9

CONCEPTS IN ACCELERATED TESTING

9.1 INTRODUCTION

The concept of accelerated testing is to compress time and accelerate the failure mechanisms in a reasonable test period so that product reliability can be assessed. The only way to accelerate time is to stress potential failure modes. These include electrical and mechanical failures. Figure 9.1 shows the concept of stress testing. Failure occurs when the stress exceeds the product's strength. In a product's population, the strength is generally distributed and usually degrades over time. Applying stress simply simulates aging. Increasing stress increases the unreliability (shown in Figure 9.1 as the overlap area between the strength and stress distributions) and improves the chances for failure occurring in a shorter period of time.

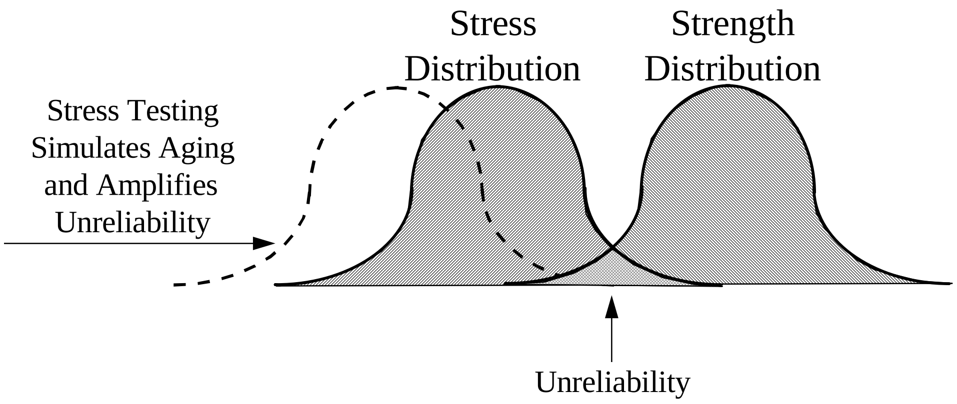

Figure 9.1 Principal of accelerated testing.

This also means that a smaller sample population of devices can be tested with an increased probability of finding failure. Stress testing amplifies unreliability so failure can be detected sooner. Accelerated life tests are also used extensively to help make predictions. Predictions can be limited when testing small sample sizes. Predictions can be erroneously based on the assumption that life test results are representative of the entire population. Therefore, it can be difficult to design an efficient experiment that yields enough failures so that the measures of uncertainty in the predictions are not too large. Stresses can also be unrealistic. Fortunately, it is generally rare for an increased stress to cause anomalous failures, especially if common sense guidelines are observed.

9.2 COMMON SENSE GUIDELINES FOR PREVENTING ANOMALOUS ACCELERATED TESTING FAILURES

Anomalous failures can occur when testing pushes the limits of the material out of the region of the intended design capability. The natural question to ask is this: What should the guidelines be for designing proper accelerated tests and evaluating failures? The answer is: Judgment is required by management and engineering staff to make the correct decisions in this regard. To aid such decisions, the following guidelines are provided:

1. Always refer to the literature to see what has been done in the area of accelerated testing.
2. Avoid accelerated stresses that cause "nonlinearties", unless such stresses are plausible in product use conditions. Anomalous failures occur when accelerated stress causes "nonlinearities" in the product. For example, material changing phases from solid to liquid, as in a chemical "nonlinear" phase transition (e.g., solder melting, intermetallic changes, etc.); an electric spark in a material is an electrical nonlinearity; material breakage compared to material flexing is a mechanical nonlinearity.
3. Tests can be designed in two ways: by avoiding high stresses, or by allowing it, which may or may not cause nonlinear stresses. In the latter test design, a concurrent engineering design team reviews all failures and decides if a failure is anomalous or not. Then a decision is made whether or not to fix the problem. Conservative decisions may result in fixing some anomalous failures. This is not a concern when time and money permit fixing all problems. The problem occurs when normal failures are put in the wrong category as anomalous and no corrective action is taken.

9.3 TIME ACCELERATION FACTOR

The acceleration factor (A) is defined mathematically by Equation 9.1 where t is the typical life of a failure mode under normal use conditions and t' is the life at accelerated test condition:

$$A = \frac{t}{t'} \qquad (9.1)$$

Since accelerated testing is designed to create failures in a shorter time frame, the life under normal use conditions is usually much longer than the life under accelerated test conditions, and A is much greater than 1. For example, an acceleration factor of 100 indicates that 1 hour in an accelerated stress environment is equal to 100 hours in the normal use stress environment. Acceleration factors, as denoted here, describe time compression. Acceleration factors may also be put in terms of parameter change. The most common application is for estimating test time-compression using the time acceleration factor.

Acceleration factors are often modeled. For example, many failure modes affected by temperature, such as chemical processes and diffusion, have what is known as an Arrhenius reaction rate given by

$$Rate = B \exp\left\{\frac{-E_a}{K_B T}\right\} \qquad (9.2)$$

where

B = a constant that characterizes the product failure mechanism and test conditions (see Reference 1),

E_a = the activation energy in electron-volts (eV) of the failure mode,

T = the temperature (in degrees Kelvin), and

K_B = Boltzmann's constant (8.617×10^{-5} eV/^{o}K).

This is a thermodynamic expression that, while treated macroscopically to describe failure kinetics, is obeyed in the microscopic world where elementary reactions are taking place in accordance with the Arrhenius model. Particles have a certain probability to overcome the potential barrier of height E_a and become activated into the reaction taking place. As more and more elementary particles are consumed, a catastrophic event takes place at some point in the macroscopic world. The rate is assumed to be inversely proportional to the time that this will occur. For example, if an experiment is performed at two temperatures T1 and T2, the failure times are then related to the rates at these temperatures as

$$\frac{t_2}{t_1} = \frac{Rate(T_1)}{Rate(T_2)} \tag{9.3}$$

Combining equations 9.1, 9.2 and 9.3, yields the temperature acceleration factor

$$A_T = \frac{t_2}{t_1} = \exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_2} - \frac{1}{T_1}\right]\right\} \tag{9.4}$$

The full model is shown in Figure 9.2 (Section 9.5). In order to evaluate the acceleration factor, the parameter activation energy E_a must be known or assumed for a particular failure mode. Often, historical information provides typical values for E_a, or these may be obtained through experimentation (see Example 9.2).

9.4 APPLICATIONS TO ACCELERATED TESTING

To estimate test time compression and devise test plans that include sample size requirements, both acceleration models and statistical analysis is required (see Example 9.7). In this section, an overview of accelerated testing is provided in which potential failure mechanisms and acceleration models found in the literature are discussed.

Accelerated verification tests in microelectronics are designed to stress four types of failure mechanisms/modes. They are 1) thermomechanical mechanisms (e.g., package cracking, ohmic contacts, wire bond/lead integrity, thermal expansion mismatch problems, metal fatigue, creep, etc.), 2) non-moisture-related thermochemical mechanisms (e.g., metal interdiffusion, intermetallic growth problems such as Kirkendall voiding, electromigration, MOS gate wearout, etc.), 3) moisture-related thermochemical mechanisms (e.g., surface charge effects, ionic leakage effects, dendrite growth, lead corrosion, galvanic corrosion, etc.), and 4) mechanical mechanisms (e.g., mechanical attachments, package integrity, fatigue, etc.). Combinations of these accelerated tests are required to properly stress each failure mechanism. The most common tests are Temperature cycle, High Temperature Operating Life (HTOL), Temperature Humidity Bias (THB), and Vibration testing, which are described here. Additionally, electromigration testing is described in this chapter. Temperature cycle stresses thermomechanical mechanisms; HTOL stresses non-moisture-related thermochemical mechanisms; THB stresses moisture-related thermochemical mechanisms; and vibration stresses mechanical failure mechanisms.

Additionally, many devices during manufacture receive some manufacturing stress. For example, surface-mount-technology (SMT) devices are subject to solder-reflow processes. Therefore, to provide a realistic verification test procedure prior to accelerated reliability testing, devices should receive a preconditining to simulate these stresses. In the case of SMT devices, a solder-reflow-type preconditioning test, such as described in JEDEC specification JESD22-A113, is commonly used.

9.5 HIGH-TEMPERATURE LIFE TEST ACCELERATION MODEL

In high-temperature life testing, devices are subjected to elevated temperature under bias for an extended period of time. Often, it is assumed that the dominant thermally accelerated failure mechanisms will follow the classical Arrhenius relationship (previously discussed). The traditional HTOL Arrhenius acceleration model is provided in Figure 9.2. The Arrhenius function is important. It is not only used in reliability to model temperature-dependent failure-rate mechanisms, but expresses a number of different physical thermodynamic phenomena (see Chapter 14). In Equation 9.2, we see that this factor is exponentially related to the activation energy. As the name connotes, in the failure process there must be enough thermal energy to be activated and surmount the potential barrier height of value E_a. Thus, as the temperature increases, it is easier to surmount this barrier and increase the probability of failure in a shorter time period. Thus, the activation energy parameter expresses a characteristic value that can be related to thermally activated failure processes. Each failure process has associated with it a barrier height E_a. In practice, when trying to estimate acceleration factor without knowing this value for each potential failure mechanism, a conservative value is used.

For example, 0.7 eV is typically used for IC failure mechanisms and appears to be somewhat of an industry standard for conservatively estimating test times (see Examples 9.1 and 9.7). That is, a low value will overestimate the test times and/or sample sizes needed to meet test objectives.

$$A_T = Exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}}\right]\right\}$$

$$Ln(t_f) = C + \frac{E_a}{K_B T}$$

Notation

A_T=Temperature acceleration factor
T_{stress}=Test temperature (°K)
T_{use}=Use temperature (°K)
E_a=Activation energy
t_f= 8.6173×10^{-5} eV/°K(Boltzmann's
C=constant)

Figure 9.2 HTOL Arrhenius acceleration and linearized time-to-failure models.

Obviously, the other important considerations are the actual use and stress temperatures. These estimates may also have errors. For example, to accurately assess time compression in testing, a device's junction temperature rise under bias needs to be taken into account. This is illustrated in the next example.

EXAMPLE 9.1 Using the HTOL Model

Estimate the test time to simulate 10 years of life in an HTOL test. The activation energies for the potential failure modes are unknown. Therefore, assume a conservative value of 0.7 eV for the activation energy. The device junction temperature rise is measured to be 15^oC above ambient. The test temperature is $+110^oC$ and the nominal use temperature is $+40^oC$.

SOLUTION: Since the junction temperature rise is 15^oC, then the actual use and test temperatures are
$T_{use}=15^oC + 40^oC = +55\,^oC$

T_{Stress}=15 ^{o}C + 110^{o}C = +125 ^{o}C
From Figure 9.2, the acceleration factor is
A_T= Exp {(0.7 eV/8.6173x10^{-5} eV/^{o}K)×[1/(273.15+55) - 1/(273.15+125) ^{o}K]} = 77.6
From Equation 9.1, the test time to simulate 10 years of life (87,600 hours) is
Test Time=Life Time/A_T=87600/77.6=1,129 hours

9.5.1 Estimating Activation Energy

Tests are often performed to determine a failure mechanism's activation energy. In this case, devices are separately tested in at least two different temperatures. Ideally, three or more temperatures can be used, then test results can be plotted on a semilog graph and the data fitted using a least-squares method. An example is the process reliability study shown in Figure 6.8 where a semilog plot is used related to the linearized model in Figure 9.2. That is, if we plot the Mean Time To Failure (MTTF) on the semilog axis versus 1/T, then according to the equation

$$Ln(MTTF) = Const + \frac{E_a}{K_B}\left\{\frac{1}{T}\right\} \qquad (9.5)$$

the slope is E_a/K_B and the activation energy can be determined as illustrated in the next example.

EXAMPLE 9.2 Determining the Activation Energy

The MTTFs at +250^{o}C and +200^{o}C are 731 and 10,400 hours, respectively, in Figure 6.8. Show that the activation energy is 1.13 eV and that the MTTF at +125^{o}C is 1.95×10^6 hours as indicated in the figure.

SOLUTION: Equation 9.4 can be solved for E_a as

$$E_a = K_B \frac{Ln\{MTTF_2 / MTTF_1\}}{\left(1/T_2 - 1/T_1\right)} \qquad (9.6)$$

Then, the activation energy is

$$E_a = 8.6173x10^{-5}\ eV/^{o}K \frac{Ln[10400/731]}{[1/(273.16+200) - 1/(273.16+250)]\ ^{o}K} = 1.133eV$$

Next, the acceleration factor at +125^{o}C must be determined. Using the procedure in Example 9.1, we have

T_{use}= +125^{o}C
T_{Stress}= +200^{o}C
A_T= Exp {(1.133 eV/8.6171x10^{-5} eV/^{o}K)×[1/(273.15+125) - 1/(273.15+200) ^{o}K]} = 187.6

From Equation 9.1, the MTTF (at +125°C) = MTTF (at +200°C) × A_T = 10400 × 187.7 = 1.951×10^6 hours. The answer is a bit off to the value shown in Fig. 6.8, due to round-off error.

9.6 THB ACCELERATION MODEL

In THB, test devices are put at elevated temperatures and humidity under bias for an extended period of time. For example, the most common THB test is a 1000-hour test at +85°C and 85% Relative Humidity. One of the most common THB models used in the industry is a 1989 Peck model (see Reference 3) shown in Figure 9.3. A derivation is provided in Chapter 14, Section 14.5.2. This includes a relationship between life and temperature (Arrhenius model) and life-and-humidity (Peck model), so that the product of the two separable factors yields an overall acceleration factor.

$$A_T = Exp\left\{ \frac{E_a}{K_B} \left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}} \right] \right\}$$

$$A_H = \left(\frac{R_{Stress}}{R_{Use}} \right)^m$$

$$A_{TH} = A_T A_H$$

$$Ln(t_f) = C + \frac{E_a}{K_B T} - m \ Ln(R)$$

Notation

A_H = Humidity acceleration Factor
A_T = Temperature acceleration factor
A_{TH} = Temperature-Humidity acceleration factor
RH_{stress} = Relative humidity of test
RH_{use} = Nominal use relative humidity
T_{stress} = Test temperature
T_{use} = Nominal use temperature
m = Humidity constant
E_a = Activation energy
t_f = Time to Fail
C = Constant

Figure 9.3 THB Peck acceleration and linearized time to failure models.

EXAMPLE 9.3 Using the THB Model

If a THB test is performed at 85%RH and +85°C, what is the acceleration factor relative to a 40%RH and +25°C environment, assuming an activation energy of 0.7 eV and a humidity constant of 2.66? How many test hours are required to simulate 10 years of life? How many test hours are required in a HAST chamber (see Chapter 5) to simulate 10 years of life at 85%RH and +110 °C?

SOLUTION: The temperature acceleration factor is

$$A_T = \exp\{(0.7\text{eV}/8.6173\text{x}10^{-5}\ \text{eV}/^{o}\text{K})*[1/(273.15+25) - 1/(273.15+85)\ ^{o}\text{K}]\} = 96$$

The humidity acceleration factor is

$$A_H = (85\%\text{RH}/40\%\text{RH})^{2.66} = 7.43$$

Therefore, the combined temperature humidity acceleration factor is

$$A_{TH} = 96 \times 7.43 = 713$$

The simulated test time to equate this to 10 years (87,600 hours) is

$$\text{Test time} = (87{,}600\ \text{hours} / 713) = 123\ \text{hours}$$

The temperature acceleration factor for the HAST test is

$$A_T = \exp\{(0.7\ \text{eV}/8.6173\times10^{-5}\ \text{eV}/^{o}\text{K})\times[1/(273.15+25) - 1/(273.15+110)\ ^{o}\text{K}]\} = 421.8$$

The humidity acceleration factor is the same as in the first part of the problem so that

$$A_{TH} = 421.8 \times 7.43 = 3132.2$$

The simulated test time to equate this HAST test to10 years is

$$\text{HAST test time} = (87600\ \text{hours}/3132) = 28\ \text{hours}$$

When Peck originally proposed this model, he reviewed all published life-in-humidity conditions versus life at +85°C/85%RH for epoxy packages. His results found good agreement with the model. Fitted data found nominal values for E_a to lie between 0.77 and 0.81 and nominal values between 2.5 and 3.0 for m. A thorough study by Texas Instruments (see Reference 4) on PEM moisture-life monitoring, found the activation energy values up around 0.9 eV. Such trends in the literature indicate higher-activation energies, which correspond to trends in improved semiconductor reliability.

9.7 TEMPERATURE CYCLE ACCELERATION MODEL

In Temperature Cycle, test devices are subjected to a number of cycles of alternate high and low temperature extremes. This cyclic stress produced in temperature cycling is related to thermal expansion and contraction undergone in the material. To relate field usage to accelerated test conditions, the most widely used model in industry is the Coffin-Manson (see Reference 1) model. This is a simple model used for estimating the temperature cycle acceleration factor (see Figure 9.4). A derivation of this model is provided in Chapter 14, Section 14.4.2.

Reasonably estimating the acceleration factor depends on the failures being caused by fatigue, subject to the Coffin-Manson law for cyclic strain versus the number of cycles to failure. Values between 2 to 4 have typically been reported in the literature for K. These values are related to the specific design. A value of 2.5 is commonly used for solder-joint fatigue, while 4 is often reported for IC interconnection failures. The lower value 2.5 is a good value for conservative estimates.

$$A_{TC} = \frac{N_{Use}}{N_{Stress}} = \left(\frac{\Delta T_{Stress}}{\Delta T_{Use}} \right)^{K}$$

$$Ln(N_f) = C - K \; Ln(\Delta T)$$

<u>Notation</u>

A_{TC} =Temperature cycle acceleration factor
N_{Stress} =Number of cycles tested
N_{Use} =Equivalent number of field cycles
ΔT_{Stress} =Temperature cycle test range
ΔT_{Use} =Nominal daily temperature change in the field
K =Temperature cycle exponent
N_f =Number of cycles to failure
C =Constant

Figure 9.4 Temperature Cycle acceleration and linearized cycle to failure models.

EXAMPLE 9.4 Using the TC Model

Estimate the number of test temperature cycles to simulate 10 years of life in the field for a test that cycles between -55°C and +150°C. It is estimated that field conditions cycle nominally between -5°C to +25°C twice a day. Assume a conservative temperature cycle exponent of 2.5.

SOLUTION: First use the expression in Figure 9.4 to find the temperature cycle acceleration factor as

$$A_{TC} = (\Delta T_{Stress} / \Delta T_{Use})^{K} = (205^{o}C / 30^{o}C)^{2.5} = 122.$$

In 10 years, the device will be cycled 2 × 365 × 10 = 7300 cycles. Therefore, from Figure 9.3, the number of test cycles to simulate this is

$$N_{Stress} = N_{use} / A_{TC} = 7300 / 122 = 60 \text{ cycles}$$

9.8 VIBRATION ACCELERATION MODEL

In vibration, devices are mounted on a dynamic shaker table and subject to either a random or sinusoidal-type vibration profile. Common random vibration tests are most frequently specified in terms of Power Spectral Density levels (see Figure 9.5). Figure 9.5 illustrates the possible Power Spectral Density test profile levels related to a similar particular use environment. The Power Spectral Density function describes the distribution of vibration energy with respect to frequency. The amount of time compression that can be accomplished is related to the Power Spectral Density test level and use level. Estimates of time compression can be made once the use level estimate and spectral density profile are established. The traditional classical time-compression model (MIL-STD 810E) is a power law model (see Figure 9.6). A derivation of this model is provided in Chapter 14, Section 14.4.3.

In applying this model, it is important to understand the failure mechanism, since in a random vibration-loading environment, the resonance of the material can dominate the fatigue life. Here, maximum vibration amplitudes and stress occurs. However, fatigue failures are not always dominated by the fundamental resonance mode. In practice, many of the stress peaks in the use environment may fall below the fatigue limit of the material, while others will be above the fatigue limit. It follows that an accelerated life test based upon this model should inherently be conservative. However, because most of the fatigue damage occurs at the highest stress peaks in both the test and in actual use, the degree of conservatism is not excessive. As noted in Figure 9.5, the Power Spectral Density is in

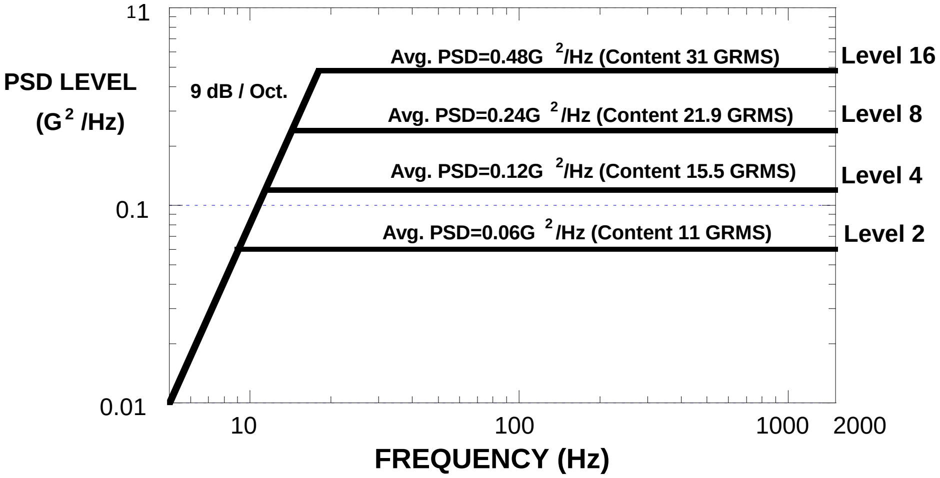

Figure 9.5 Example of common PSD test levels.

units of G^2/Hz. The square of the G stress level at the resonance frequency is directly proportional to the Power Spectral Density level ($W \sim G^2$), so the model can be put in terms of either random or sinusoidal resonance G-stress loading. In the model, the fatigue parameter is related to experimental slope of the stress to cycles to failure data. This exponent varies depending on the fatigue life of the materials involved. For example, the value of $b \approx 5$ is commonly used for electronic boards. However, conservative value for the fatigue parameter b is about 8 (e.g., $M_b=4$). MIL STD-810E (514.4-46) recommends b = 8 for random loading.

$$A_V = \frac{T_{Use}}{T_{Stress}} = \left(\frac{W_{Stress}}{W_{Use}}\right)^{M_b}$$

$$\left(\frac{W_{Stress}}{W_{Use}}\right)^{M_b} = \left(\frac{G_{f_{STRESS}}}{G_{f_{USE}}}\right)^{2M_b}$$

$$Ln(t_f) = C - M_b \ Ln(W)$$

<u>Notation</u>

A_V = Vibration Acceleration factor
T_{Stress} = Vibration duration
T_{Use} = Vibration duration (Nominal)
W = Random Vibration input PSD across the resonance bandwidth (G^2/Hz). W_{stress} is the PSD test stress and W_{use} nominal use PSD
G_f = Resonant G Sinusoid Vibration level
M_b = b/2 where b is the fatigue parameter
t_f = Time to failure
C = Constant

Figure 9.6 Vibration acceleration and linearized time to failure models.

EXAMPLE 9.5 Using the Vibration Model

Estimate the test time to simulate 10 years of life in the field for an assembly that is tested to a Level 4 PSD random vibration test condition, shown in Figure 9.5. It is estimated that the assembly will undergo a worst case Level 1 type random vibration exposure 1% of the assembly's life. The rest of the assembly's life is relatively benign in terms of vibration exposure.

SOLUTION: First use the expression in Figure 9.6 to find the vibration acceleration factor. Since Level 4 has a PSD of 0.12 G^2/Hz, then Level 1 is 0.03 G^2/Hz. Therefore,

$$A_V = (W_{Stress} / W_{Use})^{Mb} = (0.12/ 0.03)^4 = 256.$$

In 10 years, the device will be exposed to a Level 1 vibration for about 87,600 × 0.01 = 876 hours. Therefore, from Figure 9.6, the number of test cycles to simulate this is $T_{Stress}=T_{use} / A_V = 876 / 256 = 3.5$ hours.

9.9 ELECTROMIGRATION ACCELERATION MODEL

Electromigration is a failure mechanism caused in a microelectronic conductor exposed to high current densities or a combination of high temperature and current density. The most common failure mode is a conductor open. This failure mechanism comes about from high current densities that create crowded electron flux in the microelectronic conductive path. Often, the term “electron wind” has been historically used for the scattering mechanism causing failure. The metal reaches a stage at which collision between the electrons and film atoms and defects sites becomes catastrophic. Electron scattering from defect sites is considered to dominate. The collision rate increases to the point that atoms of the metal film drift in the direction of the electron flow. Eventual catastrophic problems result due to local inhomogenous regions in the metal combined with the metal movement.

Generally, the Black equation (see Reference 6 and 7) is widely used for making MTTF electromigration predictions in the literature. For the electromigration acceleration factor due to the Black equation, see Figure 9.7. Numerous values for the Black equation parameters n and E_a have been reported in the literature. As lower values are used, the estimates become more conservative. Numerous experiments have been performed under various stress conditions in the literature and values for n have been reported in the range between 2 and 3.3 and between 0.5 to 1.1 eV for E_a.

EXAMPLE 9.6 Using the Electromigration Model

An electromigration experiment performed on aluminum conductors at $+185^oC$ and a current density of 3×10^5 A/cm^2 found a MTTF of 2000 hours. Estimate the MTTF at a use condition of $+100^oC$ and a current density of 2×10^5 A/cm^2. Use conservative parameter estimates of $E_a = 0.5$ eV and $n = 2.0$.

SOLUTION: First find the temperature acceleration factor, which is

$$A_T = \left(\frac{J_{Stress}}{J_{Use}}\right)^n Exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}}\right]\right\}$$

$$Ln(t_f) = C + \frac{E_a}{K_B T} - nLn(J)$$

<u>Notation</u>

A_J =Electromigration acceleration factor
T_{stress} =Test temperature (°K)
T_{use} =Use temperature (°K)
E_a =Activation energy
K_B = 8.6173×10^{-5} eV/°K (Boltzmann's constant)
J =Current density
n = Current density exponent
t_f =Time to failure
C =Constant

Figure 9.7 Electromigration acceleration and linearized time to failure model.

$$A_T = \exp\{(0.5\ \text{eV}/8.6173\times10^{-5}\ \text{eV}/^{o}\text{K})\times[1/(273.6 + 100) - 1/(273.6 + 185)\ ^{o}\text{K}]\} = 17.9$$

The current density factor is

$$A_c = (3\times10^5\ \text{A/cm}^2 / 2\times10^5\ \text{A/cm}^2)^2 = 2.25$$

The product provides the electromigration acceleration factor

$$A_J = A_T A_c = 17.9 \times 2.25 = 40.3$$

The MTTF at use condition can then be estimated as

$$MTTF_{Use} = MTTF_{Stress} \times A_J = 2000 \times 40.3 = 80{,}600 \text{ hours} = 9.2 \text{ years}$$

9.10 FAILURE-FREE ACCELERATED TEST PLANNING

There are numerous types of accelerated tests. Any test that in some way accelerates environmental use conditions is an accelerated test. Two of the most common types of accelerated tests used in industry are catastrophic and failure-free testing. In a catastrophic accelerated test, a frequent objective is to estimate the failure rate at a use condition. A number of examples to estimate the MTTF at use condition (see Example 8.7) have been provided. Note that in each case, one had to assume conservative values of model parameters such as the activation energy. Example 9.2 illustrated how in a process reliability study, the activation energy for a particular failure mode can be estimated.

In Chapter 4, Design Maturity Testing (DMT) was discussed. DMT is based on failure-free testing. The main objective of a DMT test is to determine whether a design will meet its reliability objective at a certain level of confidence. This requires that a statistically significant sample size be tested in a number of different stress tests. This topic was introduced in Section 4.6. In Chapter 8, an example was provided on accelerated demonstration versus statistical sample planning. However, at this point, we would like to illustrate how to conservatively plan a DMT to demonstrate that a particular reliability objective can be met.

EXAMPLE 9.7 Designing a Failure-Free Accelerated Test

Plan accelerated tests for a failure-free DMT to demonstrate that a plastic-packaged IC will meet its reliability objective of 400 FITs (Objective 4, Figure 4.3) at the 90% confidence level. Estimate the sample size required and test times needed to show that this component is failure-free of any HTOL, THB, and TC type failure modes. Use the acceleration factors found in Examples 9.1, 9.3, and 9.4 in your design.

SOLUTION: A full DMT test for this component will include nonaccelerated tests as well. Figure 4.5 illustrates the concept and Chapter 4 describes DMT in detail. To design the accelerated testing portion, first estimate a practical test duration. For example, we can target the test to last about a 1000 hours for HTOL and THB, and about 100 temperature cycles. Once we have fixed the test time, we next must estimate a statistically significant sample size at the 90% confidence level. We can assume that each test will check for different failure modes. This means that each test should be allocated a portion of the failure rate. One allocation plan is described in Section 4.2 where THB, TC, and HTOL type failure modes were assigned 20, 30, and 50% respectively of the total reliability. Using this plan, the 400 FITs is broken up with 80, 120, and 200 FITs to THB, TC, and HTOL tests, respectively. At this point, a single-sided chi-square estimate for sample size planning can be used. This is detailed in Section 4.6 where the sample size N is given

$$N(HTOL)=\chi^2(90\%, 2Y+2)/2\lambda At$$

For example, the TC values are

$Y=0$ Failures

$\chi^2(90\%, 2)=4.605$

$\lambda=120$ FITs$=1.2 \times 10^{-7}$ failure/hour

$A=122$ (from Example 9.4)

$t=100$ cycles x 24 Hours=2400 equivalent test hours

Thus,

$$N=4.605/(2\times 1.2\times10^{-7}\times 122 \times 2400)=66 \text{ devices}$$

Using this same approach for the other tests, the results are summarizes below.

Table 9.1 Summary of DMT Test for Example 9.8

Accelerated Test	Acceleration Factor	Test Time	FITs	Sample Size
HTOL	78	1000	200	148
THB	713	1000	80	41
TC (100 Cycles)	122	2400	120	66

9.11 STEP-STRESS TESTING

Step-stress testing is an alternative test to life testing. In step-stress testing, usually a small sample of devices are exposed to a series of successively higher and higher steps of stress. At the end of each stress level, measurements are made to assess the results to the device. The measurements could be simply to assess if a catastrophic failure has occurred, or to measure the resulting parameter shift due to the step's stress. Constant time periods are commonly used for each step-stress period. This provides for simpler data analysis. The concept is shown in Figure 9.8. Note that the failure distribution over the stress levels is usually experimentally found to be normally distributed. This is a consequence of a normally distributed strength distribution (see Figure 9.1). Therefore, the plot of CDF versus stress should be plotted on a normal probability plot. In general, if the data does not fit a normal probability plot, other distributions should be tried. An example of a CDF that is normally distributed over temperature step-stresses, is provided in Example 9.10, in Section 9.12.1 (see Section 8.4.3 on normal probability plotting). Although not shown in this plot, stress data at high stress levels will often deviate from normality. This most likely indicates that high stress levels can cause nonlinear changes in the material under test such as a phase change, thus the materials strength departs from observed normality.

There are a number of reasons for performing a step-stress test, including:

- Aging information can be obtained in a relatively short period of time. Common step-stress tests take about 1 to 2 weeks, depending on the objective.
- Step-stress tests establish a baseline for future tests. For example, if a process changes, quick comparisons can be made between the old process and the new process. Accuracy can be enhanced when parametric change can be used as a measure for comparison. Otherwise catastrophic information is used.
- Failure mechanisms and design weaknesses can be identified along with material limitations. Failure-mode information can provide opportunities for reliability growth. Fixes can then be put back on test and compared to previous test results to

assess fix effectiveness.

- Data analysis can provide accurate information on the stress distribution in which the median-failure stress and stress standard deviation can be obtained. This then provides an MTTF estimate at the median failure stress level.

9.11.1 Temperature Step-Stress

Probably the most common step-stress is temperature. In a Temperature Step-Stress, catastrophic data are plotted on a normal probability plot with the cumulative failure percent versus 1/temperature (in ^{o}K). Data is plotted this way because the CDF is a function of 1/T. This is shown later in Section 9.12.1, Example 9.10. Figure 9.9 is an example of this type of plot. The data (see Example 9.8) resulted from two Temperature Step-Stress experiments, one having equal 10-hour time steps and the other with 150-hour time steps. From Figure 9.9, the mean stress points (where 50% of the distribution has failed) are +139°C and +225^{o}C. Since these are mean stress points, it also provides a MTTF estimate for the step time. For example, these points can be used to estimate the activation energy for the failure mode (see Example 9.8).

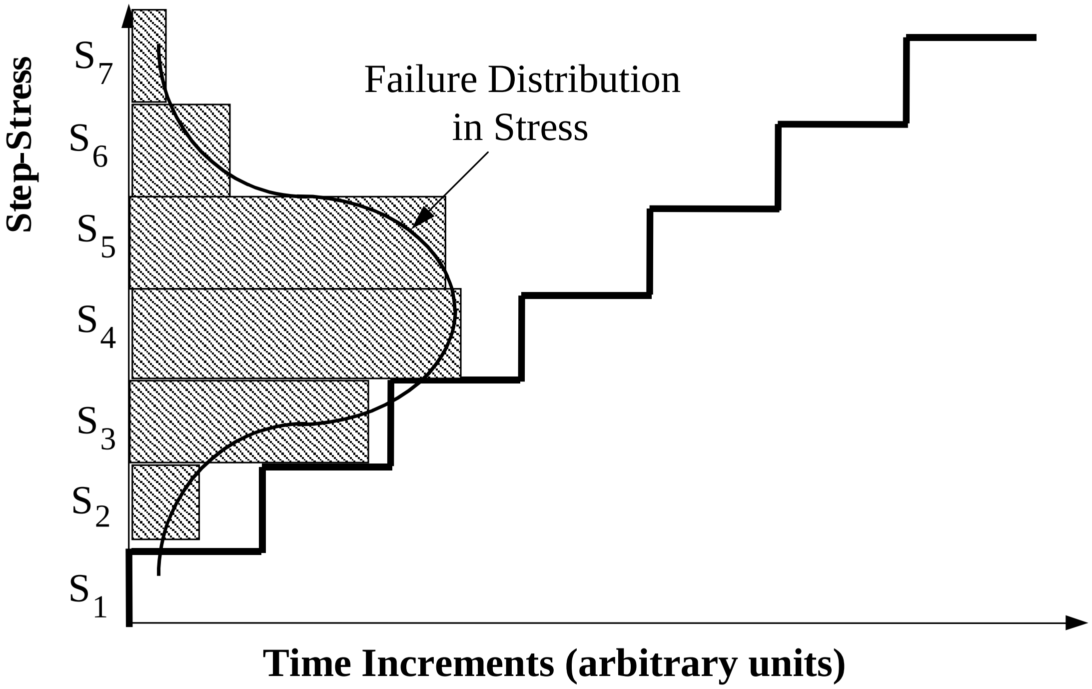

Figure 9.8 Concept of step-stress testing.

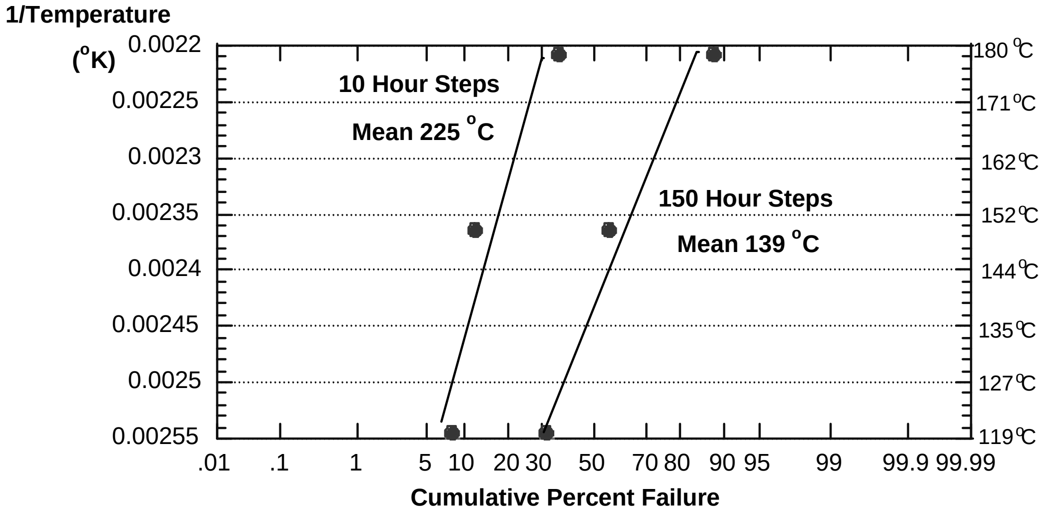

Figure 9.9 Data plot from two temperature step-stress tests.

Since step-stress data has been carried out in constant time steps, some accumulation of residual effects at each step occurs from previous stress-steps. This makes the data slightly off. A step stress correction can improve accuracy of estimating the mean stress point. The next example will illustrate how step-stress accuracy can be improved.

EXAMPLE 9.8 Temperature Step-Stress Analysis

The data for two temperature step-stress times from an experiment is provided in Table 9.2. Twenty-four parts were tested. In the first Temperature Step-Stress test, 10-hour steps were used; in the second experiment, 150-hour steps were used. Plot the data, determine the mean stress values, and estimate the activation energy for the two tests. Provide a correction for each data point and re-estimate the activation energy from the correction. When is it reasonable to provide a correction? What is the estimated MTTF at +25°C.

Table 9.2 Temperature Step-Stress Data for Figure 9.9

Temperature (°C)	1/T(°K)	No. Failures 10 Hour Steps	Cum % Failure 10 Hr. Steps	No. Failures 150 Hr. Steps	Cumulative % Failure 150 Hr. Steps i/(n+1)
120	0.002545	2	8	8	32
150	0.002364	1	12	6	56
180	0.002208	6	36	8	88

SOLUTION: The number of failures is shown in Table 9.2. In Temperature Step-Stress data, 1/T (°K) is plotted versus the cumulative percent failure. Therefore, data are arranged in the table for plotting directly. Note that the cumulative percent failure is obtained as described in Chapter 8 using i/n+1 values. The data has been plotted previously in Figure 9.9 and the mean stress values are +225°C and +139°C for the 10-hour and 150- hour tests, respectively. Note these times are MTTF values at their respective temperatures. With these values, an activation energy can be obtained similarly to Example 9.2 as

$$E_a = 8.6173\times10^{-5}\ \mathrm{eV}/^{o}\mathrm{K}\ \ln[150 / 10]/\{1/(273.15+139) - 1/(273.15+225)\} = 0.557\ \mathrm{eV}$$

The accuracy of this data can be improved with a Temperature Step-Stress correction. If the stress steps are incrementally large enough, usually a correction is not necessary. In this experiment, the stress steps are 30°C apart, which is borderline. Therefore, a correction may improve accuracy. Consider the 10-hour TSS data. First, correct the +150°C data point. Devices received 10 hours of exposure at +150°C, but they had already been exposed to 10 hours at +120°C. According to Example 9.1, the acceleration factor between +120°C and +150°C with an E_a of 0.56 is

$$A_T= \exp\{(0.56\ \mathrm{eV}/8.6173\times10^{-5}\ \mathrm{eV}/^{o}\mathrm{K})\times[1/(273.15+120) - 1/(273.15+150)]\ ^{o}\mathrm{K}\} = 3.23$$

Therefore, devices failing at the +150°C point had received 10 hours at +120°C and now 10 hours at +150°C prior to failing. The total exposure is actually equivalent to

$$10 + 10/3.23 = 13.1\ \text{hours}$$

at +150°C. However, to replot this data point more accurately as a 10-hour failure point, find the temperature at 10 hours that is equivalent to 13.1 hours of exposure at +150°C. To do this, solve Equation 9.4 for T_2 in degrees centigrade. This is

$$T_2(^{o}\mathrm{C}) = [(0.000086173/E_a)\times\ln(t_1/t_2)+1/(T_1+273.15)]^{-1} - 273.15$$

Inserting the appropriate values, the temperature correction is

$$T_{\mathrm{Correction}}(^{o}\mathrm{C}) = [(0.000086173/0.56)\times\ln(10/13.1)+1/(150^{o}\mathrm{C}+273.15)]^{-1} - 273.15=157.6^{o}\mathrm{C}$$

Therefore, the corrected temperature is +157.6°C. This is a more accurate temperature value for plotting the failures at this 10-hour step-stress point. In a similar manner, one can estimate that the 10-hour equivalent temperature at +180°C, which is +192.6°C. The corrected values are shown in Table 9.3. As an exercise, the reader can verify these values. The data can now be repotted. This is not shown here as the plot is very similar to Figure 9.9. However, the means obtained from the corrected plot are +224°C and +143°C for the 10-hour and 150-hour steps, respectively. With these new values, our estimates can be refined for the activation energy. The new estimate with these corrected temperatures is

$$E_a = 8.6173\times10^{-5}\ \mathrm{eV}/^{o}\mathrm{K}\ \ln[150 / 10]/\{1/(273.15+143) - 1/(273.15+224)\} = 0.596\ \mathrm{eV}$$

Using this value, the MTTF at +25°C can be predicted. The acceleration factor between +25°C and +143°C is 719. Since the MTTF at +143°C is 150 hours, then at +25°C the predicted MTTF is 107,813 hours (= 719 x 150).

It is important to note when it is reasonable to provide Temperature Step-Stress corrections. Since in many step-stress experiments, devices are measured only once, at the end of each step, the exact failure time is not known. In this case, it is probably not worth providing a correction, especially if the correction is relatively small, since devices could have failed at any point during the step time. However, if devices are monitored during the test period, and exact failure times are recorded, then the correction can be helpful.

Table 9.3 Corrected Temperature Step-Stress Data

Test Temperature (°C)	10 Hour Time Equivalent	150 Hour Time Equivalent	Temperature Correction (Same for both Time steps!)
120	10	150	120
150	13.1	196.5	157.6
180	14.7	221.1	192.6

9.12 DESCRIBING LIFE DISTRIBUTIONS AS A FUNCTION OF STRESS

It is instructive to illustrate how to incorporate a stress model into a life distribution. This can be illustrated for both the power law form and the Arrhenius function. These will be incorporated into the CDF and PDF for the log-normal distribution. Consider the Arrhenius temperature and the vibration models given in Figures 9.2 and 9.6. The time to failure is written in linear form and repeated here for convenience. For Figure 9.2, this is

$$Ln(t_f) = C + \frac{E_a}{K_B T}$$

and for Figure 9.6, it is

$$Ln(t_f) = C - Mb\ Ln(W)$$

Experimentally, the time to failure can be assessed at any time. For the log-normal distribution, these parameters apply to the median time to failure, $t_f = t_{50}$. This allows for a direct substitution into the log-normal distribution functions of Figure 8.15. Inserting the Arrhenius function into the PDF reads

$$f(t,T) = \frac{1}{\sigma_t(T)t\sqrt{2\pi}} \quad \exp\left\{-\frac{1}{2}\left(\frac{Ln(t)-\left(C+\dfrac{E_a}{K_B T}\right)}{\sigma_t(T)}\right)^2\right\}$$

and for the vibration model, this is

$$f(t,W) = \frac{1}{\sigma_t(W)t\sqrt{2\pi}} \quad \exp\left\{-\frac{1}{2}\left(\frac{Ln(t)-\left(C - Mb\ \ Ln(W)\right)}{\sigma_t(T)}\right)^2\right\}$$

Similarly, inserting the Arrhenius model into the Cumulative Distribution Function (using the error function form in Figure 8.15) reads

$$F(t,T) = \frac{1}{2}\left[1 + erf\,(\frac{Ln(t) - \left(C + \dfrac{E_a}{K_B T}\right)}{\sqrt{2}\sigma_t(T)})\right]$$

and for the vibration model, this is

$$F(t,W) = \frac{1}{2}\left[1 + erf\,(\frac{Ln(t) - \left(C - Mb\ \ Ln(W)\right)}{\sqrt{2}\sigma_t(T)})\right]$$

Similar expressions can be found for the CDF and PDF of any life distribution function when t_f is appropriately found. As an exercise, find these for the common Weibull function given in Table A.2, Chapter 8. (Hint: assume that $t_{.632}=t_f$, this then is the characteristic life α_w in the table.)

9.12.1 Stress Dependent Standard Deviation

In these above expressions, note that sigma may be temperature dependent. Usually, there is not enough data to determine this dependence and sigma is treated as a constant over stress. If we did wish to determine it experimentally, this can be obtained or modeled. For example, sigma can be determined at each stress level and fitted over stress. That is, stress can be empirically modeled as some function of x [Ref. 1] i.e.,

$$\sigma(x)=f(\gamma+\gamma_0 x)$$

However, in an experiment, such as life tests over temperature stress, we already have a failure time model and most likely the mean-time-to-failure has been fitted at each temperature level. That is

$$Ln(\bar{t}_f) = C + \frac{E_a}{K_B T} = C_{50\%} + \frac{E_{a50\%}}{K_B T}$$

is experimentally estimated from the data. Here the constants have been identified from fitting the mean-time-to-failure fit over stress. Additionally, we could also obtain a fit to the data at the 16th percentile points in the distribution over stress denoted here as

$$Ln(t_f)_{16\%} = C_{16\%} + \frac{E_{a16\%}}{K_B T}$$

This gives a model for sigma based on the physical aging law and the data itself as

$$\sigma_t(T) = Ln(\bar{t}_f) - Ln(t_f)_{16\%} = \Delta C + \frac{\Delta E_a}{K_B T}$$

EXAMPLE 9.9 CDF as a Function of Stress

For the vibration function, let C = -7.82, Mb = 4, and find F(t,W) for t = 10 years and W = 0.0082 G^2/Hz. Find F at 10 years. Use $\sigma=2.2$ for your estimate. If the stress level is reduced by a factor of 2, what is F?

SOLUTION: Inserting these values into the CDF above reads,

$$F(t,W) = \frac{1}{2}\left[1 + erf\left(\frac{\ln(87600) - \left(-7.82 - 4 \quad Ln\left(0.0082\right)\right)}{\sqrt{2}\left(2.2\right)}\right)\right]$$

or

$$F(87600,0.0082) = \frac{1}{2}\left[1 + erf\left(\frac{-0.0139}{\sqrt{2}\left(2.2\right)}\right)\right] = \frac{1}{2}\left[1 - erf\left(\frac{0.0139}{\sqrt{2}\left(2.2\right)}\right)\right] = 0.497$$

Thus, at this stress level, 49.7% of the distribution is anticipated to have failed in 10 years. (Note, in the above derivation, the error function values can be found from tables or in Microsoft Excel type, =erf(0.00447) to obtain the above value.) If the stress level is reduced by a factor of 2, then W = 0.0041 G^2/Hz. The anticipated percent failure at 10 years is reduced to F(87600,0.0041) = 10.27%.

EXAMPLE 9.10 Relationship Between a Stress and Time Standard Deviation

Provide a CDF model for the temperature stress distribution and find a relationship between the standard deviation for stress σ_T and for time σ_t. Use this relationship to estimate σ_t from a step-stress experiment. The temperature step-stress experiment was run with 24-hour increments. Data indicated that 50% of the devices fail at 250°C (523°K) and 16% fail at 200°C (473°K). The failure mechanism activation energy is 1.3 eV.

SOLUTION: The model for the combined CDF time and stress distribution is given above by F(t,T). We can substitute in the general relationship for the time to fail

$$Ln(t_f) = C + \frac{E_a}{K_B T}$$

which holds for both the MTTF and for any time giving

$$F(t,T) = \frac{1}{2}\left[1 + erf\left(\frac{\left(C + \frac{E_a}{K_B T}\right) - \left(C + \frac{E_a}{K_B \overline{T}}\right)}{\sqrt{2}\sigma_t}\right)\right]$$

Simplifying this expression gives

$$F(t,T) = \frac{1}{2}\left[1 + erf\left(\frac{\left(\frac{1}{T} - \frac{1}{\overline{T}}\right)}{\sqrt{2}\,\frac{K_B}{E_a}\sigma_t}\right)\right] = \frac{1}{2}\left[1 + erf\left(\frac{\left(\frac{1}{T} - \frac{1}{\overline{T}}\right)}{\sigma_S}\right)\right]$$

By comparison, the relationship between the standard deviations is

$$\sigma_t = \frac{E_a}{K_B}\sigma_S$$

To solve for the second part of the problem, note from any normal distribution table that $(1/T)_{50\%}$-$(1/T)_{16\%}$ is approximately one standard deviation apart. Therefore,

$$\sigma_S \approx \frac{1}{473} - \frac{1}{523} = 0.000202 \quad \text{and}$$

$$\sigma_t = \frac{1.3eV}{8.62x10^{-5}} 0.000202 = 3.05$$

9.13 SUMMARY

In this chapter, accelerated testing has been described. The general objective in accelerated testing is to accelerate time and predict information about the products reliability. However, a further objective not discussed is to grow reliability through testing and fixing failure modes. This is the topic of the next chapter.

9.14 REFERENCES

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