the stresses likely to occur in a product's operation. However, for complex products subjected to multiple stresses during operation, this may not be feasible due to the test complexity, the cost of running the test and the cost of building the test equipment to perform the test. In this situation, engineering analysis must determine which stress factors have to be tested simultaneously and which can be tested independently. If a significant interaction effect occurs between the stresses, these stresses must be included in the same HALT. An example of such an interaction is a device that is subjected to both high pressure and extremely high temperatures during operation, such as superheated steam pipes. The interaction is the reduction of strength, caused by the high temperatures, that causes a pressure induced failure. Hence, both temperature and pressure must be applied simultaneously.

An example of the type of HALT the author prefers is the Design Margin Evaluation Tests that were run by the US Navy in the 1960's. The author is quite familiar with these tests as he designed the most complex of them and did the associated data analysis. In this test entire missiles were subjected to combined temperature, altitude and random vibration tests. Three levels of each environment were applied in a 3X3X3 nested factorial experiment. The first level of each environment was the average operating level and all the other levels were progressively higher. This testing sequence identified several weak areas and resulted in partial product redesign. It also showed that there was a serious interaction between temperature and random vibration. This type of test design has its place, but it is probably more complex than necessary for most routine HALTs.

The first lesson in designing a HALT, or any other reliability related test, is to take time to make sure that all factors have been considered. Time and money spent on a thorough test analysis and design will result in less costly tests that yield more information critical to a reliable design. Figure 2 is an example of a typical step-stress HALT.

6. *FMEA/FMECA*

FMEA was developed during the 1950's by the Grumman Aircraft Company. Since then it has been adopted and improved by many other companies. FMEA analysis has evolved from an ad hoc technique, dependent on the designer's experience, to a formal and accepted analysis tool. Failure modes can be described functionally and the functional system model can be analyzed early in the design phase of a product or process development. If conducted manually, an FMEA can be very tedious. Fortunately, several software packages, such as the one by ReliaSoft, are available to aid in conducting FMEAs

Failure Mode and Effects Analysis (FMEA) as well as Failure Modes, Effects and Criticality Analysis (FMECA) are methodologies designed to identify potential failure modes for a product or process. Both are used to assess the risk associated with failure modes, to rank the issues in terms of their importance and to identify and carry out corrective actions to address the most serious concerns. FMEA/FMECA provides a structured framework and documentation for the evaluation of products and processes.

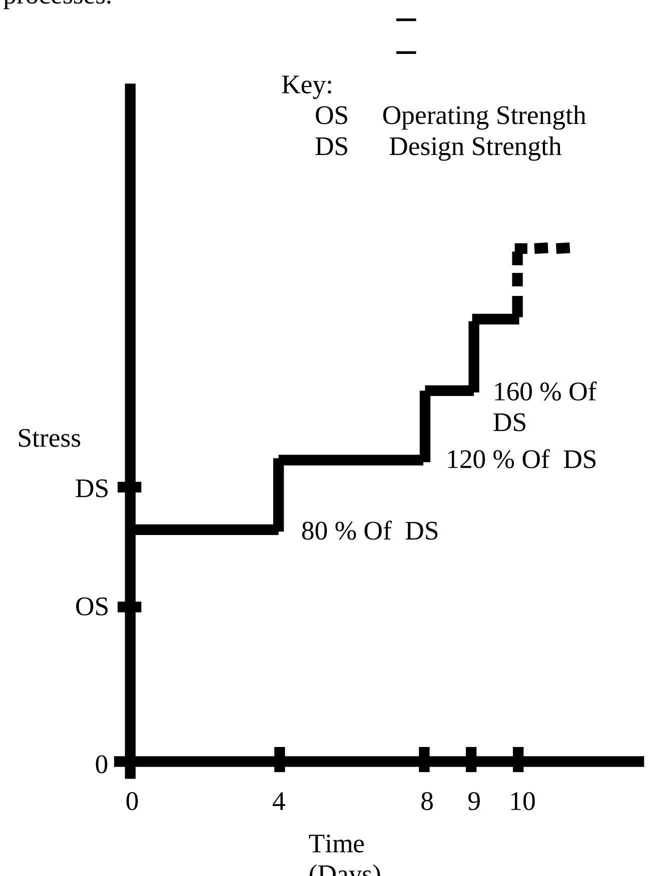

Figure 2, Example Step Stress HALT Test
Five Items on Test

The timing depends on the type of analysis and the particular product/process. For maximum benefit, FMEA/FMECA should be performed before the event. In addition, FMEA/FMECA is intended to be a dynamic and iterative process in which the practitioners review and update the analysis as new information becomes available.

FMEA analyses are often referred to by type, such as System FMEA, Design FMEA (DFMEA), Process FMEA (PFMEA), Machinery FMEA (MFMEA), etc. Although the purpose, terminology and other details can vary according to type, the basic methodology is similar for all.

FMEA is a tool that has been adapted in many different ways for many different purposes. It can contribute to improved designs for products and processes resulting in higher reliability, better quality, increased safety, and reduced costs. Some of the applications and benefits of FMEA follow:

(1) Contributes to the identification of requirements for built-in test equipment (BITE).
(2) Contributes to the development of effective maintenance procedures.
(3) Provides a knowledge base for future troubleshooting efforts.
(4) Provides tools to investigate reliability of existing systems/processes.
(5) Contributes to other types of system analyses, such as Reliability Block Diagram (RBD), Markov Processes, Fault Tree, etc.
(6) Provides a central location for reliability-related information for the system/process.
(7) Provides a learning tool for new engineers
(8) Meets a customer requirement and/or to comply with Safety and Quality requirements, such as: ISO 9001, QS 9000,ISO/TS 16949, Six Sigma, FDA Good Manufacturing Practices (GMPs).

7. *PRELIMINARY SYSTEMS RELIABILITY PREDICTION*

Obtaining accurate preliminary reliability estimates is one of the most difficult areas of reliability analysis as these estimates are not usually based on a quantitative test results. There are data bases and associated soft-ware, such as the Bellcore-Telcordia data base, to help in obtaining reliability estimates for electronic components. However, this method has been the topic of many papers in the literature where its accuracy has been repeatedly challenged, primarily due to how the data is collected and the underlying analysis assumptions.

The author does not know of any centralized data base for mechanical components. There is information on a few select components such as bearings. However, most data on particular products is proprietary.

The ideal situation is to have in-house historical information on similar existing systems and to use the results of the products FMEA, component Over-Stress tests and sub-system HALTs to demonstrate that the reliability of the new system should be as good or better that that of the existing system.

If data from similar existing systems does not exist, the preliminary system level reliability estimates will be highly dependent on expert opinion. These results will be highly dependent on the experience of the experts and may or may not be accurate.

This entire scenario demonstrates the importance of the quantitative reliability evaluation tests that are conducted later in the systems design maturing process.

8. *RELIABILITY EVALUATION TESTS*

The purpose of Reliability Evaluation Testing is to estimate the probability of a component, subsystem and/or system performing its intended mission while operating in its intended environment. Originally these were real-time tests conducted in simulated environments. However, because of the long life times of modern products, the inappropriateness of assuming constant failure rate, and the short time between design specification and release time, real time life tests are not possible. Hence, some type of accelerated "time" life test (ALT) must be conducted. The two primary types of ALTs covered in this report are increased stress tests and time compression tests. In an increased stress ALT, the test stress levels are significantly above the operating stress levels thus reducing the time necessary to cause failure. In a time compression test, the device is cycled at a significantly higher rate than the operational rate thus reducing the time necessary to cause failure.

A properly designed ALT is based on accurate data on the (1) mission profile, (2) operating environment, (3) likely failure modes and (4) strength relative to the operating stress, for the product. This last requirement is unique to increased stress ALT. The accuracy of the resulting reliability prediction is highly dependent on the accuracy and detail of the input data. Each of these four critical factors will be discussed in general.

The author is a proponent of multi-level constant stress ALTs as they provide more information than many other types. Figure 3 is an example of such an ALT. In such an ALT, the test stress levels are significantly above the operating stress levels thus reducing the time necessary to cause failure.

8.1 *Failure Modes*

Most potential failure modes are obvious to a professional, but the ones that are not obvious are the ones that cause the problems in the field. This is when an in-house mature professional with many years of experience with similar products is invaluable.

8.2 *Design Strength*

In the design of an ALT, knowledge of the product design strength relative to its mission profile and operating environment is critical. To obtain a reasonable acceleration factor, the product design strength must be considerably higher than the operational stress. The tests are designed with test levels above the operational stress, but not much higher than the product design strength.

Product design strength is initially established by analysis and when possible verified by component Over-Stress tests as well as sub-system and system HALTs. Consequently, the component Over-Stress test and sub-system and system HALT should be designed looking forward to the Reliability Evaluation Tests.

9. *EXAMPLE ALT TESTS*

9.1 *Hydraulic System Time Compression ALT,*

The operational environment for an under-ocean hydraulic device is quite unique. To design an ALT, detailed and accurate data must be obtained on the under-ocean environment and operational profiles. Many questions must be answered prior to designing the ALT. For example, should absolute pressure or differential pressure be considered in the ALT design? If differential pressure is important the ALT can be conducted in a laboratory. If absolute pressure is important, the tests will probably have
to be conducted on the ocean floor.

Key:
OS Operating Strength
DS Design Strength

Stress Level 1 OS +.05(DS-RS).10 Items On Test
Stress Level 2 OS+.40(DS-OS), 6 Items On Test
Stress Level 3 OS+.75(DS-OS), 4 Items On Test
Stress Level 4 OS+.1.1(DS-OS), 4 Items On Test

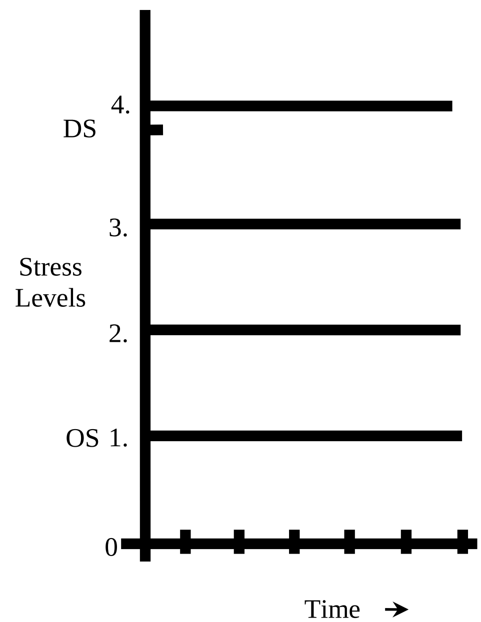

Figure 3, Example of Constant Stress ALT

The actual test will consist of cycling the hydraulic device at the highest rate that still insures correct operation. The ratio between the operational cyclic rate and the laboratory cyclic rate determines the acceleration factor. The system should be operating during the test and the test profile should simulate the actual operational environment. Every different product will require an ALT designed to simulate its actual operational environment and mission profile. Some stress factors in the operational stress profile may be eliminated in the ALT design by an engineering analysis that indicates they are not likely to contribute to product failure. Stress factors should never be eliminated out of convenience.

9.2 *Hydraulic Systems ALT Pressure Tests*

These tests are used for non-cyclic products. The primary accelerating factors are:

(1) Hydraulic fluid temperature and pressure
(2) Oil temperature and pressure
(3) Oil velocity and abrasiveness.

These factors should be run at levels considerably above the operating stress levels, thus accelerating time to failure. The actual levels should be determined for each individual product based on data obtained during design process and associated component Over-Stress tests and subsystems and systems HALTs.

9.3 *Electrical Systems ALT*

ALTs for electronic products are traditionally conducted with the product operating and subjected to some combination of temperature and broad band random vibration. However, it is the author's opinion that these tests should use the stresses the product will see in operation. Test levels should be established based on design strength, operating environment, and mission profile. Factors such as voltage and/or current, power surges, internal device temperature, vibration, shock, salt spray and humidity may apply. Sound engineering judgment should be used to determine which factors need to be considered in the ALT designs.

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9.4 *Structural Accelerated Load Tests*

These tests are conducted more to insure the structural integrity of the device than to estimate its reliability. They are usually conducted by loading the structure with a significantly higher load than it will see in operation. These loads can be either static or dynamic. For most large structures, the testing equipment will have to be built to run the test.

Dynamic loads are the most difficult to analyze as they cause fatigue failures. Most people think the age of an aircraft is the most important factor in failures. This may be true for engines, but most structural failures are fatigue failures caused by the compression and expansion of the aircraft body due to up and down cycling. Thus a short haul Boeing 737 that, on the average, is subjected to 6 up and down cycles per day will fatigue at 6 times the rate of a Boeing 747 that on the average is subjected to only one up and down cycle per day. HALT using the actual operational dynamic loading profile as a basis may be the most difficult test to conduct.

9.5 *Structural Accelerated Vibration Test*

Vibration tests for large structures require special equipment such as thrusters to run. Usually, low frequency swept sinusoidal vibration is used. The test levels are set, considerably above the predicted operational levels, to accelerate time to failure. It is difficult to obtain reliability prediction information from these tests. Consequently, their primary purpose is to insure that the natural frequency of the structure is not close to the operational excitation frequency or any of its harmonics. This problem can be solved by adjusting the stiffness of the structure, increasing the mass of the structure or adding damping to the structure. These tests should be conducted during the design phase with mock equipment installed and repeated on a limited scale during the reliability evaluation stage with all the operational equipment they are to support installed.

If systems level reliability tests cannot be conducted because of the size and complexity of the system, the subsystems level test data will have to be used along with the systems level reliability logic diagrams to get a systems level reliability estimate. There are several commercially available computer software packages to aid in such calculations. ReliaSoft's BlocSim is the newest and most comprehensive of these packages. When a system level estimate must be obtained in this manner, interface failures that occur in the connections between subsystems, could result in future problems. Consequently, it is extremely important that the interfaces be given critical consideration during the product design process.

10. *RELIABILITY GROWTH TESTS*

Reliability Growth is the continuous improvement in reliability over time. This improvement can occur as the result of modification of the manufacturing process or modification of the product design. The basic assumption in Reliability Growth is that reliability improves over time as a result of both of these types of changes. There are many models for reliability growth in existence including several proposed by the author. However, the model most often used is the Duane-AMSAA model.

The basic procedure for Reliability Growth testing is to life test a sample of the product until a failure occurs. This test may be a real time or accelerated time test. Each time a failure occurs the testing is stopped and the failure mode is analyzed. If corrective action is considered necessary, to either the product or process design, they are instituted and the testing is continued until another failure occurs. This procedure is called a TAFT i.e. test analyze, fix and retest.
Reliability Growth Tests are quantitative tests. The accuracies of the reliability estimates obtained from Reliability Growth Tests are influenced by the assumed growth model and, if the test is accelerated, by the assumed acceleration model.

11. *MANUFACTURING SYSTEMS DESIGN*

Manufacturing systems design is like all systems design in that it is necessary to carefully define the mission profile before the process is designed and the associated reliability and quality procedures are incorporated. However, the mission profile for a manufacturing system is considerably different than that for most operational systems. Some of the information in a manufacturing systems mission profile is as follows:

(1) A mature product design.
(2) The production rate (through-put) per day.
(3) Will the process operate continuously or be shut down for part of each day?
(4) Will there be a single production line or multiple lines?
(5) What types of operations will be involved in the process?
(6) Will all subsystems be manufactured or assembled as part of the process, or will some be purchased from venders?
(7) Will the venders supply components and subsystems that have been subjected to Over-Stress tests or HALT consistent with the products mission profile and its operating environment?

Process control procedures should be integrated in the process design and should change as the design changes from a preliminary specification to a mature design. The most important factor in the design of the process control system is the production rate. Process control for high volume production is based on the use of Statistical Process Control (SPC) procedures. Process control for low volume production is usually based on 100% inspection. In either case, the purposes of process control are to detect changes that occur over time in critical quality characteristics of the product and to take appropriate corrective action.

11.1 *Inspection/SPC Procedures*

Both variable data and attribute data are obtained during product inspection. Variable data results when quality characteristics such as strength, dimensions, voltage, current and others are actually measured. Attribute data is some times called classification or count data, as it results when the quality characteristic of interest is the number of defective products or the number of defects per product. A defective product either fails to operate or operates but does not meet specifications during inspection. Failure to meet specifications is usually determined by (go no-go) gauges and not by actual measurements. Defects are irregularities in the product, such as sub-standard solder joints, blemishes in paint or pits in a sand casting that in limited numbers do not effect the product's operation, but in large numbers might.

Measured quality characteristics are usually monitored using X-Bar and R charts. Fraction defective is usually monitored using either P or NP charts. Defects per unit are usually monitored using U or C charts. There are many other types of SPC charts available, but most have special purpose applications.

Automatic inspection is usually used if 100% inspection of a quality characteristic is considered necessary during high volume production. Manual inspection is usually used for 100% inspection of quality characteristics during low volume production. SPC inspection is usually done manually, but for very high volume production it is often automated.

Inspection stations should be installed after each stage of the production process where a critical quality characteristic is added to the product. Frequent application of process control procedures in the production process is usually very cost effective, relative to down stream inspection, as only one quality characteristic is inspected at a time and inspection is relatively easy. If the same quality characteristic is inspected down stream it will usually be much harder to inspect, and if the process is found to be out of control, all the work added during the previous manufacturing stages will be wasted.

11.2 *ESS Procedures*

Today's competitive market forces companies to spend considerable time and money in improving the quality and associated reliability of their products. Much of this effort is spent evaluating and improving both product and process design. Despite this extensive up-front effort, many products fall short of their "designed-in" goals. Because many major business decisions impacting corporate profits are made based on the predicted reliability of a product, it is imperative that a product achieve its reliability goals.
Unfortunately, many products do not achieve their designed-in reliability goals due to defects introduced in the product during manufacturing. Defects are usually classified as hard defects or latent defects. Hard defects are those easily found during normal quality control procedures. Latent defects are those that can only be found through the use of stress screening. The Environmental Stress Screen process (ESS) transforms the latent defects into hard defects thus facilitating their elimination prior to the product entering the field. Different stress environments will detect different types of latent defects. Thus it is necessary to employ the type of screen appropriate to each stage of the production process. Defects that are not detected by the ESS process in the factory will likely cause failures in the field where it may cost more than 100 times the cost of detecting the defect before it leaves the factory.

ESS and Burn-In are sometimes confused due to the fact that they both have the same goal: reducing the occurrence of early failures in the field. The major difference is that ESS is conducted using accelerated test conditions, where as Burn-In is conducted using operating conditions. The ESS conditions are more severe than operating conditions and in some cases include stresses not seen in operation. The author prefers an ESS stress level about half way between the operating conditions and the design strength. ESS has an economic advantage over Burn-In since it detects defects in a much shorter time that Burn-In. In both cases, it is important that testing time is sufficient to detect most of the latent defects, but not long enough to significantly impact the product operational life.

The establishing of the test time is probably best done by testing a small sample of the product until defects are being detected at a very slow rate. It should be understood that ESS and Burn-In procedure will not detect all the latent defects without effecting the products operational life time. Several recognized experts in the field have suggested that ESS detects only about 90% of the latent defects. Hence, it is extremely important that as information becomes available from the quality procedures and the EES, the process design is continually upgraded to reduce the occurrence of all defects.

Screening can be performed at the component, sub-system or system level. Components are screened for a specified duration before being assembled into a sub-system. Defects introduced during the assembly of the components into a subsystem are screened at the subsystem level. Defects introduced during final assembly are screened at the system level. The screening environments will vary from assembly level to assembly level.

It should be emphasized that both ESS and Burn-In are primarily quality procedures, not reliability procedures. They improve a product's reliability by improving the products out-going quality and hence, reliability. Their intent is to insure that the outgoing product's reliability is close to that estimated during the reliability evaluation tests.

11.3 *Manufacturing Systems Test*

During the initial production run, problem areas in the manufacturing process should be corrected. Some questions that need to be addressed are:

(1) Does the process flow correctly or are there problems such as blockages that can be corrected by resizing buffers and/or adding additional parallel machines?

(2) Should the method of manufacturing some components and/or sub-systems be changed? Once the process is running, SPC and ESS procedures may indicate that a particular area of the manufacturing process will never be able to produce to quality standards. Perhaps a better and less costly way of manufacturing a component or sub-system may be identified. It may seem that these types of problems should have been eliminated before manufacturing starts, but quite often they are not. In addition, a modern manufacturing process should be continually improved as new manufacturing methods are developed.

(3) There may be interface problems between SPC and/or ESS and manufacturing. It should be emphasized that SPC and ESS are integral parts of manufacturing and the results obtained should be used to improve the quality of the outgoing product. Often SPC and/or ESS are treated as appendages and the results obtained from them are ignored, especially if they are in disagreement with management's objectives.

(4) Often manufacturing interface problems occur. These problems are usually manifested in difficult or almost impossible assembly, caused by incorrect tolerances or faulty product design.

(5) There are often difficulties in performing high speed functional test at the sub-system of system level.

(6) These are just a few of the manufacturing problem areas that might be identified during prototype production.

The second objective of the initial production run is to obtain systems and/or sub-systems for HALT and Reliability growth testing. Even though the manufacturing system is being improved, an attempt should be made to insure that the products produced are very similar to the final products. This is usually accomplished by some manual corrective action or other kluge procedures. It should be noted that prototype products usually yield inaccurate results if used in reliability evaluation tests.

11.4 *Production Run*

At this point in the product and process evolution, the manufacturing system has been tested and improved during the initial production and its semi-final design is in place. The systems level HALT and Reliability Growth Tests have been conducted and the product design has been revised based on their results. The manufacturing process is now ready for a trial production run. The number of systems or sub-systems produced is usually determined by the number needed in the reliability evaluation tests.

One of the major problems that occur, if no additional problem areas are identified by the trial production run, is that management does not want to or can not wait for the reliability evaluation test results before starting full production. This often occurs if the manufacturing equipment is very expensive and/or if the operating crew is large and in place. If production is started before the reliability evaluation test results are available, the product should not be shipped until these results are available and it is determined if design changes are necessary to meet reliability standards. Based on these results, retrofits may have to take place, prior to shipping the product.

12. *FINALIZE MANUFACTURING SYSTEMS DESIGN*

Based on the results of the system or subsystem level HALT and Reliability Growth Tests the product may need to be partially redesigned. Once these design changes are implemented and the manufacturing system is modified accordingly, the manufacturing process is ready for a production run.

13. *A RECOMMENDED RELIABILITY ORIENTED DESIGN PROGRAM*

The following is a recommended list of the steps that should be taken to improve the reliability of products. Each of these items should be converted to detailed instructions and/or actions to meet the specific needs of a particular product.

1) Management must understand and support the effort.

2) Technicians and Engineering must receive training in the rudiments of applied reliability.
3) An in-house reliability data base must be established that includes failure rates of components, their mission profile and operating environment.
4) A list of component vendors that have delivered high quality components in the past should be compiled and made available to all design teams.
5) Problems that have occurred on past products should be documented including successful engineering changes. This data must be readily available to designers. It is extremely important that past mistakes not be repeated in the future.
6) Resources must be committed to reliability early in a product's developmental cycle.
7) Component selection should be based primarily on in-house data on similar components. If information is not available on past similar components over-specification is dictated.
8) All critical components and those where problems have occurred in the past should be subjected to accelerated environment and/or time compression reliability demonstration testing.
9) The location of all components and sub-systems in the product should be reviewed to insure that the components most likely to fail are the most accessible. A high-time to failure and a low-time to repair are critical to high systems availability.
10) Components that need preventive maintenance should also be readily accessible.
11) Both sub-system and system designs should be subject to FMEA.
12) After problems identified in the FMEA are addressed, the sub-system or system design should be subjected to a comprehensive design review. To obtain an independent perspective, the review teams should include members that are not on the design team. The use of outside experts may be cost effective.
13) Where possible, sub-systems should be subjected to accelerated life reliability demonstration testing. Comprehensive sub-system functionality testing should always be done.
14) After a prototype tool is produced, a group of experienced engineers, including some from outside the organization, should review the product in concert with the list of previous problems.
15) Comprehensive systems level functionality testing is mandatory on the prototype products. It may not be possible to demonstrate reliability in the laboratory, but it is possible to demonstrate that the product will perform its intended function in the field. The design of these tests is critical. A test design team should be constituted to insure that all possible in-the-field scenarios are incorporated. Emphasis should be placed on the likely sequencing of events.
16) Initially, all products should be Burn-In-tested prior to shipping. This test should be similar to the functionality tests, but shorter in duration.
17) An inspection procedure should be established and applied to all production tools. The assurance of consistent high quality is mandatory.
18) Field service technicians and engineers should receive comprehensive training on product operation, preventive maintenance and corrective maintenance. Inspection and operating procedures must be in place to insure that improperly performed maintenance does not result in reliability problems. This is critical as a small oversight by a field service technician or engineer, while performing in-field maintenance, can result in huge losses.
19) Once the product is in the field, detailed data collection is paramount. Actual time to failure data should be recorded to minimize warrantee costs, provide information for design changes in the present tool and to facilitate the design of reliable future tools.
20) When a significant failure occurs, a design review team should be instituted to review the present design to determine what action is mandated.
21) All engineer change orders should be reviewed by a design review team before implemented. If the change is at the sub-system level, an FMEA is also recommended.
22) Data on the performance of all engineering changes should be recorded for future use.

When the above proposed steps are implemented, other problems will be identified. Any viable approach to reliability improvement must be up-graded as new problems are identified.

14. *ACKNOWLEGMENTS*

The author would like to thank the following people who have recently had a direct or indirect influence on the thinking behind this document.

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There have been many others in the past.

Reliability from Design Inception to Product Retirement

Prepared by
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Introduction

Reliability Definition

Reliability is:

1. the ***conditional probability***, at a given
2. ***confidence level***, that equipment of a given
3. ***age***, will
4. ***perform*** its intended function, for a specified
5. ***time***, while operating in its
6. ***operational environment***.

Scope of Presentation

In this presentation, an outline of a cohesive structure for reliability testing throughout a product's life cycle is presented. In this structure the design of each successive test is based on analysis, expert opinion, past data obtained from similar products in the field, and data from earlier tests.

Scope (Cont.)

The appropriate location and use of:

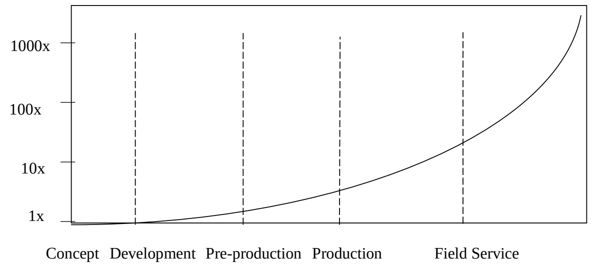
1. Over Stress Tests,
2. Design Reviews,
3. FMEAs,
4. Reliability System Analysis,
5. Accelerated Life Tests,
6. Real Time Life Tests,
7. Reliability Growth Tests,

Scope (Cont.)

8. Environmental Stress Screens,
9. Burn-In and
10. Statistical Process Control

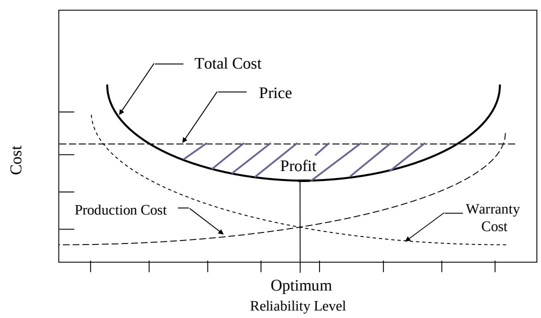
are discussed. Finally, field failures and the steps necessary to assure that the resulting engineering change orders yield improved reliability are covered.

Corrective Action Cost as a Function of Design Phase



The Earlier A Reliability Improvement Is Implemented, The Lower The Cost Of The Corrective Action.

Figure 2, Impact of Reliability on the Producer



Highest Reliability Is Not Necessarily the Most Economical

Cost Benefit of Investment in Reliability

- A 5% increase in **Reliability Focused** development costs will return a 10% reduction in warranty costs.
- A 20% increase in **Reliability Focused** development costs will typically reduce warranty costs by Half.
- A 50% increase in **Reliability Focused** development costs will reduce warranty cost by a factor of Five .

Reference: The Cost and Benefits of Reliability in Military Equipment, Rand Corp, 1988

Key Elements To Achieving Reliability

1. Make reliability a high priority requirement in each specification development.
2. Reach a common understanding between buyer and supplier of reliability expectations early in relationship.
3. Discuss the operating environment, mission profile, expected reliability and maintainability with potential customers.
4. Recognize the cost of poor reliability.

Key Elements To Achieving Reliability, Cont.

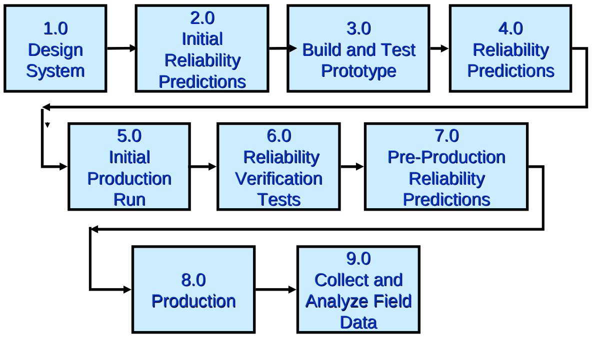
5. Understand that reliability is a long-term goal.
6. Dedicate additional resources to reliability in design and development.
7. Focus on establishing processes and selecting methods that support the design objective.
8. When failures occur, assess to determine if part replacement or corrective action is dictated.

Key Element To Achieving Reliability, Cont..

9. Improve technology.
10. Reduce operational stress.
11. Reduce variation during production.
12. Incorporate expert opinion.

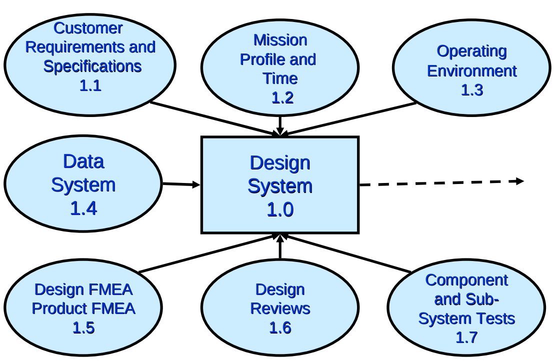
For Any or All To Be Effective, Each Must Be Customer Centric

Reliability from Design Inception to Product Retirement



Design System
1.0

Design System 1.0



Design System, 1.0 Cont.

Customer Requirements and Needs, 1.1

- Reach a common understanding between buyer and supplier of reliability expectations early in relationship.
- Make reliability a high priority requirement in each specification development.
- Establish an agreed on mission profile, mission time and operating environment.
- Insure that both buyer and supplier recognize the cost of poor reliability.
- Understand that reliability is a long-term goal.

Mission Time 1.2

Mission time has to be measured in appropriate units. Some appropriate units are:

- Electronic devices - operating hours.
- Light bulbs - operating hours and on-off cycles.
- Hydraulic valves - actuations.
- Cars and trucks - miles.
- Airplanes - hours and up-down cycles.
- Others.

Example Mission Profile, 1.2

The more information provided in the mission profile that is integrated into the design process, the more reliable the product. The following is a hypothetical example of a mission profile for a hydraulic-actuated valve designed to control the flow of oil from an underwater well head:

Example Mission Profile, 1.2 Cont.

1. The oil that flows through the valve is grit laden. Data on the amount and characteristic of the grit is available.
2. The oil temperature is 300 to 350 deg. F.
3. The relative oil pressure is 400 to 450 psi.
4. The oil flows at 100 to 120 ft. per sec.
5. During the valve's operation the hydraulic fluid pressure varies from 0 to 1000 psi.

Example Operating Environment, 1.3

The operating environment is sometimes more important than the mission profile. In some situations the operating environment has a greater effect on device life than mission profile. This is often the case for electronics. The following hypothetical mission profile data incorporates some of the *worst* possible operating conditions for an electronic device.

Example Operating Environment, 1.3 Cont.

The device is a controller for a radar in Alaska. It is mounted externally to the actual radar and controls the electric motors that determine the orientation of the radar.

1. The controller operates in an environment where the temperature varies from -60 to 105 deg. F. Actual data is available on temperature profiles outside and internal to the device in both operating and stand-by modes.

Example Operating Environment, 1.4 Cont.

2. The relative humidity can vary from 10% to 100%. Actual relative humidity profiles external to the device are available.
3. The controller is subjected to acoustically generated broad band random vibration and low frequency sinusoidal vibration. Frequency and levels are available.
4. The controller operates in a salt spray and wind blown snow environment.

Mission Profile and Operation Environment, 1.2 - 1.3

Information on the mission profile and operating environment is best obtained by actual measurement, but this is not always possible. Hence, sources such as past history of similar products and expert opinion may have to be used. The more accurate the operational data, the more reliable the product will be.

Reliability Data System 1.4

A data acquisition system is an integral part of reliability design. All available in-house and externally available reliability data should be used in system design and for predicting the hazard rate (failure rate) and/or the reliability of components, subsystems, or systems.

Reliability Data System (1.4 Cont.)

- In-house reliability lab test reports.
- Field service reports on similar products.
- Safety analysis reports.
- Failure analysis reports.
- Manufacturing records.
- Quality control records.
- Suppliers of quality components.
- MIL-HDBK-217, etc.
- Others.

FMEA/FMECA, 1.5 Cont.

FMEA is a tool that has been adapted in many different ways for many different purposes. It can contribute to improved designs for products and processes resulting in higher reliability, better quality, increased safety, and reduced costs.

FMEA/FMECA, 1.5 Cont.

Failure modes can be described functionally and the functional system model can be analyzed early in the design phase of a product or process. If conducted manually, an FMEA can be very tedious. Fortunately, several software packages are available to aid in conducting FMEAs, such as the one by ReliaSoft.

Design Review Teams 1.6

- After a subsystem or system is designed, a group of experienced engineers, including some from the outside, should review the design in concert with a list of problems that occurred in previous similar products.
- The designers should present the design, with emphasis on why it will work, to a group of experienced engineers for critiquing.

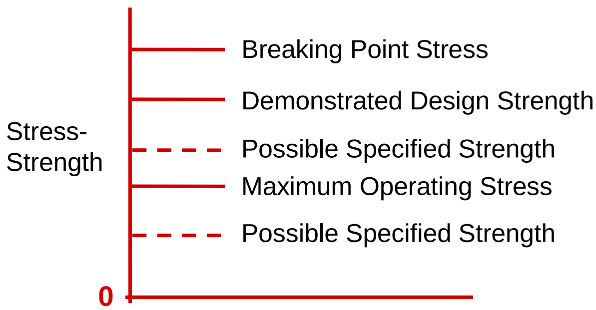
Design Review Teams, 1.6 Cont.

- Design reviews are different from FMEAs in that they concentrate on actual physical functionality of the product.
- The primary objectives of design review teams are to obtain functionally superior and more reliable products at lower costs.

Tests During Design, 1.7

The primary purposes of reliability and reliability-related tests, conducted during the product design phase, are to identify design changes necessary to insure that design strength is met and to identify the stress levels necessary to cause failure. This latter knowledge is critical when designing the Accelerated Life Tests (ALTs) that come after design completion.

Hypothetical Stress-Strength Relationship



Types of Tests During Design, 1.7 Cont.

There are two primary types of reliability tests used during the design process. These are:

(1) component over-stress tests and

(2) subsystem and system Highly Accelerated Life Tests (HALT).

These tests are similar in concept, but are performed at different times in the product design and consequently have somewhat different objectives.

Tests During Design, 1.7 Cont.

Both of these types of tests are qualitative, not quantitative. They are intended to improve the product design, not provide direct reliability estimates. However, if well designed they should provide critical information necessary to design the subsequent quantitative tests.

Component Overstress Tests, 1.7 Cont.

Component over-stress tests are a very important part of the design process. These tests are conducted early in the design cycle. Hence, they cost less than subsystem and system level tests and can be run relatively quickly. Ideally, all critical components should be over-stress tested and their strength improved to where it is considerably above the maximum operating stress level.

System and Subsystem HALT, 1.7

HALTs are conducted at the subsystem and systems levels. Because they occur further along in the product design process, they are more complex and cost more to conduct than component over-stress tests. If all components have been adequately over-stress tested, a HALT should identify only interface problems such as weak connectors, bad solder joints, incorrect tolerances and others.

Tests During Design, 1.7 Cont.

The author is a proponent of step-stress tests for component over-stress tests and HALT tests. If properly designed they can provide information on both the maximum stress levels where components will operate and the stress levels where they will fail. The maximum stress level where a component will operate should be above its design strength.

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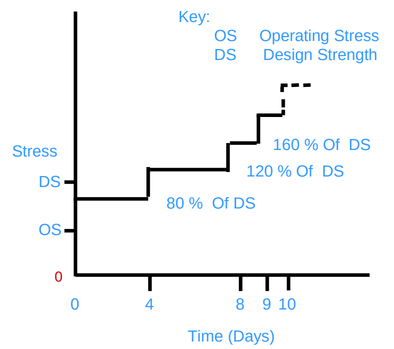
Example Step Stress Over-Stress or HALT Test,



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Reliability Tests During Design, 1.7 Cont.

After failure occurs, a failure mode analysis should be conducted and the product design should be improved to incorporate the changes dictated by the results of the over-stress tests and the subsequent failure mode analysis. The entire process should then be repeated until the product demonstrates that it meets or exceeds its design strength.

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Tests During Design, 1.7 Cont.

The first step in designing a HALT, or any other reliability-related test, is to take time to make sure that all factors have been considered. Time and money spent on a thorough test analysis and design will result in less costly tests that yield more information critical to a reliable design.

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Tests During Design, 1.7 Cont.

If frequent component failures occur during the HALT, the components have not been adequately over-stress tested.

In the author's opinion, HALT should use step-stress multi-environment tests, simultaneously incorporating all the stresses likely to occur in a product's operation.

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Tests During Design, 1.7 Cont.

However, for complex products subjected to multiple stresses during operation, this may not be feasible due to the test complexity, the cost of running the test and the cost of building the test equipment to perform the test. In this situation, engineering analysis must determine which stress factors have to be tested simultaneously and which can be tested independently.

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Tests During Design, 1.7 Cont.

If a significant interaction effect occurs between the stresses, these stresses must be included in the same HALT.

An example of such an interaction is a device that is subjected to both high pressure and extremely high temperatures during operation, such as superheated steam pipes.

Tests During Design, 1.7 Cont.

The interaction is the reduction of strength, caused by the high temperatures, that causes a pressure induced failure. Hence, both temperature and pressure must be applied simultaneously.

Product Design Strength

Product design strength is initially established by analysis, and when possible, verified by component over-stress tests and subsystem and system HALT tests. Consequently, the component over-stress tests and sub-system and system HALT tests should be designed looking forward to the Reliability Verification Tests.

Example Test, 1.7 Cont.

As a hypothetical example of a component level test procedure, consider the mission profile for the control valve previously described. During operation, the mission profile of this valve contains five stress factors. These are oil pressure, oil velocity, oil temperature, grit level and hydraulic fluid pressure.

Example Test, 1.7 Cont.

Engineering analysis concluded that there is also one critical operational environmental factor. Ocean currents cause flexing of the pipes that lead into and out of the valve. There are several questions that must be resolved by engineering analysis before a test is designed.

Example Test, 1.7 Cont.

1. Can and should any of these factors be eliminated from consideration?
2. Do any of these factors interact?
3. Is it physically possible and economically feasible to perform tests that include all the factors not previously eliminated by engineering analysis?

Example Test, 1.7 Cont.

Stress factors are eliminated from testing by engineering analysis and possible re-design. In this example, the stress factors to be considered are oil pressure, oil temperature, oil velocity, grit level, and inlet and outlet pipe flexing.

Example Test, 1.7 Cont.

Some of these might be eliminated from consideration as follows:

1. The pipe flexing problem could be resolved by attaching the pipes to the frame, but this must be done in a way that does not cause a compression/expansion problem due to external and internal temperature variation. If this temperature variation is small it may be ignored.

Example Test 1.7 Cont.

2. Engineering analysis indicates that oil temperature is not a significant factor, hence can be excluded.
3. Because the hydraulic actuators that operate the valves are external to the actual valve, the effects of this stress factor can possibly be evaluated by a separate less expensive test.

Example Text, 1.7 Cont.

Hence, the only three factors that need to be considered in the over-stress test design are:

1. oil pressure,
2. oil temperature, and
3. grit level.

Example Test, 1.7 Cont.

In the author's opinion, the following is a realistic hypothetical test design. Five components will be subjected to over-stress testing. Engineering analysis has concluded that test grit level can be kept constant, and a level is selected 20% above the measured maximum operating level. Since oil pressure and oil velocity are physically dependent factors, they will be ramped up at the same time.

Example Test, 1.7 Cont.

A mean test level, 10% above the maximum operating levels, is chosen as the starting point and the mean test level will be ramped up in steps of 30% of the maximum operating stress. Each ramp step is 24 hours in duration. During the test the oil pressure and velocity will be cycled about their mean levels consistent with the cycling that occurs in operation.

Example Test, 1.7 Cont.

Testing is continued until all components fail or a component fails below the design strength. If a component fails below the design strength, testing is stopped, a failure mode analysis is conducted and corrective action is taken. This corrective action must result in a product design change or a manufacturing process change.

Example Test, 1.7 Cont.

The test sequence will be repeated with five new components that incorporate the changes instituted during corrective action. If all additional failures occur above the design strength, testing is stopped and the design is frozen. If no failures have occurred and testing has reached levels of 200% of design strength, testing is also stopped and the design frozen.

Example Tests, 1.7 Cont.

It should be emphasized that the design strength must be significantly above the estimated maximum operating stress level. If the design strength is set too low, the component will never be reliable. When establishing the design strength, all mission profile and operational environment factors must be considered.

Example Tests, 1.7 Cont.

Also, factors such as material variation, manufacturing process variation and others specific to a particular product must be considered. Establishing the design strength is one of the most important parts in the design of a high reliability product.

Component Selection, 1.8

- Since hardware reliability is a function of component reliabilities and their fitness for the task, component choice cannot be overemphasized. The choice is often between standard parts, which just meet the requirements, or special parts, which theoretically exceed the requirements but are unproven.

Component Selection, 1.8 Cont

- Component selection should be based primarily on in-house data on similar components. If information is not available on past similar components, derating or over-specification is dictated.
- If components are standard parts, estimated failure rates can sometimes be found in manufacturer's handbooks, commercial databases, or *Mil-Std Handbooks*.

\

Component Selection, 1.8 Cont.

- All critical components and those where problems have occurred in the past should be subjected to component over-stress testing.
- The location of all components and sub-systems in the box should be reviewed to insure that the components most likely to fail are the most accessible. A high time-to-failure and a low time-to-repair are critical to high system availability.

A Reliability Oriented Design Program

The following is a recommended list of the steps that should be taken to improve the reliability of products. It is organized in the sequence that each will occur in the life of a system. Each of these items should be converted to detailed instructions and/or actions to meet the specific needs of a particular system.

A Reliability Oriented Design Program (Cont)

- Management must understand and support the effort.
- Technicians and Engineers must receive training in the rudiments of applied reliability.
- An in-house reliability database must be established that includes failure rates of components, their mission profile and operating environment.

A Reliability Oriented Design Program (Cont)

- Both subsystem and system designs should be subject to FMEA.
- After problems identified in the FMEA are addressed, the subsystem or system design should be subjected to a comprehensive design review. To obtain an independent perspective, the review teams should include members that are not on the design team. The use of outside experts is usually cost effective.

A Reliability Oriented Design Program (Cont)

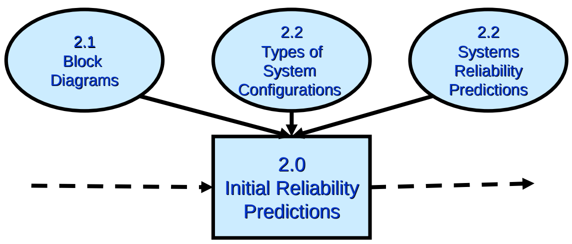
- Components that need preventive maintenance should be readily accessible.
- Component selection should be based primarily on in-house data on similar components. If information is not available on past similar components, over-specification is dictated.

A Reliability Oriented Design Program (Cont)

- All critical components and those where problems have occurred in the past should be subjected to over-stress testing.
- The location of all components and subsystems in the box should be reviewed to insure that the components most likely to fail are the most accessible. A high time-to-failure and a low time-to-repair are critical to high system availability.

Initial Reliability Predictions 2.0

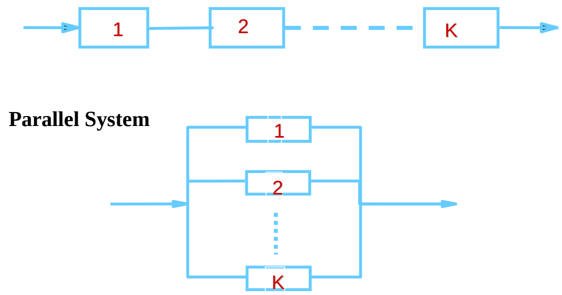
Initial Reliability Predictions, 2.0



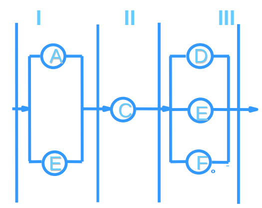
Block Diagrams, 2.1

The system design reliability block diagram describes relationships between the system, its subsystems and/or components. The diagram aids in setting up the subsystem reliability goals, identifying methods of reliability improvement and obtaining system reliability estimates.

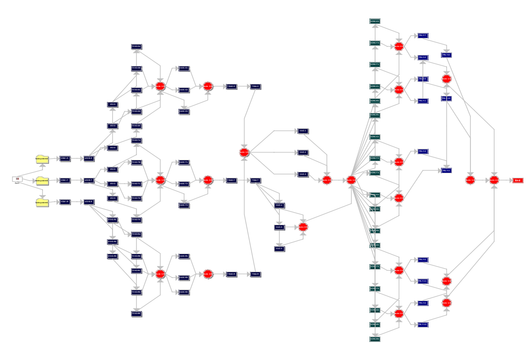
Types of System Configurations



Parallel Series System Reliability Diagram



Complex Configuration



System Level Reliability Predictions, 2.0 Cont.

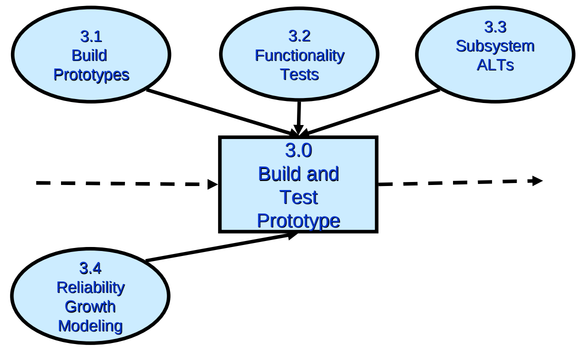
Once a system level reliability block diagram is developed and component selection and testing is done, the component and/or subsystem reliability estimates can be incorporated in the system level block diagram to obtain a system level reliability prediction.

Systems Level Reliability Predictions, 2.0 Cont.

There are several commercially available computer software packages to aid in System Reliability calculations. ReliaSoft's BlockSim is the newest and most comprehensive of these packages. When a system level estimate is obtained in this manner, there is always the possibility of interface failures that occur in the connections between components and/or subsystems.

Build and Test Prototype 3.0

Build and Test Prototype, 3.0



Build Prototypes, 3.1

- The overall system reliability and maintainability results from the inherent reliability of chosen components, their quantity, the method of interconnection, and the configuration - this is referred to as the *Design Reliability*.
- The activities of manufacturing, operation and service may cause additional failures.

Build Prototypes, 3.1 Cont.

- The reliability and maintainability achieved in the field are usually less than the theoretical design levels and often less than the levels demonstrated during laboratory life tests.
- The primary consideration in building prototypes is to make them as similar as possible, physically, to the systems that will eventually come off the manufacturing line.

Functionality Tests, 3.2

Comprehensive system level functionality testing is mandatory on prototype systems. It may not be possible to demonstrate reliability in the laboratory, but it is usually possible to demonstrate that the system will perform its intended function in the field. The design of these tests is critical. A test design team should be constituted to insure all possible in-the-field scenarios are incorporated. Emphasis should be placed on the likely sequencing of events.

ALT Tests, 3.3

- In the design of an ALT, knowledge of the product design strength relative to its mission profile and operating environment is critical. To obtain a reasonable acceleration factor, the product design strength must be considerably higher than the operational stress. The tests are designed with test levels above the operational stress, but not much higher than the product design strength.

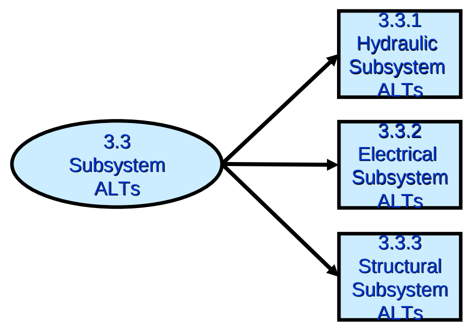
ALT Tests, 3.3 Cont.

- Every different product will require an ALT designed to simulate its actual operational environment and mission profile. Some stress factors in the operational stress profile may be eliminated in the ALT design by an engineering analysis that indicates they are not likely to contribute to product failure. Stress factors should never be eliminated.

ALT Tests, 3.3 Cont.

- The two primary types of ALTs covered in this report are increased stress tests and time compression tests.
- In a time compression test, the device is cycled at a significantly higher rate than the operational rate thus reducing the time necessary to cause failure.
- In an increased stress ALT, the test stress levels are significantly above the operating stress levels thus reducing the time necessary to cause failure.

Example of Subsystem Level ALT, 3.3



Mission Profile, 3.3 Repeat

The more information provided in the mission profile and integrated into the design process, the more reliable the product. The following is a hypothetical example of an ALT for a hydraulic-actuated valve designed to control the flow of the oil from an underwater well head:

Hydraulic System Time Compression Example, 3.3.1

The actual test will consist of cycling the hydraulic device at the highest rate that still insures correct operation. The ratio between the operational cyclic rate and the laboratory cyclic rate determines the acceleration factor. The system should be operating during the test and the test profile should simulate the actual operational environment.

Hydraulic Systems ALT Pressure Tests 3.3.1 Cont.

The primary accelerating factors are:

1. oil temperature and pressure
2. oil velocity and abrasiveness

The actual levels should be determined for each individual product based on data measured in the field, data obtained during the design process and data from the associated component over-stress tests and subsystems and systems HALT.

Electrical Systems ALT, 3.3.2

ALTs for electronic products are traditionally conducted with the product operating and subjected to some combination of temperature and broad band random vibration. However, it is the author's opinion that these tests should use the stresses the product will see in operation.

Electrical Systems ALT, 3.3.2 Cont.

Test levels should be established based on design strength, operational environment, and mission profile. Factors such as voltage and/or current, power surges, internal device temperature, vibration, shock, salt spray and humidity may apply. Sound engineering judgment should be used to determine which factors need to be considered in the ALT designs.

Structural ALTs, 3.3.3

Structural ALTs are usually conducted by loading the structure with significantly higher loads than it will see in operation. These loads can be either static or dynamic. For most large structures, the testing equipment will have to be built to run the test.

Structural ALTs, 3.3.3 Cont.

Dynamic loads are the most difficult to analyze as they cause fatigue failures. Most people think the age of an aircraft is the most important factor in failures. This may be true for engines, but most structural failures are fatigue failures caused by the compression and expansion of the aircraft body due to the up and down cycling.

Structural ALTs, 3.3.3 Cont.

Thus, a short haul Boeing 737 that, on the average, is subjected to 6 up and down cycles per day will fatigue at 6 times the rate of a Boeing 747 that, on the average, is subjected to only 1 up and down cycle per day. An ALT using the actual operational dynamic loading profile as a basis may be the most difficult test to conduct.

Structural ALTs, 3.3.3 Cont.

Vibration tests for large structures require special equipment such as thrusters to run. Usually, low frequency swept sinusoidal vibration is used. The test levels are set, considerably above the predicted operational levels, to accelerate time to failure. It is difficult to obtain reliability prediction information from these tests.

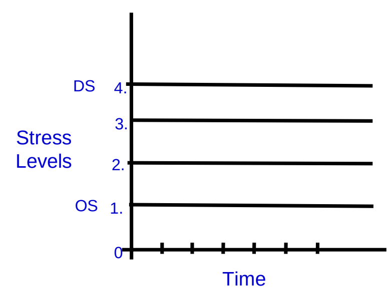
Structural ALTs, 3.3.3 Cont.

Consequently, their primary purpose is to insure that the natural frequency of the structure is not close to the operational excitation frequency or any of its harmonics. This problem can be solved by adjusting the stiffness of the structure, increasing the mass of the structure or adding damping to the structure.

Multi-Level Constant Stress ALTs

The author is a proponent of multi-level constant stress ALTs as they provide more information than many other types. The following is an example of one. There are software applications available to analyze these tests, such as ReliaSoft's ALTA and ALTA PRO.

Example of Constant Stress ALT



Example of Constant Stress ALT, Cont.

Key:

- OS Operating Strength
- DS Design Strength

Stress Level 1	OS+.05(DS-OS), 10 Items On Test
Stress Level 2	OS+.40(DS-OS), 6 Items On Test
Stress Level 3	OS+.75 (DS-OS), 4 Items On Test
Stress Level 4	OS+1.1(DS-OS), 4 Items On Test

Reliability Growth Models, 3.4

During early development, the reliability of a system or subsystem is much lower than its potential value due to hardware design related deficiencies as well as manufacturing deficiencies. Predictions of potential reliability at some future time are most often based on present data or on past data from identical or similar systems. The reliability growth during testing is predicted using a model such as the AMSAA model.

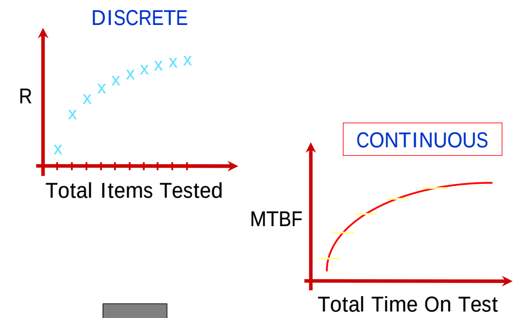
Reliability Growth Definition

- Reliability growth is defined as the positive improvement in reliability, mean time before failures or failure rate. It can also be defined as the current assessment of reliability, mean time before failures or failure rate of a system or subsystem in order to establish trend data.

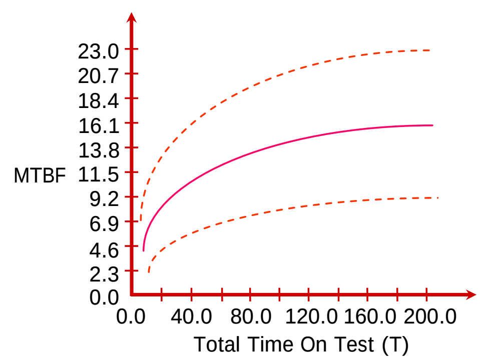
Reliability Growth Definition, Cont.

- Reliability growth is the direct result of corrective action taken to remove defects in the future by changes in either the design and/or manufacturing techniques. The objective is for a subsystem or system to reach its potential reliability, mean time before failures or failure rate.

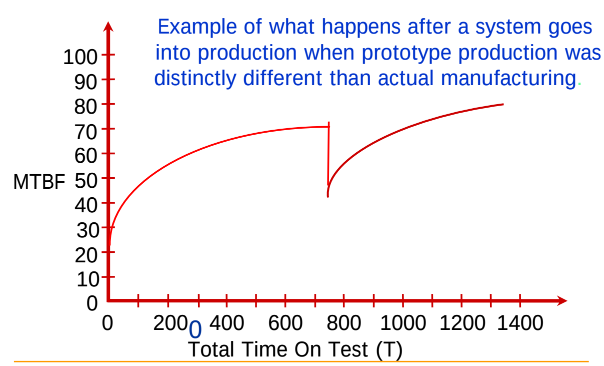
Reliability Growth Models, 3.4 Cont.



Example Reliability Growth, 3.4 Cont.



Reliability Growth Experience, 3.4 Cont.



Reliability Growth, 3.4 Cont.

There is software available to aid in reliability growth modeling, such as ReliaSoft's RGA 6.

Initial Production Run 5.0

Reliability Predictions 4.0

Initial Production Run, 5.0

- Initial production runs are usually made on high volume production products to check out the operation of the production line and to test the product quality control procedures.
- Products produced late in this run may be of good enough quality to be used for reliability verification testing. If not, reliability verification testing will have to be done using products produced later in the production process.

System Reliability Predictions, 4.0

- If system level reliability tests cannot be conducted because of the size and complexity of the system, the subsystem level test data will have to be used along with the system level reliability logic diagrams to get a system level reliability estimate. This is usually the situation for most complex equipment.
- In this situation it is extremely important that the interfaces be given critical consideration during the product design process.

Reliability Verification Tests 6.0

Reliability Verification Tests, 6.0

- These test are similar to those presented in section 4.0.
- The primary intent of these tests is to demonstrate a product reliability, not to improve it as during prototype testing.
- These tests can be either real-time or accelerated life tests.

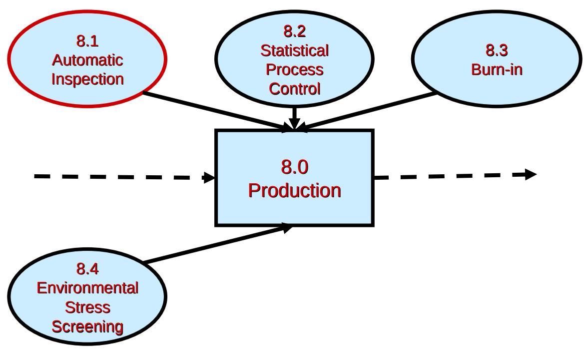
Pre-Production Reliability Prediction 7.0

Pre-Production Reliability Predictions, 7.0

Pre-production reliability predictions are obtained using the same tools as those presented in section 2.0 on Initial Reliability Predictions and section 4.0 on Reliability Predictions.

Production 8.0

Production, 8.0



Types of Data

Both variable data and attribute data are obtained during product inspection. The following are examples:

1. Variable data: quality characteristics such as strength, dimensions, voltage, current and others that are actually measured.
2. Attribute data: numbers or percentage of latent defects, fraction of defective components, subsystems and systems and others.

Product Inspection, 8.1

Inspection stations should be installed after each stage of the production process where a critical quality characteristic is added to the product. Frequent application of process control procedures in the production process is usually very cost effective relative to down-stream inspection, as only one quality characteristic is inspected at a time and inspection is relatively easy.

Product Inspection, 8.1 Cont.

- If the same quality characteristic is inspected down-stream it will usually be much harder to inspect, and if the process is found to be out of control, all the work added during the previous manufacturing stages will be wasted.

Automatic Inspection, 8.1 Cont.

- Automatic inspection is usually used if 100% inspection of a quality characteristic is considered necessary during high volume production. Manual inspection is usually used for 100% inspection of quality characteristics during low volume production.

Statistical Process Control, 8.2

- SPC inspection is usually done manually, but for very high volume production it is often automated.
- Measured quality characteristics are usually monitored using X-Bar and R charts. Fraction defective is usually monitored using either P or NP charts. Defects per unit are usually monitored using U or C charts. There are many other types of SPC charts available, but most have special purpose applications.

Burn-In, 8.3

Environmental Stress Screen (ESS) and burn-in are sometimes confused due to the fact that they both have the same goal: reducing the occurrence of early failures in the field. The major difference is that ESS is conducted using accelerated test conditions, whereas burn-in is conducted using operating conditions. In some cases an ESS may include stresses not seen in operation.

Defects

- Hard defects are those easily found during normal quality control procedures.
- Latent defects are those that can only be found through the use of stress screening.

Environmental Stress Screen, 8.4

The Environmental Stress Screen process (ESS) transforms the latent defects into hard defects thus facilitating their elimination prior to the product entering the field.

Different stress environments will detect different types of latent defects.

ESS, 8.4 Cont.

Screening can be performed at the component, subsystem or system level. Components are screened for a specified duration before being assembled into a sub-system. Defects introduced during the assembly of the components into a subsystem are screened at the subsystem level.

EES, 8.4 Cont.

The author prefers an ESS stress level about halfway between the operating conditions and the design strength. ESS has an economic advantage over burn-in in that it detects defects in a much shorter time than burn-in. In both cases it is important that testing time is sufficient to detect most of the latent defects, but not long enough to significantly impact the product's operational life.

ESS, 8.4 Cont.

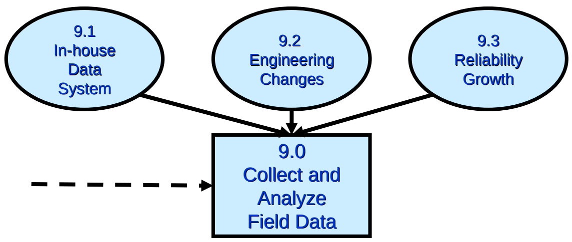
Several recognized experts in the field have suggested that ESS detects only about 90% of the latent defects. Hence, it is extremely important that as information becomes available from the quality procedures and the ESS, the process design is continually upgraded to reduce the occurrence of all defects.

ESS, 8.4 Cont.

- It should be emphasized that both ESS and Burn-In are primarily quality procedures, not reliability procedures. They improve a product's reliability by improving the product's out-going quality and hence, reliability.
- Their intent is to insure that the outgoing product's reliability is close to that estimated during the reliability evaluation tests.

Collect and Analyze Field Data 9.0

Collect and Analyze Field Data, 9.0



Data System 9.1

- All data relevant to any maintenance, repair or re-design action should be recorded in the in-house data system for use in the design of future products.

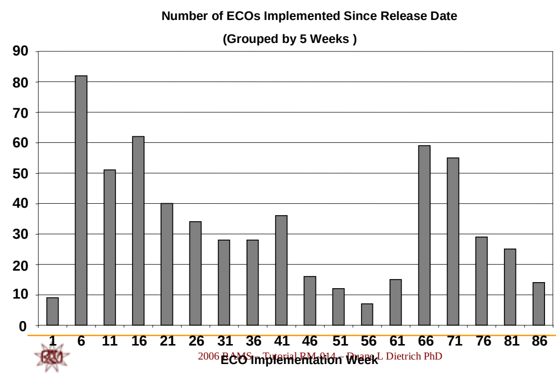
Engineering Change Orders, 9.2

- Failures that repeatedly occur in the field usually result in component upgrades or subsystem redesign.
- Before any system, subsystem or component is re-designed the following should be required:

Engineering Change Orders, 9.2 Cont.

- A detailed description of the mission time, mission profile and operating environment should be written.
- Design specifications should be written that include the concepts discussed in this presentation.
- The designer should be prepared to discuss why he/she thinks the redesign will be reliable.

Example of ECOs Implemented, 5 Week Intervals, 9.2 Cont.



Engineering Change Orders

In the late 1980s, IBM saw a similar trend in one of its products. Investigation indicated that 80% of all ECOs were the direct result of previous ECOs.

Reliability Growth, 9.3

- Both FMEAs and Design Reviews should be conducted on the redesigned component, subsystem or system.
- Reliability growth should be monitored for all systems in the field when design and manufacturing improvements are continuing to be made.

Final Product Reliability