Multiple Stress Level Test - Common Analysis

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PRACTICAL ACCELERATED LIFE TESTING

James A. McLinn, CRE, Fellow ASQ

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Accelerated Life Testing (ALT) is one of the most important topics for any reliability engineer. Few reliability engineers know more than the basics of a few techniques. Most test people do not know the wide range of testing applications that do exist. ALT theory is often covered by journal articles showing a few isolated applications, techniques or explanations to existing techniques. Creation of new ALT techniques through development of theory are likewise scattered through a number of journals.

This short book is an attempt to bring a variety of tools and techniques together and present them as a coherent package. No attempt was made to cover all the useful techniques of ALT. Hence, vibration fatigue applications, thermal cycling, step-stress methods and HALT techniques are missing from this work. However, the critical and often under emphasized steps of preparation of an ALT and administration are included. Ground rules and guidelines which are contained within will help the reader avoid the most common pitfalls. The last two sections look at the analysis of some ALT life data. The combination should aid the reader when performing most types of Accelerated Life Tests.

References are at the end of the work with a two-page supplemental reading list. These go beyond the scope of this work.
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Preface - Second Edition

This edition was updated as a response to the need for a more examples that are clear, concise and engineering oriented explanations for critical topics of Accelerated Life Testing. A number of reliability engineers had expressed frustration that the ALT topics were covered by only two books published in the last 10 years. This book began as a series of short articles published in the Reliability Review in the late 1990s that addressed some simple examples and subjects. It has increased in size from the original 125 pages, yet some valuable ALT topics will always remain unaddressed.

In this work, as in the earlier edition, the statistics and complex math was kept to a minimum. It is assumed that the reader has a basic knowledge of reliability and some basic knowledge of how to set-up and run an ALT. It was not the intent to turn this work into a statistical primer, so statistics are kept to a minimum. Canned software packages are mentioned, as these are the tools that most people employ to solve their own problems. Weibull tools and other web resources are discussed. New topics including some that cover HALT, HASS and ESS are included in this edition. Readers are encouraged to use this book as a learning tool. Be sure to show it to co-workers, and look at the reading list at the end for further information. Many of these refer to RAMS proceedings, Quality Engineering, The Journal of Quality Technology and other conferences.

A number of people who have helped improve the original articles and the first edition. Definitely the biggest help came from my wife, Connie, who reviewed this monograph and the first edition. She made numerous suggestions and improvements on both. With out her help, it would not have turned out so well.

James McLinn
Hanover, Minnesota
March 2010
Preface - First Edition

This monograph was created as a response to the need for a clear, concise and short explanation for some of the topics of Accelerated Life Testing. A number of reliability engineers had expressed frustration that the ALT topic was covered by only one book. This began as a series of short articles published in the Reliability Review to address some simple examples and subjects. It has doubled the size from the original six articles, yet some of this valuable ALT topic must remain unaddressed.

In this work, the statistics and math were kept to a minimum. It is assumed that the reader has a basic knowledge of reliability and some knowledge of ALT. It was not the intent to turn this work into an ALT statistical primer, so statistics are only occasionally mentioned. Software aids are mentioned, as these are the tools that most people employ to solve their own problems. Readers are encouraged to use this short book as a tool, to show it to co-workers, and move on to the reading list at the end for further information.

I wish to thank a number of people who have helped improve the original articles and encouraged me during the creation of this monograph. These include Hal Williams of Reliability Review, William Stoner of Amway Corp., Norb Santoski, Reliability Consultant, Valter Loll of Nokia, Copenhagen and Patrick O'Connor of Great Britain.

Perhaps my biggest help came from my wife, Connie, who reviewed this monograph and made numerous suggestions and improvements. Without her, it would not have turned out so well.

James McLinn
Hanover, Minnesota
April 2000
Practical Approaches for Accelerated Life Testing

1.0 The History and Background of ALT –

Modern reliability tools and techniques for Accelerated Life Tests (ALT) have been developed primarily over the last 30 years. The modern concepts and tools actually reach all the way back to the 1940s and 1950s when reliability was in its infancy. Many approaches were the outgrowth of the needs of the U.S. military [23] to achieve and demonstrate long-lived, reliable electronics equipment. In the 1940s, the expectation was that 25 to 50% of electronic equipment would not work when called upon to do so. The worldwide use of hardware in a variety of applications and environments represented a major challenge. Separate tools and techniques have also been developed for mechanical applications and some are detailed in the Mechanical Design Reliability Handbook [24]. The approaches for mechanical acceleration are usually somewhat different from electronic applications because of the difficulty of accelerating materials, mechanical components and assemblies. Software is also subject to accelerated testing, but software topics will not be discussed in this book.

1.1 A Short History of ALT Approaches –

The original and current purposes of running ALT are typically for one of the following reasons:
1) Demonstrate that a design was ready for release.
2) Show that a product would last for a minimum amount of time.
3) Verify that a design is robust.
4) Create an estimate of the warranty failures.
5) Demonstrate a minimum time to failure.
6) Identify some of the failure modes to be expected in the field.
7) Demonstrate the robustness of a design for operation in the customer's environment.

An ALT might be performed as a test at the end of manufacturing to show the customer that a system would work well or exceed some minimum length of time in a harsh environment. These early life tests were typically called "demonstration tests", "evaluation tests", "customer acceptance tests", "verification tests", "validation tests" or even "Wald sequential tests". These tests were often run at nominal laboratory conditions or occasionally at the typical customer conditions. Accelerated tests might be run at worst-case customer conditions or at some other high stress level. The more adventurous might use two or more stresses to test a design. Since reliability was in its infancy during the 1950s, the development of accelerated tests was often documented at that time by statistical journals such as Annals of Mathematical Statistics or the Journal of the American Statistical Association. In 1955, a conference on electrical contacts and connectors was started, emphasizing reliability physics and understanding failure mechanisms. Other conferences began in the 1950s to focus on some of these important reliability topics. That same year, the Reliability Analysis Design Center, RADC, issued “Reliability Factors for Ground Electronic Equipment.” This was authored by Joseph Naresky. By 1956, ASQC was offering papers on reliability as part of their American Quality Congress. The radio engineers, ASME, ASTM and the Journal of Applied Statistics were contributing research papers. The Institute of Radio Engineers, IRE, was already holding a conference and publishing proceedings titled “Transaction on Reliability and Quality Control in Electronics”. This began in 1954 and continued until this conference merged with an IEEE Reliability conference and became the Reliability and Maintainability Symposium (RAMS).[23] Today, this conference is one of the biggest sources of ALT information. Other early sources include the Bell System Technical
Journal and the Department of Commerce, which also sponsored research and improvements of early accelerated life testing. References [1] to [6] provide examples of these early efforts.

The military services each began studying the ALT problem in earnest during and after World War II because of the poor performance of electronic and electrical devices. A solution was proposed and a joint military study was initiated in 1952. The primary impetus for the study was the widespread recognition that modern electronic gear supplied to the US military were not performing up to desired reliability levels. After a four year period of study, a report was generated. This report came to be known as the AGREE report, an acronym for the Advisory Group on Reliability of Electronic Equipment [6]. This publication in 1957 is probably the best places to begin any modern history of accelerated life testing. The vacuum tube radio systems studied by AGREE were found to follow a bathtub-type curve. It was easy to develop replaceable electronic modules, later called Standard Electronic Modules (or SEMs), to quickly restore a failed system and they emphasized modularity of design. Hence, there was early emphasis on maintainability topics. Additional recommendations included running formal demonstration tests with statistical confidence for products. Also recommended was running longer and harsher environmental tests that included temperature extremes and vibration. This came to be known as AGREE testing and eventually turned into Military Standard 781. The last item provided by the AGREE report was the classic definition of reliability. The report stated that the definition is “the probability of a product performing without failure a specified function under given conditions for a specified period of time”. Another major report on “Predicting Reliability” in 1957 was that by Robert Lusser of Redstone Arsenal, where he pointed out that 60% of the failures of one Army missile system were due to components. He showed that the current method for obtaining quality and reliability for electronic components were inadequate and that something more was needed. ARINC set up an improvement process with vacuum tube suppliers and reduced infant mortality removals by a factor of four. This decade ended with a lot of promise and activity. Papers were being published at conferences showing the growth of this field. Over the next several decades, Birnbaum made significant contributions to probabilistic methods, the reliability of complex systems, cumulative damage models, competing risk, survival distributions and mortality rates.

The 1960s dawned with several significant events. RADC began the Physics of Failure in Electronics Conference sponsored by Illinois Institute of Technology (IIT). A strong commitment to space exploration would turn into NASA, a driving force for improved reliability of components and systems. Richard Nelson of RADC produced the document “Quality and Reliability Assurance Procedures for Monolithic Microcircuits,” which eventually became Mil-Std 883 and Mil-M 38510. Semiconductors came into more common use as small portable transistor radios appeared. Next, the automobile alternator became possible with the use of low cost germanium diode later replaced by better silicon diodes and able to meet the under-the-hood stress and environment requirements. Dr Frank M Gryna published a Reliability Training Text through the IRE. The nuclear power industry was also growing by leaps and bounds at that point in history. The demands of the military ranging from missiles to airplanes, helicopters and submarine applications drove a variety of technologies. During this decade, a number of people began to use, and contribute to the growth and development of, the Weibull analysis methods and applications which are closely tied to the analysis of ALT. Professor Gumbel demonstrated that the Weibull distribution is a Type III Smallest Extreme Value distribution. This is the distribution that describes a weakest link situation. Dr. Robert Abernethy was an early adaptor at Pratt and Whitney, and he developed a number of applications and analysis methods.

During the decade of the 1970s, reliability work progressed across a variety of fronts. In this decade, the use and variety of ICs increased. Bipolar, NMOS and CMOS all developed at an amazing rate. In the middle of the decade, ESD and EOS were covered by several papers and eventually evolved into a conference by the decade end. Likewise, passive components which were once covered by International Reliability Physics Symposium, IRPS, moved to a Capacitor and Resistor Technology Symposium (CARTS) for continued reliability advancement for discrete
components. A few highlights of the decade were the first papers on gold-aluminum intermetallic products, accelerated testing, the use of Scanning Electron Microscopes for analysis and loose particle detection testing (PIND). Perhaps the two most memorable reliability papers from this decade were one on soft error rates caused by alpha particles (Woods and May) and on accelerated testing of ICs with activation energies calculated for a variety of failure mechanisms by D.S. Peck. By the end of the decade, commercial field data were being collected by Bellcore as they strived to achieve no more than 2 hours of downtime over 40 years. This data became the basis of the Bellcore reliability prediction methodology.

The Navy Material Command brought in Willis Willoughby from NASA to help improve military reliability across a variety of platforms. During the Apollo space program, Willoughby had been responsible for significantly improving spacecraft reliability. He insisted that all contracts contain specifications for reliability and maintainability instead of just performance requirements. Willoughby's efforts were successful because he attacked the basics and worked upon a broad front. Wayne Tustin credits Willoughby with first emphasizing temperature cycling and random vibration, which later became ESS testing.

The 1980s was a decade of continued great change. Televisions had become all semiconductor. Automobiles rapidly increased their use of semiconductors with a variety of microcomputers under the hood and in the dash. Large air conditioning systems developed electronic controllers, as had microwave ovens and a variety of other appliances. Communications systems began to adopt electronics to replace older mechanical switching systems. Kam Wong published a paper at RAMS questioning the bathtub curve. Developments in statistics made an impact on reliability. Contributions by William Meeker, Gerald Hahn, Richard Barlow and Frank Proschan developed models for wear, degradation and system reliability and so fit nicely with ALT methods. The Air Force issued the R&M 2000 which was aimed at making R&M tasks normal business practice. Altogether, the 1980s demonstrated progress in reliability across a number of fronts from military to automotive and telecommunications to biomedical.

By the 1990s, the pace of IC development was picking up. New companies built more specialized circuits and Gallium Arsenide emerged as a rival to silicon in some applications. These changes drove IC manufacturers to perform more ALTs. It quickly became clear that high volume commercial components often exceeded the quality and reliability of the small batch specially screened military versions. Early in the decade, the move toward Commercial Off the Shelf (COTS) components gained momentum. The Army started the Electronic Equipment Physics of Failure Project and engaged the University of Maryland CALCE center, under Dr. Michael Pecht, as part of the process. RAC issued a six set Blueprint for Establishing Effective Reliability Programs in 1996 including one to discuss ALT (RBPR-4).

While there is much to credit to the early roots of reliability testing, the ALT field itself has rapidly changed primarily over the last 30 years. This may be credited to the increasingly sophisticated number of software tools developed and the increasing customer needs for more sophisticated, yet more reliable products. The need to develop new and different materials for NASA and biomedical applications as well as finding ways to improve all manufacturing processes have helped drive interest in ALT. Few comprehensive books on the accelerated life topic have been produced. More often than not, a small chapter of a general reliability book has attempted to cover this broad and important topic. Dr. Wayne Nelson, in his classic work, Accelerated Testing, provided a prophetic statement. He stated in that 1990 publication that "Statistical methodology is improving rapidly. Thus, books over 5 years old lack important developments, and books over ten years old are seriously out of date." He predicted such would be the fate for his own book and updated it in 2004 with Accelerated Testing: Statistical Models, Test Plans, and Data Analysis The breadth of applications for accelerated life testing included in
Nelson's 1990 work is amazing. His list of references and additional information runs the full gamut, running several pages long and citing industries citations as diverse as concrete technology, metals and ceramics, pavement and soils, the Plastic and Rubber Institute, the U.S. FDA Center for Drugs and Biologics, the National Lubricating Grease Institute and the National Nuclear Data Center. This length of this initial list was increased by Dr. Dimitri Kececioglu and Dr. Feng-Bin Sun when they provided additional references at the end of chapter one in a more recent related work, *Environmental Stress Screening*, 1996. It is now 2010, twenty years having passed since he wrote those words and new books have come onto the market. In 1998, ReliaSoft issued the *Accelerated Life Testing Reference* with their new ALTA™ software. Gregg Hobbs added to this with his *Accelerated Reliability Testing: HALT and HASS* book in 2000. The *Accelerated Stress Testing Handbook* was produced by Anthony Chan and Paul Englert in 2001. Harry McLean published a *HALT, HASS & HASA Explained* that same year and updated it in 2009. A last book of note is titled *Accelerated Testing: A Practitioner’s Guide to Accelerated and Reliability Testing* by Bryan Dodson and Harry Schwab.

By 2010, journals and conference proceedings continue to document the advancements made in the last 10 years. Some new and different approaches to ALT have come into more common during the last 20 years. Often, these special approaches were developed internally at companies wishing to improve their products. For the most part the ALT tests have evolved from steady state operating conditions at customer limits to rapidly changing environment conditions at or beyond the specification limits. These extreme test conditions serve a variety of purposes. Some of these special approaches will be covered in later sections. I document the use of newer test software, test equipment and guidelines for improved methods such as HALT, (Highly Accelerated Life Test), HASS (Highly Accelerated Stress Screen) and step-stress techniques.

The application of accelerated techniques has spread far beyond the few original traditional military arenas to almost every aspect of modern life. The need to quickly evaluate new products and technologies now extends to computers and computer products, such as hard drives, appliances of all types, farm equipment - from tractors to hay bailers, recreational vehicles of all types, implantable biomedical devices - from pacemakers to nerve stimulators, miniature electromechanical modules or MEMs, automobiles - from engines to air conditioners, airplanes - from small consumer to large commercial units, telephones and telecommunications equipment, satellite applications and almost all building structures.

1.2 Applications of ALT Techniques -

The application of ALT might be divided into a small number of areas for clarity. These areas include the following range of parts and materials.

1) New materials test and evaluation. This includes lubricants, oil, paints, concrete, new metals, ceramics, fibers, MEMs, rubber products, memory metals, plastics, adhesives, nanotubes, nano technology and adhesive products and tapes.

2) Component test and evaluation. Included in this category include Silicon semiconductors, Gallium Arsenide devices, Indium Gallium Phosphide transistors, a variety of digital and linear microcircuits, many different formulations of resistors, the wide range of capacitors, switches, crystals that now exist as well as all batteries, ball and roller bearings, sliding mechanisms of made with Teflon and a variety of other materials, inductors and magnetic components, motors, actuators, light bulbs, hand tools, power tools, and building materials.

3) Hardware systems, with test and evaluation of software controlled hardware. These types of products include gas powered cars, electrical cars, bicycles, motorcycles, boats
and boat motors, computers, hand held devices ranging from cell phones to personal assistants, all household appliances and white goods, recreational vehicles, including motorcycles, snowmobiles and sailboats, farm equipment of all types, airplanes, military hardware of all types, space-rated systems, submarines and underwater vehicles, nuclear and coal-fired power plants, medical instruments and sensor devices and all types of power generation systems.

4) Software packages with test and evaluation. This includes all software packages, both standard and custom software, all firmware, software-controlled systems, including warning and safety systems are included. These cover all modern applications and aspects of software.

It is easy to identify additional products, materials or applications for each of these four categories. Thus, we can get a better understanding of why so many companies are now trying to apply Accelerated Life Test techniques for common products of everyday life. The need for such tests is closely tied to product improvement, fewer warranty failures and market share.

1.3 Reasons for Employing ALT Techniques -

Incentives for employing ALT techniques during modern product development projects or to enhance any released product include the following activities:

1) Provide a way to more quickly evaluate an early product design.
2) Evaluate or estimate the projected life of a product early in the design phase.
3) Examine the influences of maintenance activities on subsequent system failures.
4) Reduce the post release product support costs and warranty costs.
5) Coordinates with other similar problem prevention tools.
6) Selecting from competing suppliers or materials during design. Determine which material or suppliers are estimated to be best.
7) Identify some major failure modes early in the design cycle in order to start corrective actions before the release to production of the system.
8) Assure that no major unexpected failures will occur after production release.
9) Identify the influences of any manufacturing process steps on the performance or longevity of the design.
10) Early ALT activities will aid the design team in making important decisions.
11) Reduce the time for qualification tests or durability tests by creating and employing shorter and more effective types of tests.
12) Identifies the need for further screening or burn-in as required.
13) Reduce the corporate risk when business decisions are required.
14) Identify the potential for hazard and safety issues before release to production.

All of these reasons for the use of ALT require more detailed explanations. These are covered in the following short paragraphs.

1) ALT provides a way to more quickly evaluate an early product design. This includes an identification of major failure modes, any weak points of a design, identifies critical supplier components and assemblies and may identify the most critical stresses. For any company wishing to get to market faster with better products, early ALT is critical. It is through such early activities, especially when performed by development engineers, that large performance and time improvements can be made. Reliability people should be part of this early activity and are often
key in setting up teams, and designing the ALT tests and stress limits for more effective development.

2) Evaluate or estimate the projected life of a product early in the design phase. ALT is the key method for determining or estimating the projected life of a product when an ALT is operated in a customer-type environment. Information about how long a typical product might last as a measure of design life is important at this phase. Some suggest operating this ALT test to double the projected field life in order to achieve reliable operation. In addition, the time to first failure should be estimated in applications where this measure is critical of customer success or to reduce filed support costs.

3) ALT examines the influence of maintenance activities on subsequent system failures. The frequency and quality of maintenance activities may influence the time to subsequent system failures. Implicitly, this also speaks to the need for improved maintenance activities to prolong the life of a product. ALT may address two possibilities by looking at proper maintenance and any degradation mechanisms that result from the maintenance. The object is to create a set of rational maintenance policies that identify ways that maintenance activities will prevent system failures.

4) ALT reduces the product support costs and warranty costs. Knowing the time to first failure, some of the failure modes and the root causes of failure early in the development history all lead to cost reductions during development, manufacturing cost reductions and reduced warranty costs in the field. Manufacturing costs are reduced by fewer in-house failures and repairs during manufacturing and fewer escapes of supplier problems. Reduced field failures is a direct saved cost, but also leads to improved customer loyalty and ensures future repeat business.

5) It coordinates with other similar problem prevention tools. Tools such as Failure Mode Effects Analysis, reliability predictions, hazard predictions and Design of Experiments. The ALT results often provide failure rate and failure mode information to feed Design and Process FMEAs and other reliability tools. The early ALT results also support reliability predictions for future projects through similarity of components and assemblies. ALT results can also influence the size and type of design of experiments activities that improve the ultimate performance of a product.

Past projects with ALT information always influence the activities for new projects through the data, test set-up and lessons learned. The past project information is very important to driving the new FMEAs, new reliability predictions and improved test methods. Alt also become an element of the management decision to move ahead while selecting performance measures and product features for new products.

6) Selecting from competing suppliers or materials during design. Material test, evaluation and supplier selection are all important for success of many projects and processes. Early in the design process, the evaluation of suppliers and materials leads to improved designs. Trade-off studies can be time consuming and sometimes costly. Having accelerated approaches for evaluation can easily reduce the time and costs.

7) Identify some major failure modes early in the design cycle. Knowing the system or component failure modes early in the design is the start of corrective action. One usually doesn’t know all the modes, but finding modes early helps reduce the cost and time involved with correcting the causes. Sample size may be important to observing variability and enough modes to be valuable.
11) **Reduces the time for qualification tests or durability tests by shorter and more effective types of tests.** Reduced time during development is a critical feature in modern product development. Often this may be as much as 3 to 6 months saved on a 2 year development. The savings primarily comes from not reworking a design for undesirable failure modes found late in the development process.

12) **Identifies the need for further screening or burn-in as required.** The advantages cover screening, burn-in and all similar types of "manufacturing screening tests" that enhance the apparent performance of a product as viewed by a customer. The need for additional HALT or HASS work may be determined from these results.

13) **Reduce the corporate risk when business decisions are required.** Occasionally near the end of a development process, if a problem is discovered, a difficult decision may need to be made. Often the choices are to hold up production until the problem is corrected, screen a less than perfect design or release the design under controlled conditions. All three choices have financial impacts. The ALT may help determine which provides the lowest impact on time, the quickest resolution and lowest financial drain. This tool provides the project manager with critical and timely information.

14) **Identify the potential for hazard and safety issues before release to production.** Avoiding hazards and safety concerns prevents serious embarrassment and recalls. Think of recent automobile recalls. About eight million cars had to be reworked for brake and accelerator problems. The total costs would exceed five billion dollars.

1.4 Outline of Accelerated Life Test Procedure –

There are some who believe that ALT is achieved solely through the introduction of environmental stresses on operating hardware. Others believe effective ALT is accomplished mainly through the statistical analysis of after-the-fact test results. No time-consuming and costly activity such as ALT should be started without a thorough outline of all the activities planned and the estimation of expected outcomes. The plans should include consideration of equipment, calibration, testing to identify degradation mechanisms, costs, sample size for statistical measures and data sensitivity and collection. This permits a series of planned activities to be performed in a proper sequence that enhances the probability of successful completion of all the steps. ALT should build upon every previous ALT run. The lessons learned and results should lead to continued product and process improvement. The following short outline of the rest of the book forms the basis for the sections covering all of the various aspects of ALT. These key sections include:

Section 2.0 - **Planning** for an ALT and selecting the type of test.

Section 3.0 - Selecting and **set-up** the test equipment, conditions and parameters.

Section 4.0 - **Administer** the accelerated test.

Section 5.0 - Bring the test to a **successful conclusion**.

Section 6.0 - Analyze the data.
2.0 Planning for an Accelerated Life Test and Selecting the Type of Test -

This critical initial activity often starts with a statement of purpose of the ALT. This is a clear statement of why the ALT is to be performed and the expected outcomes. The following list covers additional reasons for running Accelerated Life Tests. The expected results noted are part of why the ALT is performed. This list covers most situations that will be encountered by reliability engineers, quality engineers, development engineers, manufacturing engineers and project managers. It covers the needs of companies for rapidly producing high reliability and high quality products for customers. The list also reflects the fact that there are eight project attributes - ranging from product performance, product features, quality in the field, reliability, development schedule (time-to-market), direct development costs, warranty costs and maintenance (see Section 4.2). These need to be simultaneously maximized for overall corporate success. Attempting to enhance one can only occur at the expense of the others.

This additional list supplements the reasons of section 1.3 and shows the range of applications of ALT to products and customers.

<table>
<thead>
<tr>
<th>Table 2.1 - A Long List of Reasons to Perform an ALT</th>
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</thead>
<tbody>
<tr>
<td><strong>A.</strong> Confirm a <strong>minimum life</strong> estimate or time to first failure of a large population.</td>
</tr>
<tr>
<td><strong>B.</strong> Look at variability or <strong>robustness</strong> of the <strong>manufacturing</strong> process.</td>
</tr>
<tr>
<td><strong>C.</strong> Determine whether <strong>screening will be required</strong> for production to meet customer requirements or market goals.</td>
</tr>
<tr>
<td><strong>D.</strong> Look at the impact of various <strong>customer environments</strong>, such as duty cycle, on the performance or ultimate life of a system.</td>
</tr>
<tr>
<td><strong>E.</strong> Determine if customer <strong>rough handling</strong>, customer abuse or customer misuse is a significant factor in the expected life of a product in the field.</td>
</tr>
<tr>
<td><strong>F.</strong> Identify the impact of <strong>software redundancy</strong> to hardware and hardware redundancy to the proper and continuous system operation.</td>
</tr>
<tr>
<td><strong>G.</strong> Determine if <strong>little-used</strong>, emergency or &quot;one-shot products&quot; will <strong>operate</strong> properly when called upon to do so. This is especially true of warning systems or emergency systems such as fire alarms or extinguishers.</td>
</tr>
<tr>
<td><strong>H.</strong> Show that <strong>no dangerous situations</strong> exist for a product. This covers all aspects of liability, hardware and software warnings and system safe operating conditions and fail-safe modes.</td>
</tr>
<tr>
<td><strong>I.</strong> Estimate the <strong>acceleration factor</strong> for a component or system with respect to a specific set of customer stresses.</td>
</tr>
<tr>
<td><strong>J.</strong> Demonstrate successful <strong>customer operation and maintenance</strong> across the many divergent customer environments and customer use conditions.</td>
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</table>

2.1 Selecting the Accelerated Life Test Method –

There is an importance to the selected test method and the limits that the test method imposes. Each purpose or reason shown in Table 2.1 may have associated with it a different set of conditions for an ALT. The ALT method is tied not only to the purpose of the test, but also to the applied stresses, the expected test conditions, the test length, the types of test equipment available and even limited by the sample size. The test method may include a decision on testing to run to complete failure versus stopping with some systems still operating. A second choice
may be to select a degradation parameter to observe during test versus running samples to failure. The third choice may be to test for specific failure modes as the primary purpose. A fourth choice may be to create an ALT test that demonstrates a minimum acceptable MTBF. The example of a fifth choice will be to set up a HALT test as a means of identifying weak points of a design.

Early in the planning stage for an ALT, the test methods or choices available should be reviewed and considered. The best test approach could then be selected from the short list of methods shown in Table 2.2 and Table 2.3. Next, a minimum sample size would be determined and then equipment availability ascertained to support the sample and method. The test methods available include:

Table 2.2 - A Short List of Methods

A. Steady state operating conditions with one or more stresses in place. The stresses may range from nominal customer to worst-case customer conditions to stresses above the worst-case customer conditions. Stresses remain fixed while systems are operated to failure. (Figure 2.1A)

B. Changing stress conditions for one or more stresses, cycling from one limit to another in some coordinated fashion if more than one stress is used. This is a common test condition when one or more stresses vary. The stress limits and the rate of change are both important. Less important is the dwell time at each extreme. (Figure 2.1 C or Figure 2.1D)

C. Rapidly changing stress is also called "rapid rate tests". These usually cycle quickly between extremes at a very high rate of change for one or more stresses. High rate temperature changes are sometimes labeled temperature shocks when the rate of change is greater than 30ºC per minute. (Figure 2.1C)

D. A progressively increasing stress state for one or more stresses. These are known as ramp stresses and are employed for specific reasons. The stresses could be in a continuous ramp or as a series of small steps. (Figure 2.1B)

E. Irregular or random application of one or more stresses. The envelope of the stresses may or may not describe a distribution. There are a limited number of stress states or conditions available. This is common with mechanical shock or vibration. (Figure 2.1E)

F. Full-reversing stresses, typically occurring only in some types of material testing or mechanical testing. This is a special type of test to limits. (Figure 2.1F)

Some of the stress conditions have familiar names as tests. A short list of some of these tests types are shown in Table 2.3. These names do vary from industry to industry and over time.
# Table 2.3 – Types of Stress Tests

<table>
<thead>
<tr>
<th>Example or Common Term</th>
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<tbody>
<tr>
<td>Run-in or burn-in test</td>
</tr>
<tr>
<td>Multiple Steady Environments</td>
</tr>
<tr>
<td>Accelerated Life Test</td>
</tr>
<tr>
<td>Short term reliability screens</td>
</tr>
<tr>
<td>&quot;Break something&quot; tests</td>
</tr>
<tr>
<td>High Temperature Life - HTL</td>
</tr>
<tr>
<td>AGREE Tests</td>
</tr>
<tr>
<td>Customer acceptance tests</td>
</tr>
<tr>
<td>Worst case conditions test</td>
</tr>
<tr>
<td>Maximum or minimum power tests</td>
</tr>
<tr>
<td>Maximum or minimum temperature</td>
</tr>
<tr>
<td>Maximum or minimum airflow</td>
</tr>
<tr>
<td>Multiple worst case conditions</td>
</tr>
<tr>
<td>Environmental Stress Screening (ESS)</td>
</tr>
<tr>
<td>Overstress Conditions Tests</td>
</tr>
<tr>
<td>Multiple Environmental Overstress (MEOST)</td>
</tr>
<tr>
<td>STRIFE (Stress-Life) Testing</td>
</tr>
<tr>
<td>Step-Stress Tests</td>
</tr>
<tr>
<td>Multiple Step-Stress Tests</td>
</tr>
<tr>
<td>Power temperature or stress cycling</td>
</tr>
<tr>
<td>Multiple Extreme Cycling Tests</td>
</tr>
<tr>
<td>Slow rate cycling (&lt; 30C/min.)</td>
</tr>
<tr>
<td>High rate cycling or shock tests ( &gt; 30C/min.)</td>
</tr>
<tr>
<td>Design Margin Evaluation (DME)</td>
</tr>
<tr>
<td>HASS - Highly Accelerated Stress Screen</td>
</tr>
<tr>
<td>HALT - Highly Accelerated Life Test</td>
</tr>
<tr>
<td>Mechanical stress loading (On-Off)</td>
</tr>
<tr>
<td>Full-reverse loading</td>
</tr>
<tr>
<td>Irregular or pulsed tests (ESD, speed bump, etc.)</td>
</tr>
<tr>
<td>Spectrum of irregular tests (power line transients, Miners Rule applications, etc.)</td>
</tr>
</tbody>
</table>

Note: these terms are not universally accepted nor do they mean the same thing at different companies. There is no standard nomenclature in this reliability area.

## 2.2 Examples of Detailed Timing Diagrams –

The following timing diagrams, shown in Figure 2.1, apply for many of ALT test methods listed in Table 2.2 and Table 2.3. They represent the common generic applications of stresses for a variety of accelerated test. Applied stress conditions may vary slightly from the timing diagrams because of equipment limits and test requirements. Not every type of test is covered in these timing examples.
Figure 2.1 - Timing Diagrams of Stress Tests

Figure 2.1A
- Steady Operating

Figure 2.1B
- Step-Stress

Figure 2.1C
- High Rate
  - Low Rate

Figure 2.1D
- + Stress
  - - Stress

Figure 2.1E
- Periodic Irregular Stresses

Figure 2.1F
- + Stress
  - - Stress
  - Periodic Full Reverse Stresses
These few timing diagrams represent just some of the possible examples of how environmental or customer use stresses can be applied to a system. It is easily possible to combine several of these single stresses into a multi-stress combined environment ALT. The complications are limited by the equipment, not the imagination. HALT is a good example of this, when random six axis vibration is combined with high rate temperature cycling and voltage margins.

2.3 Plan for Success as well as Failure - before the test begins

One often underutilized area of ALT is the "plan for failure" portion of a test. Often it is assumed that the systems under test will fail at some convenient time and/or in some convenient way and so the test results will be easily gathered, data collected and coherent. Some time should be devoted to thinking about what can happen in the real world. The goal is to prevent the many types of undesirable situations that can occur during real life tests. Table 2.4 is a short list of examples of common ALT problems. This list is not exhaustive and ranges from possible undesirable test outcomes to total failures of the ALT test itself.

Table 2.4 - A List of Undesirable ALT Events or Possible Occurrences

A. About two hours after the systems are placed on test, some to most of the systems fail suddenly and catastrophically. The systems were not watched or monitored continuously after about 20 minutes, so this undesirable outcome was discovered until the next day. The time of failure would be uncertain unless continuous monitoring was in place.

B. During the first over-night of test, the systems begin to fail when no one is around. Same issues as A above about continuous monitoring early in the test.

C. During the first weekend after the test began, the systems begin to fail in when no one is around. Same issues as A above about continuous monitoring early in the test.

D. After about 3 weeks on test, the systems begin to fail in large quantities for no apparent reason and with no warning. This is unexpected, so no one is prepared for the sudden event. Continuous monitoring during the test is key to catch this problem.

E. After the start of test, the systems begin to fail catastrophically and burn-up, leaving little left to analyze for cause. A corollary of this is the failed systems also damage and/or destroy the test chamber and supporting test equipment. Either case represents a double catastrophe as both precious samples and test equipment are lost.

F. No failures occur over a six week period of accelerated test time and the test needs to be stopped without failure having occurred. What should one do now? What conclusions can be drawn from the no-failure test?

G. No failures occur in the first three steps of a step-stress test and many of the systems fail early in the fourth step. What should one do now? What conclusions can be drawn from the no-failure test?
H. Halfway into an accelerated life test, it is discovered that a piece of monitoring equipment is not calibrated and appears to have been drifting over time. It is unclear whether this was a recent event or if the equipment was drifting before the test began. What should one do now? What conclusions can be drawn from the test?

I. A piece of monitoring equipment fails in test and no one notices for some time. Several failures are found to have occurred during the time that the monitor was not properly operating. The times of failure are now uncertain for these units. There was no warning to indicate that the monitoring equipment would fail.

J. A piece of recording equipment fails during test so no one is able to say exactly what stresses were present during the changing stress test. Thus, it is not possible to say what conditions appeared to cause the failures or to estimate the accumulation of stress.

K. A test is continually interrupted (stopped) to fix a piece of support equipment, causing questions about the trustworthiness of the equipment and the test results. What should one do now to finish the test successfully? What conclusions can be drawn from the interrupted test?

L. There are three stresses present in an accelerated life test and you suspect at some point that at least two stresses might be interacting. Only two failures have occurred during the accumulated test time so there is not enough information for any reasonable calculations. What should one do now to finish this test successfully? What conclusions can be drawn from the current test?

M. The test is stopped periodically to measure the performance of the systems under test before placing them back into test. This typically takes about 24 hours to complete the samples. You wonder if these long and frequent interruptions have any impact on the test results. What should one do now to finish this test successfully? What conclusions can be drawn from the current test?

The examples in Table 2.4 raised a number of interesting questions on some of these tests. Many represent common test outcomes that may be undesirable. None are answered or directly addressed in this section. However, in a later section, there will be some discussions covering how to handle of these undesirable results. Some answers will be provided, but it is best to avoid the negative results whenever possible by proper selection of test equipment, changing test conditions, improving monitoring equipment or more carefully watch the accelerated test for unusual behavior.
3.0 Selecting and Setting Up Test Conditions and Parameters -

Once the decision is made to run an Accelerated Life Test, planning for success becomes very important. The critical elements of planning include the selection and validation of the test equipment and any test loads that are required. This test equipment may also include thermal chambers for high and low temperature, all vibration tables any sources of humidity, dust or ultraviolet light. In addition to the required environmental equipment, there is often additional equipment needed. This might be equipment for electrical or mechanical stimulation of the samples in order to simulate the customer conditions. These stresses might range from voltage sources to a dynamic actuator for placing mechanical stress on the samples. One of the most neglected areas of ALT testing is selecting the best loads for the samples under test. These loads are meant to simulate the outside world under a variety of dynamic conditions. Too little attention is paid to the loads as they are often generated as passive load devices such as resistors. In the real world loads are usually dynamic and changing. Examples of this might be a real system with a typical load that is a mixture of 1000 Ohms resistance in parallel with 2.0 micro Henries of inductance and 10.8 micro Farads of capacitance. This is the nominal load and it changes by ±30% depending upon the operating conditions. Such a dynamic load could not be modeled by a simple resistor alone treating the inductance and capacitance as if they were negligible. With the wrong load, the ALT can’t reflect the real world.

3.1 Selecting the Test Equipment –

Begin by asking what type of ALT test equipment is readily available and how it would be employed in the test. Consider the choice of a thermal cycle chamber (temperature only), a thermal shock chamber, a multiple stress chamber (temperature, one axis vibration, humidity) or other specialized chambers such as a HALT system (high rate temperature cycle, high levels of multi-axis vibration, and humidity). Often the available equipment sets fundamental limits on what stresses can be used and how they will be applied. A few details of the differences between the four chambers are described in the following.

**Thermal Cycle Chamber** – This chamber typically operates over the range of -40°C to 150°C. The rate of change of interior air temperature is usually limited to about 10°C to 15°C per minute for any small loads. The test samples in the chamber will change temperature at an even slower rate because of the limited thermal capacity of the chamber. No other source of system stimulation is present in this type of simple chamber. These chambers may vary in size from a desk top model of 3 ft.³ to 4 ft.³ to as large as an 800 ft.³ walk-in chamber for testing an automobile.

**Thermal Shock Chamber** – This chamber typically operates from -60°C to 200°C. The rate of change of interior temperature around the systems is limited to about an effective rate as low as 50°C per minute to a modern change rate of 100°C per minute. Typically, two chambers exist in this approach. One chamber is held at the hot extreme and the other chamber held at the cold extreme. The test systems move back and forth quickly from one chamber to the other to obtain the high rate air change. The systems respond more quickly to the high rate stresses in this type of chamber, but the limits are set by the thermal capacity of the chamber itself. No other source of system stimulation is present in this type of chamber. No vibration, no humidity, no voltage margins are present. These chambers are typically limited in size from about 3 ft.³ to about 25 ft.³.
Multiple Stress Chamber - This chamber has a temperature rate of change of 10°C to 20°C per minute with extreme limits about -50°C to 150°C. It is typically capable of one axis vibration that may operate to 10 times the force of gravity, or 10 g’s. Additional stresses such as humidity may be present in the chamber. The three stresses (temperature, humidity, vibration) are usually tightly controlled so that they may be applied independently and in a coordinated fashion. Humidity can be set and controlled from about 20% RH to 95% RH over most of the temperature range from 3°C to 150°C. The thermal capacity of the chamber usually limits the temperature rate of change to the low numbers noted and the one vibration axis table has many limits. It is possible to add a two or three axis vibration capability to the $60,000 one-axis chamber, but the cost then will usually exceed $250,000. The chamber size may be from 8 ft. to as large as 120 ft.

HALT Chamber - This type of chamber was designed with multiple-stress capability to push the limits of temperature cycling. It typically has a temperature rate of change of 30°C to 50°C per minute with chamber extreme limits about -60°C to 200°C. A high capacity cooling unit coupled with a very high rate of air flow achieves such rapid air temperature changes. It has typically six axis vibration capability, three translation axes of X, Y and Z motion and three rotational axes about X, Y and Z. The applied g forces may be 50 times the force of gravity for small parts and as low as about 25 gs for larger parts and assemblies. Humidity is typically present in the chamber. The three stresses noted are usually tightly controlled so that they may be applied independently and be coordinated. Humidity can be set and controlled from about 20% RH to 95% RH over most of the temperature range from 3°C to 150°C. The thermal capacity of the chamber usually limits the temperature rate of change to the numbers noted, though very large masses in the chamber sometimes further reduces the change rate. Vibration is limited to 3 g’s at the low end in this large chamber, though small table top units will operate at lower values. These chambers are limited in size to about 80 ft. with present technology.

Other Specialty Chambers - These specialty chambers may meet the needs of a special test system or unusual life test requirements. Most of the time these are built as customer chambers, as modified from some existing model. They may be very large walk in units over 100 ft. or very small table top units of about 2 ft. 3

3.2 Selecting the Test Conditions –

Pushing the limit of extreme testing often drives the need for improved capable test equipment capability. This is both in pushing for absolute extremes such as -60°C to 250°C as well as rapid rate of change of the stresses. It is the combination of system size, end use customer environment and chamber capability defines the levels of stress that can be applied. Other considerations include how stresses may be applied for as long the ALT may operate. Thermal cycle rate is usually limited by the equipment capability. As a general rule it is the cooling capability (e.g. 20 horsepower cooling at 747 Watts per horsepower) that usually sets the limit on the rate of cool thermal change. Thus, a 25 horsepower system running at 50% efficiency delivers only 12.5 horsepower cooling (about 9.3 KW) while consuming almost 19.6 KW from the wall. This is 82 Amps for a 220 VAC system or 41 Amps for a 440VAC system. This level of power requires a special set up for power handling in most buildings.

The interior dimensions of the test chamber, the total mass within the chamber, the heat capacity of the chamber walls and the heat capacity of any internal chamber masses all impact the speed at which the chamber is able to go from the hot extreme to the cold extreme. The sum of all these heat capacities combined with the cooling capability of the equipment normally set the time limit of the chamber for cool temperature change. It is much easier to generate 20 KW to heat a chamber than to generate the same amount of cooling. The total mass
within the test chamber should be kept to a minimum when high rate of temperature changes are desired. Therefore, it is often best to place system electrical or mechanical loads outside the test chamber as well as all support equipment that is not required in the chamber. These loads may still need to be cycled up and down in temperature in a separate chamber in order to simulate the real-world load fluctuations for the system.

In many situations an elaborate fixture may need to be created to hold the test systems in the thermal chamber. This fixture, in addition to negatively impacting the thermal cooling rate of the chamber, will also have a negative impact on any planned vibration. It is common that the mass of the fixtures often exceed the mass of the systems under test. Special light alloys of aluminum or magnesium are therefore employed to reduce the mass of any necessary fixtures.

Ultimately, after the chamber limitations are noted, the choices of test conditions may be further limited by the ability of the applied voltages and/or mechanical actuators to simulate a high stress version of the customer environment. These stresses may include UV light, the circulation of dust, humidity or the inclusion of a salt spray. Most of the time corrosive chemicals are kept out of an expensive test chamber. Usually only humidity may be present and only in a stainless steel chamber.

One last concern is that these stresses may interact. That is, when two stresses such as temperature and humidity are combined, the effects are greater than would be expected for simply adding the effects. An example of this is a degradation test in which a certain temperature over a certain time causes the systems to degrade by 25%. When humidity alone is applied to the same systems for the same time, they degrade by 8%. When both stresses are applied simultaneously for the same length of time, the systems degrade by 42%. This number is larger than the simple sum of 33% (25% plus 8%). Add a third stress such as vibration and the results may get rapidly more complex. These possibilities will be covered in detail by modeling in a later section. A familiarity with Design of Experiments is a great help for this analysis.

What are the optimal test conditions to select for an ALT? Select conditions that simulate the customer use conditions, but go beyond the worst case customer conditions. This ensures that a system will be robust when released to the field. Another rule of thumb is to select as many of the field stresses as possible and combine as many as possible in one test chamber. This approach allows a variety of field possibilities to be covered with a minimum of equipment. This works well for getting an overall estimate of the life of the system or the main failure modes of the system. It has limits, however. This "as many stresses as possible" approach does not facilitate learning the root cause of the failure modes. It may be difficult to associate specific failure modes with specific single stresses. This doesn’t have to be a hindrance, but it may be helpful in the corrective action process. Treat the situation as a Design of Experiments for several test conditions and stresses. This can help reduce the number of test chambers or time required. It permits the identification of failure modes with stresses and even the identification of interacting stresses. Such an approach is much more difficult and can be time consuming, sample intensive and it often requires many chambers. Ultimately, schedule, equipment availability and resources help to determine what test conditions will be employed. At some point compromises on test size, length, conditions and support will arise.

3.2.1 Thermal Capacity of a Chamber –

The cooling capacity of a chamber often determines how quickly the interior of a chamber can transition from hot extreme to cold extreme. A sample calculation will help clarify how to “size a chamber”. This is to determine how large a chamber is required? This suggests the cooling characteristics and capacity that should be purchased to assure a minimum high rate of temperature change. If it is desirable to be able to go from 100°C to -50°C within 20 minutes, what size of cooling in the chamber is required for a fixed chamber load of 30 pounds?
First, estimate the interior size of the chamber required to support the systems, fixtures and loads that may be inside the chamber. Look at the volume of the systems, fixtures and loads and quadruple this volume. This number is the minimum interior size required. Next look at the masses involved. Here, we will use a 30 pound fixture in the chamber that supports twenty pounds of systems during thermal cycling. The fixture is 12 inches high by 24 inches wide by 6 inches deep and is an open structure that surrounds the systems and loads. This fixture size is 1 ft.\(^3\), so the chamber has to be at least 4 ft.\(^3\). The suggested chamber size would be at least 18 inches high by 36 inches wide by 18 inches deep, giving at least 6 inches on each side for sufficient air flow. Then, the desired chamber volume is 1.5 ft. x 3 ft. x 1.5 ft. or 6.75 ft.\(^3\). This makes the interior **chamber surface area** equal to \(2[(1.5 \times 3) + (1.5 \times 1.5) + (3 \times 1.5)]\) or 22.5 ft.\(^2\). The thermal load (for cooling) presented by the air volume inside the chamber and surface area of the chamber can be approximated with the quick calculations.

**Volume thermal load** = \((6.75 \text{ ft.}^3)(0.16 \text{ lbs./ ft.}^3) = 1.08 \text{ equivalent "pounds of air" (3.1)}

**Surface area thermal load** = \((22.5 \text{ ft.}^2)(1.3 \text{ lbs./ ft.}^2) = 29.25 \text{ equivalent "pounds of air" (3.2)}

These calculations are based upon some very simple assumptions about the surface material (stainless), finish of the chamber (nice smooth polish), air heat capacity, the chamber materials (mainly stainless with rubber gaskets and seals on door and ports) and geometry (cube with small windows). The volume of the systems, the equipment and the loads has been ignored up to this point. The calculation is therefore only approximate, but looks at a worst case.

The total equivalent chamber thermal load is equal to \(1.08 + 29.25 = 30.33 \text{ pounds of air at 70ºF and 40% humidity, based upon the volume and the surfaces to be heated and cooled. This gives us an approximation for later calculations of cooling capacity required.}

**Example 3.1** - What is the energy required to cool this 30 pound load from 100ºC to -50ºC or to traverse a 150ºC total range? Note, the heat capacity of air varies a little over this temperature range, but it averages close to 1 Cal./gram/ºC and we will use this for the whole range.

\[
\text{Energy Required to cool} = (30.33 \text{ lbs. of air})(\sim 1 \text{ Cal./gram/ºC for air})(150ºC) = (13,770 \text{ grams})(1 \text{ Cal./gr./ ºC})(150ºC) = 2,065,500 \text{ Calories required. = 2,066 Kilo Calories = (2,066 KCal.)(0.0015586 Horsepower-Hrs.}/\text{KCal.)}
\]

**Energy Required = 3.22 Horsepower-Hrs. (3.3)}

Thus, to transition a total of 150ºC in only 20 minutes requires \((3)(3.22) = 9.66 \text{ Horsepower just to cool the chamber and the air inside. This is a minimum of 7.2 Kilo Watts of cooling capability. If cooling inefficiencies are included, this requirement will double to about 14.4 Kilo Watts or just about 20 Horsepower. To transition the 15ºC in only 10 minutes requires almost 40 Horsepower of cooling or 28.8 KW of energy.}
Place a 30 pound "mixed metal" load in the chamber. This consists of the test systems, fixtures and test load. There is an additional cooling energy requirement for the chamber that is about:

Energy = 30 pounds (~6 Cal./gr./°C)(150°C) = (13620 gr.)(6 Cal./gr./°C)(150°C)
Energy required = 12,258 KCal. \hspace{1cm} (3.4)

This is an additional (12,258)(0.0015586) = 19.1 Horsepower-Hrs. or an additional total Horsepower of 54.9 Horsepower for a desired 20 minute temperature swing.

Based upon this simple calculation, a total of 28.8 + 54.9 = 83.7 Horsepower or 62.5 KW would be required to meet the 20 minute temperature transition requirement. At the 50% efficiency for a mechanical cooling system already included, this requires 200 Amp service at 440V. This cooling requirement pushes the limits of many large capacity chambers, so select a chamber with sufficient cooling capacity or accept the temperature transition time that comes with the chamber and the load present. One option for achieving high cooling capacity is to add a liquid nitrogen tank (LN2) for extra cooling. This reduces the mechanical cooling required typically by about a factor of 2. This is exactly what chamber manufacturers do to achieve rapid rate of cooling. Changing the air flow and reducing the heat capacity of the chamber itself will further reduce the cooling required. This has been the approach taken by manufacturers of high capacity, high rate of change chambers. Thus, a chamber with 30 Horsepower cooling and a LN2 boost can make this extreme transition with only 100 Amp service at 440VAC. The only additional cost is the additional capability for the LN2 tanks nearby. This often includes installation and maintenance costs if a large external LN2 tank is used.

3.3 Selecting Applied Stress Test Methods –

A variety of applied stress test methods are available as discussed in section 2.0. Stresses may be applied as steady state stresses, ramp-type stresses, step stress, or by stresses that vary periodically over time. These include sinusoidal applied stresses or other cyclic stresses. Even randomly applied stress conditions may be considered as often occurs with vibration. The \textit{envelope of all the random stresses} may be defined or approximated by a statistical distribution in these cases. There are also situations in which the random stresses may not correspond to a statistical distribution, but can be described and reproduced by equipment. Figure 2.1 provides some examples of the timing of applied stresses for common ALT situations. All of these methods have some advantages as well as some disadvantages. It is up to the reliability engineer to determine which method represents the best option for the samples, test chamber and support equipment that is available.

Options for multiple stress levels also exist during test. Multiple stresses are sometimes required if a projection to another stress level (usually lower) is desired. One example is a system operated at stresses of 120°C, 100°C and 75°C with the results used to estimate the customer operating life at 40°C. Only this stress was accelerated and other customer stresses that might be present should also be considered. If the customer operates in a humid environment then multiple humidity conditions might be included in an ALT. Multiple test chambers may be required to perform a matrix of conditions.

Caution, it is sometimes believed that a single high stress level with an assumed reliability life model is sufficient to project life at another set of lower stress conditions. This approach sometimes provides misleading estimates and should be approached with caution. Unless good history has already been obtained, the assumption of a stress-life model and the unknowns contained within the model may lead to incorrect estimates. This will be discussed in detail in the section on data analysis.
The most common methods of applied stresses tend to be steady stress, cyclic stresses or step stress. Only one or two stresses are typically employed in any of these examples, but analysis methods exist for three or more levels of stress [25]. A variety of test plans have been generated in the past with these more complex approaches. A later section will show some typical calculations of acceleration factors from a variety of test conditions. That section will address the theory about these issues of interacting stresses and stress-life models. The later section will show specific examples.

3.4 Selecting Sample Sizes for Meaningful Tests –

This area is often treated as the most important feature of an ALT. After all, the number of test samples is closely tied to other reliability goals, test equipment capability, the test stress severity and even test length. Sample sizes are often determined either by practical means or by calculation of statistical sample sizes. Either approach may fill your particular ALT need, depending upon the original purpose of the ALT, the product development time allowed and the expected outcomes. Sample size can drive the conditions of an ALT, but remember with acceleration and prior knowledge sample size changes. Be careful about the method selected for sample size, some are better than others.

3.4.1 Statistical Sample Sizes -

A "statistical sample size" is always preferred when they are available. A statistical sample can be established through several different common formulas. Each of the different approaches to sample size determination does not take into account applied stresses, test conditions or even test time. It is wise to avoid any statistical approach not closely related to fundamental items test stresses or conditions such as those mentioned. Most of the time, stress level, test length and test conditions and definition of failure are related to sample size and reliability goals. Related measures such as MTBF or minimum percent failure might also be tied to picking a sample size. The following is a short summary of some of the possible approaches to sample size.

3.4.1.1 The Distribution-Free Approach –

This is an example of one approach that should be avoided whenever possible. The simple distribution-free always leads to the biggest sample size and longest test. This formula for sample size is based upon a reliability goal and confidence limit only. This sample size calculation method may actually be derived from binomial confidence limits [9]. Since this approach is not directly related to any of the critical test factors, test conditions or test length, the large sample size determined by this method should be suspect. Unfortunately, this method appears in many older reliability text books without sufficient explanation, qualifications, warnings and limits suggested. Few books published in the last 10 years still carry this approach in a few examples. This approach is appropriate only when little information is available about the product to be tested and only pass-fail tests can be determined. This approach is simply an attribute test of pass-fail. There are several variations of this method and all may be labeled distribution-free. The following two short examples are shown for clarity. Both make no assumptions about the underlying distributions of time to failure or stress versus life, since neither appear in these simple estimates. This might be better labeled information-free approach.
Example 3.1 - Let the probability of being successful over a certain period of time at a given nominal operating stress level be \( P \). If there are \( N \) independent samples, what is the reliability in a failure-free situation?

Here we have:

\[
\text{Reliability} = \frac{\text{Survivors}}{N - \text{Samples}}
\]

If we require all samples to operate successfully we have

\[
\text{Probability} = (R)^N = 1 - \text{Confidence}
\]

so

\[
N = \frac{\text{Ln}(1 - \text{Confidence})}{\text{Ln}(R)}
\]

(3.5)

Example 3.2 - How many items need to be tested for the full life with no failures to demonstrate a reliability of 0.95 at 90% confidence?

\[
N = \frac{\text{Ln}(1 - \text{Confidence})}{\text{Ln}(R)} = \frac{\text{Ln}(1 - 0.90)}{\text{Ln}(0.95)} = \frac{-2.30259}{-0.05129} = 44.89 \approx 45 \text{ samples}
\]

All of the samples must operate failure-free over the expected life time and operating conditions specified.

Example 3.3 - What is the sample size required to demonstrate a reliability of 0.92 at 95% confidence using the success-run approach.

An approach labeled "success-run" and is similar to the above distribution-free method. The following example is based upon O'Connor, page 307 [10]. He recognized this as an approximation method and showed an example where failures also occurred during test.

\[
N + 1 = \frac{\text{Ln}(1 - \text{Confidence})}{\text{Ln}(R)}
\]

(3.6)

\[
N + 1 = \frac{\text{Ln}(1 - 0.95)}{\text{Ln}(0.92)} = \frac{-2.99573}{-0.08338} = 35.93 \approx 36 \text{ samples}
\]

All of the samples must operate failure-free over the time and stress conditions specified.

A third approach is possible and that will be described in the next example.

3.4.1.2 The Constant Failure Rate Model –

This approach to sample size selection is based upon the exponential model for reliability. This model is very simple and does not correspond to electronic or mechanical systems. We treat it as a rough approximation. We recognize that this MTBF calculation is very familiar. In addition we have added the confidence estimate to MTBF. The equation is:
\[
MTBF = \frac{2N t (A.F.)}{\chi^2_{1-C,2f+2}}
\] (3.7)

This equation might be treated as an estimate of a real-life situation when the hazard rate is known by independent information to be close to constant. The equation relates the desired sample size, N, as a function of \textbf{five other independent} variables. These variables are:

1) An MTBF goal
2) A desired confidence, C, which is one sided here
3) The test length, t, or the time all units on test accrue
4) The acceleration factor, A.F., based upon any stresses
5) The permitted number of failures, f, that occur during the test.

A hidden assumption may be present. It is that items on test are either repaired or replaced upon failure. Hence, the combination "Nt" represents the total test time of the samples.

The acceleration factor may be identified from prior history of similar tests or from a well-formed current multi-level stress test. This factor is often estimated or calculated. The test time and the sample size may not be independent variables since the devices under test might be repairable. The combination "Nt" represents the total time on test at a given level of stress.

**Example 3.4** - Let a non-repairable module be placed on an Accelerated Life Test at constant stress equal to the field operating stress. The test has a goal of demonstrating a reliability of at least 0.97 at 500 operating hours. A 95\% confidence is desired. What sample size is required?

**Solution** - Fix the number of failures at zero, the minimum time to establish the reliability goal. We are asking in essence the time to the first failure for this sample. The following two formulas exist to help solve the problem.

\[
R = e^{-\frac{t'}{MTBF}}
\] or

\[
MTBF = -\frac{t'}{LnR}
\] (3.8)

and

\[
MTBF = \frac{2N t' (A.F.)}{\chi^2_{1-C,2f+2}}
\]

with A.F. = 1.0,

\[
\chi^2_{0.05,2} = 5.99147, \text{ for zero failures or two degrees of freedom at 95\% confidence}
\]

Since A.F. = 1.0, then \(t' = t\), there is no difference between the \textbf{time on test, } t' \text{ and the clock time, } t.

Now solving these two equations yields:
\[ -t \frac{1}{\ln R} = 2Nt \frac{(A.F.)}{\chi^2_{0.05,2}} \]  \hspace{1cm} (3.9)

or after eliminating \( t \) and rearranging, we have:

\[ 2N = -5.99147 \frac{\ln R}{-0.030459} = 196.6 \text{ samples} \]

thus, \( N = 98.3 \text{ samples minimum, or 99 samples are required} \)

The conditions are **no failures and all samples operate 500 hours** to meet the requirement.

**Example 3.5** - Decide the ALT will no longer be a failure-free test in Example 3.4, but rather run to at least 3 failures in order to obtain some failure mode information. Past history suggests the acceleration factor we select for test to be at least 2.5 at this level of stress.

Then, \( \chi^2_{0.05,3} = 15.5073 \) for three failures and the new MTBF goal becomes 16,415.4 hrs.

This is calculated as follows from equation 3.8.

\[ \text{MTBF} = -t \frac{1}{\ln R} = 500 \frac{-0.030459}{-0.030459} = 16,415.4 \text{ hours} \]

And with equation 3.7

\[ \text{MTBF} = \frac{2Nt(2.5)}{\chi^2_{1-C,2f+2}} \]

so we have

\[ 16,415.4 = \frac{2(2.5)N}{15.5073} t = \frac{5[(N-3)t + t_1 + t_2 + t_3]}{15.5073} \]

with \( t_1, t_2, \) and \( t_3 \) representing the times of the first three failures. These failures are not replaced or repaired, so they appear overtly in the equation.

\[ (N-3)t + t_1 + t_2 + t_3 = 50911.7 \text{ hours} \]  \hspace{1cm} (3.10)

These first three times to failure are **unknown** at the start of the test, so \( N \) must be selected first since time cannot be estimated. Let \( N = 12 \), this is large enough to be meaningful, but may not be statistically significant. Equation 3.10 becomes:

\[ 9t + t_1 + t_2 + t_3 = 50911.7 \]  \hspace{1cm} (3.11)
Assume all 3 failures occur very near the end of the test, say within about 500 hours of the end, just so we have a rough estimate. Then we have the approximate solution to Equation 3.10 becomes:

\[ -9t + (t-300) + (t-200) + (t-100) = 50911.7 \]
\[ 12t - 600 = 50911.7 \]

so the test must run at least \( t = 4292.6 \) test hours minimum.

In real life the failures did not occur based upon our assumption, but are usually more spread out in time.

With the statement that reliability is 0.97 in example 3.4 and MTBF is estimated at 16,415.4 hours we could have estimated the times to failure as 1428 hours, 2993 hours and 4722 hours. This last estimate is still rough and based upon assumptions.

Example 3.6 – An Alternate solution Example 3.5 - We will let the total time to failure of the first three failures total to 5250 hours, not as shown in equation 3.11. Thus:

\[ t_1 + t_2 + t_3 = 5250 \text{ hours} \]

then equation (3.10) above becomes:

\[ 9t = 45661.7 \]

solving yields:

\[ t = 5073.5 \text{ hours} \]

This is the minimum test length to accumulate 3 failures, but we do not know when the three failures occurred. The answer to Example 3.5 does depend upon when the failures actually occur, which is information not available at the start of the test. Thus, the ALT is run and the test analyzed along the way to see if the necessary conditions have been met. Along the way, an estimate of the total test length is automatically provided. Said another way we run to three failures and look at the results.

Example 3.7 - Let the acceleration factor for a life test in Example 3.5 be determined by the following stress-life equation.

\[ \text{Life} = B \text{ (Stress)}^{-3} \quad (3.12) \]

The stress is increased for the test by 60% over the normal conditions. If the test is stopped at the first failure, what is the minimum test time?

We have \( \chi^2_{0.05,2} = 5.99147 \)

and so \( \text{MTBF} = 16,415.4 \) hours from Example 3.5.

Calculating the new A.F. yields:
A.F. = \frac{Life_1}{Life_2} = \frac{(1.0)^{-3.0}}{(1.6)^{-3.0}} = (1.6)^3 = 4.1 \quad (3.13)

Filling in Equation 3.9 provides:

\[ 16,415.4 = \frac{2Nt(A.F.)}{5.99147} \]

and so

\[ Nt = 11994.2 \text{ hours} \]

With \( t = 500 \) hours as a minimum test time to first failure, the minimum required sample size is

\[ N = 23.988 \approx 24 \text{ samples} \]

If the test is planned for 500 hours duration as the minimum time to first failure, then \( N = 24 \) samples required. If the test were planned for 1000 hours duration to the first failure, then only 12 samples are required, in theory. This equation suggests that we may trade off sample size and test length with no loss of information. This is clearly not true as the next section will show.

3.4.1.3. - The Weibull Model for Selecting Sample Sizes

The Weibull Approach – Non-Constant Failure Rate Let a sample of repairable or non-repairable systems be placed into a life test. What sample size is required if zero failures are desired in this test. The following formula covers this situation when a Weibull Model of time to failure is employed.

\[ \eta = \sum_{i=0}^{N} [(t_{A.F.})]^\beta \frac{1}{-\ln(1-C)} \]  

(3.14)

with \( \text{MTBF} = \eta \Gamma(1 + 1/\beta) \)  

(3.15)

Where:

The sample size is \( N \).

The individual test time for each sample is \( t_i \).

The unknown, \( C \), represents the confidence level desired.

The term, A.F., is the acceleration factor.

This formula requires an estimate of \( \beta \), which is the shape parameter of the Weibull Distribution, while \( \eta \) is the characteristic life of that distribution.

Equation 3.14 is for zero failures only. The term, -\( \ln(1-C) \), may be replaced by 0.5 times the standard Chi-Square term for failure situations as has been suggested by Dr. Wayne Nelson in a 1985 paper [11].
In the situation of a test that operated to multiple failures, the value of $\beta$ could actually be determined through the test itself. That is, the Weibull analysis of the first 3, 4 or 5 failures may provide a reasonable estimate of $\beta$ for a one-level stress test. The acceleration factor will remain unknown in a single stress level test. Since this unknown is needed in all situations except under normal operating conditions, at least a second stress level would be required. The following is a simple example of the use of this equation.

**Example 3.8** - Let $R$ be estimated as 0.97 at 500 hours with an A.F. = 2.0, at $C = 95\%$ and $\beta = 2.5$ based upon past history for a no failure test. What is the sample size required?

The basic Weibull two-parameter formula is:

$$R = e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (3.16)$$

Filling in the equation with the information from above we have:

$$0.97 = e^{-\left(\frac{500}{\eta}\right)^{2.5}}$$

solving this equation gives:

$$\eta = 2020.6 \text{ hours}$$

Next, this number will be filled into Equation 3.14, and when all samples are run the same length of time we have:

$$\eta^\beta = \frac{\sum_{i=0}^{N} [t_i(A.F.)]^\beta}{-\ln(1-C)}$$

$$(2020.6)^{2.5} = \frac{N[(2)(2.0)]^{2.5}}{-\ln(1-0.95)} = \frac{N[(2)(500)]^{2.5}}{2.9957}$$

$$5.49806 \times 10^8 = N(1000)^{2.5} = N (3.1623 \times 10^7)$$

and

$$N = 17.38 \text{ samples} \sim 18 \text{ samples}$$

Thus, the test should run 500 hours **with no failures** with a sample size of 18 to demonstrate the requirement of 0.97 at 500 hours with 95% confidence. This is a different size of samples because the value of $\beta$ is 2.5. When the failure rate is constant the value of $\beta$ is 1.0.

**Example 3.9** - Let $R = 0.97$ at 500 hours, A.F. = 1, $C = 95\%$, $\beta = 2.5$ from past history. The test is planned to stop at first failure test. If the characteristic life is $\eta = 2020.6$, as before, what is the test length required?

Filling in Equation 3.14 as before, selecting the appropriate Chi-Square term for 2 degrees of freedom and 95% confidence, we have:
If we select a sample size of 12 for this test and plan to stop at the first failure, we have:

\[ (t)^{2.5} = 45,817,201 \]

\[ t = 1159.9 \text{ test hours to first failure} \]

Thus, the test conditions meet the requirements if no failure occurs until this point in time.

### Table 3.1 - The Trade-Off Between Sample Size and Test Length

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Test Length</th>
<th>Total Cumulative Test Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sample</td>
<td>3133.9 hours</td>
<td>3133.9 hours</td>
</tr>
<tr>
<td>5 samples</td>
<td>1646.2 &quot;</td>
<td>8231 &quot;</td>
</tr>
<tr>
<td>10 samples</td>
<td>1247.6 &quot;</td>
<td>12,476 &quot;</td>
</tr>
<tr>
<td>15 samples</td>
<td>1060.8 &quot;</td>
<td>15,912 &quot;</td>
</tr>
<tr>
<td>20 samples</td>
<td>945.5 &quot;</td>
<td>18,910 &quot;</td>
</tr>
<tr>
<td>25 samples</td>
<td>864.8 &quot;</td>
<td>21,620 &quot;</td>
</tr>
<tr>
<td>50 samples</td>
<td>655.4 &quot;</td>
<td>32,770 &quot;</td>
</tr>
<tr>
<td>100 samples</td>
<td>496.7 &quot;</td>
<td>49,670 &quot;</td>
</tr>
<tr>
<td>200 samples</td>
<td>376.4 &quot;</td>
<td>75,280 &quot;</td>
</tr>
<tr>
<td>500 samples</td>
<td>260.9 &quot;</td>
<td>130,450 &quot;</td>
</tr>
<tr>
<td>1000 samples</td>
<td>197.7 &quot;</td>
<td>197,700 &quot;</td>
</tr>
</tbody>
</table>

We can see that, as the sample size increases, the test length decreases, but not in proportion so that the total test hours required actually rapidly increases. Treat the increased cumulative test hours as increased information. If the number of failures were increased, then the value of \( \beta \) could be determined independently. The Weibull formulas get rapidly complex for non-repairable and multi-failure situations, as was the case in Example 3.9. In the two-parameter Weibull, Example 3.9, the A.F. was assumed. The more realistic test situation is when the Acceleration Factor is not known before the start of the test. A second major purpose of the ALT is to identify an appropriate stress-life relationship and to look at the failure modes. Thus, in this situation, the
ALT is analyzed "on the fly", and the relationships are calculated at or near the end of the test. These situations, presented in some reliability texts, will be covered in later sections.

The next example covers the situation of having several failures in test using the Weibull Model. Earlier, we used the Weibull formula, Equation 3.14, to estimate reliability in a no-failure case. The following is the formula to be used for this failure situation. The unknowns are the same as before.

$$\eta = \frac{2 \sum_{i=0}^{N} [(t_i)(A.F._i)]^\beta}{\chi^2_{1-C,2f+2}}$$

(3.17)

Example 3.10 - The following data set of an electronics test consists of 12 systems on test operated for 1000 hours. Three units failed and were not replaced. Failure times are 458 hours, 677 hours and 855 hours. Ninety percent confidence is desired and $\beta$ is estimated at 0.8 which is typical for many electronic systems early in life showing a decreasing failure rate. What is the characteristic life when the acceleration factor is 1.0?

Solution - Plotting the data on the Weibull graph (following page) showed the first three failures consistent with a shape parameter of 2.46, not 0.8. This suggests that something unusual may actually be happening with the electronic modules, since $\beta = 2.46$ suggests an increasing failure rate situation. Failure analysis is required to determine the causes of the failures and why the unusual behavior at this point. We will ignore this analysis situation. Filling in the Equation 3.17 gives:

$$\eta = \frac{2 \sum_{i=0}^{N} [(t_i)(A.F._i)]^{2.46}}{\chi^2_{1-C,2f+2}}$$

$$\eta^{2.46} = \frac{2[9(1000)^{2.46} + (458)^{2.46} + (677)^{2.46} + (855)^{2.46}]}{13.362} =$$

$$\eta^{2.46} = \frac{4.89828 \times 10^8}{13.362} = 3.6658 \times 10^7$$

$$\eta = 1188 \text{ hours}$$

This estimate is different from the one derived by Weibull analysis (see Figure 3.1). The reason for this is the different methods used. Here, we employed the Weibull formula and performed a hand calculation at 90% confidence. The Weibull analysis, Figure 3.1, was performed with a software package and the Maximum Likelihood Estimator, MLE at 50% confidence. A different formula is employed by the software package to evaluate the 12 data points. Note also that the best fit MLE line does not go through the three data points. That is because the MLE weighs the suspensions (unfailed systems on test) as heavily as the failures [12]. A 90% confidence line on this graph would bring the estimate of the characteristic life close to the calculated one. These confidence limits are shown as well in Figure 3.1, but the hand analysis remains different from the canned program.
3.5 Considering Other Reliability Goals or Measures –

This area is often expressed either as a reliability number at a specified time or as a MTBF number. Either of these numbers may be employed and both depend upon assumed models for the relationship between reliability and time or the relationship of MTBF and reliability. Other measures that complicate this description of reliability include the life-versus-stress relationship. Measures such as the median and mode will not be discussed in this monograph as they are primarily distribution measures. This area is most often covered by the detailed models associated with ALT and reliability. A multi-level stress example in Section 7 will show such an example. One may also use the moments of the distribution to describe some of the aspects of reliability. Table 3.2 shows a short summary of the first 4 moments of a distribution for several common distributions.
<table>
<thead>
<tr>
<th>Moment</th>
<th>Description</th>
<th>Formula – Normal Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Average or Mean</td>
<td>$\mu = \int_{-\infty}^{\infty} xf(x)dx = \frac{\sum_{i=1}^{N} X_i}{N}$</td>
</tr>
<tr>
<td>Second</td>
<td>Variance</td>
<td>$\sigma^2 = \int_{-\infty}^{\infty} x^2 f(x)dx = \frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N-1}$</td>
</tr>
<tr>
<td>Third</td>
<td>Skew</td>
<td>Skew = $\int_{-\infty}^{\infty} x^3 f(x)dx$</td>
</tr>
<tr>
<td>Fourth</td>
<td>Kurtosis</td>
<td>Kurtosis = $\int_{-\infty}^{\infty} x^4 f(x)dx$</td>
</tr>
</tbody>
</table>

### 3.6 Selecting the Number of Test Failures –

There is no single answer to selecting the number of test failures that should be encouraged or permitted in the ALT plan. This item may be selected to fit other requirements. For example, the quote "Run the life test until at least four failures occur" is one simple philosophy. This failure number is sufficient for testing data and trending failure modes.

The alternative to this is a zero failure approach. In this situation, life tests may provide only a crude estimate. Failure mode information, which is as valuable as knowing when failures occur, is also not available. Most of the time, this zero failure approach is not desired so long as sufficient time is available. A physics of failure approach may be desired as a means of obtaining more information about the ALT.

### 3.7 Selecting the Time to Failure Distribution –

This relationship or distribution is commonly assumed before the start of an ALT. It can not be shown or proved until after the completion of the ALT, if at all. The four most common reliability distribution choices are Exponential, Weibull, Normal and Lognormal. Once in a while, another distribution such as Extreme Value, may be selected. For complex ALT results a combination of distributions may appear during the analysis of the ALT data. When multiple stresses are present, interaction between the stresses may add to the difficulty of any analysis.

A number of common distributions of time to failure are possible. Only a few of the continuous distributions will be mentioned here. These cover over 90% of the distributions, applications and situations likely to be encountered in ALT analysis.
3.7.1 The Exponential Distribution

This distribution may be formed with up to 2 unknowns to describe this distribution. A failure rate and position locator such as a time-offset are the two unknowns for the exponential distribution. Not all software analysis programs have the two-parameter Exponential version available, so this is rarely used in favor of the one-parameter Exponential. See references 7 and 12 for examples and derivations. The two-parameter Probability Density Function, PDF, and Reliability may be written for the exponential as:

\[ f(t) = \lambda e^{-\lambda(t-\gamma)} \quad \text{PDF, where } \lambda > 0 \text{ and } t > \gamma \]  

\[ R(t) = e^{-\lambda(t-\gamma)} \quad \text{Reliability equation} \]

Here, \( \lambda \) corresponds to the failure rate and \( \gamma \) to the time offset. Complete statistical solutions are possible for both one and two-parameter situations for both Rank Regression and Maximum Likelihood approaches. Most of the time the math is rather complex and so is performed by a custom reliability statistical package. It is beyond the capability of most people to take a standard package, such as Excel\textsuperscript{TM}, and then write the necessary equations to create reliability solutions.

The Exponential distribution appears when the hazard rate (for this distribution only it is the same as the failure rate) is constant over time. There are a small number of situations for systems when this may occur. The traditional middle portion of the bathtub curve is sometimes shown as constant. This constant hazard rate seldom happens for components, as they tend to be dominated by wear for mechanical components or declining failure rate for electronic components. This distribution does not appear very frequently in the analysis of accelerated life data.

**Example 3.11** - Consider the following time to failure data set of a dishwasher. Eight systems were run under accelerated conditions with times to failure of 23 hours, 48 hours, 67 hours, 100 hours and 134 hours. The remaining three units were unfailed at 140 hours. What is the failure rate?

**Solution** - Past experience has suggested that the dishwashers followed an exponential distribution in time to failure. A simple hand calculation of hazard rate shows.

\[ \lambda = \frac{5 \text{ Failures}}{23 \text{ hrs.} + 48 + 67 + 100 + 134 + 3(140)} = \frac{5}{792} = 0.0063 \text{ fails/hour} \]

A check for hazard rate, \( \lambda \), and time offset, \( \gamma \), was made with ReliaSoft Weibull ++ 6.0 and the two-parameter analysis with MLE showed best fit values of:

\[ \bar{\lambda} = 0.0082 \quad \text{and} \quad \bar{\gamma} = 23.00 \]

These are probably a better fit to the estimates calculated by hand. As with any accelerated life test, the failure modes should be reviewed after failure analysis and the information compared to past history.

3.7.2 The Weibull Distribution - This distribution has up to 3 unknowns to describe the various possibilities. These are defined as: a scale factor, \( \eta \), a distribution shape parameter, \( \beta \), and location parameter, \( \gamma \), also called a time offset. The three-parameter Weibull Probability Density Function, PDF, and Reliability may be written as:

\[ f(t) = \frac{\beta}{\eta} \left( \frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left( \frac{t-\gamma}{\eta} \right)^\beta} \]

\[ R(t) = e^{-\left( \frac{t-\gamma}{\eta} \right)^\beta} \]
\[ f(t) = \left( \frac{\beta}{\eta} \right)^{\gamma - 1} t^{\beta - 1} e^{-\left(\frac{t - \gamma}{\eta}\right)^\beta} \quad \text{PDF, where } t \geq \gamma, \beta > 0 \text{ and } \eta > 0 \quad (3.19) \]

\[ R(t) = e^{-\left(\frac{t - \gamma}{\eta}\right)^\beta} \quad \text{Reliability} \]

Complete statistical solutions are possible for both two and three-parameter Weibull models for both the Rank Regression and Maximum Likelihood approaches. It is the two-parameter Weibull that we typically graph and employ with Weibull analysis. Examples of the analysis of two and three parameter solutions will be provided in Section 7 when multilevel ALT data is considered.

### 3.7.3 The Normal Distribution

- This distribution may be described by up to 3 unknowns. These are defined as: a mean, \( \mu \), a standard deviation, \( \sigma \), and location parameter, \( \gamma \) not shown in Equation 3.20. The two-parameter Probability Density Function, PDF, is written as:

\[ f(t) = \left( \frac{1}{\sigma \sqrt{2\pi}} \right) e^{-\left(\frac{1}{2}(t - \mu)^2\right)} \quad \text{PDF, where } \sigma > 0 \quad (3.20) \]

The reliability function is not easily described and usually tables are employed. The Normal Distribution often appears in ALT through a component or system with many failure modes. Examples include batteries and incandescent light bulbs, both of which often have a normal distribution in time to failure.

### 3.7.4 The Log-Normal Distribution

- This distribution may be described by up to 3 unknowns. These are designated as a Ln mean, \( \mu' \), a Ln standard deviation, \( \sigma' \), and location parameter, labeled \( \gamma' \) and not shown in Equation 3.20. The two-parameter probability density function is:

\[ f(t) = \left( \frac{1}{t \sigma' \sqrt{2\pi}} \right) e^{-\left(\frac{1}{2}(\ln(t) - \mu')^2\right)} \quad \text{where } \sigma' > 0, t > 0 \quad (3.21) \]

Where

\[ \text{Mean} = e^{\mu'} e^{\left(\frac{\sigma'}{2}\right)} \]

The Lognormal distribution often appears in ALT through a component or system with many failure modes subject to slow degradation. The Lognormal distribution may appear in the analysis of bearings, semiconductors or some materials.

### 3.8 Other Distributions for Reliability

- Distributions, such as the Binomial, Poisson, Extreme Value or Logistic Distribution, may be employed to describe a specific reliability situation. These are less common and will not be discussed in this monograph. Reference 12 has examples.
3.8.1 Spliced Solutions or Multiple Straight Lines - Some ALT problems have unusual behavior and are best described by the "multi-Weibull" or "mixed-Weibull" models. These are often tied to failure modes or time-dependent failure mechanisms uncovered in the test. A few examples of these will appear in the analysis of ALT data section. Other complex solutions exist based upon the three-parameter Weibull. These appear as combinations of two and three-parameter distributions from the list above and can cause interesting analysis problems.

Additional complexity may exist, when multiple stresses are present in a ALT. The presence of two or more stresses may lead to an interaction between the stresses which is reflected in the behavior of the data. At times it can be very difficult to separate the effects of interaction when few failures have occurred or when it is difficult to separate the impact of each stress. A few examples will be shown in Section 7. The reader is referred to references 7, 13, 14 and 22 for examples and details.
4.0 Administering the Life Test

Actually running the ALT is important to getting data and results. Performing an accelerated life test and administering the details of the test have been planned, is an important task. Selecting the best stresses and environmental operating conditions is the next most important task to sample size. The list of likely or critical stresses may include any of those listed in Section 4.1. Other, more exotic stresses, do exist for some applications. The selection and use of these are similar to the ones shown here. The problem is how to determine what the "best stresses" should be for any particular situation. Consider the following methods for selecting these best stresses. Best is a relative term, and often people are limited by the equipment at hand.

4.1 Methods for Selecting Test Stresses

Start with the selection of the stresses that are standard for the particular customer, environment or market. Consider also the relevant specifications from government organizations or industrial specifications. Keep in mind that these stresses have typically been established typically more than 10 years prior may not be as relevant today. Even though, a review of the historical practices is often the best place to begin. Examples of the standard type stresses with associated failure modes are included in Table 4.1. These are closely tied to Physics of Failure. Table 4.2 shows the process for selecting a stress for a given failure mode or mechanism.

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Applied Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromigration</td>
<td>Current Density or High Temperature</td>
</tr>
<tr>
<td>Thermal Cracks</td>
<td>Dissipated Power or High Temperature</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Humidity or Temperature</td>
</tr>
<tr>
<td>Mechanical Fatigue</td>
<td>Repeated cycle of vibration</td>
</tr>
<tr>
<td>Thermal Fatigue</td>
<td>Repeated Temperature cycles</td>
</tr>
</tbody>
</table>

**Table 4.2 - The Selection of Applied Stresses**

A) Select **standard environmental stresses**, including items such as high temperature, low temperature, random vibration, dust or humidity.

B) Select **cyclic stress conditions**, such as temperature cycling, humidity cycling, stress cycling or sine wave vibration.

C) Select stresses that are frequently called out in the **Military Standards** and have been found useful to demonstrate conformance to stringent military customer environments.

D) Select stresses based upon **tradition** for the market or business. These may be unique to an industry or situation.

E) Select stresses based upon the expected **customer environment or industry**. This includes consideration of worst-case customers, abusive customers and customer who fail to perform suggested maintenance.
F) Select stresses based upon known or anticipated failure modes or physics of failure for critical components or system functions. Such stresses are thought to dominate the operation of a system.

G) Select stresses based upon customer safety or liability considerations.

H) Select stresses based upon long term degradation modes such as corrosion or material degradation.

Standard stresses may be very useful and are often employed in some industries and companies. These standard stresses then serve to be a test of robustness of the design and manufacturing processes. However, they may or may not correlate well with the current customer use environment, the market needs or reveal potential field failure modes. It takes time to develop the important tests and to demonstrate that they work well to identify customer problems. It may be a few years before the tests become a specification that the industry will accept and most people begin to use. About 10 to 15 years after the initial use of any stress to improve products in the customer markets, there is sufficient information to create a meaningful specification. But time may have passed for technology to change, the customers’ environment to change or knowledge about the usefulness of the stress to change. The specification may already be obsolete in a quickly-changing situation. The following example, based upon personal experience, echoes this possibility of slow development.

Example 4.1 – The following three example show what can happen with ALT. The first example describes an implantable biomedical product that is subjected to a centrifuge (i.e. spin) test at high g force level. This test had been employed for years as a "proof of robustness of all new designs" at one company. No one there remembered or knew what this test did as a stress, or whether or not it was relevant. It did not reveal any failure modes of interest or any new information over the period of 30 years. It was once a standard industry test, when products first were marketed. In more than 15 years no product had ever failed the test or appeared to be degraded by the stress conditions. Every new product had to go through this stress as part of the design qualification. The company decided that it was easier to continue this meaningless test then to try to explain to the regulatory agency why it should be dropped. Tradition is not always a good thing.

Most standard tests have much more value than the one just noted. A second example is a standard test condition for a high temperature bake of 85ºC for 168 hours. This test was developed to look at some of the stability characteristics of an integrated circuit. This test occasionally produced a few failures and showed some long term degradation. These potential degradation failure modes could be correlated with lot-to-lot performance because some of the failure modes were sensitive to high temperature. Thus, this standard test produced some useful information on future failures in-house and possible correlation to the field. It also provided quick feedback for future process changes and supports improvements.

A last real-life example is a vacuum cleaner that was tested to an industry standard of Accelerated Life Test conditions. Ten samples were operated and their performances observed and measured over time. At the end of the test, any design that passed without showing degradation would be acceptable. Any design that showed problems or too much performance degradation would need to be improved before it could be released. This test was correlated with eventual field performance and was considered an essential test by the company.

4.2 Military Standards
At one time, there was a plethora of military standards that described the suggested testing of components, assemblies and systems for the military markets. These tests were often developed over time as a solution to specific military hardware problems. Sometimes these problems were failure to perform in the field at temperature or under vibration. At other times, these standards were ways to identify a weak design or a flawed manufacturing process. In any case, military standards issued in the 1960s and 1970s became well-accepted by military suppliers in the 1970s. Eventually, these standards spread to other industries such as NASA, automotive and biomedical by the 1980s and continue to be used today. The need for highly reliable components and systems drove the use of these standards in a variety of other markets and applications. These standards, through their recommended stresses and test conditions, tended to correlate with specific failure modes when they were developed. The customer environments and expectations of the current decade were two driving forces for selecting stress types, stress levels and stress duration. Yet, time did show the stress combination to be harsh enough to identify some design weaknesses and even some systematic manufacturing or supplier component problems. Eventually, the consumer, commercial, and automotive markets, through design improvements and improved technology, made these original stress conditions, effectively obsolete by 1990. Some of these original military standards proved to be less meaningful and effective for the product development cycles of the 1980s and 1990s. It is no surprise that knowledgeable people began looking for something better. In some cases, the older military standards were updated and made more relevant. That was the ultimate point of the R&M 2000 process when it began in the early 1990s.

In some cases, industries had developed their own reliability methods and standards based upon earlier military standards. Examples include FMEA and ISO type standards in industries such as automotive, telecommunications, gas industry, commercial aviation and even the semiconductor industry. The abundance of standards were developed to aid work with component suppliers, improve the internal development process, create more robust products and deliver long-lived, low life-cycle cost products for the customer. This process has been one of learning, combined with trial and error for over 40 years now. Market acceptance, reduced development costs, reduced development time, international competition and the applications of new technology have driven most markets. Yet in the late 1990s, the unimaginable happened - some military specifications were recognized as obsolete and abandoned without being replaced. The plan at that time was to improve the procurement side for components and assemblies for military application by issuing updated specifications for Commercial Off The Shelf components, or COTS, using equivalent standards. The older specifications and standards disappeared without being replaced in a timely fashion by the COTS specifications as originally planned. Thus, once again reliability professionals are on their own for suggestions and help when developing Accelerated Life Tests. The following are real examples of the use of past test standards; some are good and some show the all too human element.

Example 4.2 - At one large military supplier in the late 1970s, a system was required to go through a 24 hour acceptance test which consisted of 6 gs of three-axes vibration combined with temperature cycling between -40°C to 100°C while operating. No electrical performance failures were permitted during the 24 hour test period. The levels of vibration were so high that an occasional integrated circuit would fly off a printed wiring board during the vibration and high temperature portion of the 24 hour test. This was usually as a result of the accumulation of fatigue from the vibration and heat. This acceptance test was thought to be a good measure of the design robustness and a measure of any residual manufacturing defects. Some correlation was obtained between the occurrence of a failure during the acceptance test and the eventual field performance. That is, a system failing the acceptance test would be repaired and run back through the acceptance test. Any system requiring three passes through this acceptance test before shipping to the field were also discovered to be problem systems in the field. No one looked at the units
passing the acceptance test to see if they failed more often than might be expected. It could be argued that this 100% test left the "good systems" passing, though with some degree of latent damage. Three passes through this 24 hour test with repairs certainly could cause additional damage. The stress level of the acceptance test probably shortened the life of the good systems. It is wise to look at the optimum stress screen time and conditions as many of the authors of ESS and Burn-In books and articles later suggested [8, 15, and 17]. Here, the reliability knowledge and theory required to understand and avoid such problems followed the practice by about 10 years.

Often the application of military standards can be an effective approach to Accelerated Life Testing if the "best stresses" are applied. Rugged customer environments and those requiring high reliability are often the best application for these standard military stresses. It is easy to overuse strong stresses such as those used in military standards. All stresses should be applied with some care and good engineering judgment. A cause-effect relationship between stress and customer environment should apply [15]. Be sure to correlate the stresses with field performance, both positive and negative when running life tests and stress tests.

**Tradition** is an all-too-frequent reason to select specific Accelerated Life Test stresses. That is, doing the same thing as has always been done, even though the designs, materials or technology may have changed. Be careful, this argument in favor of keeping to tradition may be subtle. As materials, designs or technologies evolve; some thought should be given to evolving Accelerated Life Tests as well. Example 4.1 provided evidence of problems with maintaining tradition and not knowing why.

**Customer Environments or Industrial** requirements often provide the biggest reasons to change or add to Accelerated Life Tests to product development. These requirements may be characterized by new market applications, new designs or new technical applications of old designs. When this happens, greater reliability numbers and more thorough tests are often required.

**Example 4.3** - The following is another real-life example of a new requirement driving reliability improvement in new markets. An existing piece of scientific equipment was employed to support a production line part time. New market applications of the products being manufactured called for "in-line" 100% use of the instrument. The line support application was recognized by customers. This instrument would be typically used eight to nine hours per day, five days a week with an availability of 0.75. This is, the equipment should be able to be used at least 75% of the time (of 9 hours per day) when desired. In essence, the desired information could be actually obtained within 24 hours with little overall impact on design or manufacturing. This situation actually dropped the required Availability to about 0.38. The new “in-line” system requirement would be operation of 24 hours, 7 days a week with the Availability requirement of about 0.95. This is a much more difficult target. The equipment would be employed more than three times as often in this role than in a line-support function. There would be little time for planned maintenance and low tolerance for equipment being in a failed state. The achievement of the new market requirements could be easily accomplished through fewer system failures. That is, improve reliability or establish longer Mean Time Between Failures, MTBF, for the equipment. Less importantly, shorter down-time or Mean Time to Repair, MTTR, for any failure reason would also increase the availability. This MTTR approach could become more important than the reliability improvements as it might be more easily obtained through equipment design changes and other design improvements. Items such as MTTR and MTBF measures do not normally appear as part of an ALT measure. Thus, any Accelerated Life Test would need to focus upon the specific applications for repair as well as the Mean Time Between Failure. The older, now obsolete military standards did have test conditions for the measurement of MTTR.
newer Semi-E10 standard which, governs the use of similar production equipment, hardly mentions or identifies the MTTR measure as important to achieving reliability goals. In some applications when MTTR can be short and the economic consequences of failure small, then measures such as Availability can be valuable.

4.3 The Relationship of Field Failures and Product Development Activities

Field failure mode information is very important to the selection of any stresses for an Accelerated Life Test [15]. This is because the reliability is often dominated by a small number of failure modes which are often tied to just a few environmental stresses. Identifying these critical few stresses and their potential impact on the system becomes an important early step for setting up any meaningful Accelerated Life Test. This is one aspect that the traditional Physics of Failure approach employs when determining the relationship between the applied stress and eventual system failure. The applied stress is coupled first through a latent defect and then a failure mechanism that propagates the flaw until it becomes large enough to become a system failure. Once the failure is recognized by the customer, it may then be labeled with a failure mode (see Figure 4.1). This sequence is commonly documented by a Failure Mode Effects Analysis (FMEA) or Fault Tree Analysis, FTA. The order is different in an FMEA. This document starts with the failure mode and works backward to a root cause. Thus, the selection of Accelerated Life Test stresses should be closely related to expected field failures and failure modes.

Figure 4.1 – The evolution of a Failure

One model of a system could be that of a marble bag. Each marble represents a failure mode of the system. The shading of the marbles relates to the applied stresses. So each marble represents a failure mode as activated by a stress, either a normal operating condition or a high stress condition. Only some failure modes are evident as a result of a given single stress. Multiple applied stresses may lead to only a few important failure modes. One of these failure modes could be the result of interaction between two applied stresses. For any given system, there are about 20 failure modes total, with only four or five dominating as a result of a single applied stress. Overstress conditions and acceleration may make some of the marbles evident more quickly.
The development process of any complex hardware or software system is really a series of difficult choices [15]. This might be described as a balancing act between the "Eight Project Factors" which are system performance, schedule of development, cost to develop, system quality, system reliability, features, long term field support (or life cycle cost) and field warranty failures. The object is to optimize the combination of all eight factors at the same time. No single factor can be neglected or else the others must bear increased expense or problems. No single factor can be improved by itself, except at the expense of some or all of the others. This model shows a complex juggling act during the development process. The object is to maximize the combination of all factors in order to achieve low cost and reliability. Accelerated Life Testing directly relates to the quality, reliability and performance issues as part of the development. Items such as schedule, features, field failures and life cycle costs are indirectly involved with the ALT.
Often, the corporate development philosophy has a strong impact on how and when ALT is performed. In the real world, a reliability professional must work within these constraints while trying to provide some objective evidence of why ALT should be increased in time, sample size or be changed in some way. Economic reasons may go a long way to help this discussion. The following section provides some information about the relative value of various applied stresses.

### 4.4 Effectiveness of Environmental Stress Screens

The use of environmental screens as part of the manufacturing process provides information about ALT stresses that could be used to improve the overall product development process. Think of the information in Table 4.3 as evidence of areas to improve. This information was derived from a large number of sources and so reflects the thinking across the years [8, 16, 26]. It still has some use for testing today and in the future. The table shows that there is a residue of problems that often remain in systems and that it is the stresses that reveal the hidden flaws.

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Cycle</td>
<td>360</td>
</tr>
<tr>
<td>Random Vibration</td>
<td>240</td>
</tr>
<tr>
<td>High Temperature</td>
<td>200</td>
</tr>
<tr>
<td>Electrical</td>
<td>150</td>
</tr>
<tr>
<td>Thermal Shock</td>
<td>140</td>
</tr>
<tr>
<td>Sine, fixed freq. vibration</td>
<td>130</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>120</td>
</tr>
<tr>
<td>Sine, swept</td>
<td>110</td>
</tr>
<tr>
<td>Combined environment</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.3A - The Value of Various Applied Stresses (US Study)
Table 4.3B - The Value of Various Applied Stresses (French Study)

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Cycle</td>
<td>150</td>
</tr>
<tr>
<td>High Temperature</td>
<td>100</td>
</tr>
<tr>
<td>Room Temperature operation</td>
<td>80</td>
</tr>
<tr>
<td>Electrical</td>
<td>75</td>
</tr>
<tr>
<td>Thermal Shock</td>
<td>70</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>65</td>
</tr>
<tr>
<td>Sine, swept</td>
<td>60</td>
</tr>
<tr>
<td>Random Vibration</td>
<td>55</td>
</tr>
<tr>
<td>Humidity</td>
<td>50</td>
</tr>
<tr>
<td>Sine, fixed frequency vibration</td>
<td>40</td>
</tr>
<tr>
<td>Mechanical shock</td>
<td>35</td>
</tr>
<tr>
<td>Acceleration</td>
<td>30</td>
</tr>
<tr>
<td>Combined environment</td>
<td>25</td>
</tr>
<tr>
<td>Altitude</td>
<td>20</td>
</tr>
</tbody>
</table>

The higher the ranking number; the more important the stress.

4.4.1 - Discussion of the Stress Effectivity Identified in Table 4.3

**Temperature Cycle** - This stress has been identified by a series of studies as the best single stress [8, 16, 26] to select when trying to identify the main failure modes of a system. This stress works well for both mechanical systems, electronic systems and most components. It may be because this stress "stresses" the materials as a result of the temperature gradients and causes sufficient internal stress to initiate and propagate both cracks and other defects in structures. This stress tends to follow a simple power law relationship in total temperature change, $\Delta T$. The stress-life relationship can be described as:

$$\text{Life} = B(\Delta T)^{-N}$$  \hspace{1cm} (4.1)

This simple model has a scale factor $B$, were $\Delta T$ is the total temperature change, and $N$ is a physical constant associated with materials. The model can be expanded to allow for more complicated geometry, various failure mechanisms, and include additional effects such a rate of temperature change. In the end, despite the increased possible complexity; the formula always looks something like Equation 4.1.

The Coffin-Manson relationship describes mechanical crack growth driven by thermal cycles. The equation for Coffin-Manson shows a similar relationship to Equation 4.1. The thermal cycles to failure are labeled $N_{TC}$, the cycle frequency is $F$ and $\Delta T$ represents the temperature difference. Thus Coffin-Manson can be written as:
\[ N_{TC} = A(F)^{b} (\Delta T)^{c} \]  \hspace{1cm} (4.2)

Where A, b and c are constants that depend upon material and how the thermal cycle is applied.

The temperature stress need not be uniform across a material, component or system. Depending upon mass and geometry, there may be stress concentrations in a system and these will dominate the failure modes.

**Vibration** - This is one of the best stresses for many systems because the vibration leads to the accumulation of fatigue usually in some weak aspect of a component or system. It works well for mechanical and electronic systems for which structure or mechanical integrity is important for proper system operation. When applied with temperature or temperature cycling, we need to be concerned about interaction of vibration with temperature. At high temperature, when many materials approach a Type I phase change, such as melting, the result of the combined stresses rapidly exhibits non-linear behavior. Some metals are subject to creep at a temperature above half their melting temperature. This is often just above room temperature. Thus the failure mode would be a deformation associated with temperature. Vibration at high temperature exacerbates creep, basic crack growth and the accumulation of fatigue in general. At low temperatures, vibration may become important especially when Type II phase changes are present. Type II changes occur when atomic, crystalline or structural rearrangement is present. Solder is a good example of such a material because it is not obvious that there are internal structure changes on going.

Vibration may be applied as a random event, as a swept sine stress or even a fixed frequency sine stress. All of these stresses may produce different results for a system. As a complicating factor, both narrow-band and wide-band frequency processes may be described by a simple power-law relationship as shown in Equation 4.2. Examples in a later section will show the use of these processes.

\[ \text{Life} = B(\text{Stress})^{-N} \]

The stress may be measured by a power spectral density, a sine frequency, or the envelop of stresses described by a g force level.

**Figure 4.4 – Temperature Cycle**

The temperature stress need not be uniform across a material, component or system. Depending upon mass and geometry, there may be stress concentrations in a system and these will dominate the failure modes.
High Temperature - This has long been tied to burn-in and shelf life tests for components and systems. This stress has been most commonly employed for ALT for a variety of products ranging from electronics to mechanical structures, most materials and even drugs. When temperatures are static, the life usually follows the Arrhenius relationship in temperature. This is simply:

\[
\text{Life} = A e^{\frac{E_a}{k_b T_k}}
\]  

(4.3)

where A is a scale factor, \( E_a \) is the activation energy in electron volts or eV, \( K_b \) is Boltzmann's constant or \( 8.62 \times 10^{-5} \text{ eV/ºK} \) and \( T_k \) is the temperature expressed in ºKelvin = 273 + ºC. This formula works for many electronic and mechanical components as well as diffusions processes.

Electrical or Operating Voltage - The electrical stress may appear as either an absolute operating voltage stress for some components, as a current density or sometimes as an on-off stress. For incandescent light bulbs, both the operating voltage and the on-off cycle may be important in determining the absolute life and many of the failure modes. This stress typically follows a power law relationship. It may be expressed as:

\[
\text{Life} = B(Voltage)^{-M}
\]  

(4.4)

or

\[
\text{Life} = B(J)^{-P}
\]

where B is a scale factor, M and P are physical constants that are typical of the materials involved, J is a current density, typically amps/cm\(^2\) or amps/cm\(^3\). The negative signs of P and M indicate that the life gets shorter as the stress increases.

Thermal Shock - This stress is similar to the thermal cycle one. The main difference is that the effective rate of temperature change is greater than 30ºC/minute for the components or systems involved. The equations are often similar to those observed with temperature cycling. Temperature shock is more effective than temperature cycles at discovering latent failures. This may be accomplished by a rapid rate of temperature change of the air, by a movement from a hot condition to a cold condition or by moving from a hot liquid to a cold liquid. Each of these three conditions will produce different results.

Sine or Fixed Frequency Vibration - This stress is considered less important than random vibration because of the limited stress frequency range involved. Typically there are limited applied g forces present with this type of stress. This tends to follow a power law relationship. The application of this stress is typically performed at one or more system resonances. Most of the time, the energy from the single stress frequency is poorly coupled into the system, so little fatigue accumulates. Fixed frequency vibration can be effective when it is at one of the resonances of the system.

Low Temperature - This is often treated as an important stress for some systems and components. Many systems react to this stress because a low temperature limit crosses a phase transition of one of the materials in use in the system. Solder is a good example of such a material. Low temperature can cause failures because the thermal change causes high stress at
some point of the design. A second reason for failure is that some materials become brittle at low
temperature and easily fail from ordinary operating stresses at this temperature.

_Swept Sine Vibration_ - This is considered less effective than fixed frequency sine
because most of the time the applied frequency is not close to a system resonance and so little
damage may be accumulated as a result of the stress. Swept sine is one way to find the system
resonances for a future dwell.

_Speed, Frequency or Load_ - These stresses are common, especially for mechanical
systems. Although not appearing in Table 4.3, any one of the stresses may be tied to a specific
failure mode and have a direct impact on life. These typically follow a power law relationship.

_Combined Stresses_ - Combined stresses are considered by some past studies to be less
effective than other single stresses. This may be because the applied stress levels in the 1980s
have traditionally not been high enough to see failures modes quickly. By the 1990s, high
combined stresses became more common, hence the development of HALT, HASS and ESS as
techniques. Future surveys will find these approaches to ALT rated higher on the scale of
effective test methods.

_Mechanical Shock_ - This stress is not commonly used by many reliability people except
when testing packaging material. It is employed primarily with shipping tests due to concerns
about damage from a drop. Vibration tends to be the mechanical stress of choice.

_Humidity_ - This stress is the least commonly used stress and typically follows a simple
power law. Humidity often appears in material evaluations and ALT for simple components. For
plastic integrated circuits and many material corrosion situations, humidity versus life follows a
simple power law. Systems tend to be too complex to describe a simple relationship. When used
with high temperature, non-linear effects must be considered. Many ASTM tests are based upon
temperature and humidity as a combination. Here RH stands for relative humidity.

\[
\text{Life} = B(\text{RH})^{-M}
\]

_Ultraviolet Light or Chemical Degradation_ - These stresses, while not in Table 4.3, are
often strongly associated with materials and products that are exposed to the outdoors. A Physics
of Failure approach may be desired with these stresses. Corrosion, chemical aging or internal
structural changes may all occur. These tend to follow a power law relationship between life and
stress.

_Biological Stresses_ - These stresses are not usually considered and are sometimes
required when a product must work in a high-humidity or condensing environment. Sterility and
shelf life environments are also important. These may measure resistance to biological attack or
the growth of simple biological products. Occasionally, a simple attack, such as by cockroaches,
mice, squirrels may need to be considered.

_Other Stresses_ - Special stresses tied to markets or environments are sometimes
employed. Examples are altitude, beta radiation, dust, ESD or air flow. Each needs to be
developed for a specific product or market. These tend to follow a simple power law.

4.5 - A Few Stress Application Examples
A few examples will help show how some of these stresses may be applied. Not every important stress is showed here. No interacting stresses are included in this section, but examples of interaction are in Section 7.

**Example 4.4** - Let the humidity stress-life relationship be determined by the following:

\[
\text{Life} = B \left( \frac{RH}{85\%} \right)^{-M} \tag{4.5}
\]

If the applied stress or humidity is raised from 30% to 60%, and \( M = 3.0 \), how much is the life shortened? We can write the equation for the Acceleration Factor, A.F. as the following:

\[
\text{A.F.} = \frac{\text{Life}_1}{\text{Life}_2} = \frac{B(30\%)^{-3.0}}{B(60\%)^{-3.0}} = (2)^3 = 8.0 \tag{4.6}
\]

This equation reflects the fact that, for the two different life conditions based upon Equation 4.5, we can write them separately and then divide the two equations to get Equation 4.6. The life would be shortened by a factor of eight when the humidity is doubled as shown by Equation 4.6.

**Example 4.5** - The breakdown of oxide in a CMOS integrated circuit has been suggested to follow the formula:

\[
A_V = e^{\frac{C}{t_{ox}}(V_1-V_2)} \tag{4.7}
\]

where \( A_V \) is the Acceleration Factor for operating voltages, \( V_1 \) and \( V_2 \). The term \( t_{ox} \) measures the oxide thickness in Å, and where the constant, \( C \), is 300 Å, and \( V_1 \) is the accelerated voltage with \( V_2 \) being the standard operating voltage. Let \( t_{ox} \) be 400 Å, with \( V_1 \) be 8 volts and \( V_2 \) be 5.0 volts. Completing Equation 4.7 with the information provided yields:

\[
A_V = e^{0.75(3.0)} = 9.488
\]

That is, each operating hour at 8 volts is equivalent to 9.488 operating hours at 5 volts. Clearly, there is an unidentified upper limit to the application voltage for this type of test. Likewise, there may be a temperature dependence or effect as well.

**Example 4.6** - Crack growth is an important failure mechanism in many components and systems. There are several models available to describe different aspects, but for short cracks the following model from Carter [18] works well for stress driven crack growth.

\[
\frac{da}{dn} = A \left( \Delta \gamma_p \right)^n (d - a) \tag{4.8}
\]
where \( A \) and \( \alpha \) are material constants, \( \Delta \gamma_p \) measures the plastic shear strain, \( a \) is the initial crack length and \( d \) is the shortest crack distance that leads to system failure. The term, \( n \), measures the number of applications of some external load. This load may be thermal cycles, mechanical stress, internal heating or even the adsorption of humidity, causing swelling. All of these stresses may lead to crack growth and development and a "common failure mode". When two or more stresses are present, interaction between stresses may occur and confuse the results of the ALT. Statistical analysis at the end of the test may need to look at this carefully and take this into account during the analysis.

Let \( A = 2.5 \), \( \alpha = -4.3 \), \( a = 0.007 \) inch, \( d = 0.050 \) inch, \( \Delta \gamma_p = 8.5 \), what is the crack growth per stress cycle, or \( \frac{da}{dn} \)?

\[
\frac{da}{dn} = A \left( \Delta \gamma_p \right)^\alpha (d - a) = 2.5 (8.5)^{-4.3} (0.017) = 1.084 \times 10^{-5} \text{ inch/stress cycle}
\]

Figure 4.5 Crack Growth in a Plane

**Example 4.7** - Vibration with intrinsic damping may be a common situation for many mechanical systems. The following vibration equation from Kececioglu [8] is a simplification of a more complex equation that works in many situations when light damping is present in a vibrating system. The equation describes the ratio of the standard deviation of the damage accumulation, \( \sigma_d \), to the total accumulated damage as measured through the Damage Coefficient, \( D \). This ratio is given by:

\[
\frac{\sigma_d}{D} = \sqrt{\frac{\Psi_1(b)}{(\xi)(n_Y^+)} (4.9)}
\]

where \( \Psi_1 \) is a constant from Table 4.4, \( \xi \) measures the level of damping and \( n_Y^+ \) measures the cycles accumulated during a specific period of time. Let the light damping be, \( \xi = 0.05 \), let \( n_Y^+ = 1909.85 \) stress cycles accumulated in 500 hours. The value of \( D = 0.9097 \) must be derived from the Equation 4.10 below, while \( \Psi_1 = 3.11 \) was taken from the Table 4.4.

The value of the Damage coefficient, \( D \), depends upon the Palmgren-Miner model of cumulative damage. This depends upon the following factors:
1) Narrow versus wide-band stressing during accelerated vibration.
2) Static versus dynamic loads during vibration.
3) Unidirectional versus full-reversing application of stresses.
4) Compression versus shear in stresses.
5) Type of material, ferrous versus non-ferrous or plastic materials.
6) Finish of the material under stress.
7) Geometry or stress concentration factors.

For a narrow-band, single peak situation, we can write the equation in the following example. It is expressed as:

\[ D = \left( \frac{\sigma_n}{2\pi} \right) \left( \frac{T}{A} \right) \left( \sigma_y \sqrt{2} \right)^b \Gamma \left( \frac{b}{2} + 1 \right) \]  \hspace{1cm} (4.10)

where:
- \( T \) is the duration of the stress, here 500 hours
- \( \omega_n \) is the natural frequency of the assembly, here 510 Hz.
- \( \sigma_y \) is the Raleigh scale factor, here 150 MPa.
- \( b \) is a Palmgren-Miner exponent, here 6.5
- \( A \) is a material constant, here 1.767 \times 10^{24}
- \( \Gamma \) is the Gamma Distribution

\[ D = \left( \frac{\sigma_n}{2\pi} \right) \left( \frac{T}{A} \right) \left( \sigma_y \sqrt{2} \right)^b \Gamma \left( \frac{b}{2} + 1 \right) = \left( \frac{510}{2\pi} \right) \left( \frac{500}{1.767 \times 10^{24}} \right) (150\sqrt{2})^{6.5} \Gamma(4.25) \]
\[ D = 0.9097 \]

<table>
<thead>
<tr>
<th>( b )</th>
<th>( \Psi_1(b) )</th>
<th>( \Psi_2(b) )</th>
<th>( \Psi_3(b) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0414</td>
<td>0.00323</td>
<td>0.0796</td>
</tr>
<tr>
<td>3</td>
<td>0.369</td>
<td>0.0290</td>
<td>0.2120</td>
</tr>
<tr>
<td>5</td>
<td>1.280</td>
<td>0.0904</td>
<td>0.6790</td>
</tr>
<tr>
<td>7</td>
<td>3.720</td>
<td>0.2230</td>
<td>2.3300</td>
</tr>
<tr>
<td>9</td>
<td>10.700</td>
<td>0.5180</td>
<td>8.280</td>
</tr>
<tr>
<td>11</td>
<td>31.50</td>
<td>1.230</td>
<td>30.00</td>
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</tr>
<tr>
<td>15</td>
<td>308.00</td>
<td>8.110</td>
<td>415.0</td>
</tr>
</tbody>
</table>

Table 4.4 - The Critical \( \Psi \) Factors for Vibration Testing, from Kececioglu [8]

Filling in this information in Equation 4.9, we have:

\[ \frac{\sigma_y}{D} = \frac{\Psi_1(b)}{\sqrt{\psi}(n_{1\psi})} \]
\[ \sigma_d = (0.9097) \sqrt{\frac{3.11}{(0.05)(1909.85)}} = 0.16417 \]

We can use the relationship for the Normal Distribution, Equation 4.11, since both D and \( \sigma_d \) are treated as if they are normally distributed. We can use the normal distribution to estimate reliability under these conditions at any point in time. With the values of \( \sigma_d = 0.16417 \) and D = 0.9097, we have:

so \[ R(t)_{500} = \Phi \left[ \frac{1 - 0.9097}{0.1642} \right] = \Phi [0.5499] = 0.7088 \quad (4.11) \]

Thus, we have an estimate of the reliability of a product under certain conditions of stress. It is helpful to have such an estimate before the start of a test because it suggests how long the test might last and may help with estimating results. All that was needed was a description of the natural frequencies of the product, material constants and an idea of the internal damping.

**Example 4.8** – Now let \( \xi = 0.03 \), let \( n^+ = 1200 \) stress cycles accumulated in \( T = 600 \) hours, with \( b = 7.5 \) and \( \omega_n \) is the natural frequency of the assembly, here 620 Hz., \( \sigma_y \) is the Raleigh scale factor, here 160 MPa and \( A = 1.61 \times 10^{23} \). Calculating the value of D first gives:

\[
D = \left( \frac{\sigma_y}{2\pi} \right) \left( \frac{T}{A} \right) \left( \sigma_y \sqrt{2} \right)^b \Gamma \left( \frac{b}{2} + 1 \right) = \left( \frac{620}{2\pi} \right) \left( \frac{600}{1.61 \times 10^{23}} \right) (160 \sqrt{2})^{0.5} \Gamma(4.75) \\
D = (98.676)(3.727 \times 10^{-21})(4.568 \times 10^{17})(9.478) = 15922.6 \times 10^{-4} \\
D = 1.5923 \\
\]

And \[ \sigma_d = (1.5923) \sqrt{\frac{5.47}{(0.03)(1200)}} = 0.6204 \]

We have \[ R(t)_{350} = \Phi \left[ \frac{1 - 1.5923}{0.6204} \right] = \Phi [-0.9547] = 0.518 \]

This situation is less reliable than the previous example.

**4.6 - Suggested Rules for Performing an Accelerated Life Test**

Many accelerated tests are defeated before they really begin. This is often due to the way they were set up and conducted. The following Table 4.5 list of suggested ground rules will help avoid some of the most common problems associated with ALTs. They are good generic advice, but as always may need to be adapted for specific situations.

**Table 4.5 – List of Suggested Ground Rules for ALT**
1) **Verify the upper limit** of the stresses by running at least one part through the full stress conditions before committing the whole sample. This also provides an opportunity to verify the equipment, calibration and all fixtures before committing all of the samples.

2) **Verify all samples are working correctly** at the start of the test as well as in the fixture in the environmental conditions in which they will operate. That is, verify that they work initially at room conditions and at the start of any environmental stresses.

3) **Closely monitor the samples** through the first few accelerated test cycles. Make sure they are operating correctly. This usually means starting the test early in a work day.

4) **Never start** a life test on a Friday or a day before a holiday, if no one will be available to monitor the test during the second day. If it is necessary to start a test on a Friday, the test must be monitored on Saturday to verify the samples are still operating correctly.

5) **Read important performance measures** for the test samples during the test. If measurements cannot be taken continuously, then make measurements at intervals. That is, take parametric measurements so the drift can be monitored during test. Do this within 24 hours after the start of the test and a few days later. The following times to check are suggested if continuous monitoring is not possible: initial reading at nominal conditions, initial reading at stress limits, and read at 24 hrs, read at 72 hrs. These would be at about 10%, 25%, 50%, 75% of the expected total test time and then at the end. These are suggestions. The timing can be modified to fit schedules, technology and materials. The issue is that periodic measures should be made to monitor drift well before any failure occurs.

6) Verify the **measuring equipment is capable** of the precision required. Do this by capability studies before the life test begins. Be sure they are calibrated. Check the equipment at least half way through the ALT and at the end to confirm the same capability is still present. Use known good samples, sometimes called "golden units" to verify measurement stability. Be sure to look at repeatability of the measures from a statistical perspective.

7) **Prepare for sudden and unexpected failure.** Assume that the test equipment, test chamber or a large fraction of the samples will suddenly and unexpectedly fail during test. Determine the back up plan for this possibility before the ALT begins.

8) **Verify the test conditions** for stress before, several times during the ALT and at the end of test. That is, use independent measures such as thermocouples, voltmeters or humidity gauges to confirm the chamber conditions, voltages and samples are as they should be. Look into any closed chambers periodically.

9) Place **some known good and marginal samples** in with the life test units if such items are available. These special units are not part of the life test, but serve as a comparison to the units being tested. Sometimes this is best done by combining Design of Experiments with the standard life test. This latter condition may apply only if sufficient knowledge and samples are present.

10) **Assume a fire or similar catastrophe will occur** during test. What will you do before the start of the test to protect the samples (with fuses, thermal cut-outs, etc.), the test equipment and the laboratory (have fire alarms, sprinklers, etc.)? Remember, these unpleasant events seem to occur when no one is around and usually take some time to develop. Even test chambers and test loads eventually fail from continued use by many ALTs.
11) **Consider the possible results** before the test begins. Create hypothetical best and worst case scenarios and look at times to failure under these circumstances. This helps visualize when significant events may occur. This is especially important in a multiple-level stress test. Here, the highest stress condition should typically have the first major change and first failure.

12) **Start any data analysis** after the second failure of each of the various stress conditions. This may seem a little premature, but permits an initial consistency check to occur while the test is still in operation. The first failure does not provide more than a crude estimate of statistical characteristics. The second failure permits the start of trending and provides better estimates. If a problem with test samples or test conditions has occurred, then this early analysis will help identify it.

13) **Verify the failure modes** by performing analysis of the failed units as they occur. Don't wait until the end of the test to look at failed samples. Be sure to check the failure modes between the different stress levels and verify they are as expected.

14) **Perform analysis on some of the non-failed units** from each stress level at the end of test. They often provide useful information about the propagation of the failure modes as well and help with identifying mechanisms and degradation information.

15) **Never assume** that the failure modes are caused by "bad parts" or explain away failures as "can never occur in the field because...". Both of these are forms of denial that is sometimes used as a reason for not improving a product, not making changes or a desire to stick to a tight schedule. All failure modes derived from an ALT are meaningful and bring value. Be sure to perform the analysis on all failed samples and **don't assume failure causes** based upon failure modes or failure symptoms.

16) **Retest any design improvements** and confirm they have the desired effects. This should be done even if the product is in production. After all, it is better to find out about a design flaw in production by an Accelerated Life Test than by waiting for customer complaints to arrive from the field.

17) **Perform a detailed and thorough analysis** of all of the data at the end of test. Make use of all the data available, including history of similar products and tests.

**4.6.1 - The most important rules**

Five of the proposed ALT rules are more important than the others and will be repeated here since they are so essential for successful completion of an ALT and start the data analysis phase. The original rule is underlined.

**Rule 3)** Closely monitor the samples through the first few accelerated test cycles. Make sure they are operating correctly. This usually means starting the test early in the work day. This rule helps ensure the ability to make parametric measurements, and even, later in the test, to be able to follow a trend in measurements that occur. The data collected on the fly during test may suggest one of three possibilities before the end of test. These include:

- a) The test may be ended early because there are significant results that suggest conclusions. Unfortunately, this happens most often with a failed test. This is, a test in which unexpected and "bad" results are the quick outcome. Remember the fundamental
law of reliability - "Bad news happens fast, but good news usually takes a long time". Occasionally, we are able to end a test early because a positive result has been reached to some degree of confidence.

b) The test will run as planned because results are within the acceptable range for numbers of failures, size of parametric changes or failure modes. Most tests fit in this group.

c) The length of the test is extended because the anticipated test results or failures have not yet occurred. This possibility happens with robust designs and with specialty testing such as Accelerated Shelf Life Tests. These latter tests are often open-ended, it is necessary to run the test until there is evidence of degradation and/or failures.

Rule 5) Read important performance measures for the test samples during the test. The goal is to make periodic measures to monitor drift or degradation. When these are not available, identify failures at the best time estimates if samples cannot be monitored continuously. It was initially suggested measurement points at initial, initial at extremes, after 24 hours, 72 hours and then at about 10%, 25%, 50%, 75% of total test time and near the anticipated end of test. These times were suggested when continuous monitoring was not a possibility. The review of Rule 11 will suggest why the spread of times proposed is a reasonable choice for most ALT situations. Special tests, limits of test equipment or unusual circumstances may suggest changes to these percentages. The greatest problem is having to interrupt the test conditions to take readings. Most of the time, such temporary interruptions have little effect on the results. Consider both possibilities carefully!

Rule 11) Consider the possible results before the test begins. Create hypothetical best and worst case scenarios and look at times to failure under these circumstances... This is especially important in a multiple-level stress test. The task here is to simply describe what types of test results are available. Most examples will assume a single stress and consider only three possible responses, unchanged, degraded or failed. With multiple stresses, the results may become more complicated. The real world is much more complex, adding noise to all measurements. The examples in the next section will illustrate some of the basics for data analysis.

Rule 14) At the end of test, perform analysis on some of the non-failed units from each stress level. They often provide useful information about the failure modes as well. This rule is always a good idea that promotes learning about the failure mechanisms and modes of non-failed components. We may then see the progression of the failure mode and mechanism. The information gathered by this activity is seldom mentioned, except in the Physics of Failure approach, as it is infrequently done.

Rule 17) At the end of test, perform a detailed and thorough analysis of all of the data. It is at this step where most books and articles on Accelerated Life Testing actually begin. The practical side of all ALT efforts is to assume that ALT tests are set up and administered properly. Sometimes, however, reliability professionals do not fully appreciate what small changes of test conditions, fixtures or monitoring equipment can do to enhance or impede the learning experience. Examples in Section 7 will highlight this and some of the problems associated with analysis of complex or "messy" data.
5.0 Models for Reliability Analysis of ALT

The analysis of all ALT data starts with the creation of a model to describe reliability versus time or a model of life versus stress. Both types of models are important and have been covered in some detail in the various references [7, 12, 13, 14, 25, and 26]. The general models for each type of distribution will be covered in this section. The reader is encouraged to pursue this through the references and recent journal articles listed at the end of the book.

5.1 Degradation Models for Systems under Test

A first model for describing the failure of a component or system is that of degradation. This model recognizes the possibility that systems and components do not fail suddenly and unexpectedly. Most of the time, components and systems provide warning through some performance measure changes indicating that some important aspect of the system function is degrading. This change leads ultimately to failure if the system is operated a sufficient amount of time. One example is that of an automobile tire. The performance measure is the tread depth. The tire tread slowly wears away until there is none left, and the tire may then fail catastrophically. For now, the focus will be on monitoring the performance measure change as a function of the applied stress and time on test. This degradation model is important when looking at a variety of systems and components.

5.1.1 Model One - Linear degradation - This occurs when there is a linear response to the application of stress to a component or simple system. The linear response is documented through a performance measure or P.M. A number of components and systems will approximate this linear degradation for some portion of the life. The following is a simple mathematical approach to this linear situation:

\[ PM = A - Bt \]  \hspace{1cm} (5.1)

Where A is an initial value, B is the degradation rate and t is time. This equation may also be expressed as degradation as a function of stress cycle. In that situation t will represent the number of cycles.

Equation 5.1 describes slow, linear degradation portion of a more complex performance curve. Often it ignores that fact that, in the real world, there may be transient events at early life time and non-linear events near the end of life. These are treated as small in comparison to the overall linear degradation in this model. Figure 5.1 shows this type of linear degradation situation through the two straight lines. One line is an example of a fast linear degradation while the other shows a slow linear degradation. The vertical scale (Y axis) of the graph is measured in the same units as the unknown A from Equation 5.1. The horizontal scale (X axis) is typically time or stress cycles. The performance measure begins with a reading of A at time zero or very near time zero, while the time ordinate is the ratio \( \frac{A}{B} \). This is, when the P.M. reaches zero, this is the implicit definition of failure in this model. It is possible to change the definition of failure and use one such as:

A) Failure is defined when a change of 20% from the initial reading occurs.
B) Failure is defined when the P.M. drops to 30% of the original value.

This model, as modified, works as an approximation for many products.
5.1.2 Model Two - Log Degradation. This model follows the relationship in the log of the performance measure. It is described as:

\[ \log(PM) = A - Bt \quad (5.2) \]

The log model is similar to Model One, but can describe a more complex, real-world situation. Here, the performance function \((A - Bt)\) is always positive, but may still describe a fast or slow degradation through the log function. This formula may be rewritten in the more familiar format of Equation 5.3 as:

\[ PM = e^{A} e^{-Bt} = A'e^{-Bt} \quad (5.3) \]

We immediately recognize this as an exponential decay when we use the natural log function to describe the P.M. versus stress relationship. A variety of situations, systems and components are described by this Equation 5.3.

5.1.3 Model 3 – Complex, Non-Linear, Degradation - Typical degradation formulas often neglect the effects of early or late non-linear behavior also known as "wear-in" and "wear-out". Wear-in occurs early in the history of a component or system and typically lasts only a short time with rapid change in P.M. Wear-out is more often a long, slow process near the end of life. Both non-linear effects are shown in Figure 5.2 and correspond to common phenomenon.

Wear-in is a measure of an early-changing characteristic for a simple component, assembly or system. It is often so short in time it can be neglected for many situations because it may be eliminated by taking a “second set” of initial readings a little while after the start of test. This occurs in the real world with batteries, gasoline engines and air conditioning systems. In those few unique situations wear-in actually occurs over a long period of time rather than quickly. Here a screening test or burn-in may be employed to remove or reduce the impact of this wear-in and stabilize the performance measure. Some electronic parts have a very long wear-in period, as measured in thousands of hours. This early portion, associated with classic infant mortality, tends to dominate the early useful life in many electronic applications. One good example is the 7000
hour infant mortality time that exists for many semiconductors [19]. During this time, a small number of a production lots rapidly change their characteristics and may become unacceptable for use after an extended burn-in. This long wear-in may be characteristic of an unstable component or process. The military specifications for burn-in were originally written with this characteristic in mind. Such a situation is shown by the width of the confidence limits in Figure 5.2 and by the example in Figure 5.3. Even at time zero, there is a finite width, scatter or large variability at time zero. These limits document the small probability that a few of the components or systems will be far from the mean performance measure and actually close to the definition of failure. We call these “outliers” and it is these extreme units that usually fail first. Thus, the degradation model can be correlated with classical reliability measures. This extended degradation situation is less true for many mechanical parts and systems because of their typically short wear-in times. The exception is for mechanical systems that have a dual stress life relationship as shown in Figure 5.4 for S-N curves (Stress versus cycle life). We normally treat these mechanical situations differently.

The term "wear-out" is customarily observed as an indicator of the end of life, hence it has always been associated with measures of reliability. It is only during Accelerated Life Tests that we see long-life, wear-out failure modes of products.

To describe the more complex curves shown in Figure 5.2, the degradation mechanism must be characterized by an inverse power. The wear-out portion can often be included with the linear degradation shown in the middle of life. The component, system or material in question will lose strength following a simple power law that covers all but early wear-in effects. This is shown in Equation 5.4:

\[
\frac{dS}{dt} = -\frac{C}{(S)^N}
\]

(5.4)

Where S is a measure of the strength parameter, N is an unknown usually related to failure mechanisms and materials. The constant C is an unknown material constant or degradation rate measure and the negative sign indicates degradation of the strength S.

![Figure 5.2 - Complex Degradation Models](image)
Rearranging Equation 5.4 leads to:

\[ S^N \, dS = -C \, dt \]  \hspace{1cm} (5.5)

Integrating we have:

\[ \int_{S_0}^{S} (S)^N \, dS = -C \int_0^t dt \]

or

\[ S^{N+1} = S_0^{N+1} - (N+1) \, Ct \]  \hspace{1cm} (5.6)

This equation provides the basic relationship between strength and time for a variety of situations. Figure 5.5 shows three possible relationships of strength (S) degradation versus time (t). The value for N is shown as an integer in this simple model, but it can be, and is often, a non-integer. Thus, any component, assembly or system with little wear-in or that can be screened past the wear-in time may be simply approximated by a power law. Equation 5.6 is a general
degradation equation that may reduce to other simpler models through the selection of the value of N.

1) The linear degradation is the case when \( N = 0 \)
2) Exponential degradation occurs when \( N = -1 \)
3) Common linear degradation, followed by a wear-out, is modeled by \( N = 3 \)

These three possibilities look like many of the common degradations we might have already observed. Consider the following short list in Table 5.1, of common degradation events.

![Figure 5.5 – Power Law Models](image)

**Table 5.1 - Common Degradation Events**

1. **Corrosion** leading to degradation of a material.

2. The loss of a **rechargeable battery** capacity due to chemical degradation (non-reversible reactions) from recharging.

3. The loss of **strength of an adhesive** over time or under applied stress.

4. The loss of **gain of a transistor** due to time, temperature or high voltage stresses.

5. The **aging of a resistor or capacitor** (loss of resistance or capacitance) due to time, temperature or high voltage stress.

6. The loss of breakdown voltage of an electronic component due to transient electrical stresses such as over voltage or ESD.

**Example 5.1** - Consider the following situation as an example of degradation. Past history suggests that an **organic adhesive** chemical degrades slowly with time. This degradation follows a power law relationship as follows:
Where $S$ measures the adhesive bonding strength of the material under study. The adhesive is required to "bond adequately" for at least three years. The minimum acceptable bond strength for retention is set at 50% of the initial strength. With this information we can set up an accelerated test to verify that any new adhesive can meet this requirement. Filling in the information now known into Equation 5.7, we have:

$$S^3 = S_0^3 - 3Ct$$  \hspace{1cm} (5.7)

and

$$C = (0.097) S_0^3$$

Thus, the one remaining unknown can be expressed in terms of the initial strength of the adhesive. If we can measure differences as small as 5% in adhesive strength, by the use of multiple samples and statistics, how long will we have to run a test to verify the adhesive meets the 3 year requirement? Filling in Equation 5.7:

$$(0.5S_0)^3 = (S_0)^3 - 3C(3 \text{ years})$$  \hspace{1cm} (5.8)

$$0.125 (S_0)^3 = (S_0)^3 - 9C$$

$$(0.875)S_0^3 = 9C$$

and

$$C = (0.097) S_0^3$$

The expected time to a 5% average decline in the adhesive strength, without acceleration is about ½ year. This assumes the whole life of the degradation follows the formula, that is, there is no "wear-in" associated with the adhesive strength degradation. Likewise we don’t have measure of the spread of the distribution of adhesive strength. This would be obtained by actually running a number of samples through the test and the time to failure adjusted. Any wear-out is covered by this equation, but we are still on the early life part of the curve and wear-out would probably not be an issue with this test.

Now, an Accelerated Life Test is performed by raising the temperature of some of the test samples above room temperature by 23ºC, setting the new test temperatures at 45ºC and at 68ºC respectively. The results of the higher temperatures are then compared to samples running at room temperature. Every week, a small number of samples are removed for evaluation of degradation. The degradation measurements are listed in Table 5.2. Only some of the weeks are shown even though measurements were made weekly during the test. The three stress levels all show changes from the initial strength. These are presented as a percentage of the initial value. Improvements at the start of the test in strength measurement technique, combined with improved statistical analysis, now permit a change in mean adhesive strength as small as 2% to be measured. This sets the resolution measurement in Table 5.2. Will this adhesive meet the three-year minimum strength requirement?
Table 5.2 - Degradation Results of an ALT

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Time</th>
<th>1 week</th>
<th>4 weeks</th>
<th>8 weeks</th>
<th>12 weeks</th>
<th>16 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room, at 22ºC</td>
<td>0 %</td>
<td>0.1%</td>
<td>0.6%</td>
<td>1.4%</td>
<td>2.1%</td>
<td></td>
</tr>
<tr>
<td>at 45ºC</td>
<td>0.1%</td>
<td>0.5%</td>
<td>1.3%</td>
<td>1.9%</td>
<td>2.3%</td>
<td></td>
</tr>
<tr>
<td>at 68ºC</td>
<td>0.2%</td>
<td>1.2%</td>
<td>2.2%</td>
<td>3.3%</td>
<td>4.1%</td>
<td></td>
</tr>
</tbody>
</table>

Mean readings of the samples

The data suggests that the noise or variability for these samples is about 0.1 to 0.2% and the ability to identify measurements is better than expected.

Completing Equation 5.7 with the information in Table 5.2 provides the following three equations at 16 weeks:

At Room Temperature

\[ (0.979) S_0^3 = S_0^3 - 3C_0 \] (16 weeks)

At + 45ºC

\[ (0.977) S_0^3 = S_0^3 - 3C_1 \] (16 weeks)

At + 68ºC

\[ (0.959) S_0^3 = S_0^3 - 3C_2 \] (16 weeks)

Other equations can be written such as:

\[ (0.978) S_0^3 = S_0^3 - 3C_2 \] (8 weeks)

\[ (0.967) S_0^3 = S_0^3 - 3C_2 \] (12 weeks)

\[ (0.987) S_0^3 = S_0^3 - 3C_1 \] (8 weeks)

\[ (0.981) S_0^3 = S_0^3 - 3C_1 \] (12 weeks)

\[ (0.994) S_0^3 = S_0^3 - 3C_0 \] (8 weeks)

\[ (0.986) S_0^3 = S_0^3 - 3C_0 \] (12 weeks)

Solving these for the best fit values of \( C_0, C_1, C_2 \) yields:

\[ C_0 = 0.000359 S_0^3 \]
\[ C_1 = 0.000516 S_0^3 \]
\[ C_2 = 0.000896 S_0^3 \]

The Acceleration Factor, A.F., for these test conditions and times can be estimated by the ratio of the values of the degradation coefficients, C.

\[ \frac{C_1}{C_0} = \frac{0.000516}{0.000359} = 1.437 \]
\[ \frac{C_2}{C_0} = \frac{0.000896}{0.000359} = 2.496 \]

Employing the factor, \( A.F._2 \), shows that this 16-week test at three stress levels estimates that a 4.0% change at room temperature will occur over:

\[ (2.496)(15.5 \text{ weeks}) = 38.7 \text{ weeks} \]

As a minimum estimate, since the data is checked only once a week, and 0.2% variability exists it is possible the failure may occur just past the 37th week. This is a lower limit estimate on the room temperature degradation process.
Either estimate is longer than the time to 5% change as estimated before the improved resolution occurred. Any estimates from the results at +45°C lead to similar results. Table 5.3 shows the relative relationship of the three curves. Our analysis has compared a single point on three curves in order to provide the estimate of time to failure at room conditions. With more test data, this estimate can be improved.

**Degradation Mechanisms** - The probability of a component failure is often directly related to one or more of the following reasons. These are all terms for “gets worse over time”. Words such as wear, fatigue, aging, erosion or degradation are in common use.

<table>
<thead>
<tr>
<th>Table 5.3 - Degradation Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear</td>
</tr>
<tr>
<td>Fatigue</td>
</tr>
<tr>
<td>Aging</td>
</tr>
<tr>
<td>Corrosion</td>
</tr>
<tr>
<td>Degradation</td>
</tr>
<tr>
<td>Chemical reaction</td>
</tr>
<tr>
<td>Erosion</td>
</tr>
<tr>
<td>Strain</td>
</tr>
<tr>
<td>Diffusion</td>
</tr>
<tr>
<td>Accumulative fatigue</td>
</tr>
</tbody>
</table>

The fact that any of these mechanisms may be ultimately related to failure is not directly included in any of the failure life distributions. Rather, we associate or correlate a life distribution with some known failure mechanisms because of the way the mechanisms propagate. We may even associate root causes and failure modes with a time-to-failure distribution. The overall relationship between applied stress and the ultimate system failure may run through latent failure, cause, mechanism or failure mode as described in Table 5.4.

<table>
<thead>
<tr>
<th>Table 5.4 The Details of the Stress to Failure Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied External Stress → Microscopic Strain → Latent Defect → Accumulation of</td>
</tr>
<tr>
<td>Fatigue → Generation of Internal Fracture or Start of Damage → Development of Crack</td>
</tr>
<tr>
<td>Growth → Macroscopic Observation of System Changes → Observation of Degradation</td>
</tr>
<tr>
<td>→ Continuation of Observed Degradation → Ultimate System Failure</td>
</tr>
</tbody>
</table>

This simple connection begins with a stress, moves through a failure mechanism, propagates, and then results in observable parametric changes or degradations and ultimately failure. The following short version is what many people present as the stress-versus-failure connection.

Stress → Failure Mechanism → Parametric Change → System Failure

**5.2.1 Activation Model of Aging** - The following simple model, from Feinberg and Widon [21], relates the simple concept of an energy well to the degradation mechanism leading to failure. This model is based upon the probability of surmounting an energy barrier of height $\phi$. This model actually follows the Maxwell-Boltzmann statistic, a common item of statistical physics and thermodynamics.

Let the probability of escape from a square potential well be $p$, as shown in Figure 5.6. This probability is proportional to a reaction taking place, which is the analogy of a propagating failure mechanism in this case. The energy of the particle is related to $\nu$, which is classically the
vibration frequency of the particle in the potential well. We can write, from the Maxwell-Boltzmann statistic, the time-dependent probability of escape as:

\[
\frac{dp}{dt} = \nu_0 e^{-\left(\frac{\varphi_0}{kT}\right)}
\]  

(5.10)

where \( K \) is Boltzmann's constant and \( T \) is the absolute temperature, \( \varphi_0 \) is the mean energy and \( \nu_0 \) is the basic vibration frequency at nominal conditions.

Figure 5.6 – Potential Well Aging Model

The degradation can be defined as a change in any related measurable parameter, here written as \( R_0 \). The change in the parameter is \( \Delta R \). Thus, we write an equation that relates the change in a measurable performance parameter to the thermodynamic model as:

\[
a = \frac{\Delta R}{R_0} \quad \text{with} \quad \frac{da}{dt} = \nu e^{-\left(\frac{\varphi}{kT}\right)}
\]  

(5.11)

where \( \nu \) is a function of the temperature, \( T \). Expanding a Maclaurin series about \( \varphi_0 \), we can write the first two terms as:

\[
\varphi = \varphi_0 + (a)Y_{10} + \frac{1}{2} (a^2)Y_{20}
\]  

(5.12)

where by definition

\[
Y_{10} = \left. \frac{\partial \varphi}{\partial a} \right|_{a=0} \quad \text{and} \quad Y_{20} = \left. \frac{\partial^2 \varphi}{\partial a^2} \right|_{a=0}
\]  

(5.13)

Using Equation 5.11 and the definitions in 5.13, we can rearrange Equation 5.11 and with Equation 5.14 we get:

\[
\nu(T) = \nu_0 e^{-\left(\frac{\varphi_0}{kT}\right)}
\]  

(5.14)
Integrating equation 5.11 yields:

\[
a = \left[ \frac{KT}{Y_{10}} \right] \ln \left[ 1 + \frac{\nu(T)Y_{10}(t)}{KT} \right] \quad \text{(5.15)}
\]

Thus, the degradation can be expressed as a function of physical constants, time and the energy of the initial state. The function, \( a \), will be similar to that shown in Figure 5.8 as \( \frac{\Delta f'}{f} \).

**Example 5.3** - The simple aging of a crystal due to defect accumulation on the surface may be described by the following equation:

\[
f' = \frac{1}{2w} \sqrt{\frac{c}{\rho}} \quad \text{(5.16)}
\]

Where \( f \) is the basic resonant frequency, \( c \) is a bulk elastic wave constant for the material, \( \rho \) is the density of the material, \( A \) is the surface area, \( w \) is the total thickness of the crystal itself, made up of the crystal and a defect film area \( w_m \) shown on one end in Figure 5.7.

With \( w = w_0 + w_m \)

![Figure 5.7 – The Aging of a Crystal](image)

Differentiating Equation 5.16 yields:

\[
\frac{df}{dt} = \frac{1}{2w^2} \sqrt{\frac{c}{\rho}} \, dw_m \quad \text{(5.17)}
\]

It is easy to show that creating a Maclaurin series around the nominal conditions will lead to:
\[ Y_{10} = \frac{-\mu}{GKf_0} \]

where \( \mu \) is the chemical potential, \( N \) is the number of defects in the crystal, \( m \) is the foreign mass of defects and \( m = NG \), where \( G \) is the gram molecular weight of the defective film.

The degradation formula becomes:

\[ \frac{\Delta f}{f} = -\Theta \ln \left[ 1 + \frac{vf}{\Theta} \right] \]  

(5.18)

with

\[ \Theta = \frac{2KTGf}{\mu} \sqrt{\frac{1}{\rho cA^2}} \]

For a small ratio of \( \frac{\Delta f}{f} \) the crystal ages slowly at a near-constant level as shown in Figure 5.8.

As \( \frac{\Delta f}{f} \) becomes larger, the crystal is forced into a large vibration mode, leading to the rapid accumulation of damage and then quickly to a catastrophic response. The time to such a catastrophic response is labeled \( t_c \) in Figure 5.8.

This aging model can be generalized to cover a variety of similar situations that depend upon chemical reactions for degradation. This is the basis of the potential well model of reliability, sometimes called thermodynamic reliability. In fact, it is possible to relate this model to the familiar Arrhenius relationship [21].

There are a number of typical aging processes that might follow a similar equation with this type of relationship. These situations include crystal aging, corrosion of thin films, cold worked metals, gate oxide stresses in semiconductors, battery life degradation, semiconductor...
aging and rechargeable battery degradation. Note that Figure 5.8 is the complement of Figure 5.2. This is a reflection of the vertical axis showing degradation as upward versus downward.

### 5.3 Creation of a Failure Model versus Time or Stress

The aging model in Section 5.2 generated a simple model for relating a performance measure versus time at a fixed stress. The performance measure can be easily turned into a failure by drawing a line on the graph such as is shown in Figures 5.4 and 5.5. In both cases one only need declare a fail zone at some low performance measure. While this may defeat the purpose of continuous monitoring of a performance parameter, in many engineering cases all we have is a simple pass/fail measure.

With multiple levels of applied stress, the absolute value of the stress may become very important as shown in the stress-life relationship of Figure 5.9. The changing relationship of stress at the highest levels makes it important to select a consistent point on the life curve when modeling or comparing the relationship between stress and life. This is easily shown by the lines drawn at 10% cumulative failure and 60% cumulative failure.

![Figure 5.9 - Weibull Graph of Stress versus Life](image)

The life distribution at various levels of accelerated stress should be similar to the life distributions at normal stress. On the Weibull graph, this would appear as a series of straight and parallel lines as in Figure 5.9. This also leads to a single straight line when the stress-life relationship is plotted on the Log-Stress versus Log-Life graph as shown in Figure 5.10.
The slope of the Log-Stress versus Log-Life graph is proportional to the acceleration present. There are two main stress-life models when a single stress is applied. These are the Arrhenius (Equation 5.19) and the Inverse Power Law (Equation 5.20) models. Equation 5.21 shows the situation where two stresses are present, here they are temperature and operating voltage. In this combined form, we will neglect the possibility of interaction between the two stresses.

\[
\text{Life} = A e^{\frac{E_a}{K_b T_s}} \quad \text{Arrhenius} \tag{5.19}
\]

\[
\text{Life} = B(S)^{-N} \quad \text{Inverse Power Law} \tag{5.20}
\]

Combined version would be:

\[
\text{Life} = A \left[ e^{\frac{E_a}{K_b T_s}} \right] [(V)^{-N}] \tag{5.21}
\]

Example 5.4 - Mechanical Corrosion - In this example, we will estimate the accelerating influences of a corrosive solution on a material. Chemical concentration will be the accelerating factor. The performance measure will be the material changes observed when exposed in a concentrated solution for a specified period of time. The approach to the problem is to first identify the definition of a failure. This forces the determination of what is important and also identifies the means and ability for making subjective measurements. The details of the test are:

<table>
<thead>
<tr>
<th>Control Sample</th>
<th>Material Soaked in Solution at Room Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>stress level 1</td>
<td>concentration of 1 part in 150 parts water - called 1/150</td>
</tr>
<tr>
<td>stress level 2</td>
<td>concentration of 1/50</td>
</tr>
<tr>
<td>stress level 3</td>
<td>concentration of 1/20</td>
</tr>
<tr>
<td>stress level 4</td>
<td>concentration of 1/5</td>
</tr>
</tbody>
</table>
**The Definition of Failure** - The surface area of the material will be fixed and a predetermined one inch square piece of material will be inspected. The corrosion will be measured in percent of surface coverage of this one square inch area on each sample. The four different concentration levels act as different stresses to drive the corrosion on the surface. Stress concentration points such as welds, bends or cracks are deliberately avoided. Other life measures that could have been selected would include the “thickness of corrosive film” or the “time to the beginning” of the appearance of corrosion. Let the following table represent a set of hypothetical corrosion results for such a corrosion resistance test.

<table>
<thead>
<tr>
<th>Table 5.5 - Results of Corrosion Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concentration</strong></td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>1/150</td>
</tr>
<tr>
<td>1/50</td>
</tr>
<tr>
<td>1/20</td>
</tr>
<tr>
<td>1/5</td>
</tr>
</tbody>
</table>

Employing a simple power law to model for analyzing this data, we can write as the stress-life relationship:

\[
\text{Life} = B(S)^{-N} \tag{5.22}
\]

If we use the time to 5% corrosion coverage by area as a measure of failure and we estimate life as measured in accelerated days of test, the following four equations can be easily developed from the results in Table 5.5. One equation exists for each concentration. Since the samples are checked once a day, this is an **interval test**. We don’t exactly know when the failure occurred, all we know is that we inspected the samples at 24 hour intervals.

\[
9 \text{ days} = B (1/5)^{-N} \quad \quad \quad 23 \text{ days} = B (1/20)^{-N} \tag{5.23}
\]

\[
28 \text{ days} = B (1/50)^{-N} \quad \quad \quad 36 \text{ days} = B (1/150)^{-N}
\]

Solving these four equations for best fit values provides:

\[
\bar{N} = 0.334 \quad \text{and} \quad \bar{B} = 6.85 \text{ days}
\]

This represents an approximation of this simple power law model as a function of stress. The time to failure model can be developed from a model based upon the information in the rows of Table 5.5.

The simple analysis does not prove that the test follows the power law. At present, all we have shown is that it is possible to fit a model to data. We could have used more test information that was available in Table 5.5 to see if the Inverse Power Law was the best model for the data. In fact, we can see that at **high concentration** this model may not be correct. A second test might be required to make a more definite statement about the model. Figure 5.11 shows a Log-Log plot.
of the concentration data at 1/5 and 1/20 since this is the most we have. The plot is a fairly
straight line for each data set which suggests that a Power Law may be a good model.

![Graph](image)

**Figure 5.11 – Ln-Ln Plot of the Concentration Data**

A quick analysis of this graph suggests that the simple power law is not sufficient for analysis of
the data set. The value of B in Equation 5.22 seems to vary with concentration. This suggests
some non-linear effect may be present and requires additional attention. Non-linear effects will be
covered in chapter 7. Additional analysis using time to failure of 3% and 10% generated the data
in Table 5.6. This is the same as the stress-life lines shown in Figure 5.9. It adds additional
evidence to the suggestion that as the concentration changes the values of B and N change. This
suggests the Log-Log graph shown in Figure 5.10 is probably not straight.

<table>
<thead>
<tr>
<th>Time to Concentration in Percent</th>
<th>Best Fit Value of N at Time to Failure</th>
<th>Best Fit Value of B at Time to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.405</td>
<td>4.41 days</td>
</tr>
<tr>
<td>5.0</td>
<td>0.334</td>
<td>6.85 days</td>
</tr>
<tr>
<td>10.0</td>
<td>0.330</td>
<td>9.76 days</td>
</tr>
</tbody>
</table>

**Table 5.6 – Additional Data of Best Fit Power Law Models**

**Example 5.5 - Burn-in results of RAM memory** - The following data in Table 5.7 shows a
summary of time to failure data for an ALT performed at 125°C [20]. All failure times are shown
in hours for the Random Access Memory, or RAM.

Figures 5.12 and 5.13 show the Weibull analysis of this single stress data set as
performed with Weibull ++ 6.0 [12]. **Figure 5.12** is the Weibull graph of the data while **Figure
5.13** presents the probability density plot of the data. Both graphs suggest that two failure modes
may exist, but this idea should be confirmed by failure analysis. The techniques of Weibull
analysis, employed to create the graphs, were discussed in *The Weibull Analysis Primer* [14].
The early failure population and the normal population are separately identified in Figure 5.12 for
their suggested Weibull parameters. One initial suggestion is that the early failure population,
about 49%, could be screened out. This percentage is so high that another method; one for
preventing the cause of the problem, should be found. In Figure 5.13, the heavy line shows the
smoothed plot of the data. The light lines suggest the make up of the two sub-populations that may be present.

Table 5.7 - RAM Memory

<table>
<thead>
<tr>
<th>Fail #</th>
<th>Time</th>
<th>Fail #</th>
<th>Time</th>
<th>Fail #</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>215 hrs.</td>
<td>2</td>
<td>301 hrs.</td>
<td>3</td>
<td>315 hrs.</td>
</tr>
<tr>
<td>4</td>
<td>319.5 hrs.</td>
<td>5</td>
<td>328 hrs.</td>
<td>6</td>
<td>347 hrs.</td>
</tr>
<tr>
<td>7</td>
<td>425 hrs.</td>
<td>8</td>
<td>452.5 hrs.</td>
<td>9</td>
<td>491 hrs.</td>
</tr>
<tr>
<td>10</td>
<td>706 hrs.</td>
<td>11</td>
<td>739 hrs.</td>
<td>12</td>
<td>944.5 hrs.</td>
</tr>
<tr>
<td>13</td>
<td>1349 hrs.</td>
<td>14</td>
<td>1482 hrs.</td>
<td>15</td>
<td>1763 hrs.</td>
</tr>
</tbody>
</table>

One unit remained non-failed at 1800 hrs.

Figure 5.12 – The Weibull Graph of RAM ALT Data


Figure 5.12 – The Weibull Graph of RAM ALT Data
Example 5.6 - A technique to estimate shelf life through ALT - The goal in the following example is to verify a two-year shelf life for a product. The test that evaluates shelf life is destructive to the material being tested. How can this best be accomplished? Select 3 or 4 levels of stress with about 24 samples for each stress level. Fifty samples are also required for the normal (non-accelerated) stress conditions. After determining a strategy, estimating the background noise in the measurements and creating definitions for failure, the test may begin. Table 5.8 represents a hypothetical set of results for this test. The amount of degradation is shown in the table as a percentage. Therefore, an entry such as 0.96 suggests this product has degraded from the initial 100% to the level of 96%. This number represents the average of the samples destroyed to make the measurement. The accuracy of the measurement is treated as 1%. That is, 96% is most probable, but there is a small probability the number is could be as high as 97% or as low as 95%.
<table>
<thead>
<tr>
<th>Non-accelerated</th>
<th>Stress Level 1</th>
<th>Stress Level 2</th>
<th>Stress Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25C and 40%</td>
<td>40C, 40%</td>
<td>60C, 60%</td>
<td>60C, 80%</td>
</tr>
<tr>
<td>Month</td>
<td>Degr. %</td>
<td>Month</td>
<td>Degr. %</td>
</tr>
<tr>
<td>3</td>
<td>0.97</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>0.94</td>
<td>2</td>
<td>0.99</td>
</tr>
<tr>
<td>9</td>
<td>0.90</td>
<td>3</td>
<td>0.98</td>
</tr>
<tr>
<td>12</td>
<td>0.87</td>
<td>4</td>
<td>0.96</td>
</tr>
<tr>
<td>15</td>
<td>0.84</td>
<td>5</td>
<td>0.95</td>
</tr>
<tr>
<td>18</td>
<td>0.80</td>
<td>6</td>
<td>0.93</td>
</tr>
<tr>
<td>21</td>
<td>0.77</td>
<td>6</td>
<td>0.93</td>
</tr>
<tr>
<td>24</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All samples were consumed at these stress levels

A simple graph or analysis of this data may lead to an estimate of the acceleration factor associated with the different levels of stress. The failure modes may be identified through analysis to assure the same root causes and mechanisms are operating at each level of stress. As one simple measure of life, consider the **time to 10% degradation**. For the non-accelerated parts, it was about 9.0 months, for stress level 1 it was estimated at 8.6 months, for stress level 2 it was estimated at 7.6 months and for stress level 3 it was estimated at 6.0 months. (This interval data may be a little noisy because the samples were pulled every 4 weeks). The time to 10% degradation was interpolated for most of the stress levels.

The first estimation of a model for this two-stress situation, assuming no interaction, can be written as:

$$
\text{Life} = A \left[ \frac{E_a}{k_b T_k} \right](\text{Humidity})^{-N}
$$

(5.22)

With these numbers, a best fit value for the model unknowns can be made. It was evaluated as:

$$
\bar{E}_a = 0.0544 \text{ eV} \quad \text{and} \quad \bar{N} = -0.3264
$$

The simple model with these numbers filled in becomes:

$$
\text{Life} = A \left[ \frac{0.0544}{k_b T_k} \right](\text{Humidity})^{-0.3264}
$$

(5.23)

Please note that details of the analysis of this data set have been skipped here since it is similar to the three prior examples. No test for interaction between the two stresses was made in this case. An interaction example and details will be shown in Section 7.0. This data set gives us both time to failure for each stress condition and acceleration between conditions. The acceleration appears low for both temperature and humidity. Even stress level three took 6 months to get to 10% degradation. Thus it is possible with a six month test to simulate 24 months. A few comments about humidity testing are appropriate here.

5.4 - Humidity Testing Issues and Non-Linear behavior
Humidity testing can be a mystery in many reliability situations. Most environmental tests can be divided into two major categories. These are durability tests, where the accumulation of wear eventually causes a product to fail. Common examples of durability tests are corrosion, vibration, thermal cycling or mechanical abrasion situations. The second type of test is a capability test. These often occur as stress tests and sometimes may be called “overstress tests”, but this term can be misleading since overstress is a relative term. The goal of all stress tests is to determine how long a product can last under stress conditions such as operating temperature or operating voltage. When stress are above the normal customer operating conditions, the life becomes short and may be used to estimate life from a short term, high stress condition.

Humidity tests may be different as humidity can cause a change of failure mode. Humidity may bring on failure mechanisms such as electro-migration, corrosion, dendritic growth, or chemical changes to materials. These induced failure mechanisms may follow a wear process or be impacted by a second stress present. If the second stress is temperature, then failure mechanisms such as chemical reactions may be increased. When the second stress is operating voltage, then dendritic growth or corrosion may be accelerated. The combined results may follow the Eyring relationship which includes interaction between the stresses. D.S. Peck had proposed [27] that the Eyring relationship for operating bipolar plastic integrated circuit could be described by

\[
\text{Life} = A \left[ e^{K_fT_i} \right] (\text{Humidity})^{-2.7} \tag{5.24}
\]

Intel, on the other hand in their 1988 handbook has suggested this relationship might best be described as

\[
\text{Life} = A \left[ e^{\frac{F_a}{K_iT_i}} \right] e^{B(RH)} \tag{5.25}
\]

A more complex relationship such as Equation 5.26 might be required to describe the interaction of temperature and humidity at some levels of stress.

\[
\text{Life} = A \left[ e^{K_fT_i} \right] (\text{Humidity})^{-2.7} \left[ e^{\frac{B(RH)}{K_iT_i}} \right] \tag{5.26}
\]

The last term, which contains both temperature and humidity is the interaction term.

All the models in Equations 5.24 to 5.26 are really for operation and not shelf life tests. We might start with similar models, but would be surprised if the operation life model was the same as the storage life model. This is because humidity often causes a change of mechanical and electrical properties of materials which often changes their susceptibility to failure mechanisms. The modulus of elasticity of many materials changes after absorbing moisture. This includes materials as diverse as wood, many plastic and some epoxies. These often become more prone to developing cracks or soften as a result of humidity exposure. Such failure mechanisms can not be easily described by any known simple models such as shown in Equations 5.24 through 5.26.

Despite this caution, many reliability engineers still apply such simple equations for life test calculations. Such simple models really are first order approximations and are easy to use. More complex models can be derived from real data coming from a thorough test. Most of us end us using a standard set of test conditions and then compare test results as a measure of differences. Standard test conditions include 85°C and 85% relative humidity. Others use 90%
relative humidity and 70°C. Any of these test conditions are often based on some historical data rather than on test rationale or good understanding of failure mechanisms that might be present. The real questions to ask before starting a temperature and humidity test include:

1) What are the expected humidity-triggered failure mechanisms for my product?

2) Are any forms or electro-migration involved with the product?

3) Will the humidity affect any of the material properties and alter the test results?

4) What type of humidity test is most appropriate for my products? Steady-state humidity, cyclic exposure, or combined environment conditions?

5) Will any of the possible failure mechanisms be accelerated in a non-linear fashion by the humidity and temperature combination?

6) Do any of the known acceleration models apply?

7) Can I trust that my test will represent the whole life of the product?
6.0 - Selecting the Best Distribution and Performing the Data Analysis

Most reliability texts and many articles about Accelerated Life Testing begin at the point of looking at a set of data generated from a test. Completed life data is often presented as a table or a short list and the task of data analysis commences. Data analysis really begins before the review of the data. Test conditions, data collection, calibration, resolution of the measurements all impact the data. Next should be a review of the test results to assure that the data points seem to be valid. There are two main methods to do this. The first is to look over the times to failure and failure mode information for basic consistency. Next, review the data from each stress level and verify consistency across these levels. This second item may be easily done by plotting the data on the Weibull graph and looking at the fit of the lines relative to the stress levels. Be sure to verify that all of the failures appear to be related to the test stresses and not an artifact of the test fixtures or accidents. Then plot the log of mean life versus the log of stress. After these cursory reviews, the next set of tasks involves more in-depth review.

6.1 Selecting the Best Distribution

With all of the possible statistical distributions to describe the failure data, how can the best distribution be selected to describe each data set? This distribution is the life distribution. It describes in detail the time to failure at each level of stress. If the Lognormal distribution is selected to describe the lowest level of stress, it should also apply at the highest level of stress in the test. If this does not create a good fit to the data for all stress levels, then the reasons for the poor fit are important. Try another distribution such as Weibull until a best fit across all stresses is obtained. A program such as ALTA™ [22] does this automatically and models the distribution and stress-life choices both quickly and provides metrics of fit.

The second "distribution" is really the stress-life relationship [7]. This need not be a statistical distribution, but is often described by a simple equation. Two common ones are the Arrhenius relationship and the Inverse Power Law. Both types of stress-life relationships may be related to common failure mechanisms such as oxidation or material degradation and so appear to describe a number of different components and simple systems. Either choice needs to be explored carefully and related to the failure modes and mechanisms observed as well as through past history.

Sample size, the number of failures, normal variation in components, incomplete information about the time of any failures and uncertainty about stress conditions all add to the difficulty of making sense of the data. Consider the following, more detailed set of guidelines for selecting the best distribution to describe the data or describe the stress-life relationship.

1) **Employ existing knowledge to help identify the best distribution choice.** - Ask the following questions about the time to failure test data.

   A) Is there history of a similar situation to guide us? What distribution was employed in the past for any similar ALT results? Was this prior analysis adequate and appropriate? Is there history or results from other people based upon similar parts or systems?

   B) Do engineering models or equations of stress versus life help? What do we know about the underlying structures or relationships between the variables and the relationships of stress to ultimate life? Many components and materials can be described by such equations.
C) Does any information on the "Physics of Failure" help select a distribution? Can the reasons for failure be described mathematically? This often starts with a microscopic description of suspected failure causes, the failure mechanism(s) and details of how the underlying defect continues to propagate, transforming a defect or flaw into a failure.

D) Does the knowledge of the failure mode(s) help in selecting a distribution of life? Can we estimate how many different failure modes exist in any particular part or assembly? Is there detailed information about each of the failure modes?

E) Can hard component or system failures be well described? Is there non-failure data concerning degradation mechanisms that can be modeled? Is there a software program to answer the question of the best distribution for the data? The following two questions may be asked at the data analysis point:

1. How can the best fit model for the data be selected?
2. Is this model still consistent with all other relevant data?

2) Select models based upon the best fit of the known data to a statistical distribution.

A) What distribution-fitting software program will best aid the modeling? Since the test data can come in a number of different ways, the answer may depend upon the software method selected. These methods include:

1. Complete data - That is, all of the samples are run to failure. The exact times or cycles to failure are known. There are no uncertainties concerning the definition of a failure and the times of failures.

2. Suspended data - This is, some of the test samples were stopped before they were run to failure. An incomplete "time to failure" distribution may be the result, especially with small sample sizes. The reasons for suspensions should have nothing to do with the test itself. These suspensions are holes in the time to failure distribution, as they occur at any time of test. In some cases, when two failure modes are present, one is treated as a suspension to the other. We should be very careful that failure modes themselves are exclusive. That is, failing for one mode excludes the possibility of another failure mode.

3. Censored data - Here, the tests end before all of the samples have failed. This is called right-censoring and is a very common situation. The most common example is a simple time-terminated test. For example, ten samples are run to four failures.

4. Grouped data - This results when multiple failures occur or are found at the same time. This measure is within the resolution of the time measuring equipment or observations. Normally this is a very short time interval. For example, a computer may slowly rotate through a set of test samples and periodically identifies any failed samples.

5. Interval data - This occurs when a periodic check of the test samples is made. Normally, the time resolution is relatively large - checking once a day or once a week or some other time interval. Samples will most often fail in between two of the check points, so the exact times of failure will not be known. This is a further complication to
6. **Small sample size and noisy data** - This is a common difficulty. With few failures in a small sample or large scatter of the times to failure, it makes fitting to any distribution difficult. Data fitting usually has a poor goodness-of-fit and two or three distributions may fit equally well.

7. **Data with multiple failure modes** - This situation occurs with many complex parts and many systems. Several failure modes and/or competing failure modes complicate the analysis of ALT data. Failure modes may need to be separated for meaningful analysis. Three non-interacting failure modes with one having non-linear behavior may cause great difficulty during the Weibull analysis or ALT analysis. These modes need to be separated first, then any remaining non-linear behavior analyzed.

8. **Data with interacting failure modes** - When multiple stresses are present, it is a real possibility to have interacting failure modes. The best examples are when the stresses are temperature and humidity or temperature and voltage. Many failure modes of components are driven by both stresses. Non-linear behavior may result in these situations.

9. **Data with high levels of stress** - There are many failure modes that may change as the level of stress increases. The best example is with crack generation. Below certain values of stress, no cracks may be generated and/or propagated. Above a given threshold, cracks can be generated by the stresses and then propagated. As the level of stress increases, the generation rate and propagation rate of the cracks increase non-linearly to the level of sudden system failure. This last possibility skips the whole earlier crack generation and propagation process.

B) The **choices of models** for fitting the ALT data to best fit lines include:

1. **MLE** - The Maximum Likelihood Estimator is often the best choice when there are a lot of suspended or censored items. Said simply, this model weights the non-failed items as importantly as the failed items. [7, 12]

2. **Rank Regression** - This is often the best choice for samples when complete data is available (no suspensions present). In this situation, a line is fitted to the failure data only. It ignores the impact of suspensions (which are few) on the Weibull slope and includes censored data primarily through the total items exposed to test and estimates of the characteristic life. This is a common situation with many analytical programs. [7, 12]

3. **Least Squares Fit** - An alternate fit for "best line" to represent the data points is the least squares fit. It is generated by minimizing the total of the squares of the data point distances from the best fit line. This is probably the least-favored choice as it typically looks only at the failure data. It may ignore the effect of suspensions and censored items as well as the impact on the Weibull slope and characteristic life. This is often the choice by programs such as Excel™. It does not have a statistical model basis and should be considered as the least desired approach to fitting data of the three mentioned.

6.2 **The Data Analysis of Accelerated Life Test**
The impact of these prior model choices will be shown by the following several examples of data analysis of several different types of ALTs. These consider some of the selections mentioned previously.

**Example 6.1 - Interval data with censoring.**

The following is an example of real data that was collected from a group of field failures. It is interval type data with the time intervals expressed in months. That is, the uncertainty about when failures actually occurred is three months. The number of failed units is five with 1100 non-failed units still operating in the field. No units are older than 12 months.

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Number failed or censored</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 to 3 months</td>
<td>1 failure and 100 non-failed in this interval</td>
</tr>
<tr>
<td>3.01 to 6 months</td>
<td>1 failure and 300 non-failed in this interval</td>
</tr>
<tr>
<td>6.01 to 9 months</td>
<td>2 failures and 600 non-failed in this interval</td>
</tr>
<tr>
<td>9.01 to 12 months</td>
<td>1 failure and 100 non-failed in this interval</td>
</tr>
</tbody>
</table>

The data in the table says that the units in test were only checked every three months. At this point a few failures were found with the vast amount of systems still operating failure free. This interval data is a little unusual, but not unreasonable. Figure 6.1 shows the four data points plotted at the middle of the four time intervals in question. The analysis is based upon the rank regression method on the Y axis (hence it is called RRY) of calculating the best fit line for all of the data. This method uses the Y axis distance of the best fit line from the data points and minimizes that distance. The best fit line is actually a close fit to the four data points which are represented by the circles placed in the middle of the time interval. The time interval is represented by the brackets in this figure. The rank regression correlation factor, $\rho$, is 0.9903, which is ordinarily a very good fit of line to data. The Weibull slope, $\beta$, is 1.224 with an estimated characteristic life, $\eta$, of 742.3 months with this method.

Figure 6.2 is a different analysis of the same data set plotted using the Maximum Likelihood Estimator or MLE. The best-fit line selected by the program goes near the center of one of the four data points, but not all four. The line is slightly biased to the right of the four data points and has a steeper slope than the rank regression line. It almost appears that the line drawn is a “deliberate poor fit” to these four data points. This is a reasonable initial conclusion, though clearly in error. The MLE model attempts to create a best-fit for all of the data, including information derived from both the 1100 non-failed units as well as the five failures. That is why the line appears to be a poor fit to the four data points. The Weibull slope in this MLE case is 2.106 and the characteristic life is 107.4 months. This life is a factor of 6.9 times lower than the same number calculated by the rank regression method. Most contrasting examples do not represent such an extreme difference. The Likelihood measure for the MLE data fit is only $L = -35.8$ as calculated by this software package. It is a reasonable fit for the data based upon the few data points and the selection of the model.
After all, what is the measure of the best fit? Is it the model that runs the line through the four data points representing the five failures out of 1105 samples? Perhaps the model that attempts to best fit all of the data points may be the better model? Clearly, the latter is the best choice. It is difficult to believe that the best model doesn't necessarily go through all five of the data points. The MLE model choice appears to be counter-intuitive, at least until further explanation. Since the MLE models all the failures and the non-failed samples, it is not surprising that the best fit line doesn't go through the 4 data points alone. The data shown in Figure 6.2 is the same as in Figure 6.1. The main difference is the slope of the line, $\beta$. The MLE analysis concluded the slope is about 2.1 which suggests a more peaked distribution and tighter time to failure distribution than the rank regression slope of 1.2.

Look at the data and be sure to include the consideration of MLE versus rank regression as a consideration in Accelerated Life Tests. Use MLE when the number of suspensions is more than a few. When performing a multilevel test, all of the stress analyses must be done the same way to have a thorough comparison of the levels. The following example shows the importance of selecting the optimum data analysis method before detailed analysis begins.
Example 6.2 - Interval Data with Multiple Stresses.

The following data set is based upon an ALT of capacitors operated at 8V, 12V and 16 V at temperatures of 125ºC, 105ºC and 85ºC in the combinations of stresses shown in the Table 6.2. There were fifty samples per each test condition and the tests were run for 1000 hours (6 weeks) and then each test was terminated. All of the test data is right-censored and the test read times are shown. These indicate that it is interval data based upon irregular intervals. Failures were not replaced during test.

Table 6.2 - Capacitor ALT Data

<table>
<thead>
<tr>
<th>Data</th>
<th>Set A</th>
<th>Set B</th>
<th>Set C</th>
<th>Set D</th>
<th>Set E</th>
<th>Set F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read</td>
<td>125ºC</td>
<td>125ºC</td>
<td>105ºC</td>
<td>105ºC</td>
<td>85ºC</td>
<td>85ºC</td>
</tr>
<tr>
<td>Time</td>
<td>8V</td>
<td>12V</td>
<td>12V</td>
<td>16V</td>
<td>12V</td>
<td>16V</td>
</tr>
<tr>
<td>24 hrs.</td>
<td>0 fails</td>
<td>0 fails</td>
<td>0 fails</td>
<td>0 fails</td>
<td>0 fails</td>
<td>0 fails</td>
</tr>
<tr>
<td>100 &quot;</td>
<td>1 &quot;</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>150</td>
<td>6 &quot;</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>250</td>
<td>6 &quot;</td>
<td>23</td>
<td>3</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>23 &quot;</td>
<td>13</td>
<td>19</td>
<td>21</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>750</td>
<td>9 &quot;</td>
<td>5</td>
<td>15</td>
<td>10</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>1000</td>
<td>3 &quot;</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Total fails</td>
<td>48</td>
<td>49</td>
<td>44</td>
<td>47</td>
<td>10</td>
<td>27</td>
</tr>
</tbody>
</table>
The complete table of the stress versus life data provides an opportunity to analyze the data for the two stresses and even look at the possibility of interaction between the two stresses. We know within the interval when each capacitor failed, but do not know the failure modes of the capacitors. The time to failure for each of the six data sets shows similar behavior. The highest stress combination (set B) experienced the most failures while the lowest stress combination (set E) experienced the fewest failures.

![Cap Set B Failure Data](image)

**Figure 6.3 – Data Set B – MLE Method**

The analysis of the data in Table 6.2 must deal with the following questions:

1. What statistical distribution(s) do these capacitors follow for the two stresses?
2. What is the temperature acceleration based upon this data?
3. What is the voltage acceleration based upon this data?
4. Is there an interaction between the stresses in this test?

Now question one may be addressed by looking at the six sets of data. These various time-to-failure distributions were tested for a “best fit” statistical distribution. The following summary is typical of the all the six data sets. Only the MLE was used for analysis.
Figure 6.3 shows the data from Set B as plotted with the MLE method and Figure 6.4 shows the same data plotted with the Rank Regression method. The basic parameters for MLE are $\beta = 1.59$ and $\eta = 332.5$. This contrasts to the same numbers as calculated with Rank Regression on Y which are $\beta = 1.63$ and $\eta = 306.1$. Data set B has only one suspension out of 50 samples. It is difficult to determine the best fit when looking at each set of the lines on the Weibull graph. Normally, the data from Rank Regression and MLE would yield closer results as was the case with data set B. It is not certain why these two methods differ so greatly for data sets D and E. The nature of the interval data undoubtedly contributes to this difference as well as the large number of suspensions for these two sets.

The two parameter Weibull appears to be the best choice per table 6.3. A three parameter Weibull doesn’t fit well and a mixed population Weibull has no basis in information. Thus, a two parameter Weibull was selected for all data sets. Perhaps the mixed population might be a better fit, but there is no evidence for multiple failure modes, so this option was discarded. The Weibull is better than the Normal and Log-Normal distribution, based upon the fit parameters, so Weibull will be used for all additional modeling and calculations of this problem. Since all test conditions finished with units non-failed, the MLE is the preferred analysis method. Figures 6.3 and 6.4 show how different these two calculations may become. The MLE data set will be the one employed to complete the analysis of the stress versus life relationship in the later sections. Table 6.5 shows additional calculations for differences between Rank Regression and MLE.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Model</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$L$</th>
<th>Portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set B</td>
<td>Weibull – 2p</td>
<td>1.59</td>
<td>332.5</td>
<td>-82.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weibull – Mixed</td>
<td>2.27</td>
<td>225.1</td>
<td>-316</td>
<td>0.694</td>
</tr>
<tr>
<td></td>
<td>2 modes</td>
<td>1.87</td>
<td>541.8</td>
<td>-316</td>
<td>0.306</td>
</tr>
<tr>
<td></td>
<td>Log-Normal</td>
<td>Mean</td>
<td>Std Dev.</td>
<td>$L$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.50</td>
<td>0.612</td>
<td>-77.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>296.5</td>
<td>196.5</td>
<td>-91.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set D</td>
<td>Weibull – 2p</td>
<td>1.92</td>
<td>540.6</td>
</tr>
<tr>
<td></td>
<td>Weibull – Mixed</td>
<td>unable to calculate for MLE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log-Normal</td>
<td>Mean</td>
<td>Std Dev.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.02</td>
<td>0.564</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>477.0</td>
<td>255.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set F</td>
<td>Weibull – 2p</td>
<td>2.35</td>
<td>1092.0</td>
</tr>
<tr>
<td></td>
<td>Weibull – Mixed</td>
<td>unable to calculate for MLE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log-Normal</td>
<td>Mean</td>
<td>Std Dev.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.83</td>
<td>0.599</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>928.9</td>
<td>383.5</td>
</tr>
</tbody>
</table>
Figure 6.4 - Data Set B – Rank Regression Method

Table 6.4 - Analysis of Life Data from Table 6.2

<table>
<thead>
<tr>
<th>Data</th>
<th>Set A</th>
<th>Set B</th>
<th>Set C</th>
<th>Set D</th>
<th>Set E</th>
<th>Set F</th>
</tr>
</thead>
<tbody>
<tr>
<td>At MTBF</td>
<td>418.2 hours</td>
<td>298.2</td>
<td>591.0</td>
<td>479.6</td>
<td>1704.2</td>
<td>967.7</td>
</tr>
<tr>
<td>Characteristic Life - $\eta$</td>
<td>470.0 hours</td>
<td>332.5</td>
<td>667.3</td>
<td>540.6</td>
<td>1923.7</td>
<td>1092</td>
</tr>
<tr>
<td>Time to 10% failures</td>
<td>132.8 hours</td>
<td>80.7</td>
<td>234.3</td>
<td>167.4</td>
<td>723.1</td>
<td>419.1</td>
</tr>
<tr>
<td>Time to 20% failures</td>
<td>202.4 hours</td>
<td>129.4</td>
<td>332.2</td>
<td>247.5</td>
<td>1002.1</td>
<td>576.8</td>
</tr>
<tr>
<td>Value of $\beta$</td>
<td>1.78</td>
<td>1.59</td>
<td>2.15</td>
<td>1.92</td>
<td>2.30</td>
<td>2.35</td>
</tr>
</tbody>
</table>
Table 6.4 shows us that there is some variation along the time to failure axis. This is because when we let each data set be calculated independently. The lines reflect the different values of $\beta$ that resulted. This means the best fit lines for each data set are not parallel, so the point for calculating the stress versus life relationship makes a difference. In the later calculations I have used the time to 10% failures for all comparisons.

Figure 6.5 shows the situation when a best fit slope was made for all of the data. The average slope was 2.10 and one can see that the best fit lines don’t always fit the data points very well in this compromise. Thus one attempts to best fit each time to failure data set or compromises with one best fit model for all of the data. Using a single best fit model for all six data sets would miss issues such as interaction between the stresses and changes to the stress-life relationship as a function of stress. Therefore, I have elected to treat the six data sets as independent samples and not use the best fit lines depicted in Figure 6.5.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>slope $\beta$</th>
<th>10% Life</th>
<th>Characteristic Life - $\eta$</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set B</td>
<td>1.59</td>
<td>80.7</td>
<td>332.5 hours</td>
<td>MLE</td>
</tr>
<tr>
<td>49 fails</td>
<td>1.63</td>
<td>76.8</td>
<td>306.1 hours</td>
<td>Rank Regression</td>
</tr>
<tr>
<td>Set D</td>
<td>1.92</td>
<td>167.4</td>
<td>540.6 hours</td>
<td>MLE</td>
</tr>
<tr>
<td>47 fails</td>
<td>2.66</td>
<td>202.3</td>
<td>472.0 hours</td>
<td>Rank Regression</td>
</tr>
<tr>
<td>Set E</td>
<td>2.30</td>
<td>723.1</td>
<td>1923.8 hours</td>
<td>MLE</td>
</tr>
<tr>
<td>10 fails</td>
<td>1.868</td>
<td>641.4</td>
<td>2139.4 hours</td>
<td>Rank Regression</td>
</tr>
</tbody>
</table>

A quick look at the data sets D and E is enlightening. Data set D, exhibited 47 total failures in the sample of 50 at 105°C and 16 Volts while data set E showed a total of 10 failures at 85°C and 12 Volts by the same 1000 hours. These are very different results, it seems the data sets should be a smooth progression from the lowest stress combination (set E) to the highest stress combination (set B). In order of increasing stress, the sets are Set E, Set F, Set D, Set C, Set A and Set B. Table 6.2 also suggests that data sets A, B and C reached a peak fall-out during test while data sets E and F may not have. Data set E is the lowest stress combination, with set F being the second lowest stress combination and only other data set similar to E. This suggests something unusual may be happening above 85°C. Such an observation would suggest a threshold for different behavior and this question will be pursed in further analysis of section 6.3. Figure 6.5 shows all of the data plotted on a single graph and this figure can’t reflect the data set differences shown in table 6.4.
6.3 - Solutions to Accelerated Life Test of Capacitors

A check of the raw data will be performed by calculating the Activation Energy and power law unknowns based upon an Arrhenius model for temperature and a power law model for voltage. The initial measure of life will employ the time to 10% failures. This measure should be fairly consistent across the various combinations of stress employed in the test as shown in Table 6.4. The formula for life based upon temperature stress is through the Arrhenius relationship as:

$$\text{Life} = A e^{-\frac{E_a(11605)}{273.2+C}} \quad (6.1)$$

The equation set from the data in Table 6.2 can be developed as:

- $125^\circ C$, $12V$: $80.7 \text{ hours} = A e^{\frac{E_a(11605)}{398.2}}$
- $85^\circ C$, $16V$: $419.1 \text{ hours} = A e^{\frac{E_a(11605)}{358.2}}$
- $85^\circ C$, $12V$: $723.1 \text{ hours} = A e^{\frac{E_a(11605)}{358.2}}$
- $105^\circ C$, $16V$: $167.4 \text{ hours} = A e^{\frac{E_a(11605)}{378.2}}$
Dividing the two lower equations in each group into the one above eliminates A and gives:

\[ 8.9603 = e^{1.2545E_a} \]  \[ 2.50358 = e^{1.7133E_a} \]

\[ 2.1928 = 3.2545E_a \]  \[ 0.91773 = 1.7133E_a \]

\[ E_a = 0.6738 \]  \[ E_a = 0.5357 \]

The third pair of points, set B, (at 125°C, 12V) and set C, (at 105°C, 12V) yields the highest value of the activation energy as \( E_a = 0.6916 \). The combined average from these three data points and the others that can be calculated is \( \overline{E_a} = 0.634 \).

These numbers show scatter, but are considered reasonably consistent if they do not show more than about 5% scatter from maximum to minimum. We accept the results as a preliminary estimate for this analysis. Ordinarily, a more detailed analysis should be considered in order to look at the consistency of the numbers.

Using the voltage versus life information we likewise calculate for an estimate for N. The power law relationship this stress versus life is taken as:

\[ \text{Life} = B(V)^{-N} \tag{6.2} \]

The three pairs of equations can be formed by the six data sets. These are shown after dividing one by the other to eliminate the unknown, B:

\[ \frac{132.8}{80.7} = \left( \frac{8}{12} \right)^{-N} \]  \[ \frac{234.3}{167.4} = \left( \frac{12}{16} \right)^{-N} \]  \[ \frac{723.1}{419.1} = \left( \frac{12}{16} \right)^{-N} \]

\[ 1.6456 = (1.5)^N \]  \[ 1.39964 = (1.33)^N \]  \[ 1.72536 = (1.33)^N \]

\[ 0.49811 = N(0.40547) \]  \[ 0.33618 = N(0.28768) \]  \[ 0.54544 = N(0.28768) \]

\[ N = 1.2285 \]  \[ N = 1.1686 \]  \[ N = 1.8961 \]

More scatter exists in these values of N than is desirable. The average is \( \overline{N} = 1.431 \), but the scatter is close to ± 35% for this value.

The scatter in the calculations of N and \( E_a \) suggest there may be a problem with noise in the data or in the simple models selected. Such scatter may also reflect problems with the components themselves, with the test method, with the measurement method, with the definition of failure or even the test equipment itself. Each should be carefully considered and then eliminated as a source of data scatter. Standard analysis can separate the effects of temperature and voltage, but may not be able to handle the possibility of stress interactions that may also complicate this case. Since there are six data points and many different stress conditions, one can evaluate this possibility and determine if stress or stress interaction has a non-linear effect on these samples.

Summarizing the same data sets by use of the time to 10% failures and time to 20% failures presents an additional chance to review the earlier analysis. This data provides:
Likewise, we can use the characteristic for each of the data samples as a way of estimating the model unknowns. The results are:

\[ \bar{N} = 1.431 \quad \bar{E}_a = 0.634 \]

\[ \bar{N} = 1.349 \quad \bar{E}_a = 0.578 \]

With these characteristic life numbers, we calculate values of \( \bar{N} = 1.185 \) and \( \bar{E}_a = 0.467 \).

Table 6.6 shows estimates for \( N \) and \( E_a \) across these different definitions of life. There is a steady downward trend in values of \( \bar{N} \) and \( \bar{E}_a \) as the life definition gets longer.

<table>
<thead>
<tr>
<th>Method of Life Estimation</th>
<th>( \bar{N} )</th>
<th>( \bar{E}_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% time to Fail</td>
<td>1.431</td>
<td>0.634</td>
</tr>
<tr>
<td>20% Time to Fail</td>
<td>1.349</td>
<td>0.578</td>
</tr>
<tr>
<td>MTBF Fail</td>
<td>1.176</td>
<td>0.463</td>
</tr>
<tr>
<td>Characteristic Fail</td>
<td>1.185</td>
<td>0.467</td>
</tr>
</tbody>
</table>

A review of the value of \( \beta \) for the same set of conditions would provide additional information about the stress dependence of the data. There appears to be some non-linear dependence between voltage and the value of \( \beta \). Figure 6.6 shows this - at the lowest temperature, 85°C, there is a different relationship between \( \beta \) then at other combinations of temperature and voltage. The value of \( \beta \) seems to follow a simple relationship with regard to temperature only, but not with temperature and voltage. This stress versus life relationship probably does have a strong impact on the test results and the models generated.

The fact that the voltage seems to show some changes suggests that this is an area to consider when looking at potential interaction issues. There may be non-linear behavior in the model of this stress.
6.3.1 - A Non-Linear Solution showing Interaction between Stresses

The possibility of interaction between stresses is strong in the previous example of temperature and voltage. One model of interaction will be explored in detail, though many others may exist. The following short list of interaction models was considered. Those marked "does not work well" in Table 6.7 may provide unphysical answers when fitted to the data.

Based upon the use of time to 10% failure as a measure of life, the following simple equation showing interaction was fitted to the data. This is the first entry in Table 6.7.

\[
\text{Life} = A \left( e^{\frac{-E_a}{273.2+T}} \right) \left[ (V)^{-N} \right] \left( e^{\frac{B(V)E_a}{273.2+T}} \right)
\]  

(6.3)

### Table 6.7 - Table of Other Potential Interaction Models

<table>
<thead>
<tr>
<th>Interaction type</th>
<th>Life Model</th>
<th>Model Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{BV}{T})</td>
<td>(e^{\frac{BVE_a}{TK}})</td>
<td>Calculated here</td>
</tr>
<tr>
<td>(\frac{BV}{KT})</td>
<td>(1 + \frac{BV}{KT})</td>
<td>Calculated here</td>
</tr>
<tr>
<td>BV + CT</td>
<td>1 + BV + CT</td>
<td>Not calculated here</td>
</tr>
<tr>
<td>VT</td>
<td>1 + BVT</td>
<td>Not calculated here</td>
</tr>
<tr>
<td>(\frac{B}{VT})</td>
<td>(e^{\frac{BE_a}{VTK}})</td>
<td>Calculated here</td>
</tr>
</tbody>
</table>
Three sets of two equations from the six stress levels can be created and these solved for some of the parameters. These equations are A & B, C & D, E & F. They are:

A  \[ 132.8 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(8)} \left[ e^{\frac{B(8)E_a}{11605}} \right] \]

B  \[ 80.7 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(12)} \left[ e^{\frac{B(12)E_a}{11605}} \right] \]

C  \[ 234.3 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(16)} \left[ e^{\frac{B(16)E_a}{11605}} \right] \]

D  \[ 167.4 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(16)} \left[ e^{\frac{B(16)E_a}{11605}} \right] \]

E  \[ 723.1 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(12)} \left[ e^{\frac{B(12)E_a}{11605}} \right] \]

F  \[ 419.1 \text{ hours} = A \left[ e^{\frac{E_a}{11605}} \right]^{(16)} \left[ e^{\frac{B(16)E_a}{11605}} \right] \]

Dividing these two equations A & B gives:

\[ \frac{132.8}{80.7} = 1.645601 = \left( \frac{8}{12} \right)^{-N} e^{-\frac{B(8)E_a}{398.2}} e^{\frac{B(12)E_a}{398.2}} \]

Working out the math and taking the ln of both sides we have:

\[ 0.49811 = N(0.405465) - 116.5744 \left( E_a \right)(B) \]

Now doing the same with data sets C and D will give:

\[ \frac{234.3}{167.4} = 1.39964 = \left( \frac{12}{16} \right)^{-N} e^{-\frac{B(12)E_a}{378.2}} e^{\frac{B(16)E_a}{378.2}} = \left( \frac{16}{12} \right)^{N} e^{\frac{368.2179(E_a)(B)}{490.9572(E_a)(B)}} \]

\[ 1.39964 = (1.333)^N e^{-122.7392(E_a)(B)} \]

\[ 0.33622 = N(0.287657) - 122.7392(E_a)(B) \]

Now doing the same with data sets E and F will give:
\[
\frac{723.1}{419.1} = 1.725364 = \left(\frac{12}{16}\right)^{N} e^{-129.5924(E_{a})(B)}
\]

\[
1.725364 = (1.333)^{N} e^{-129.5924(E_{a})(B)}
\]

\[
0.557808 = N(0.287657) - 129.5924(E_{a})(B)
\]

It is easy to eliminate \(N\) and solve for \((E_{a})(B)\), Taking the equations from C &D and E & F gives:

\[
0.33622 = N(0.287657) - 122.7392(E_{a})(B)
\]

\[
0.557808 = N(0.287657) - 129.5924(E_{a})(B)
\]

\[
\begin{align*}
-0.221566 &= 6.8532 (E_{a})(B) \\
\text{or } (E_{a})(B) &= -0.032334
\end{align*}
\]

Doing this several times and finding an average values yields:

\[
\overline{(E_{a})(B)} = -0.012088
\]

with the following equations, one can solve for \(N\)

\[
0.49811 = N(0.405465) - 116.5744 (E_{a})(B)
\]

\[
0.49811 = N(0.405465) + 1.409151
\]

\[
-0.911041 = N(0.405465)
\]

\[
N = -2.2469
\]

After several other equations we calculate \(\overline{N} = -3.2475 = -3.25\)

Taking equations for data sets D & E gives:

\[
723.1 \text{ hours} = A \left[ e^{\frac{E_{a}(11605)}{358.2}} \right] \left[ (12)^{-N} \right] \left[ e^{\frac{B(12)E_{a}(11605)}{358.2}} \right]
\]

\[
167.4 \text{ hours} = A \left[ e^{\frac{E_{a}(11605)}{378.2}} \right] \left[ (16)^{-N} \right] \left[ e^{\frac{B(16)E_{a}(11605)}{378.2}} \right]
\]

dividing gives

\[
4.3196 = e^{1.7133E_{a}} (1.333)^{N} e^{-102.18(E_{a})(B)}
\]

\[
4.3196 = e^{1.7133E_{a}} (1.333)^{N} e^{+1.2352}
\]
1.46316 = 1.7133 \text{E}_a + N(0.287657) + 1.2352

1.46316 = 1.7133 \text{E}_a - 0.934022 + 1.2352

1.16198 = 1.7133 \text{E}_a

or \quad \text{E}_a = 0.678

Solving the set of equations for the other values leads to:

\[ \bar{N} = -3.247 \quad \bar{E}_a = 0.678 \quad \bar{B} = -0.012088 \]

Does this result solve the problem with the data? The answer is an emphatic no! All that was done was to find a model with interaction that seemed to fit the data. This is not proof that it is the right solution or the best solution. The exercise is one of model fitting only. The fact that N is negative should be a warning that something may be amiss such as stress dependent results. There is not enough data to resolve this question.

Note that the values of N and E have different from that found in section 6.3 where \( \bar{N} = 1.431 \) and \( \bar{E}_a = 0.634 \). This is because the suggested interaction including a value for "B" strongly impacts the other two unknowns. The same change would have been observed with A if this unknown had been calculated. This suggests that the small value of B is big enough to significantly change the relationship of the unknowns.

Another model of Table 6.7 was also tried using the exponential interaction model, which is the last entry of the table.

\[
\text{Life} = A \left[ e^{\frac{E_a(11605)}{273.2+C}} \right] \left[ (V)^{-N} \right] \left[ e^{\frac{BE_a(11605)}{(V)273+C}} \right]
\]

The results of this exponential model with the same data set was:

\[ \bar{N} = -2.695 \quad \bar{E}_a = 0.560 \quad \bar{B} = +2.9249 \]

A last model of Table 6.7 was also tried using the linear interaction model, which is in the middle of the table.

\[
\text{Life} = A \left[ e^{\frac{E_a(11605)}{273.2+C}} \right] \left[ (V)^{-N} \right] \left[ 1 + \frac{BV}{KT} \right]
\]

The results of this linear model with the same data set were:

\[ \bar{N} = +2.4426 \quad \bar{E}_a = 0.581 \quad \bar{B} = -0.27027 \]

This result of the linear model seems the most sensible of the three calculated and is the closest to the results of section 6.3 calculations that had no correction for interaction.
7.0 – Degradation Test Methods

This section will briefly summarize some of the knowledge presented in the prior sections and then point the direction for future ALT work. Additional examples are shown in this section. The emphasis is on degradation approaches to ALT conditions. Most often these conditions are experienced with mechanical components and systems, wear dominated situations and some electronic assemblies.

7.1 Background

An outline of the expected ALT activities was developed earlier. These represent crucial activities required to be successful. If we were to estimate the time that should be allotted for each of the preliminary activities, the following percentages might be typical for many situations and test plans.

1) Planning the ALT - About 5% of the total test time for a six week test might be placed in this area for a first-time test. This would be from about 20 to 50 man-hours total. Often less than 10 hours is spent by many engineers for planning purposes. It is easy to neglect preparation time when tests are repeated or are similar to something that may have been performed before. Ten hours is too little time, when one considers that equipment should be checked, calibration should be performed and samples collected and randomized.

2) Setting up the Life Test - The initial tests of the equipment and any calibrations required should consist of about 3% of the total time for a first-time test. This is about 30 man-hours in a 1000 hour test. This is equipment check-out, set up of the fixtures, verification of the set-up and initial readings to verify components. Be sure to measure noise and repeatability of the measures. For a repeat test this could fall to as few as five hours for well-designed, calibrated and proven equipment.

3) Administering the Test - This stage should consume about 7% of the total test time or up to 70 man hours for a first-time test with first time equipment and fixtures. It includes time for periodic electrical and mechanical checks of all the samples at several points during the test. Less than this may be consistent with a short test or one that has automated monitoring. This total time includes quick calculations, any consistency analysis and checks on the fly. If testing of samples is long this stage could easily double in length.

4) Successful Conclusion Stage of Test - This stage might consume about 3% of the total test time or up to 30 man-hours for a first-time test. This assumes that no unusual test sample behavior, equipment failure, calibration problem or sudden catastrophic sample failures. This stage includes all final tests with any special tests required to complete the ALT and document changes. Repeat ALT tests may be accomplished with less time.

5) Analyzing the Data - This stage may consume up to about 4% of the total time of the test or perhaps 40 man-hours to analyze and summarize all of the test results. One should also produce a formal report for management and for the future. Less time may be required with repeated tests or for automated data collection and analysis systems. Be sure to close the loop on any failures with some failure analysis.

Now that all of the preliminary stages have been totaled, the actual test time for the test samples might be defined as about 78% of the total test. That is the six weeks or the “Test Time” is:
Test Time = 100% - (5% + 3% + 7% + 3% + 4%) = 78%

This 78% is the minimum active test time for the test samples. Thus, a 1000 hour test could really take about 1280 hours or as high as 1425 hours to run from the start to finish for a first-time test. This is just under 9 weeks and hasn’t allowed all the needed time for failure analysis near the end. Repeated tests may lower this time to as low as 1150 hours, but most are longer than 1200 hours. These numbers are not unusual, but it is easy to find situations where some of these percentages may get larger or smaller. About 3/4 of the planning time, (3/4 of 22%) or 15%, actually went into a series of proactive activities associated with planning, setting up, calibrating and administering. The remaining percentage, or 7%, covers the remaining completion activities. The message is to be proactive for ALT tests, but then to pay close attention to the analysis. Don’t assume your tests will run as planned and be completed in a minimum time.

The engineering portion of any Accelerated Life Test might be said to be made up of studying the failure modes, the cause and effect relationship between applied stress and the resultant response of the system. Items such as time to failure, failure mechanisms and the Physics of Failure should all be studied. Accelerated Life Test results are often comprised of the projected device life, any system robustness or resistance to customer abuse and all the maintenance activities required to keep a system operating in the field. These activities all lead to more than customer satisfaction. Rather they are directly tied to corporate reputation, corporate profits and future market expansion or contraction.

Think of these five ALT steps as part of a ballet. A ballet is a planned and choreographed activity that requires preparation, timing and practice to do it consistently well. A number of different seemingly chaotic activities are brought together in a carefully timed sequence to achieve balance and harmony. A hockey game, on the other hand, is a disorganized activity. While a hockey coach plans plays and has the team practice these set plays before any game, once the game begins, things sometimes change quickly. The referee starts the game by blowing the whistle and then "drops the puck". The next thing that happens is people are skating all over the ice, with each team trying to simultaneously implement both an offensive and defensive game plans. This usually leads to neither plan working as expected, since opponents have their own plans. So the players "make it up as they go" and skating may or may not follow game plans. There have never been two hockey games that were the same because of the need to adjust the game plans on the fly. The hockey game approach to Accelerated Life Test is to be avoided. The ballet is preferred.

7.2 The Concept of Degradation

Degradation is the slow change of characteristics of a system that occur while the system operates under stress with environmental conditions. Sometimes simple un-lubricated operation is sufficient for degradation. At other times environmental factors such as humidity or salt air may drive degradation. One needs to look at degradation situations differently. Many times it is hard to make a meaningful, noise free measurement since the when the characteristic being measured is slowly changing. The application of statistics may be required to “pick the signal out of the noise”. A few examples may help enlighten these challenges faced by such an ALT.

Degradation models can reduce the size of samples needed to determine reliability because the time to failure shows a smooth and progressive change. Statistical methods aid the measure of performance degradation since it is usually smooth. This continuous situation is always better than a pass-fail (binomial) model of time to failure. A model is required for degradation and the parameters of this model may be dependent upon the stresses present. For more complete understanding it is best to tie the model to failure modes and Physics of Failure. Degradation testing is commonly used for basic semiconductors, linear integrated circuits, tensile
strength of materials, corrosion situations, resistance changes, breakdown voltage changes of many components, gain of transistors, flexural strength of materials, elongation changes (plastic behavior) of materials, creep, wear, lubrication and other failure modes.

Example 7.1 - The Accelerated Life Test of an Electro-Mechanical Assembly – This example highlights degradation through all five steps ranging from planning to set-up to the final data analysis. Now think of something that would help put you and keep you into the ballet mood. Practice is essential to ballet as it is to ALT. The results are based upon a real ALT test I ran for a component supplier.

Background - Imagine you work as a reliability engineer for a manufacturer of a small electromechanical component. A test lab with sensitive equipment and a reasonable test budget is available to you. Periodic accelerated life tests are run to qualify new products and processes. The information will usually go directly to management, marketing and perhaps to some select customers as a detailed report. The following data was collected as part of the ALT run to determine how long a product would last in the field. All conditions are accelerated unless otherwise noted.

I - Planning the Test - Select a series of typical samples of the new product to be tested. We assume that you wish to know the relationship, if any, between some of the product performance variables and the device life as a function of applied stress. Now select the most important stresses to be employed in the test and select the levels of the stress. Be sure to consider the worst case customers, the tendency for customer abuse and any other field information.

Fifty conforming samples were selected randomly from pre-production. These samples were only tested at room temperature and nominal conditions. Divide the 50 samples into three groups of unequal size. One group was selected because it is at, or near, the low end of some performance specification. Similarly, the second group was selected because it is in the middle of the performance range and the last group was selected because it is at, or near, the high side of some performance specification. Figure 7.1 shows these three selected groups. Note, we are assuming that all the samples are in specification or at the edge of specification and that samples actually cover the full range of the specification in a reasonable fashion. The statistical distribution is shown by Figure 7.1. The bulk of the quantity is near the middle of the specification with some parts marginally beyond the limits of specification. Normally, these out of conformance parts would be removed at some quality conformance step. In our case, some of the out-of-specification parts will be deliberately included in these accelerated tests for information purposes. These out of specification units might add about 10 more samples to the total in test.

The test levels will be selected as three different temperatures, 70°C, 105°C and 145°C. This stress will be combined with three different operating voltages, +12 V DC, +16 VDC and a ±12 VDC, alternating voltage condition, that changes direction every hour. A total of nine test conditions can be run with three different test chambers. A definition of failure is selected as a component change from the initial measure by more than 10%. All units will remain on test until the test ends, a catastrophic failure of the part occurs or some major event. The ±12VDC condition was selected to address a specific failure mode.
II - Setting up the Test - This stage of the test will involve getting the three chambers and test equipment ready. At this step, the measuring devices that will be used are checked and recalibrated as necessary. The test chambers are checked to be sure they actually operate as desired and none of the equipment will go out of calibration before the test ends.

Next, a small repeatability study looks at the noise from measuring and re-measuring some of the samples using five "golden units". These are also checked to verify the readings remain consistent. These "golden units" are similar devices that have a long history of stable measurements. One golden sample should be near the middle of the specification range. A second sample should measure at the upper edge of specification. A third sample should measure at the lower edge of specification. Of the remaining two golden samples, one should measure just "out of specification" on the low end and one just "out of specification" at the high end. These will be used for correlation during the periodic test stops that are used to make performance measurements. All other equipment to be employed in the ALT will be given a brief check to verify stability and sensitivity. All of the samples are labeled and then initial readings taken. A noise figure is estimated for each sample from the three independent readings taken for each.

III - Administering the Test - This step starts with dividing up the approximately 60 samples into nine groups. Six samples will be placed in each of the nine groups. The distribution of the six samples will be as follows: Three samples will be from the middle of the distribution specification range, one sample will come from the high sample range and one sample from the low sample range. In addition, one "out-of-specification" sample (if available) will be placed in with each of the nine different test conditions. Thus, these six samples at each condition cover the range of devices. Three of the five remaining good samples and one bad sample will go into the lowest temperature chamber bringing the total of to eight each at these test conditions. The remaining five golden samples will be kept in reserve as needed for correlation. These will be periodically rechecked during the ALT.

The test is planned for 1000 hours or about six weeks. Periodically, the test will be stopped and the samples removed from the test chambers and allowed to cool to room temperature and then the appropriate specifications will be measured. This measurement of all the test samples and the golden (correlation) units will occur at zero hours, at 24 hours, 96 hours, 192 hours, 384 hours, 768 hours and 1000 operating hours or at the most convenient test times close
to these proposed test points. There is nothing magic about these times for check, but they are spread apart enough to quickly identify the possibility of changing performance measures.

A check of the required measuring equipment ensures it will be available throughout the test. A backup piece of measuring equipment may also be identified, and if necessary, initial measurements could be made with this equipment as well as the original equipment. Thus, a qualified alternate piece of measuring equipment would be available.

**IV - Bring the Accelerated Life Test to a Successful Conclusion.** - At this stage, the ALT should have been running for at least 400 hours. During that time some slight changes of the good samples and the out-of-specification samples have already been observed. Table 7.1 provides the details of the results at this point in time. We will use the analysis of these results to make decisions as we move ahead.

<table>
<thead>
<tr>
<th>Sample Conditions</th>
<th>Operating Test Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24 hrs.</td>
</tr>
<tr>
<td>70°C 12 VDC</td>
<td>+0.08%</td>
</tr>
<tr>
<td>105°C 12 VDC</td>
<td>+0.14%</td>
</tr>
<tr>
<td>145°C 12 VDC</td>
<td>+0.12%</td>
</tr>
<tr>
<td>70°C 16 VDC</td>
<td>+0.07%</td>
</tr>
<tr>
<td>105°C 16 VDC</td>
<td>+0.04%</td>
</tr>
<tr>
<td>145°C 16 VDC</td>
<td>-0.01%</td>
</tr>
<tr>
<td>70°C ±12 VDC</td>
<td>0.00%</td>
</tr>
<tr>
<td>105°C ±12 VDC</td>
<td>+0.02%</td>
</tr>
<tr>
<td>145°C ±12 VDC</td>
<td>+0.05%</td>
</tr>
</tbody>
</table>

The repeatability of the good samples is well within expectations so far. The golden samples show about 20% smaller repeatability measures at this time. This sets a lower limit on the noise of the measurements. None of the samples have met the ±10% change for failure. All
samples are below 1% change so far. Table 7.1 presents the average of all the originally good test samples in each test condition.

Some conclusions can be drawn at this early point of the test. It is not too early to begin such trend analysis. These conclusions might include:

A) The higher the temperature, the sooner the initial increase begins and the larger the subsequent decrease becomes.

B) Voltage may have a slight effect. A good statistical test should be performed to look at this possibility. A simple analysis with DOE may be sufficient.

C) The samples that alternate the polarity of the voltage show smaller changes.

**V - Analyzing the Data** - At the end of the 1000 hours, the data was summarized into Table 7.2 and then analyzed.

<table>
<thead>
<tr>
<th>Sample Conditions</th>
<th>24 hrs.</th>
<th>96 hrs.</th>
<th>Operating Test Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>200 hrs.</td>
</tr>
<tr>
<td>70°C 12 VDC</td>
<td>+0.08%</td>
<td>-0.19%</td>
<td>-0.28%</td>
</tr>
<tr>
<td>105°C 12 VDC</td>
<td>+0.14%</td>
<td>-0.23%</td>
<td>-0.36%</td>
</tr>
<tr>
<td>145°C 12 VDC</td>
<td>+0.12%</td>
<td>-0.30%</td>
<td>-0.49%</td>
</tr>
<tr>
<td>70°C 16 VDC</td>
<td>+0.07%</td>
<td>-0.24%</td>
<td>-0.44%</td>
</tr>
<tr>
<td>105°C 16 VDC</td>
<td>+0.04%</td>
<td>-0.29%</td>
<td>-0.38%</td>
</tr>
<tr>
<td>145°C 16 VDC</td>
<td>-0.01%</td>
<td>-0.32%</td>
<td>-0.47%</td>
</tr>
<tr>
<td>70°C ±12 VDC</td>
<td>0.00%</td>
<td>+0.02%</td>
<td>-0.03%</td>
</tr>
<tr>
<td>105°C ±12 VDC</td>
<td>+0.02%</td>
<td>+0.06%</td>
<td>-0.05%</td>
</tr>
<tr>
<td>145°C ±12 VDC</td>
<td>+0.05%</td>
<td>+0.01%</td>
<td>-0.12%</td>
</tr>
</tbody>
</table>

# - One initially out of specification sample changed more than 10%, the average of all samples is shown
@ An initially in specification sample changed more than 10%
The following is a list of conclusions drawn from the data of Table 7.2:

A) It appears there is an **initial short term increase** in the performance measure by the 24 or 96 hour test point. This is followed by a consistent decrease in the measurement out to the end of the life test. The initial increase may reflect a "wear-in" situation of the product. All of the samples and test conditions showed the initial wear-in change. Failure analysis could not identify a physical cause for such behavior. This behavior had been seen before in other ALTs and was thought to be a characteristic of this family of components. Physics of Failure should be studied for the initial wear-in. One can conclude there are two microscopic processes occurring for these samples. The first process causes the increase, while the second process leads to a long term decrease.

B) The higher the operating temperature, the sooner the initial increase in percentage. It also appears that the initial increase may also be related to the operating voltage. Results from +12V show a bigger initial increase than +16V. The alternating voltage shows the smallest initial increase.

C) The higher the temperature and voltage, the larger the subsequent decrease in the readings as measured by percentage. There also appears to be a slight correlation between the size of the **increase at 24 hrs.** and the size of the **decrease at 750 hours.**

D) Voltage has an initial effect as well as temperature. A simple DOE analysis should be run to confirm this interaction. I leave it to the reader to conduct this analysis. The assumptions of the DOE may not all be accurate, so be a little cautious about conclusions.

E) The samples in the alternate voltage polarity show **smaller changes under all test** and stress conditions. That is, these samples have a smaller increase and a smaller decrease than the constant polarity conditions. The reversing voltage condition appears to be important. The decreased change is typically 5 to 10 times below that of the normal 12 VDC test condition. The low degradation under this special condition cannot all be explained by having survived only half the time in the forward voltage direction. The reverse voltage must have some mollifying effect on the failure mode or failure mechanism. Failure analysis did confirm there was something different going on with this alternating voltage sample, but could not pinpoint a mechanism.

F) There was **only one failure** (more than a 10% change) among the 50 initially good samples at 1000 hours. There were three failures among the 10 samples that were initially out of specification. The long term drift **seemed larger** for the units at the lower edge of specification. This suggests what ever leads to low initial readings is related to the long term drift.

### 7.3 – Models of Degradation Testing

Figure 7.2 shows a typical degradation curve for this type of data. This will be typical of all of the possible curves and so a family of curves are not shown. Degradation can be linear, exponential or logarithmic. These models are shown in Equation 7.1. Each describes the basic time dependence of a curve. We need to select the most appropriate model for the data.

\[
\Delta = A - B(t) \quad \text{Linear decrease} \quad (7.1)
\]

\[
\Delta = A e^{-Bt} \quad \text{Exponential decrease}
\]

\[
\Delta = A - B[\ln(t)] \quad \text{Log decrease}
\]

\[
\Delta = A - B(t)^N \quad \text{Non-Linear decrease}
\]
Other forms of degradation exist and the reader is referred to Nelson [7] for additional models. Fitting the data shown in Table 7.2 to one of the equations shown in Equation 7.1 would lead to possible parameters. These degradation models can also be combined with stress terms to show the impact of these terms.

Now Figure 7.2 shows a short term increase and a long term decrease. Therefore, we select a model that can cover both events. This form of the degradation will be:

$$\Delta = A + B(t) - e^{C(t)}$$  \hspace{1cm} (7.2)$$

This model yields the following for the unknowns A, B and C with this data set.

$$\overline{A} = 0.99698, \overline{B} = -0.00159 \text{ and } \overline{C} = -0.006202$$

Pick another model such as a simple linear model:

$$\Delta = A - B(t)$$

and

$$\overline{A} = -0.002334 \text{ with } \overline{B} = +0.0000139$$

This simple model is a poor fit at low time since it doesn’t address the increase. A more complex model would be needed. Use the power model below:

$$\Delta = A - B(t)^N$$

Yields

$$\overline{A} = -0.003226, \overline{B} = 4.41 \times 10^{-8} \text{ and } \overline{N} = 1.861$$

This model is also a poor fit at low time.

![Figure 7.2 – The Change in Characteristics at 145°C and 12V](image-url)
If an Eyring Model is employed to relate the change of characteristics to the applied stresses, we can express it as Equation 7.3. This is:

\[
\Delta = D(Voltage)^N e^{\frac{E_a}{RT}}
\]  

(7.3)

The best fit unknowns for this stress-life equation and the whole data set is:

\[
\overline{N} = 2.10, \quad \overline{E_a} = 0.102 \text{ eV} \quad \text{and} \quad \overline{D} = 0.000308.
\]

This model assumes no interaction between the two variables of voltage and temperature. This is not known in the case of the samples and there isn’t enough data to determine if interaction exists between the two variables.

No simple model stress versus life model can be deduced for the alternating voltage condition because only one test conditions was employed in test. The overall analysis of this degradation data can go many different directions from here. It is now left to the reader to take the analysis and support or deny any other theories or conclusions.

**Example 7.2 - The Life of Insulating Oil** - Table 7.3 contains the time to failure of an insulating fluid at various levels of high voltage stress. The original data set is from Nelson [7, pages 89 and 129] and he treats this as an example of the Power Weibull degradation model. In this model, the characteristic life is a power of the stress. This is:

\[
\eta = e^{C(V)^{-B}} = A(V)^{-B}
\]  

(7.4)

<table>
<thead>
<tr>
<th>Stress</th>
<th>Time to Insulation Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 KV</td>
<td>5.8, 1579.5, 2323.7 minutes</td>
</tr>
<tr>
<td>28 KV</td>
<td>68.9, 108.3, 110.3, 426.1, 1067.6 minutes</td>
</tr>
<tr>
<td>30 KV</td>
<td>7.7, 17.1, 20.5, 21.0, 22.7, 43.4, 47.3, 139.1, 144.1, 175.9, 194.9 minutes</td>
</tr>
<tr>
<td>32 KV</td>
<td>0.27, 0.40, 0.69, 0.79, 2.8, 3.9, 9.9, 14.0, 15.9, 27.8, 53.2, 82.9, 89.3, 100.6, 215.1</td>
</tr>
<tr>
<td>34 KV</td>
<td>0.19, 0.78, 0.96, 1.3, 2.8, 3.2, 4.2, 4.7, 4.9, 6.5, 7.4, 8.0, 8.3, 12.1, 31.8, 32.5, 33.9, 36.7, 72.9 minutes</td>
</tr>
<tr>
<td>36 KV</td>
<td>0.35, 0.59, 0.96, 0.99, 1.7, 2.0, 2.1, 2.6, 2.7, 2.9, 3.7, 4.0, 5.4, 13.8, 25.5 minutes</td>
</tr>
<tr>
<td>38 KV</td>
<td>0.09, 0.39, 0.47, 0.73, 0.74, 1.1, 1.4, 2.4 minutes</td>
</tr>
</tbody>
</table>

A review of the data suggests one point appears in question. It is the test failure time at 5.8 minutes at 26 KV. This appears **far too early** as compared to the remaining two times at 26 KV. When the data at 28 KV is also considered, this time to failure still seems too short. A statistical analysis of this point confirms this point does not appear to be part of the data set at 26 KV. The remaining data (less the 5.8 minute point) was analyzed by the MLE via Weibull. Table 7.4 is the summary of the times to failure from the raw data of Table 7.3. Based upon the results shown in Table 7.4, a three parameter Weibull analysis was selected. The goodness-to-fit is also shown in this table. The two-point version of 26 KV has a low goodness-to-fit, but the two-point version was selected for the overall analysis because the 5.8 minute time to failure is so far out of what might be expected at 26 KV.

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**Figure 7.3 – Basic Analysis of Oil Degradation**

**Table 7.4 - MLE Weibull Analysis of Insulating Fluid**

<table>
<thead>
<tr>
<th>Stress</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$\gamma$</th>
<th>$\mathcal{L}$</th>
<th>MLE Goodness-of-Fit Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 KV 3 points</td>
<td>1.74</td>
<td>1912</td>
<td>-409</td>
<td>-24.8</td>
<td></td>
</tr>
<tr>
<td>26 KV 2 points</td>
<td>13.75</td>
<td>4447.5</td>
<td>-2323.9</td>
<td>-14.7</td>
<td></td>
</tr>
<tr>
<td>28 KV</td>
<td>3.82</td>
<td>1572.2</td>
<td>-1068</td>
<td>-36.9</td>
<td></td>
</tr>
<tr>
<td>30 KV</td>
<td>4.22</td>
<td>297.9</td>
<td>-195</td>
<td>-62.3</td>
<td></td>
</tr>
<tr>
<td>32 KV</td>
<td>4.12</td>
<td>279.8</td>
<td>-215</td>
<td>-83.4</td>
<td></td>
</tr>
<tr>
<td>34 KV</td>
<td>4.43</td>
<td>95.2</td>
<td>-72.9</td>
<td>-84.1</td>
<td></td>
</tr>
<tr>
<td>36 KV</td>
<td>4.17</td>
<td>32.8</td>
<td>-25.5</td>
<td>-50.9</td>
<td></td>
</tr>
<tr>
<td>38 KV</td>
<td>1.15</td>
<td>0.88</td>
<td>+0.07</td>
<td>-6.6</td>
<td></td>
</tr>
</tbody>
</table>

Beta=0.7534, $K=2.8487\times10^{-28}$, $n=17.3040$
Table 7.4 shows that the time offset for the two-point analysis at 26 KV is consistent with the rest of the data in the table. The original data set (three-points) version at 26 KV is not consistent with the rest of the data. The data at 38 KV must also be suspect because the times are so short and the slope, $\beta$, is very different from all of the other slopes. The data at 26 KV should not be used in any analysis of stress versus life, since it also has a very different slope. Better yet, additional data points should have been obtained at 26 KV when the test was originally performed. The use of only three points at 26 KV seems to be too few for reliable results. Some additional testing is typically required with questionable results. Further analysis will be done without this one stress condition. Figures 7.3 and 7.4 shows the five stress levels ranging from 28 KV to 36 KV. These seem to be similar to each other, but one is a common slope while the other is an independent analysis of the data.

Employing the power Weibull model as shown in Equation 7.4, yields the following fit to the unknowns for this equation.

$$A = 3.04 \times 10^{24} \text{ with } B = 15.33$$
Figure 7.5 shows the same data set as Figure 7.4, except that the data is presented as a 3 parameter Weibull analysis. This model was selected as the best fit approach to the degradation data. Most of the Weibull slopes range from 0.47 to 0.87.

![Graph showing Weibull analysis of oil degradation data](image)

- Data 1: \( \beta = 0.7949, \eta = 3.7443, \gamma = 0.2670 \)
- Data 2: \( \beta = 0.7578, \eta = 12.0442, \gamma = 0.0609 \)
- Data 3: \( \beta = 0.4929, \eta = 22.7072, \gamma = 0.2555 \)
- Data 4: \( \beta = 0.8709, \eta = 65.1352, \gamma = 0.0930 \)
- Data 5: \( \beta = 0.4714, \eta = 221.0165, \gamma = 67.8925 \)

Figure 7.5 – The Three Parameter Analysis of Oil Degradation

Figure 7.6 shows a graph of the log of Stress versus the Log of Life which was employed to calculate the unknowns for Equation 7.3. This graph suggests that there may still be some non-linear behavior present with these five stress levels. As a whole, the results from these five stress levels are acceptable when the data from 26 KV and 38 KV are excluded. When the two extremes are included in the stress versus life model, it is not possible to produce a simple model for stress versus life. Otherwise, this example met the requirements outlined in this section. This data set is not atypical of such ALT results. Most of the time, additional test samples would be run to solidify the questions at highest and lowest stress conditions.
This graph shows the there is a reasonable relationship between the applied stress on the oil and the expected life. At higher stresses, this relationship may break down quickly as new failure modes may arise. At lower stress this relationship may extend for a few KV, but it is expected that it would become non-linear at some point.
References

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