RELIABILITY EVALUATION OF INTERCONNECTION PRODUCTS

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This paper describes several new reliability evaluation methods and tools and specific examples of how they are used to design reliability into new interconnection products. The methods include early identification of risk sites and stress factors, design of failure-mode-specific test vehicles, and efficient execution of accelerated testing programs through computer-controlled data-acquisition systems. With such tools, accurate and realistic accelerated testing can now be done during an aggressive product development schedule.

Introduction

One of AT&T's highest priorities is to satisfy our customers' expectation of quality and reliability in all of our products. To achieve this, we design quality and reliability directly into our products and then test the products against customer reliability requirements. However, reliability testing must not only characterize product reliability accurately, it must also be done in a timely, cost-effective way to meet a development schedule and cost objectives.

With shorter development cycles, reliability evaluation programs must begin early and be an integral part of a development project. Shorter cycles also need shorter reliability testing programs. Thus, it becomes important to use *accelerated life testing* (ALT) efficiently and to improve techniques for extrapolating ALT results to operating conditions.

Technology-related trends, driven by the requirement to interconnect increasingly complex silicon integrated circuits, can have a significant effect on reliability evaluation. Higher interconnection densities mean higher stresses on materials and this raises questions about their capability to perform reliably. In addition, the increasing use of electronics in severe and uncontrolled environments and the trend toward higher thermal loads raise new concerns about reliability and broaden the range of tests needed.

The increasing number of material and processing choices for interconnections is also important. Leading edge technologies need higher performance materials while cost-sensitive applications need assured reliability at the lowest possible cost.

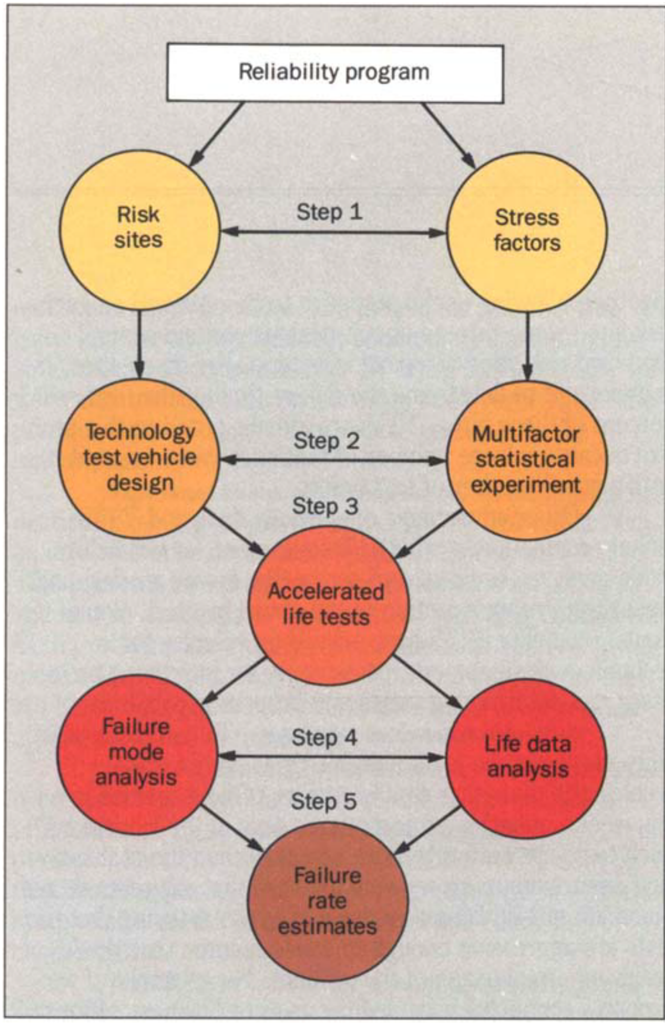


Figure 1. Reliability method flow chart.

Reliability Evaluation Methods

The Interconnection Systems and Assembly Reliability department of AT&T Bell Laboratories has developed a method for reliability evaluation that meets the needs discussed above.[1] Although reliability assessment programs can vary considerably in detail, the underlying strategy remains the same. A generic reliability program, shown in the flow chart in Figure 1, consists of five steps:

- Risk site and stress factor identification
- Test vehicle design and experiment design
- Accelerated life testing
- Life data and failure-mode analysis
- Failure rate estimates.

Risk Site and Stress Factor Identification. The first step involves close examination of the technology under study to identify potential areas of failure and stresses that could lead to failure. It is extremely important that this step be done thoroughly and carefully and that all risk sites be identified. For an existing technology, this step may be straightforward. For a new technology, it may take considerable analysis to identify risk sites. Common stress factors include temperature, humidity, voltage or current bias, corrosive atmospheres, and mechanical stress. The stress factor may be held constant (as in a thermal aging or static bending test), or it may vary during the test (as in a temperature cycling or vibration test).

Test Vehicle Design and Experiment Design. Once risk sites and stress factors have been identified, a test vehicle must be designed. In many cases (e.g., with connectors) the product itself can be used to build an appropriate test vehicle. The test vehicle should give a realistic simulation of the factory, shipping, and system usage stresses on the product. Products such as printed circuits, however, cannot usually be used as test vehicles; for these it is necessary to design a specific *technology test vehicle* (TTV). TTVs are an important part of reliability assessment programs and will be discussed in more detail below.[2]

Accelerated life tests (ALT) are usually based on a multifactor statistical experiment. The design of this experiment is closely related to the TTV design. The two designs must be closely coordinated. The experiment design may include a screening test to identify weaker risk sites as well as a factorial experiment to provide a database for failure rate estimates under circuit operating conditions. Because several stress factors can be involved simultaneously in an experiment, the experiment design should be as efficient as possible to minimize the number of test vehicles required, the cost of the program, and the time required to complete testing. Some new tools used in experiment design are discussed later.

Accelerated Life Tests. In this step, test vehicles are life tested at accelerated stress conditions. Such conditions must accelerate the degradation mechanisms normally active in the product while not activating extraneous processes. These tests require specialized equipment, such as temperature-humidity-bias test chambers and automated data-acquisition equipment to record degradation or failure as a function of time.

Life Data and Failure-Mode Analysis. Data from the ALTs are analyzed to give failure rate estimates at accelerated conditions. A failure-mode analysis is performed on test vehicles to verify the failure mechanisms for each risk site.

Failure Rate Estimates. The final step in the program is to build a model that serves as a basis to extrapolate the failure rates at accelerated conditions to failure rates at operating conditions. This model is developed using acceleration transforms or acceleration factors,[3] which will be discussed later.

If several risk sites are involved, a model is developed for each site. The failure rate for a specific product can then be estimated by counting each type of risk site, multiplying each number by the appropriate failure rate and summing to obtain the total failure rate.

Reliability Evaluation Tools

Technology Test Vehicles. The reliability of a complicated structure such as a multilayer printed circuit depends on several factors, including the materials and processes used to make the circuit and the environmental stress under which the circuit must operate. However, reliability also depends on the design of the circuit itself; factors such as complexity or density and the spacing between isolated conductors can affect reliability. It is generally not efficient to test actual printed circuit products; such testing often yields limited data restricted to a particular design. With properly designed TTVs for a given technology, it is possible to estimate the reliability of any circuit design made using that technology.

A TTV is a failure-mode-specific test coupon (sample) that contains a statistically appropriate number of one or more risk sites and that is made using the technology under study. A test point in a TTV can contain from one to more than one hundred risk sites connected together, allowing useful statistics to be obtained on each risk site. Some printed circuit designs contain several thousand risk sites of a particular type. For these sites, it is important to determine the failure time of the first ≈ 0.1 percent of these sites. TTVs are ideally suited to this problem because a large number of risk sites can be tested with a small number of test points.

Other advantages of specially designed TTVs include compatibility with ALT equipment, easier failure-mode analysis, avoidance of competing failure modes, and an accurate representation of the actual product. Sometimes, reliability TTVs have served as vehicles for technology development, particularly for improving processes and determining yields and process capabilities.

Calibrated Accelerated Aging Tests. To complete reliability testing in the least possible time, we must use accelerated tests that simulate years of field service in a few weeks, months, or sometimes days in the laboratory. Such tests are naturally more stressful than the real service environment, so we must be sure that the tests do not cause unrealistic failure modes while also assuring that the tests are aggressive enough to cause failures that would occur in normal usage of the product. For example, if we expose a connector intended for use in a business office to a salt spray test, we will be unable to say anything about its failure rate in its application environment because the dominant failure mechanisms caused by salt spray do not typically occur in a business office.

When developing an accelerated aging test, we identify a failure mechanism, then devise a method to accelerate it without introducing other, inappropriate failure mechanisms. Finally, we calibrate the behavior of our product in the test against its behavior in actual usage in the field.

For example, copper alloy springs are an important part of many connectors. Atmospheric corrosion of exposed copper in the connector contacts is a potential cause of failure. We developed a test to accelerate this process without causing certain other processes, such as copper sulfide migration, which is very rare in office environments. The thickness and chemistry of corrosion films on copper alloys in connectors in field service was analyzed and the accelerated test conditions adjusted to give similar films on copper alloys.[4] By using this approach, we were able to avoid both underdesign and overdesign of the product, both of which carry severe penalties in the marketplace.

Experiment Design and Extrapolation. In most interconnection reliability programs, the only way that results can be achieved in an acceptable length of time is with ALTs. This presents two problems: the design of the ALT itself and how to extrapolate the results to operating conditions. Both problems are closely related and have been receiving more attention in recent years. New and improved tools are being developed and several have been used to evaluate interconnection reliability.

The design of ALTs for interconnection products is complicated by two facts. First, the failure modes are often affected by several factors simultaneously (e.g., temperature, humidity, and bias). As a result, ALTs must be multifactor experiments. In addition, complicated material systems are used that are not always well controlled or characterized.

A multilayer board, for example, contains primarily copper, epoxy, and glass cloth reinforcement. Each of these materials may have come from one of several suppliers. When combined with normal manufacturing process variations, the result is a product that meets all specifications but that has subtle, uncontrolled variations that show up in ALTs. Thus, the sample size must be large enough to characterize the variability in reliability.

In a typical reliability program, TTVs with several risk sites are tested at several levels of three or more stress factors. A full factorial experiment in which every risk site is tested at every combination of stress levels is clearly impossible. One way to reduce the number of tests required is to use a screening experiment. Testing all risk sites at a single set of high stress conditions will pinpoint the weakest sites. These sites can be tested further. However, it may be possible at this stage to eliminate some risk sites from further testing, or at least postpone the testing to a later phase of the study.

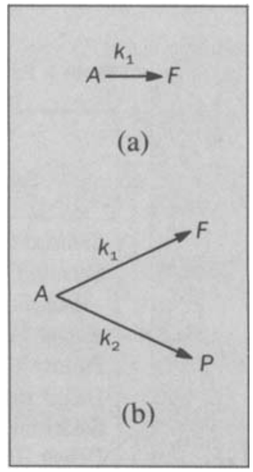


Figure 2. Arrow diagrams of the kinetics of specified degradation processes.

The set of multilevel tests can also be made more efficient with fractional factorial designs. In a fractional factorial design, information about possible interactions among the factors under study is often lost. However, sometimes it is known that certain interactions are unimportant and the fractional design is thus quite suitable.

Experiment designs based on orthogonal arrays[5] are very efficient and have been used widely in process optimization. When the interactions between factors are few or unimportant and the goal is to identify the factors affecting reliability, this technique is very useful. A specific case using an orthogonal array will be described later.

The central part of any reliability program based on ALTs is the model used to extrapolate results at accelerated stress conditions to operating conditions. The most commonly used extrapolation model is the acceleration factor model, also known as the *accelerated life model.*[6]

In this model, the failure time distribution at operating conditions is a simple scalar multiple of the failure time distribution at accelerated conditions (i.e., the distributions all belong to the same scale family). It is our experience in studying the material systems used in interconnection technology that this model usually does not fit the data gathered in ALTs. We have, thus, explored alter-

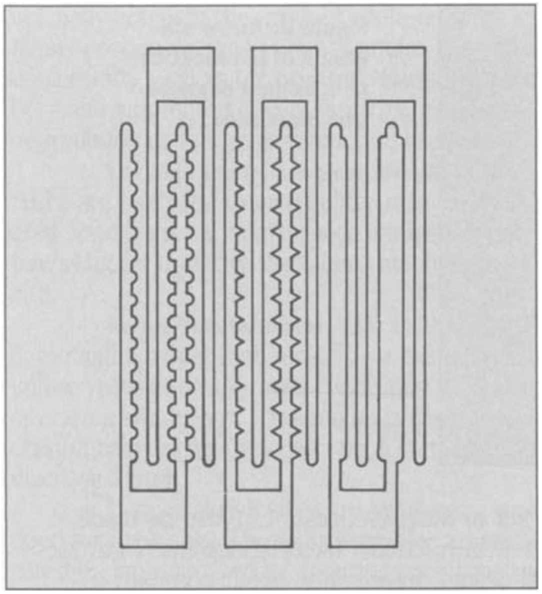


Figure 3. Clearance defect comb patterns.

Table I. Factors Affecting Clearance Defect Failure

Factor		Level 1	2	3	4	5	6	7	8	9
Temperature	°C	85	70	55						
Relative humidity	%	85	75	55						
Voltage	V	10	50	200						
Polarity†		+	+	−						
Defect shape		S1	S2	S3						
Solder mask		SM1	SM2	SM3						
Defect clearance†	mils	1	1	2	2	3	4	5	10	10

NOTE: S1 = pointed; S2 = rounded; S3 = parallel;
SM1 = thermally cured epoxy; SM2 = laminated dry film;
SM3 = UV-cured acrylate
†The extra positive polarity and and 1-, 2-, and 10-mil clearance levels were required to preserve orthogonality.

nate methods for extrapolation involving acceleration transform models.

Acceleration transforms are based on the postulate that the degradation processes that lead to failure can be described kinetically. Thus, the way failure distributions change with stress must be consistent with the way the kinetics of degradation processes change with stress. Acceleration transforms are not empirical but are based on approximations to the kinetics of degradation processes.

Consider the two degradation kinetic situations shown in Figure 2. In Figure 2(a) the material system, A, degrades to a failure producing product, F, with a rate constant k_1. In Figure 2(b), A degrades to F with a rate constant $k_1$and to P, a nonfailure producing product, with a rate constant k_2 where k_1 and k_2 are dependent on the stress level. These two degradation processes can be described by the following differential equations:

$$\frac{\partial [A]}{\partial t} = -k_1[A]; \frac{\partial [F]}{\partial t} = k_1[A] \quad (1)$$

for the first case, and

$$\frac{\partial [A]}{\partial t} = -(k_1 + k_2)[A]; \frac{\partial [F]}{\partial t} = k_1[A] \quad (2)$$

for the second.

If it is assumed that the initial concentrations of A and F are $[A]_o$ and 0, respectively, and that the concentration of F at failure is $[F]_f$, then it is easily shown by solving the differential equations that t_f, the time to failure, is the solution to

$$\frac{[F]_f}{[A]_o} = 1 - exp(-k_1 t_f) \quad (3)$$

for the first case, and

Table II. Orthogonal Experiment Design

Expt No.	Factor Levels: Temperature (°C)	Relative humidity(%)	Solder mask	Clearance (mils)	Shape	Bias (volts)	+/−
1	85	85	1	1	2	10	+
2	85	85	2	3	1	50	+
3	85	85	3	10	3	200	−
4	85	75	1	1	3	10	+
5	85	75	2	4	1	50	−
6	85	75	3	5	2	200	+
7	85	55	1	2	2	10	−
8	85	55	2	2	3	50	+
9	85	55	3	10	1	200	+
10	70	85	3	1	2	50	+
11	70	85	1	4	3	200	+
12	70	85	2	5	1	10	−
13	70	75	3	2	1	50	+
14	70	75	1	2	2	200	−
15	70	75	2	10	3	10	+
16	70	55	3	1	3	50	−
17	70	55	1	10	1	200	+
18	70	55	2	10	2	10	+
19	55	85	2	2	3	200	+
20	55	85	3	2	1	10	+
21	55	85	1	10	2	50	−
22	55	75	2	1	2	200	+
23	55	75	3	3	3	10	−
24	55	75	1	10	1	50	+
25	55	55	2	1	1	200	−
26	55	55	3	4	2	10	+
27	55	55	1	5	3	50	+

$$\frac{[F]_f}{[A]_o} = \left[\frac{k_1}{k_1 + k_2}\right](1 - exp(-(k_1 + k_2)t_f)) \qquad (4)$$

for the second case.

The quantity $[F]_f / [A]_o$ represents the extent of degradation at failure for a particular risk site. We assume $[F]_f$ does not vary with stress level, but may vary between risk sites, as may $[A]_o$. Thus, for a selection of nominally identical risk sites, there will be a distribution of $[F]_f / [A]_o$ values, and hence, t_f values. To construct an acceleration transform, we consider two stress levels and choose times corresponding to equal degradation extents (i.e., equal quantiles in the failure distributions will correspond to the same degradation extents).

Thus, for the first case, if t^1 and t^2 represent the failure times for the same quantile in the failure time distributions at two stress levels and k_1^1 and k_1^2 represent the rate constants at the two stress levels, then we may write

$$1 - exp(-k_1^1 t^1) = 1 - exp(-k_1^2 t^2)$$

$$\text{or} \quad t^1 = \theta t^2 \quad \text{where} \quad \theta = \frac{k_1^2}{k_1^1} \qquad (5)$$

Here, θ is just a simple acceleration factor. The acceleration factor model is thus derived from the simplest acceleration transform model, namely the case in which the degradation process is controlled by a single, rate-limiting step.

For the second case, we have

$$1 - exp(-\theta_1 t^1) = \theta_2(1 - exp(-\theta_3 t^2))$$

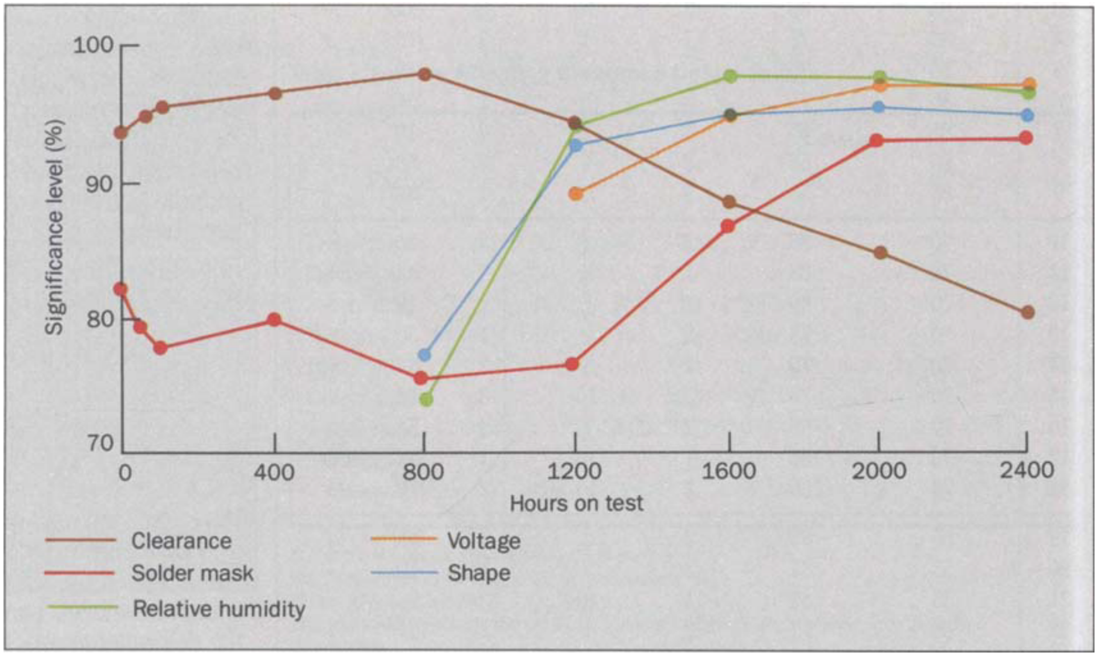
$$\text{where } \theta_1 = k_1^1 + k_2^1; \ \theta_2 = \frac{k_1^2(k_1^1 + k_2^1)}{k_1^1(k_1^2 + k_2^2)}$$

$$\text{and } \theta_3 = (k_1^2 + k_2^2) \qquad (6)$$

This transform can be solved, explicitly yielding $t^1 = (-log(1 - \theta_2(1 - exp(-\theta_3 t^2))) / \theta_1$. Here the relationship between failure times at different stress conditions is clearly nonlinear. The acceleration factor model would not apply to data from a degradation process following these kinetics.

Several kinetic models in addition to these two are discussed elsewhere.[3] We are now developing new extrapolation techniques that are based on reasonable kinetic models for degradation and that allow us to recognize and

Figure 4. Significance level as a function of time for various factors. Temperature and polarity are not shown here because their significance level is consistently less than 75 percent.



handle failure distribution data that can not be linearly transformed from an accelerated stress condition to an operating condition.

Computer Aids. Most reliability evaluation programs involve acquisition, processing, and analysis of tens or hundreds of thousands of data points. Interconnection reliability programs rely heavily on computers and computer aids. The printed circuit ALT facility for temperature-humidity-bias testing, for example, has a capacity of 2160 test points. Measurements at these points are taken automatically at 4- to 24-hour intervals by a microprocessor. The results are transferred daily to a mainframe computer where they are appended to previous results. Engineers can view updated summaries of ongoing tests easily and as often as necessary.

Computer-based instrumentation is essential in the reliability evaluation of connectors because such programs require many precision resistance measurements. Using such instrumentation, we are able to gather and process the large amount of data required to assess the reliability of a product with a failure rate below 1 FIT (1 failure in 10^9 hours). The computer also allows us to build error checking and diagnostic routines into the measurement process to detect and screen out device problems that are actually failures elsewhere in the measurement circuitry and instrumentation. This capability is essential because the individual connector contacts under test may be more reliable than the connections to the measurement system.

The large databases generated by ALTs are analyzed with the help of a new reliability data analysis tool, STAR,[7] and a special statistical analysis tool, S,[8] which reside on the mainframe. The STAR software package provides a computing environment for statistical analysis of reliability data. It is particularly useful for real-time evaluation of how well specific parametric models fit the observed failure data. S is used for general data presentation and analysis and for building specific programs for analyses not available in STAR.

The acceleration transforms discussed earlier require considerable computer time. Often it is not apparent initially which acceleration transform is most suitable in a particular case. It may be necessary to test several possible models to determine which one is applicable. Most transforms can not be determined explicitly and nonlinear estimation techniques must be used. These analyses would be completely impossible without adequate computer facilities.

In addition, all record keeping and report writing can be done conveniently on the same machine that stores and analyzes data. For these activities, our computer uses a UNIX® System V, version 2 (V.2) operating system.

Examples

Clearance Defect Study. Clearance defects are isolated regions of reduced clearance between separate conductors. A study of the effects of these defects on the reliability of double-sided printed circuits illustrates the power and efficiency of orthogonal array experiments.[9] In part of this study, a specially designed clearance defect coupon was tested at accelerated conditions. The coupon pattern, shown in Figure 3, contains three segments, each with a different shape of clearance defect. Separate patterns were used to obtain different clearance spacings.

The study was to determine the effect on reliability of the seven factors listed in Table I. Each factor was to be studied at the levels indicated. A full factorial experiment would require 2,916 combinations. The orthogonal array design chosen required the 27 experiments shown in Table II.

Analysis showed that failures during the first 1200 hours of testing were because of infant mortality and occurred mainly in 1- and 2-mil clearance samples. Beyond 1200 hours, the failures were because of wear out typical of printed circuit products.

A standard analysis of variance was used to analyze survival data. The significance level for each of the seven factors was calculated for test times up to 2400 hours. The results, shown in Figure 4, showed that only the clearance was statistically significant above a 90-percent level for the infant mortality regime (< 1200 hours). Thus, clearance defect failures in this regime are not accelerated by the other factors. Because of this and because clearances at 2 mils and above did not exhibit a significant infant mortality failure rate, the clearance defect limit could be significantly reduced for double-sided rigid circuits without impacting on reliability.

Acceleration Transforms. Failure mechanisms in epoxy-glass printed circuits under accelerated temperature, humidity, bias conditions have been under investigation for several years. Recently, a study of these mechanisms was done based on designed experiments and acceleration transforms.[3] Printed circuit coupons were tested at the temperature, humidity, and bias conditions shown in Table III. The experiment is shown in stress space in Figure 5. The numbers shown in Figure 5 correspond to the condition indices given in Table III. To analyze the results of the experiment, condition 1 [90°C, 85-percent relative humidity, 200 volts (V)] was chosen as a reference condition. The transform that best transformed the failure distribution observed at the reference condition to the failure distribution observed at each of the other experimental conditions was determined. For some points, the best fit was obtained with the acceleration factor transform (shown as A); the best fit for the remainder was obtained using the competing process transformation (the second model described in the preceding section, shown as B). The two models are listed in the last column of Table III, and pictured in stress space in Figure 6. Notice that as the relative humidity decreases (going from the front of Figure 6 toward the back), there is a transition from model A to model B. This transition is easy to understand in the context of kinetic model B. Further statistical analysis of the data based on the model shown in Figure 2(b) suggests that the rate constant k_1, associated with the failure causing process is strongly dependent on the applied stress, but k_2 is apparently independent of stress.

Table III. Experimental Conditions and Results

Condition index	Temperature (°C)	Relative humidity (%)	Bias (volts)	Model
1	90	85(85)	200	A
2	80	85(82.4)	200	A
3	60	85(85)	200	A
4	90	85(85)	25	A
5	60	85(85)	12.5	A
6	80	75(75.4)	200	B
7	75	75(74)	50	B
8	90	60(57)	200	B
9	80	60(62.8)	200	B
10	60	60(65)	200	B
11	90	60(57)	12.5	N.A.
12	80	50(49.5)	200	B

NOTE: Numbers in parentheses are actual relative humidity values obtained in the experiment.

In high stress regimes, k_1 dominates, thus giving an apparent acceleration factor model. In intermediate regimes there is mixed control, where the kinetics are described by model B, and in low stress regimes (including most operating conditions) k_2 dominates, precluding failure. This result provides a theoretical basis and a verification for conclusions drawn from a previous study in which a humidity threshold was observed below which failure would not occur. The difference is that this time the conclusion was reached in a few months using designed experiments and acceleration transforms. The previous study required over two years to reach the same conclusion.

The results from the designed experiment were used to estimate failure probability at use conditions. Table IV shows the predicted failure probability for a printed circuit with 96 risk sites operated at 25°C, 50-percent relative humidity, 350-V bias after 1 year of operation and over the next 9 years. The 95-percent upper confidence bounds are shown in parentheses. For comparison, the failure probabilities are also shown using an analysis based on acceleration factors. The predicted failure rate for the first year is not very different for the two models. However, the acceleration factor model predicts a very significant fraction will have failed after 10 years, whereas the acceleration transform model predicts a negligible fraction failing. Many circuit boards have been in service for many years under conditions similar to those assumed above. Investigations have not shown evidence of circuit failures and thus support the predictions of the acceleration transform model. Failures at the rate suggested by the acceleration factor model would have resulted in a significant number of field failures.

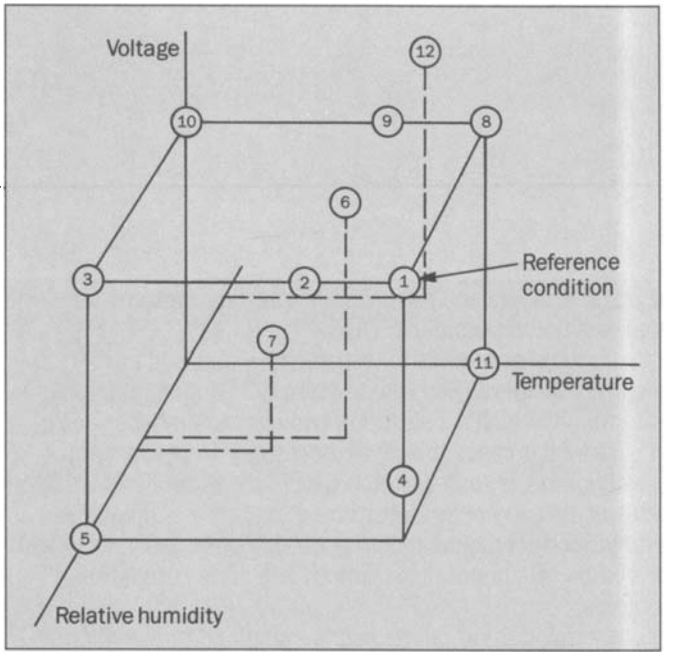


Figure 5. Arrangement of design points in stress space.

New Tools and Connector Reliability Evaluation. Over the years, evaluation of connectors has evolved from time-consuming field trials to ever more rapid laboratory testing procedures. Careful study of connector degradation mechanisms and development of laboratory tests to accelerate the appropriate processes has reduced a full-scale reliability study of a new connector from a program requiring a year or more to one that can be completed in three months or less. At the same time, improvements in computer-based measurement capability have enabled us to expand the size of each evaluation to improve confidence in the results. Present development work is likely

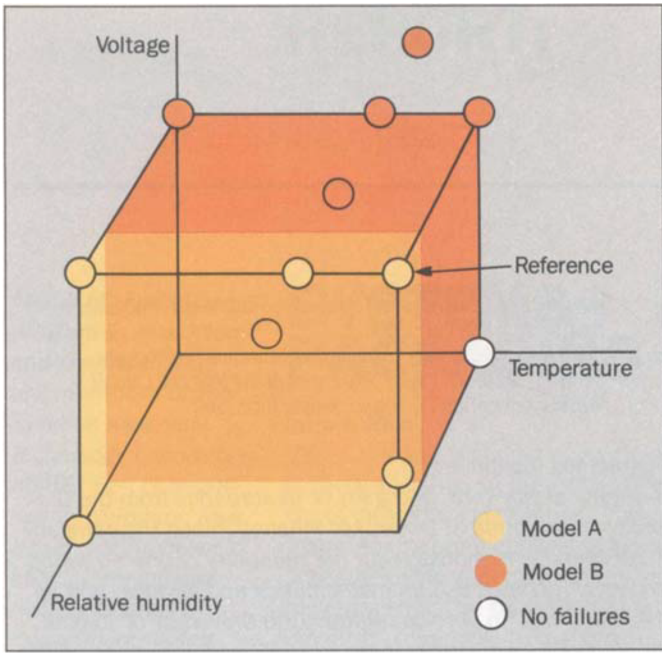


Figure 6. Arrangement of selected transforms in stress space.

to give us tests and procedures that will further shorten test time.

Summary

AT&T customers have high expectations of the quality and reliability of our products. Satisfying these expectations requires that quality and reliability be designed into a product at the very beginning of the product realization cycle. In addition, however, timely, cost-effective reliability analysis must be performed on products to assure their reliability—that is, performance over time.

Shorter development cycles coupled with technology trends, such as higher interconnection density, higher thermal stresses and broader operating environments, have mandated development of new reliability methods and tools.

The methods developed include the early and effective identification of risk sites and stress factors, design of failure-mode-specific test vehicles and efficient execution of accelerated testing programs through computer controlled data acquisition systems.

Many reliability evaluations require examination of multiple risk sites that are tested over several stress factors at different levels. Execution of a full factorial experiment could involve thousands of experiments and would be too costly or impossible to execute. Through the use of failure-mode-specific test vehicles and efficient fractional factorial experimental designs, accelerated testing can now be done within the confines of an aggressive product development schedule.

Extrapolation of accelerated test data to operating conditions has usually assumed that failure time distributions at accelerated stresses are a simple scalar multiple of the failure time distribution at operating conditions. For advanced material/process-intensive technologies, such as printed circuit boards, this assumption often does not apply. Consequently, a new, more general method using acceleration transforms, which are based on chemical kinetics, has been developed and successfully applied.

The increased complexity and technological demands on interconnection products (printed circuit boards, connectors, and assemblies) have placed an even higher priority today on being able to perform timely, relevant reliability analysis on technologies and products. The new reliability methods and tools described in this paper are an important aspect in the development and successful use of our rapidly advancing interconnection technology.

Table IV. Predicted Failure Probabilities

	Year 1	Years 2–10
Acceleration Factor	1.3×10^{-2}	1.38×10^{-1}
Acceleration Transform	$4.54 \times 10^{-3}(1.0 \times 10^{-2})$*	$5 \times 10^{-7}(1.8 \times 10^{-3})$*

*95 -percent upper confidence bounds.

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Biographies (continued)

University at Hayward, and a Ph.D. in statistics from the University of California at Davis. Mr. Mitchell joined the company in 1963 and is responsible for the reliability of printed wiring products. He has a B.A. in mathematics and physics, and an M.A. and Ph.D. in physics, all from the University of Toronto. Mr. Sproles joined the company in 1978 and is working on the reliability evaluation of connectors marketed by common components and power systems. He has a B.S. in metallurgy from the Pennsylvania State University and an Sc.D. in material science from Massachusetts Institute of Technology.

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