♦ Reliability Growth and Forecasting for Critical Hardware Through Accelerated Life Testing

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Lucent Technologies performs accelerated life testing (ALT) for critical hardware sub-assemblies used in telecommunication systems. Critical hardware includes power amplifiers, radio units, and other sub-assemblies that have a strong impact on system reliability. ALT is used to evaluate potential product weaknesses and performance degradation over a simulated operational lifetime. These weaknesses can be remedied through design changes prior to volume manufacturing and field deployment. ALT also provides statistical information that can forecast the steady-state product reliability under the expected field conditions, and measures progress towards satisfying field reliability requirements. Results indicate that a well-executed ALT program is an effective method to achieve reliability growth and forecast steady-state reliability. This paper reviews the ALT strategy, supporting models, product case studies, and program benefits. Case studies provide examples of design changes to achieve reliability growth, and demonstrate favorable comparison between the observed steady-state field reliability and the ALT predictions.

Introduction

Lucent Technologies performs accelerated life testing (ALT) for critical electronic sub-assemblies that are integrated into telecommunication systems. The ALT program was initiated in the 1990s. This paper describes the ALT program as part of a comprehensive product assurance strategy for internally developed and outsourced electronic sub-assemblies. The paper reviews the ALT practices, supporting models based on degradation mechanisms and failure statistics, case studies for a radio unit and power amplifier, program benefits for high-reliability product design, and planned activities to enhance the ALT statistical model. The case studies represent typical ALT practices applied within Lucent Technologies.

ALT is an integral part of a comprehensive product assurance program in Lucent Technologies based on environmental stress testing (EST). EST is an industry-recognized process to systematically evaluate product design margin, precipitate latent potential design and assembly weaknesses early in the product development cycle, identify options for corrective action and risk mitigation, and screen sampled manufactured product for faults prior to ship [8, 10, 15]. The overall EST process includes early design-level

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EST and production-level EST during volume manufacturing. The design-level EST regimen augments traditional product assurance testing, such as design verification testing and compliance testing following industry standards. Failure mode analysis (FMA) and root cause analysis (RCA) are necessary follow-through activities for the EST program, in order to diagnose the underlying weaknesses and implement subsequent corrective action. This integrated product assurance program results in reliability growth and performance improvement.

Lucent Technologies implements a consistent EST procedure that is supported by controlled process documents and specifications for the required stress-testing regimens. The platform EST process is applied internally [4, 5, 18] and is deployed to strategic suppliers and electronics manufacturing services (EMSs) [13]. ALT is initiated early in the product development cycle for critical electronic hardware with new or complex design technology, relatively high cost, and strong influence on system reliability.

Panel 1. Abbreviations, Acronyms, and Terms

ALT—Accelerated life testing
ARR—Annualized return rate
EMS—Electronics manufacturing service
EST—Environmental stress testing
FMA—Failure mode analysis
FMA-RCA—Failure mode analysis-root cause analysis
MTBF—Mean-time-between-failures
NHPP—Non-homogeneous Poisson process
PA—Power amplifier
RCA—Root cause analysis
RF—Radio frequency
SM—Surface mount

Overview of ALT for Long-Term Reliability Assurance

Both ALT and EST can stimulate potential failure mechanisms to provide an indication of design robustness and product performance after field deployment. Whereas EST focuses on near-term product performance, ALT can evaluate product performance over a simulated operational lifetime. Unlike EST, ALT can be used to provide a statistically based forecast of steady-state product reliability, which can be used to measure conformance to the reliability requirements in the product specification. Steady-state refers to the time period of product operation where failures are considered random and have a corresponding near-constant failure rate. The steady-state performance interval is discussed in greater detail later in this paper when developing the ALT statistical model.

ALT can stimulate embedded failure mechanisms to provide an understanding of performance degradation over time. Similar to EST, latent weaknesses can be uncovered by ALT early in the product development cycle and remedied. Any resulting corrective action is evaluated by performing additional ALT to validate its effectiveness. By resolving performance weaknesses through successive design iterations, the product achieves reliability growth before volume deployment at customer locations.

ALT can also provide a statistically based forecast of the steady-state product reliability under the expected use conditions. This forecast follows from a statistical model that is based on a recognized acceleration model for the degradation and failure mechanisms under evaluation [1, 10, 16, 19]. The acceleration model measures the "time compression" of performance degradation under the amplified stress conditions in the life test, relative to the anticipated conditions in the field. The Arrhenius [10, 15] and MIL-HDBK-344A [19] acceleration models describe the overall functional degradation of the electronic module under test; the Norris-Landzberg acceleration model [1, 16] specifically applies to the progressive fatigue damage of surface mount solder interconnections. There is a continuing evaluation of well-documented acceleration models for use in forecasting steady-state field reliability through ALT.

Accelerated thermal cycling is a commonly applied stress profile used in ALT programs in Lucent Technologies. The accelerated stress parameters under thermal cycling are typically the unit-level high-temperature extreme, overall temperature excursion, and cycling frequency. When the acceleration model is coupled with the empirical failure statistics [2, 3, 11] under ALT, it is possible to estimate the reliability under the expected field-use conditions and operational life. The ALT forecast can be used to measure progress towards satisfying the long-term field reliability requirements in the product specification.

ALT is commonly applied at the unit level or shelf level, as opposed to stress testing a fully configured telecommunication system. ALT programs typically require dedicated environmental chambers and functional test equipment for the unit under test, ancillary hardware and software, *in situ* functional monitoring for fault detection, near-continuous event logging to track failure statistics over test time, and failure mode analysis–root cause analysis (FMA-RCA) to confirm and diagnose performance weaknesses. The sample size and test duration are critical parameters for determining the forecasted long-term reliability. Depending on the allocated sample size of 12 to 24 units and the failure mechanism under evaluation, the required duration of life tests can be 3 to 12 months. Because of the resource, cost, and time commitments associated with large-scale ALT programs, this type of specialized stress testing is limited to electronic assets with complex design technology, relatively high cost, and strong influence on system reliability.

Prior to initiating an ALT program, a test plan is developed and reviewed by a cross-functional team representing various organizations involved with product development and reliability assurance. The test plan defines the responsibilities of the team members and the critical test parameters, including the sample size, performance specifications, stress profile, and steady-state field reliability target for the product. During ALT, a test log records every confirmed failure or other significant event. Recommendations for corrective action require consensus of the cross-functional team. At various milestones during ALT, the team reviews the progress towards meeting the field reliability target. Upon completion of the ALT program, a comprehensive test report is issued that summarizes the major results, FMA-RCA activities, statistical inferences for field reliability, conclusions, and recommendations. The test report is distributed to the design and management teams, and is part of the quality records for the product development project. A successful completion of specific ALT milestones is required before the product can advance to volume manufacturing.

Life Characteristic Curve for Electronic Components and Representative Defects

The functional life of common electronic (and mechanical) components follows the life characteristic curve or so-called bathtub curve shown in **Figure 1**. Three distinct product performance regions characterize this curve. An initially high, rapidly decreasing failure rate, shown as curve 1 in Figure 1, defines the early life of the product. This initial period is known as infancy or the infant mortality region. Failures found in this region are primarily due to obvious, or patent defects, as well as latent defects, which are present but not easily detected [19]. Patent defects are usually preventable and include incorrect component, wrong polarity placement, loose or missing part, missing wire, and broken latch. During volume manufacturing, patent defects are typically removed with in-circuit or functional testing. Latent defects are inherent to the product and are more difficult to detect. Left undetected, they can result in a failure that occurs after some period of normal operation. Latent defects include electro-static discharge damage, marginal solder interconnections, insulation damage, contamination in semiconductors, ionic migration, and dendrite growth in radio frequency power transistors.

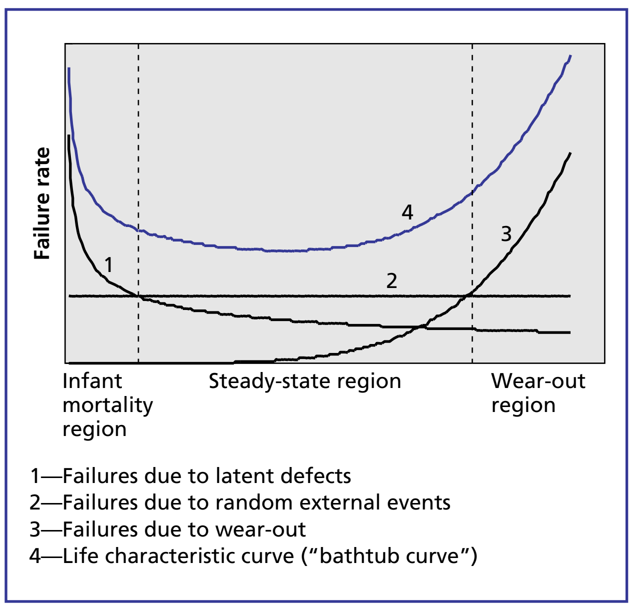


Figure 1.
Life characteristic curve depicts the failure rate over the lifetime of the unit.

Beyond the infant mortality region, the product exhibits a constant or near-constant failure rate. This period is known as the steady-state region. Failures in this region are dominated by random external events that occur at a constant rate as depicted by curve 2 in Figure 1. Examples of external events include voltage or current spikes, thermal shock, and may also include damage caused by human interaction. The steady-state region also includes residual latent defects, as well as the leading edge of wear-out related failures, which continue into the next region.

As wear-out related failures begin to dominate, the life curve enters the final region. The wear-out region is characterized by an increasing failure rate, represented by curve 3 in Figure 1. The increasing failure rate is caused by factors such as solder fatigue, dielectric breakdown, and electromigration. At this point, the product is considered to have reached its end of life, since the increase in repair actions makes it uneconomical to continue to service and operate it. The combined curve, shown as curve 4 in Figure 1, is the life characteristic curve, which is often referred to as the bathtub curve.

For ALT, failures are defined as any out-of-specification condition that adversely affects the unit when it is normally operated. ALT can effectively precipitate failures that occur during infancy, as well as any latent or wear-out related failures that occur during the steady-state region. The majority of failures in ALT typically occur well within a test interval that simulates 10,000 field hours. These relatively early performance weaknesses commonly exhibit a decreasing failure rate, indicative of infant mortality failures, rather than progressive wear-out.

In addition, since ALT employs *in situ* functional monitoring for fault coverage, it is able to detect soft failures. Soft failures are those failures that occur under specific stress conditions, such as high temperature, and recover when the stress is reduced or removed. These failures are often difficult to detect during normal verification tests and may lead to no-trouble-found field returns. Identifying the causes of these failures, and initiating design changes to prevent their occurrence, result in reliability growth of the product.

ALT Statistical Model for Field Reliability Forecasting

This section reviews the principal components of the ALT statistical model that is used to forecast steady-state field reliability. The statistical components include the supporting hazard rate model, methods to estimate the model parameters from empirical failure statistics, and confidence limits for the model parameters. The acceleration factor is a thermo-physical component of the ALT model that measures the time compression for performance degradation during thermal exposure. The model parameters and automated calculations are detailed in a table of input-output information and a process flowchart.

Hazard Rate Model for Repairable Systems

The life stages of a product can be modeled with the use of various statistical reliability distributions, such as the Poisson, lognormal, exponential, gamma, and Weibull distributions. Crow [3] proposed the use of a non-homogeneous Poisson process (NHPP) with Weibull intensity function to model the reliability of repairable systems. The NHPP allows the system failure intensity (hazard rate) to change as operating time increases. The hazard rate $h(t)$ as a function of time t for a repairable system is given by

$$h(t) = \lambda \beta t^{\beta - 1}, \quad t > 0 \qquad (1)$$

where β and λ are model parameters. The parameter β determines the slope of the hazard rate function when equation (1) is linearized using logarithmic scales. Using equation (1) and other supporting statistical tools, the ALT model can forecast the steady-state hazard rate at the end of the infant mortality region shown in Figure 1.

When the slope parameter $\beta < 1$, the hazard rate is decreasing, an indication that the product is in the infancy region of the life characteristic curve shown in Figure 1. The slope parameters observed in ALT programs are typically in the range of 0.3 to 0.8. For the condition $\beta = 1$, the product is in the steady-state region, where the exponential reliability distribution applies. When $\beta > 1$, the hazard rate is increasing, an indication that the product is in the wear-out region. Although the mathematical form of the hazard rate in equation (1) is similar to the hazard rate for a standard two-parameter Weibull distribution, it is cautioned that this form is not a Weibull distribution. The Weibull distribution terminology, interpretation of hazard rate estimation, and other statistical procedures do not apply.

Using equation (1), the expected value function $E(t)$ generally defines the expected number of failures $N(t)$ in a system as

$$E[N(t)] = \int_0^t \lambda \beta t^{\beta-1}\, dt \tag{2a}$$

or

$$E[N(t)] = \lambda t^{\beta} \tag{2b}$$

In a life test running k units for a total of T hours, the expected number of failures N will be

$$N = k\lambda T^{\beta} \tag{3}$$

Variations of equation (3) are useful in planning large-scale life tests, in terms of forecasting the expected number of failures over a specified time interval or the total test time required to precipitate a specified number of failures.

Estimating the Test Parameters β and λ

In product assurance testing, high reliability, test costs, and development schedules make it impractical to run a test sample to the end of the actual product life. The concept known as censoring can be used to determine how the life test is terminated. Censoring falls into the categories of Type I, Type II, and the general form of multi-censored data. In Type I censoring, the product is tested for a specified period of time. This type of life test is also known as a time-terminated test. All failure times are recorded during the test. Failed units are repaired and returned to the test in the shortest time period. The repair time is considered negligible compared to the overall test duration, and is not included in the unit-level test time. The number of failures is a random variable. In Type II censoring, a fixed number of failures is specified at the beginning of the life test. This test is also known as a failure-terminated test. During the test, the failures are counted until the specified number of failures is reached. In this case, the test time is a random variable. This paper concentrates on the time-terminated life test, since many ALT programs in Lucent Technologies follow this methodology.

Using the maximum likelihood estimate for a time-terminated test (Type I censoring), the model parameters λ and β for k systems can be estimated using the Crow [3] formulation. The parameter estimates $\hat{\lambda}$ and $\hat{\beta}$ are respectively given by

$$\hat{\lambda} = \frac{\sum_{q=1}^{k} N_q}{k(A_F T)^{\hat{\beta}}} \tag{4}$$

and

$$\hat{\beta} = \frac{\sum_{q=1}^{k} N_q}{\sum_{q=1}^{k} \sum_{i=1}^{N_q} \ln\left(\frac{T}{X_{iq}}\right)} \tag{5}$$

where N_q is the number of failures experienced by system q, T is the test truncation time, A_F is the acceleration factor for test-to-field time compression, k is the number of systems under test, q is the q-th system, and X_{iq} is the i-th failure time of the q-th system ($i = 1, 2, \ldots, N_q$ and $q = 1, 2, \ldots, k$).

Reliability Target for Electronic Components

The mean-time-between-failures (MTBF) is a common metric used to measure the steady-state reliability of a repairable unit. The MTBF is a measure of the mean lifetime of the unit, and is usually expressed in hours or years. As reliability increases, the MTBF increases proportionally. The definition of MTBF is the mean or average time between failure events. This interval includes the working or "up time" as well as the repair time.

In this paper, the MTBF notation is used since the product is considered a repairable unit. During ALT, it is not uncommon for units to have multiple, consecutive failures. However, when counting test time and generating statistics from the ALT data, the repair time is not counted. Typically, the repair interval is short compared to the MTBF, and neglecting this has little impact on the MTBF forecast.

With this assumption, the inverse of the MTBF is the hazard rate. Since the MTBF applies to the steady-state region where β is approximately unity, the hazard rate is assumed constant and equal to the steady-state failure rate. These assumptions are used throughout the remainder of this paper.

Studies on the behavior of electronic components in telecommunication products [11] have empirically demonstrated that the infancy period for these devices lasts for nominally one year (approximately 10,000 hours). A point in the life characteristic curve at 10,000 hours of operation has been selected to define the end of the product infancy region in Figure 1. After the initial 10,000 hours, the exponential reliability distribution can be used to model the failure rate during the extended useful life of the product. The ALT failure statistics are used for determining the infancy characteristics of the product for warranty cost purposes, as well as to define the transition period of the product into the steady-state region.

In the case where the parameters β and λ for a repairable electronic system are known, the MTBF statistic can be calculated by [11]

$$\text{MTBF} = \frac{1}{h(t = 10{,}000)} = \frac{1}{\lambda\beta \; 10{,}000^{\beta - 1}} \tag{6}$$

Statistical Confidence Limits for Model Parameters λ and β

In ALT, it is important to know the upper confidence limit for the test parameter λ at a predetermined statistical confidence level. The upper confidence limit of λ is used to determine the minimum MTBF for the product at that specified confidence level. Combining equation (4) and a Chi-square formulation [17] for a time-terminated test, the $(1-\alpha) \times 100$ percent upper confidence limit on λ, λ_{UCL}, can be calculated as

$$\lambda_{\text{UCL}} = \frac{\chi^2(\alpha, 2N + 2)}{2k(A_F T)^{\beta}} \tag{7}$$

where α is the level of significance. For example, for a 90% upper confidence limit, the corresponding level of significance is $\alpha = 0.1$.

Using equation (6), the corresponding lower confidence limit for the MTBF statistic, $(\text{MTBF})_{\text{LCL}}$, is given by

$$(\text{MTBF})_{\text{LCL}} = \frac{1}{\lambda_{\text{UCL}}\, \beta 10{,}000^{\beta - 1}} \tag{8}$$

The upper and lower two-sided confidence limits for the model parameter β, β_{UCL} and β_{LCL}, using the Chi-square distribution, are, respectively, determined from [2]

$$\beta_{\text{UCL}} = \frac{\chi^2\left(1 - \frac{\alpha}{2}, 2N\right)}{2N} \hat{\beta} \tag{9}$$

and

$$\beta_{\text{LCL}} = \frac{\chi^2\left(\frac{\alpha}{2}, 2N\right)}{2N} \hat{\beta} \tag{10}$$

The upper and lower two-sided confidence limits for the slope parameter β are calculated in order to obtain a better estimate of where the true β for the test lies. The parameter β is used to estimate the infancy characteristics and to determine the MTBF of the product at the onset of steady-state failure rate at 10,000 hours.

Acceleration Models for Functional Degradation During Stress Testing

The ALT strategy is based on significantly reducing the test time required to demonstrate the high-reliability requirements for modern electronic products. One method to achieve this "time compression" is to physically accelerate the functional degradation and related failure mechanisms for the product. It is important to control the level of applied acceleration, so as not to introduce extraneous failure modes that would not be present during normal operation. There are several stress stimuli that accelerate embedded failure mechanisms, such as vibration, voltage margining, humidity, and elevated temperature. This paper concentrates on test acceleration through moderate thermal cycling, below the threshold for unit-level thermal shock. This section reviews three industry recognized acceleration models for thermal stress conditions: the Arrhenius model [8, 10], Norris-Landzberg model [1, 16], and MIL-HDBK-344A model [19].

The Arrhenius acceleration model [8, 10] is based on the fact that the failure of electronic components is driven by certain thermo-physical and chemical processes, such as ion drift and intermetallic compound formation. The Arrhenius acceleration factor A_F relative to two applied temperature conditions is given by

$$A_F = e^{\frac{E_A}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \tag{11}$$

where E_A is the activation energy in electron volts, k is Boltzmann's constant, and T is the absolute temperature in °K. The temperatures T_1 and T_2 can be interpreted as the field-use temperature and accelerated-test temperature, respectively.

The Arrhenius acceleration factor has been found to be useful in cases where the product operates under constant or near-constant temperature in its field-use and test environments. Kececioglu and Sun [10] have proposed a modification to the Arrhenius acceleration factor for thermal cycling test conditions. The acceleration factor given by equation (11) is scaled by the ratio of the high-temperature dwell time to the overall cycle time, resulting in a reduced acceleration.

The Norris-Landzberg acceleration model [1, 16] specifically applies to surface mount solder interconnections that progressively degrade due to cumulative fatigue damage during operational thermal cycling. This empirical model is a version of the Coffin-Manson fatigue life model specialized for common solder alloys. The Norris-Landzberg model accounts for the temperature excursion, high-temperature extreme, and time-dependent thermomechanical behavior of lead-bearing solder alloys related to stress relaxation. The model accounts for the empirical observation that extended dwell time in low-frequency thermal cycling accelerates fatigue damage and induces earlier failure of high-risk solder connections [6, 14].

The standard formulation for the Norris-Landzberg acceleration factor A_F from [1] is

$$A_F = \left[\frac{(\Delta T)_t}{(\Delta T)_u}\right]^{1.9} \left(\frac{f_u}{f_t}\right)^{\frac{1}{3}} e^{b\left[\frac{1}{(T_{\max})_u} - \frac{1}{(T_{\max})_t}\right]} \tag{12}$$

where the subscripts "t" and "u," respectively, denote the test and use conditions, ΔT is the unit-level temperature excursion in °K or °C, $T_{\max}$ is the unit-level absolute high-temperature extreme in the thermal cycle in °K, f is the thermal cycling frequency in cycles per day, and b is a composite constant that ranges from 1200 °K to 1414 °K.

The MIL-HDBK-344A acceleration model [19] accounts for the composite degradation and failure mechanisms during thermal cycling. The empirical model is based on a stress constant K_{TC} that measures the exponential rate of failure precipitation under the accelerated-test and field-use conditions. The composite acceleration factor A_F is the ratio of the stress constants for use conditions and test conditions.

The stress constant K_{TC} is given by [19]

$$K_{TC} = (1.73 \times 10^{-3})(\Delta T + 0.6)^{0.6}[\ln(R + 2.718)]^3 \tag{13}$$

where ΔT is the unit-level temperature excursion in °C and R is the unit-level temperature transition rate in thermal cycling in °C per minute. The composite acceleration factor A_F is then expressed as

$$A_F = \frac{(K_{TC})_u}{(K_{TC})_t} \tag{14}$$

where the stress factors $(K_{TC})_u$ and $(K_{TC})_t$ are, respectively, determined by the thermal environment under use and test conditions.

Preliminary comparisons of the steady-state failure rate for deployed products and results forecasted through ALT suggest that the MIL-HDBK-344A acceleration model better accounts for the composite failure modes typically observed in life testing and field returns, and more accurately measures the overall acceleration imposed in thermal-cycling life testing. This acceleration model is applied in an ALT case study in this paper, with good correlation to the observed long-term reliability for the fielded product.

Rapid Calculator for ALT Statistics and Steady-State Field Reliability

The ALT statistical model is based in part on the NHPP with Weibull intensity function and an acceleration factor relevant to the failures observed during stress testing. The statistical model provides a practical method to forecast the steady-state reliability of selected critical electronic sub-assemblies. The statistical model is currently used to support internal ALT programs and supply-chain product assurance initiatives [13].

Table I. Input and output parameters for ALT statistical model to forecast steady-state field reliability.

Input test and statistical parameters	
Activation energy (eV)	Field-condition high-temperature extreme in thermal cycle (°C)
Test-condition high-temperature extreme in thermal cycle (°C)	Field-condition low-temperature extreme in thermal cycle (°C)
Test-condition low-temperature extreme in thermal cycle (°C)	Field-condition temperature transition rate in thermal cycle (°C/min)
Test-condition high-temperature dwell time in thermal cycle (min)	Field-condition thermal cycling frequency (cy/day)
Test-condition temperature transition rate in thermal cycle (°C/min)	Sample size under test
Duration of test-condition thermal cycle (min)	Test duration (hr)
Test-condition thermal cycling frequency (cy/day)	Distributed failure times during test (hr)
	Statistical confidence limit (%)
Output parameters and reliability statistics	
Acceleration factor for Arrhenius model	Nominal parameter β for distribution of test failures, applied to field failure distribution
Simulated cumulative field hours for Arrhenius acceleration factor	Nominal parameter λ for distribution of test failures, applied to field failure distribution
Acceleration factor for Norris-Landzberg model	Lower and upper statistical confidence limits for field parameter β
Simulated cumulative field hours for Norris-Landzberg acceleration factor	Lower and upper statistical confidence limits for field parameter λ
Acceleration factor for MIL-HDBK-344A model	Lower and upper statistical confidence limits for forecasted field MTBF and corresponding steady-state failure rate
Simulated cumulative field hours for MIL-HDBK-344A acceleration factor	One-sided confidence limit for forecasted field MTBF and corresponding steady-state failure rate

ALT—Accelerated life testing
MTBF—Mean-time-between-failures

A spreadsheet was developed to facilitate the statistical calculations related to ALT. **Table I** shows the input and output parameters of the spreadsheet. Once the life test parameters are specified, the spreadsheet calculates the relevant acceleration factor, empirical statistics, and predicted MTBF and corresponding annual failure rate at the specified confidence level. The flowchart in **Figure 2** details the sequence of calculations and the specific applied equations. The automated calculation process allows for real-time consideration of "what if" scenarios that support effective planning for test duration and resources.

ALT Case Study—Forecasting the Field Performance of a Radio Unit

An example of an ALT program for a radio unit is discussed in this section, which shows how the results of the ALT program are used to predict the field performance of the radio. Radios represent a critical hardware asset that is integrated into wireless telecommunication systems. High reliability is required since a radio failure can result in reduced system coverage. In addition to identifying weaknesses in design and manufacturing, this case study shows how ALT can be used to predict the field reliability.

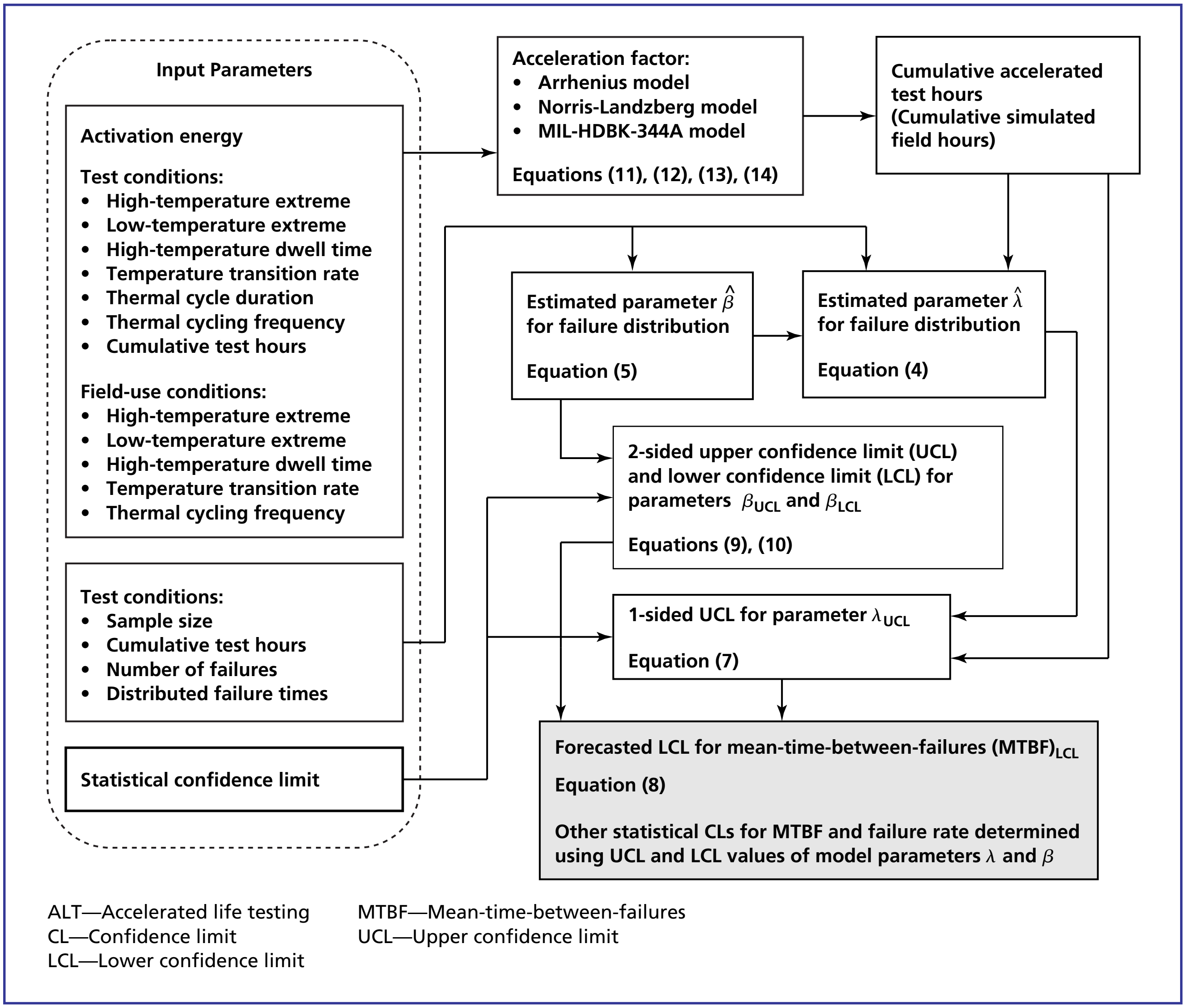


Figure 2.
Flowchart detailing the sequence of calculations for ALT model.

Radios for wireless base station systems have by necessity a high level of design complexity. Radios have both digital and radio frequency (RF) sections with a significant number of components. The radio discussed here primarily uses surface mount components, including several area-array devices, resulting in a high density of surface mount solder interconnections. This is a significant concern, since the radio can be used in an outdoor application, where it is subjected to both steady-state temperature extremes as well as daily temperature cycling.

During ALT, the radios accumulated a total test time in excess of 90,000 non-accelerated unit-hours. An aggressive test profile was used that applied thermal cycling between −5 °C and + 65 °C (70 °C temperature excursion) and a frequency of approximately 10 cycles per day. By comparison, the expected field-use conditions are 1 cycle per day and a unit-level temperature excursion of nominally 13 °C.

Four radio failures were confirmed during the ALT program. The failed components were removed and sent to the component suppliers for FMA, which identified various latent failure modes. Steps were taken by the component suppliers to address the FMA findings through improvements in the manufacturing process.

Based on the observed failure modes, the acceleration model from MIL-HDBK-344A [19] was used, due to the fact that the number of failures found during ALT was relatively small and represented mixed failure mechanisms. Using the ALT parameters, an overall acceleration factor of 145 was calculated. The calculated acceleration factor implies that 1 hour of ALT simulates the cumulative performance degradation under 145 hours (nominally 6 days) of expected field-use conditions. Using this acceleration factor, the composite accelerated test time exceeds 13 million unit-hours.

A common metric used to measure field performance is the annualized return rate (ARR). The ARR is calculated by dividing the number of field returns n_t observed over the last 12 months by the average in-service quantity $\overline{N}$ during the same time interval. The ARR can be expressed as

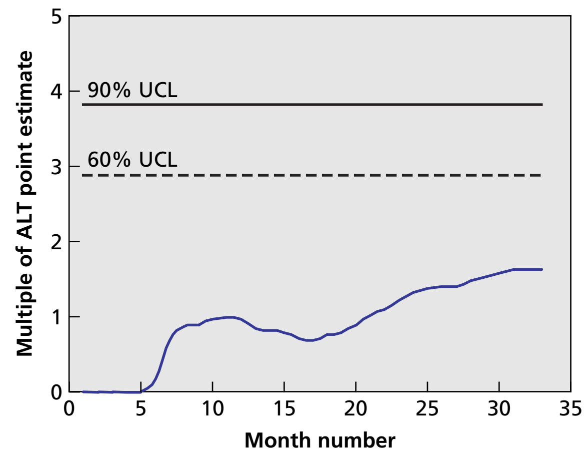
$$\mathrm{ARR} = \frac{\sum_{t-12}^{t} n_t}{\overline{N}} \qquad (15)$$

When there are fewer than 12 months of returns, a factor 12/m is included to estimate the number of returns in a full year, where m represents the number of months with return data. Generally, a minimum of 12 to 24 months is necessary to establish the steady-state ARR.

For the results that follow, the reliability data have been normalized using the point estimate of the steady-state failure rate. The point estimate is derived from equation (1) with time $t = 10{,}000$ hours and the model parameters $\hat{\lambda}$ and $\hat{\beta}$, as determined by the failure statistics through equations (4) and (5). In other words, when the normalized ARR = 1, it exactly matches the ALT forecast based on the nominal model parameters.

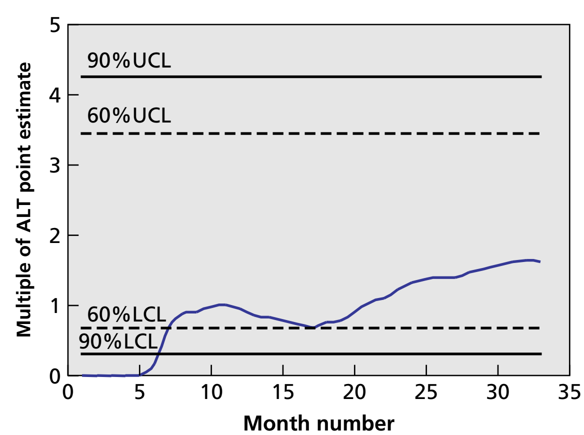
Figure 3 shows the normalized ARR for the radio along with the ALT-forecasted normalized one-sided upper 60% and 90% confidence limits. From month 10 through month 20, the observed ARR closely tracks the normalized prediction. Beyond 20 months the observed ARR increases, but remains well within the predicted statistical confidence limits.

A comparison between the ARR and the normalized two-sided confidence limits is shown in **Figure 4**. In this situation, the uncertainty associated with the upper confidence limit is decreased (resulting in an increased upper confidence limit) and a lower confidence limit has been added. Figure 4 shows that beyond the first few months of field returns, the ARR consistently tracks between the upper and lower limits. Uncertainties associated with the customer's installation date for new products and delays in tracking field



ALT—Accelerated life testing
UCL—Upper confidence limit

Figure 3.
Annualized field return rate and ALT-forecasted one-sided 60% and 90% confidence limits.



ALT—Accelerated life testing
ARR—Annualized return rate
LCL—Lower confidence limit
UCL—Upper confidence limit

Figure 4.
Comparison of ARR and normalized two-sided confidence limits.

returns can induce ARR fluctuations during early deployment. Over time, the ARR will typically stabilize, as it appears to be doing by month 30. However, this example highlights other issues that deserve further discussion.

First, the ARR is based on all failures, not only the failures from the steady-state region shown in Figure 1. Failures during the infant mortality period are not excluded, which tends to inflate the overall return rate. Over time, experience has shown that the ARR will decline as more fielded product enters the steady-state region. In addition, any failures caused by external events or user interaction would not be duplicated during ALT. It has been determined that part of the increase in the ARR that occurs after month 20 was due to factors that were not present during ALT. Therefore, while it is expected that the ALT-forecasted failure rate will be a good predictor of the unit's intrinsic failure rate, additional factors may be present which cause the ARR to be marginally higher.

Also, as with any statistical extrapolation, it is expected that there is an inherent level of uncertainty associated with the ALT prediction. Typically, the uncertainty is associated with a single parameter. In the NHPP, there is uncertainty associated with both model parameters β and λ. When calculating a given confidence level, a higher confidence level must be used for each statistical parameter. When the confidence levels associated with both parameters are the same, they are equal to the square root of the composite confidence limit. For example, when calculating the composite 60% confidence limit, both parameters β and λ must be calculated at 78% confidence limits [2]. This compounds the variation that would be associated with a single-parameter statistical model.

This case study shows how the ALT results can be used to predict steady-state field performance. The results demonstrate favorable comparison between the observed field reliability and the ALT-generated prediction.

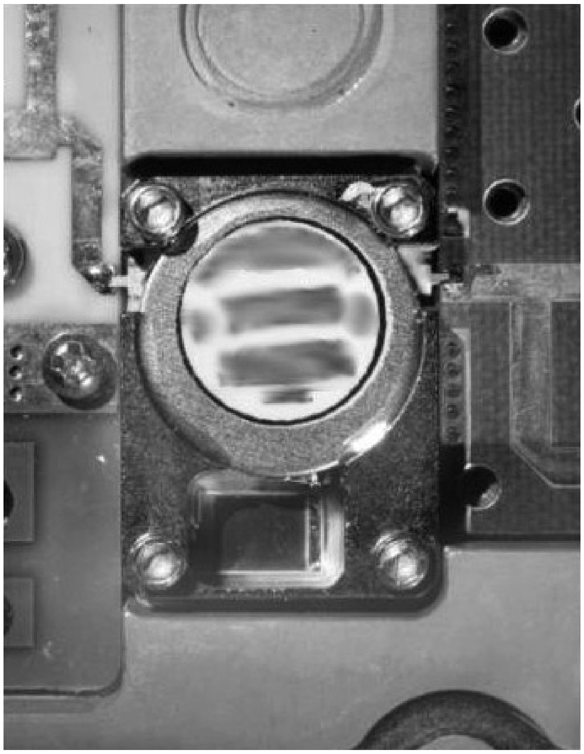
ALT Case Study—Reliability Improvements to RF Power Amplifiers

RF power amplifier (PA) modules represent another important electronic sub-assembly in a wireless telecommunication system. Product specifications require that ALT be performed on PAs, as part of a comprehensive product assurance program that includes design-level and product-level EST [13]. This section covers an ALT case study that demonstrates the effectiveness of ALT in early detection of latent weaknesses, corrective-action response to test results, and subsequent improvements to assembly robustness and reliability.

ALT programs for PAs typically apply accelerated thermal cycling under uniform nominal power and airflow conditions, as covered in the product specifications. Representative test conditions are an ambient temperature cycle of nominally 0 °C to 50 °C at a frequency of 6 to 12 cycles per day. A relatively large sample of 12 to 24 pre-production units is allocated for ALT. By comparison, 3 to 5 pre-production units are typically allocated for other design-level EST procedures that impose more aggressive thermal stress testing. The duration of the ALT program is on the order of 6 months, depending on the product sample size, accelerated stress profile relative to the anticipated field-use conditions, target field reliability indicated by the specified MTBF or corresponding annual percent failure rate, and empirical failure statistics. The cumulative failure statistics at interim test milestones are used to forecast the long-term field reliability and support informed decisions on PA volume deployment before the ALT program is fully completed.

The ALT programs for PAs uncover weaknesses in solder interconnection, thermal management, component quality, mechanical assembly, temperature compensation, and functional testing procedures. Surface mount (SM) solder interconnection risk conditions are evaluated for RF components such as isolators and power transistors in ceramic-like packaging. The potential SM attachment risk in these leaded devices results from the relatively high global component-to-substrate thermal expansion mismatch, local thermal expansion mismatch at the lead-to-solder interfaces, insufficient strain-relief provided by the mounting leads, degraded solder metallurgy due to intermetallic content, and marginal assembly workmanship [7, 14].

Figure 5 shows a typical RF isolator component assembled in a PA module. The component is usually



RF—Radio frequency

Figure 5.
RF isolator component assembled to a circuit-board in a power amplifier module.

placed in a cavity within the underlying aluminum heat-sink and interconnected to the surrounding circuit-board through two flat mounting leads on opposite sides of the package. The leads are soldered to RF traces on the circuit-board. The mounting leads are frequently cut relatively short by the component suppliers for improved RF performance, which reduces the opportunity for a robust solder-wetted length along the mounting leads. The mounting leads may not be sufficiently coplanar with respect to the traces on the circuit-board, and provide inadequate strain relief [12] to accommodate the relative movement between the component and circuit-board over operational temperature excursions. The non-coplanar leads typically need to be depressed towards the trace in order to form the soldered interconnection. The resulting low-volume SM solder connections are under combined tensile and cyclic shear loads, respectively induced by the initial lead displacement and global component-to-substrate thermal expansion mismatch.

Figure 6 shows the SM solder interconnection failures on the isolator component that were precipitated during the ALT program. The subsequent FMA-RCA identified several concurrent design and assembly weaknesses that increased attachment risk. These risk conditions included insufficient lead length, inadequate strain-relief, poor lead coplanarity, and marginal solder joint volume.

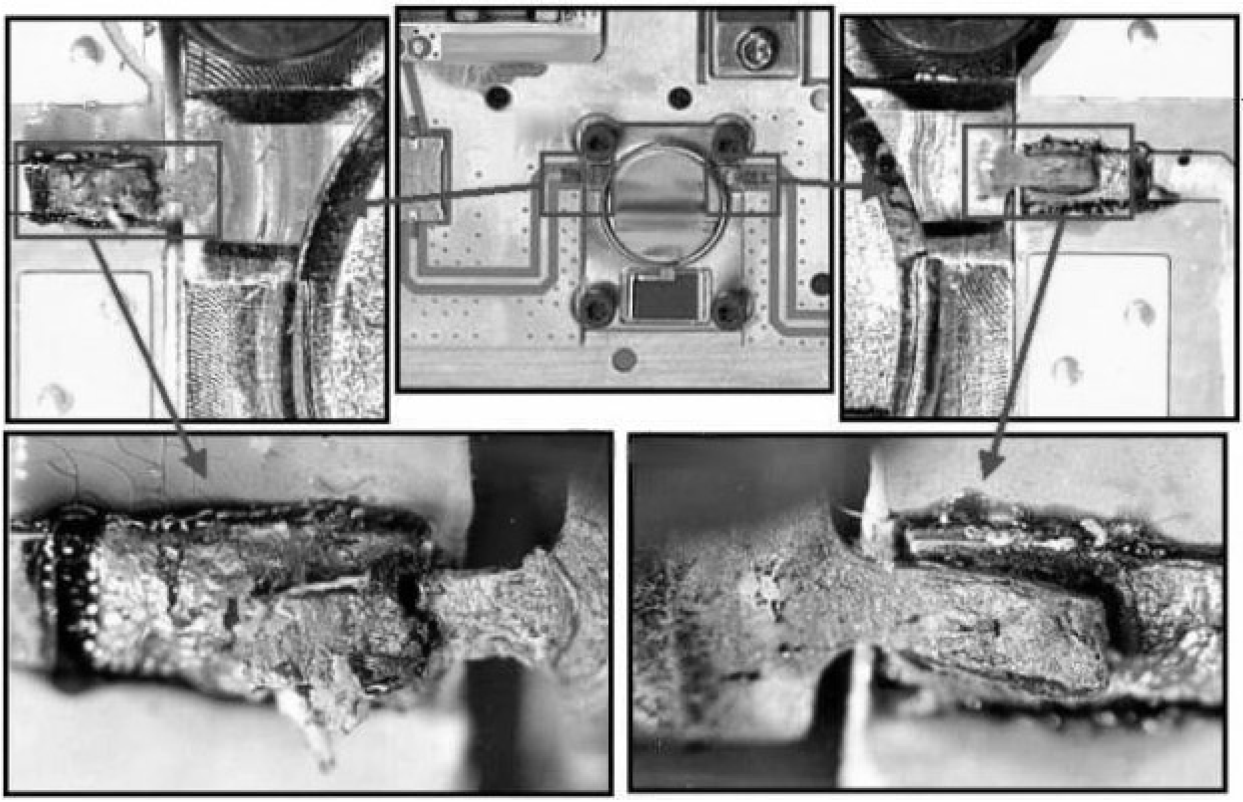
Based on the SM interconnection weaknesses observed during ALT, corrective action programs were initiated to improve the long-term solder attachment integrity of the at-risk components. The isolator supplier increased the lead length of the component and implemented a custom gull-wing lead shape to improve strain relief. In addition, the board traces were modified to accommodate the extended lead foot, which was pre-tinned to increase solder joint volume after assembly. Work instructions for assembling critical RF components were upgraded and additional manufacturing process controls and inspection procedures were implemented.

A follow-up ALT program was implemented for PA modules with the improved isolator assembly to validate the corrective action. There were no solder interconnection failures on the retested PAs. The design and assembly improvements for the isolator component, along with other lessons learned from prior EST initiatives, have been applied in subsequent PA development, with favorable product performance results in the new ALT programs.

This case study demonstrates the effectiveness of ALT in early detection of embedded design and assembly weaknesses in a critical RF sub-assembly. The resulting redesign and assembly improvements provide lessons learned that are implemented in new product introductions, as a means to assure SM interconnection robustness and long-term field reliability.

Continuing Development of ALT Statistical Model

The ALT model will be periodically evaluated in terms of the supporting acceleration factors, statistical practices, and effectiveness relative to the



ALT—Accelerated life testing
RF—Radio frequency

Figure 6.
Representative surface mount solder interconnection failures on the RF isolator component precipitated during ALT of the power amplifier module.

observed reliability of fielded electronic hardware. There is a continuing review of acceleration models for electronic components that measure the time compression of degradation under thermal-cycling stress conditions. Alternate statistical analysis methods are under evaluation that are applicable to the relatively small number of failures typically encountered in ALT [9]. These statistical methods may lead to improved estimates for the empirical slope parameter and forecasted steady-state failure rate. There is a continuing effort to validate the ALT model through comparison with the observed reliability of deployed hardware. Hardware assets in mature telecommunication systems provide long-term reliability statistics useful for comparison with forecasts from the ALT model.

Summary

Product development and reliability engineering organizations in Lucent Technologies have practiced ALT as part of an integrated program for robust design and product assurance testing since the 1990s. Consistent EST-ALT requirements are deployed to development and manufacturing teams through controlled product specifications. The ALT programs effectively identify latent design and assembly weaknesses early in the product development cycle, providing an opportunity for corrective action and risk mitigation before volume manufacturing and field deployment. The empirical failure statistics from well-executed ALT programs are used to forecast the steady-state field failure rate for critical hardware that strongly affects system reliability.

Preliminary evaluation of the predicted and observed steady-state failure rates for fielded hardware indicates that the ALT model provides practical reliability bounds that support informed decisions on product performance and volume deployment. There is a continuing effort to improve and validate the supporting model, through the integration of recognized acceleration models and further comparison with the observed steady-state reliability for deployed hardware. The integrated EST-ALT practices within Lucent Technologies are continuously improved to support reliability growth, refine predictive competency, and enhance customer satisfaction.

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