LIFE TESTING

Modern electronic products demonstrate very high reliability when operated in their intended normal usage environment. Therefore, it is difficult to perform a reliability test for wear-out failures. One approach to obtain meaningful life data for reliability prediction is accelerated life testing. In accelerated testing, the reliability characteristics of products are measured quantitatively under accelerated stress conditions that are more severe than the normal operating level, in order to induce failures within a reduced time period. The advantages of accelerated tests are the economic saving and quick turnaround during development of new products or mature products subject to manufacturing and process changes.

The accelerated life tests have been conducted in many applications such as failure mode examination, endurance/durability investigation, environmental stress screening, and reliability improvement/growth management. Failure mode examination tests attempt to identify the main failure modes and site of a system under certain environmental conditions. Endurance/durability tests are used to provide reasonable assurance that life requirement will be met. Accelerated environmental stress screening is an approach to remove causes of the early failure resulting from defects due to inadequate manufacturing and assembly processes. Accelerated reliability improvement/growth tests are used to achieve ultimate reliability goals by improving the design or manufacture based on the information obtained from the tests.

The objective of accelerated life testing is to estimate mean time to failure, failure rate, and life distribution of the products and extrapolate the results to normal usage condition. Since the interest is to obtain absolute value of the life, the applied stress should be based on the operating stress in-service mission profile. Although the data obtained from these tests can be treated in a relative manner, the product failures in these tests must be associated with failure that could arise under field use conditions. It is very important to identify the failure mechanism and elevate the accelerated stress only to the extent that the failure mechanism is not changed. In accelerated life test design and test data interpretation, it is always necessary to understand what acceleration model will be used for a particular failure mechanism, how it is influenced by the nature of the testing, and how varying the rate of application of the accelerated stress influences the life of a product.

The technique of accelerated life testing incorporates the selection of accelerated stress and acceleration level, test procedure design such as multiple level acceleration or step stress acceleration, and test data extrapolation including physical model determination and statistical inference model selection.

TYPES OF ACCELERATED TESTING

The accelerated life tests can be classified into constant stress test, step stress test, progressive stress test, cyclic stress test, and random stress test based on the pattern of applied stresses.

Constant Stress Test

The constant stress life test is a most common accelerated test, which is used by many standard test methods such as the military standard for the electronics industry. In this type of test, each specimen is run at a constant stress level for a prespecified time period or until failure. Usually, the products are tested at different levels. As shown by the stress–life plot in Fig. 1, the time-to-failure (life) data of seven products at the second stress level are depicted by solid circles. At stress level 1, another seven products are tested; five products run to failure, and two remained unfailed at a prespecified time shown by open circles.

Two advantages of the constant accelerated life test are that it is easy to maintain the test conditions and easy to perform the test data analysis. The inference models for the constant stress test are well developed and empirically verified, and there are historical data of similar products for comparison.

Step Stress Test

In the step stress test, specimens are tested initially at an operational stress level but after a certain holding time the stress level is increased step wise to different levels for the same holding times until failure. Usually all specimens go through the same specified stress pattern. Sometimes different stress patterns are applied to different specimens. Figure

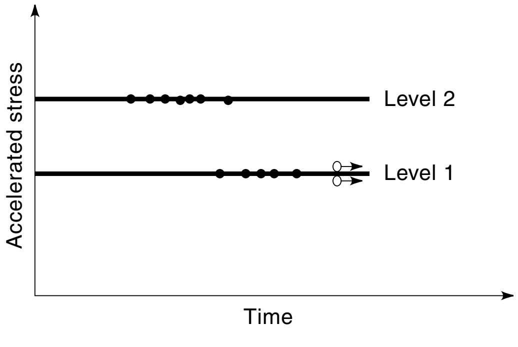


Figure 1. Constant stress acceleration.

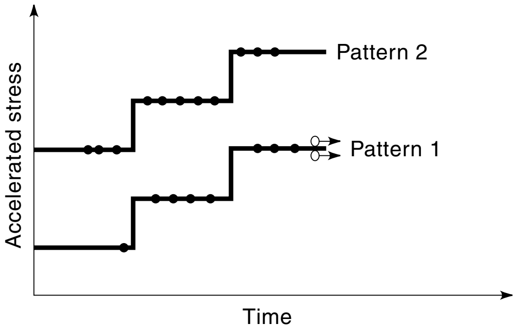


Figure 2. Step stress acceleration.

2 depicts two stress patterns with the failure data represented by solid circles and unfailed data represented by open circles. Compared to the constant stress test, step stress testing reduces test time and assures that failure occurs quickly. This assurance comes from correctly selecting the stress level and holding times.

The failure mechanism at high stress levels may be different from the one at lower stress levels, and this is something engineers often fail to note. The reliability inference model to account for the effect is usually very complicated. The step stress tests are therefore often carried out as comparisons for products with different designs and manufacture, or as preliminary activity before more complex and expensive constant stress tests. Compared to constant stress tests, the step stress tests generate a life test more quickly. However, these data might be less precise due to the simplified hypotheses that each step is not influenced by previous ones.

Step stress testing is often performed with temperature acceleration. The stress steps between various temperatures are around 25°C. The step stress tests are relatively easy to accomplish and do not require many samples.

Progressive Stress Test

In the progressive stress test, a specimen undergoes a continuously increasing level of stress. Different groups of specimens may undergo progressive stresses at different rates. Figure 3 depicts such a test with two linear increasing stress rates. Usually, specimens tend to have a longer lifetime before failure at a lower stress rate. Compared to constant stress acceleration, the progressive stress test is difficult to perform, especially in accurately controlling the applied stresses.

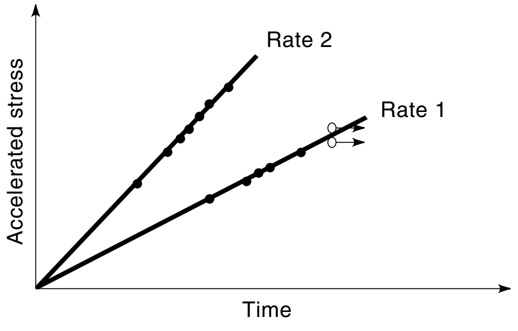


Figure 3. Progressive stress acceleration.

Cyclic Stress Test

Many products repeatedly undergo cyclic stress due to environmental temperature change, device power cycles, mechanical vibration, dc voltage, and so on. A cyclic stress test for a product repeatedly loads a specimen with the same stress pattern at a high level of the stress range, a high level of mean stress, or a high frequency, as shown in Fig. 4. For most products, the stress cycle is sinusoidal. If the mean stress is always zero, the accelerated stress can be characterized by the level of stress range or stress amplitude, as shown by Fig. 4(a). For the purpose of modeling and data analysis, such cyclic stress is regarded as a constant, and it can be depicted as in Fig. 1, where the vertical axis should be the stress range or stress amplitude. A cyclic stress can also be accelerated by increasing the level of the mean stress or frequency, as shown by Fig. 4(b,c).

Random Stress Test

Some products in operation undergo randomly changing levels of stress, as depicted in Fig. 5. For example, airplane components undergo wind buffeting, while automobile electronic systems undergo random vibration. An accelerated test typically employs random stress with the same distribution as actual random stress but at high levels. Like cyclic stress tests, random stress models employ some characteristics of the stress distribution, such as root mean square (rms) or power spectral density (PSD). In Fig. 5 the irregularity of the

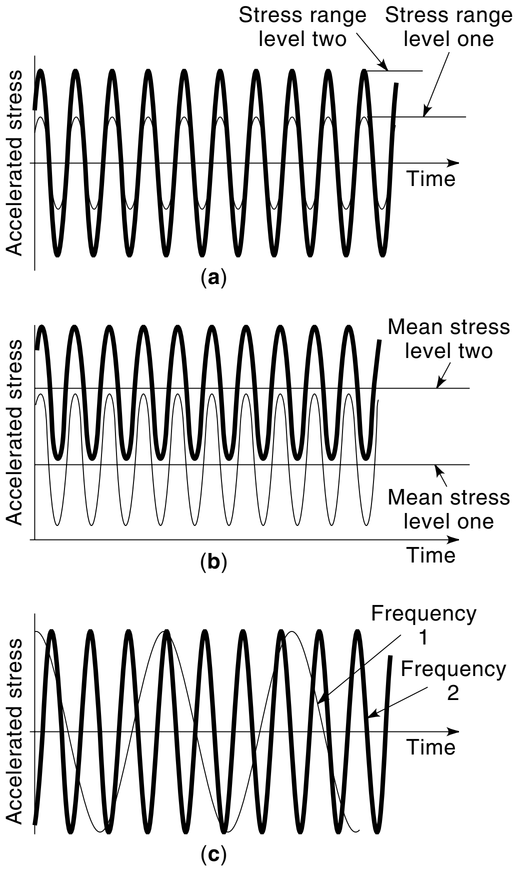
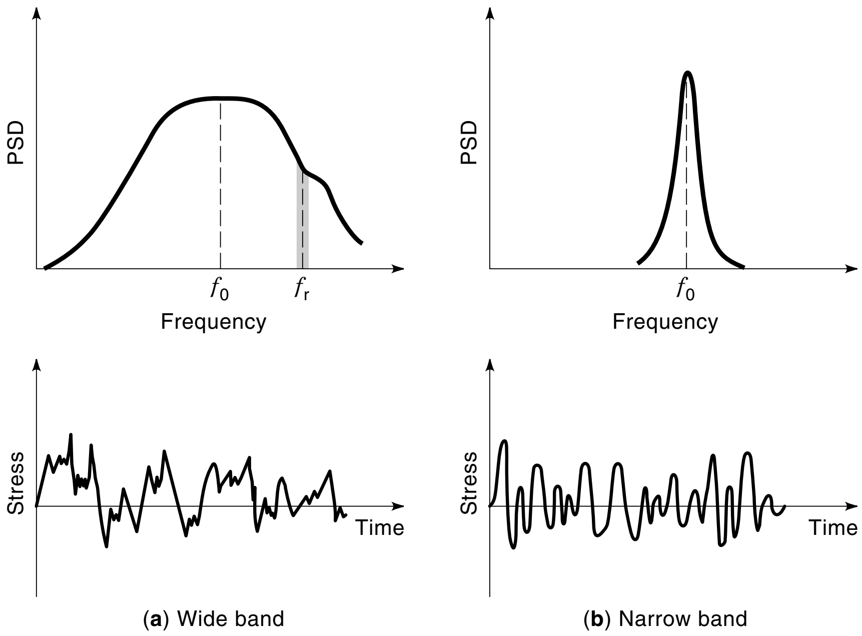


Figure 4. Cyclic stress acceleration.



(**a**) Wide band

(**b**) Narrow band

Figure 5. Accelerated random vibration.

random stress can be represented by the bandwidth of the PSD diagram.

Termination of Accelerated Tests

In accelerated life tests, there are two ways to terminate the test: time-terminated tests and failure-terminated tests. Time-terminated tests are terminated after a predefined number of test clock-hours T_o, have elapsed. The number of failed components during the test time, n_f, and the corresponding time to failure of each component are recorded. At the end of the test there are $n - n_f$ survivors, where n is the total number of tested products. All that is known about the survivors is that the times of failure are beyond T_o. The time-terminated test has the advantage of ensuring that schedules are met, since the test duration is set in advance. However, as a random quantity, the number of total failures is not established. Since the precision of the hazard function depends on the number of failures and not on the number of total components being tested, a bad choice of sample size or test conditions may result in insufficient information.

Failure-terminated tests are terminated when a predefined number of component failures, n_f, have occurred. The time to failure of each failed component and the time, T_{n_f}, that the last failure occurred are recorded. This procedure has an advantage in guaranteeing adequate data. However, the length of test time is random and open-ended.

The degree of stress acceleration in an accelerated life test is usually expressed by an acceleration factor (AF), which is defined as the ratio of the mean time to failure (MTTF) under normal use conditions, $\mathrm{MTTF_n}$, and that under the accelerated condition, $\mathrm{MTTF_a}$:

$$\mathrm{AF} = \frac{\mathrm{MTTF_n}}{\mathrm{MTTF_a}} \tag{1}$$

The acceleration factor can be calculated from a damage model that gives a functional relationship between MTTF and accelerated stress. In calculating the acceleration factor, one must be careful because the damage model may be valid only for a certain range of the stress values and may not apply outside these limits. One should keep in mind that a shift in failure mechanism may occur, calling for the use of a different model.

ACCELERATED STRESSES

In accelerated life testing, the physical quantity that directly causes or is the predominant cause of the time-dependent failure is selected as the accelerated stress. Accelerated stresses can include thermal stress, such as temperature, temperature cycles, or rate of temperate change; chemical stress, such as humidity, corrosives, acid, or salt; electrical stress, such as voltage, current, or power; and mechanical stress, such as vibration loading, mechanical stress range, or strain range. The most commonly used accelerated stresses are discussed next.

Accelerated Temperature

Temperature is known to vary the rates of many physical and chemical reactions. Because the failure mechanisms of many electronic products are basically physical/chemical processes, temperature is often used as the acceleration stress in life testing. The life dependence of a product on temperature can be modeled by the Arrhenius model:

$$\ln(\mathrm{MTTF}) = \ln(A) + (E_A/k)(1/T) \tag{2}$$

where E_A is the activation energy for the failure mechanism under consideration, k is Boltzmann's constant (8.617×10^{-5} eV/K), and T is the absolute temperature. Equation (2) illustrates that the natural logarithm of time to failure varies linearly with the inverse of the absolute temperature for a given mechanism. Figure 6 shows a plot of the inverse of junction temperature versus the time to failure of a device on a log scale.

The Arrhenius model should be used when only one failure mechanism occurs, so that E_A has a constant value that char-

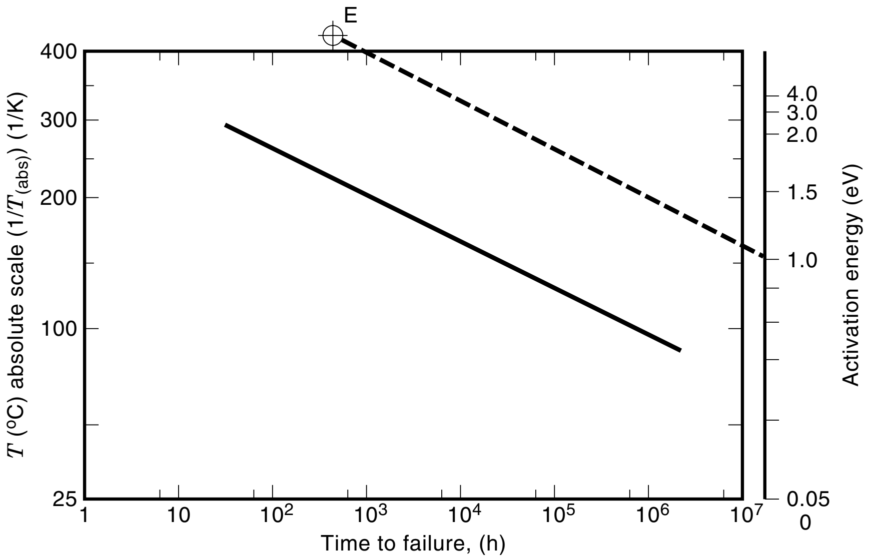


Figure 6. Accelerated temperature.

acterizes the failure mechanism. As shown in Fig. 6, the activation energy can be obtained by drawing a line from the reference point E parallel to the curve obtained. The intercept of this line (dashed line in Fig. 6) on the right-hand side scale gives the activation energy of the failure mechanism. Table 1 lists activation energies for various failure mechanisms.

The acceleration factor for the Arrhenius reaction rate model is

$$\mathrm{AF} = \exp\left[\frac{E_\mathrm{A}}{k}\left(\frac{1}{T_\mathrm{n}} - \frac{1}{T_\mathrm{a}}\right)\right] \tag{3}$$

where T_n and T_a are the temperatures in a normal usage environment and under accelerated test conditions, respectively.

Accelerated Humidity

The failure mechanisms affected by humidity include corrosion of metallization, electrolytic conduction between electrically biased metallization paths, and charge separation on the surface of metal oxide semiconductor (MOS) structures. In plastic encapsulated devices, the failure related to moisture absorption results mainly from corrosion of the aluminum

Table 1. Activation Energies for Various Failure Mechanisms of Silicon Devices

Sensitive Element	Failure Mechanism	Relevant Factors[a]	Accelerating Stress[a]	Typical Activation Energy
Dielectric and interfaces Si dielectric	Accumulation of surface charges	T, E/V	T, V	1.0–1.05 eV (leakage-type failures)
	Breakdown	T, E/V	E, T	0.3–0.6 eV (0.36 eV for MOS gate structures)
	Oxide pinholes	T, E/V	E, T	1.0 eV (dielectric breakdown of bipolar devices)
	Ionic contamination	T	T	1.0 eV
	Hot carrier trapping in oxide	E/V, T	E, T	−0.06 eV
	Charge loss	E, T	E, T	0.8 eV (MOS)
Metallization	Electromigration	T, J	T, J	1.0 eV (large grain Al, glassivated)
		Grain size		0.5 eV (small grain Al)
				0.7 eV (small grain Cu-Al)
	Contact electromigration	T, J	T, J	
	Si in Al			0.9 eV
	Al at sidewalls			0.8–1.4 eV
	Contact metal migration through barrier layer	T	T	1.8 eV
	Corrosion	Contamination	H, E/V, T	0.3–0.7 eV (Al)
	Chemical			0.6–0.7 eV (for electrolysis)
	Galvanic			0.65 eV (for corrosion mechanism)
	Electrolytic			E/V may have thresholds
Metal interfaces	Intermetallic compounds (Au, Al)	T, impurities, bond strength	T	1.0 eV (for open wires or high-resistance bonds at the pad bond due to Au-Al intermetallics)
Wafer fabrication and assembly-related defects	Metal scratches	T, V	T, V	0.5–0.7 eV 0.7 eV for assembly-related defects

[a] H = humidity, V = voltage, E = electric field, T = temperature, J = current density.

metallization. The chemical reaction of aluminum with hydroxyl and hydrogen ions, produced by the electrolysis of water aided by the applied bias, leads to the formation of aluminum hydroxide and alumina. This finally results in failure due to an open circuit. The corrosion mechanism is accelerated by condensed moisture, temperature, and the applied bias. Although application of forward bias results in an increase in the junction temperature, it does not accelerate the corrosion mechanism because increased temperature due to operation of a device at a rated current inhibits the condensation of moisture inside the package (a prerequisite for corrosion). In the reverse bias state, moisture can condense but adequate temperature acceleration is not provided.

When the temperature is kept as a constant, the acceleration factor due to humidity acceleration is often expressed as

$$\mathrm{AF} = \exp\left[E_{\mathrm{H}}\left(\frac{1}{\mathrm{RH_n}} - \frac{1}{\mathrm{RH_a}}\right)\right] \tag{4}$$

where E_{H} is a humidity activation energy, and $\mathrm{RH_a}$ and $\mathrm{RH_n}$ are the relative humidity values under accelerated and field use conditions, respectively. There are several other models for accelerated humidity testing. All include the effect of relative humidity and temperature.

Galvanic corrosion cannot be accelerated significantly by humidity because it depends on the flow of electrons across metals of different electrochemical potentials in contact.

Accelerated Cyclic Temperature/Humidity/Bias

The temperature, humidity, and bias (THB) test uses reverse bias conditions to ensure that localized heating does not cause a reduction in relative humidity. The THB test is often carried out at 85 °C and 85% relative humidity with the device operating under reverse bias conditions. Because of low current, the power dissipated by the device is low and the package retains a high level of humidity. The THB (85/85) test usually requires a thousand hours of testing time. In order to reduce the test time, the highly accelerated stress test (HAST) was developed to apply high temperatures (100°C to 175°C) at controlled humidity levels (relative humidity of 50% to 85%) and electrical bias as stress factors.

Failures of plastic encapsulated devices are often related to moisture absorption, resulting in the corrosion of the aluminum metallization. The chemical reaction of aluminum with hydroxyl and hydrogen ions, produced by the electrolysis of water aided by the applied bias, leads to the formation of aluminum hydroxide and alumina. This finally results in an open circuit (failure). Thus the corrosion mechanism is accelerated by both water vapor and the applied bias. The application of forward bias, however, results in an increase in the junction temperature, which causes the test sample to emit moisture.

The failure mechanism of charge separation on the surface of MOS structures was observed. Moisture on the surface of field effect devices provides mobility to insulator surface charges, extending the gate potential over the nearby surfaces. In certain structures, or with processing defects, parasitic gates become operable, causing malfunction of the product. This effect will occur as soon as sufficient humidity and suitable fields are available.

The failure mechanisms of electrolytic conduction between electrically biased metallization paths were also observed in accelerated humidity tests. The rate of transfer of metal from one electrode to another, across a conductive surface, will depend on (among other things) the electrolytic current flow. The conductivity of the surface is a function of the amount of moisture on the surface. The degree of metal transfer shows up as a leakage current (and eventually a short) resulting from a developing metal–metal compound film in the transfer path. The time required for failure will depend on the sensitivity of the circuit to interpath leakage, the spacing between metal traces, the applied voltage, the metals involved, and the character of the insulating surface.

Accelerated Voltage

Voltage, in conjunction with temperature, is an agent of many surface degradation processes. At low power dissipation, the voltage-activated failure mechanisms of the cellular diode dominate, while at high temperatures, failure of the emitter diode caused by thermal runaway becomes significant. When an electronic product is subjected to a high voltage, there is an increased tendency for failures related to accumulation of surface charge, dielectric breakdown, dendritic growth, electrical overstress, and ionic contamination. In most cases, tests have to be performed at voltages not much higher than those used under normal operating conditions, because device breakdown voltages are not very much higher than normal operating voltage. High electric fields increase the mobility of any contaminating ions that may be present. This effectively changes the relative proportion of majority and minority carriers and deviation from designed performance parameters would be observed. The rate of galvanic corrosion also depends on the voltage difference across two metals in contact when the device is biased. This voltage difference may get superimposed on the already existing electrochemical potential difference between the metals and may alter the rate of reaction significantly.

The failure rate for a device depends on both the collector base voltage, V_{cb}, and the junction temperature, T_{j}. The commonly used models for accelerated voltage tests are the Eyring model and the Kemeny model, which relate failure rate, λ, of the device to the device junction temperature, T_{j}, and the applied collector base voltage, V_{cb}. The Eyring model is expressed as follows:

$$\lambda = AT_{\mathrm{j}}\left[\exp\left(\frac{-B}{kT_{\mathrm{j}}}\right)\right]\left[\exp\left(CV_{\mathrm{cb}} + \frac{DV_{\mathrm{cb}}}{kT_{\mathrm{j}}}\right)\right] \tag{5}$$

where k is Boltzmann's constant, and A, B, C, D are constants to be determined experimentally. The Kemeny model is expressed as follows:

$$\lambda = \left[\exp\left(C_0 - \frac{E_{\mathrm{A}}}{kT_{\mathrm{j}}}\right)\right]\left[\exp\left(C_1\frac{V_{\mathrm{cb}}}{V_{\mathrm{cb,m}}}\right)\right] \tag{6}$$

where E_{A} is the activation energy, $V_{\mathrm{cb,m}}$ is the maximum allowable collector base voltage, and C_0 and C_1 are constants. The first part of the above relationships describes the dependence of failure rate, λ, on the junction temperature, T_{j}. The second exponential term represents the dependence of λ on applied voltage, V_{cb}. In fact, if V_{cb} is set equal to zero, the Kemeny model reduces to the Arrhenius equation. The value of the constant C_1 has been found to be 1.5. This value is valid for low to medium-voltage devices, up to $V_{\mathrm{cb}} = 60\,\mathrm{V}$. For higher-voltage devices, C_1 should be chosen between 1.5 and 2.305, depending on the voltage rating of the product. Having determined C_1 for a failure mechanism with known activation energy, the Kemeny model can be used to find C_0 by conducting a single life test. The upper junction temperature limit to be used was 200°C to 230°C for germanium devices and beyond 300°C for silicon planar devices. Above these limits, atypical failure mechanisms occurred, defeating the purpose of accelerated tests.

Keeping temperature as a constant, the acceleration factor can be derived to be

$$\mathrm{AF} = \left(\frac{V_{\mathrm{a}}}{V_{\mathrm{n}}}\right)^{m} \tag{7}$$

where V_{a} and V_{n} are voltages under accelerated and normal use conditions, respectively, and m is a constant.

Accelerated Mechanical Stress

Electronic components are required to withstand both constant and cyclic mechanical stresses. In many electronic systems, the alternating stress induced by both thermal cycling and mechanical vibration is a dominant stress, and the failure mechanisms of greatest significance are those related to cumulative fatigue damage. Most of the failures start from defects and flaws that vary from gross drilled-hole misalignment, solder joints, and chemical contaminant to crystalline imperfections.

The *S-N* curve is used to interpret the relationship of the cycle-to-failure and applied stress amplitude from thermal cycling or vibration. For high-cycle fatigue, material behaviors present the following relationship between applied stress range and fatigue life:

$$N = C\sigma_{\mathrm{r}}^{m} \tag{8}$$

where N is the mean value of the cycles-to-failure, σ_{r} is cyclic mechanical stress range, and C and m are fatigue constants to be determined from accelerated testing. For low-cycle fatigue, the following equation was proposed to predict the thermal fatigue life:

$$N = \frac{1}{2}\left(\frac{\epsilon_{\mathrm{r}}}{2\epsilon_{\mathrm{f}}}\right)^{b} \tag{9}$$

where ϵ_{r} is the strain range, and ϵ_{f} and b are the fatigue ductility coefficient and exponent. As for material properties, these constants should be determined by accelerated testing. Figure 7 shows that both Equations (8) and (9) give straight lines on a strain-versus-cycle diagram with a logarithmic scale. In accelerated fatigue tests, the stress or strain range was elevated by accelerating the mechanical loading cycles or the thermal cycles. An acceleration of stress range in testing may shift the failure mechanism from high-cycle fatigue to low-cycle fatigue. Therefore the prediction of fatigue life based on linear extrapolation of accelerated test data (dotted line in Fig. 7) may give an overly conservative prediction if the stress range is accelerated only to a certain level.

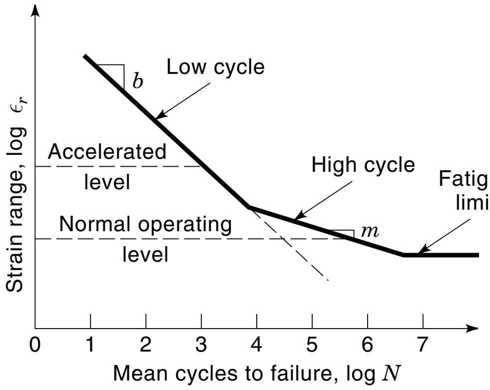


Figure 7. Stress–life curve (*S-N* curve).

Accelerated Frequency

Frequency increase is usually a good accelerated test method for a product subject to cyclic stress, although the acceleration factor to be achieved is not very large. Since frequency is not an acceleration parameter, the acceleration of frequency generally will not induce the failure mechanism to shift. However, if the service conditions of the product are high temperature or a corrosive environment, frequency acceleration may also shift the failure mechanism because failure will be sensitive to the frequency of stress cycles in a corrosive environment, and fatigue damage will be mixed with creep damage at high temperatures. For example, in a solder joint fatigue test, the high frequency acceleration may induce insufficient dwell time for complete stress relaxation, which contributes largely to a low-cycle fatigue. Thus the test results may provide a misleading reliability prediction for surface mount attachments because accelerated tests do not closely simulate the failure mechanism under service conditions.

Accelerated Random Vibration

The accelerated life test under random vibration stress is usually conducted by elevating the power spectral density (PSD) function of stress, displacement, or acceleration of a product. The main application of PSD acceleration is for stress screening and qualification tests. The addition of random vibration to a “burn-in” program greatly speeds screening and reduces costs. Failures can be due to flaws that vary from gross drilled-hole misalignment, cold solder joints, and chemical contaminants to crystalline imperfections. For printed circuit board (PCB) level tests, random vibration reduces the ratio of root mean square displacement at the board center to that at the board edge from 25 with sinusoidal vibration tests to 5. The accelerated random vibration tests are also conducted for fatigue reliability prediction because many electronic products are installed on ships, automobiles, and aerospace vehicles, where the operational environments tend to be random in nature.

Under a random vibration environment, the dominant motions are due to the fundamental resonant mode, and the stress cycles associated with these dominant motions at a failure site are directly proportional to the square root of the PSD at the resonant frequency. In general, the value of the PSD function is not explicitly related to the fatigue life as the

S-N curve, because the relationship between input displacement or acceleration and stress is nonlinear. For some special cases, there is a relation between PSD and fatigue life:

$$\mathrm{MTTF} = C_0(\mathrm{PSD_R})^{m/2} \tag{10}$$

where MTTF is proportional to cycles to failure, C_0 and m are constants, and $\mathrm{PSD_R}$ is the PSD stress value at resonant frequency. From Eq. (10) the acceleration factor for random vibration becomes

$$\mathrm{AF} = \left(\frac{\mathrm{PSD_{R,n}}}{\mathrm{PSD_{R,a}}}\right)^{m/2} \tag{11}$$

where $\mathrm{PSD_{R,a}}$ and $\mathrm{PSD_{R,n}}$ are PSD values at fundamental resonant frequency under accelerated and normal use conditions, respectively.

LIFE ESTIMATION FROM TEST DATA

The *life,* or time to failure, of a product (or a component or system in the product) depends heavily on various factors in random nature, such as applied stresses, material properties, failure mechanisms, and failure modes. The term "life" may also represent any suitable measure of exposure, such as the number of thermal or vibration cycles or the number of missions.

The life of a product can be described by mean time to failure (MTTF), failure rate, life deviations, and life distribution. The objective of the life evaluation is to estimate these statistical measures from observed testing data. Because of the random nature of the life data, such an evaluation is usually incomplete due to the limitation of the data sample size. The result of any life calculation is only an estimation of the life at a certain statistical confidence level, to account for the sampling and testing variations.

Estimation of Mean Time to Failure

The common method to estimate MTTF is sample point estimation, that is, the ratio of the total component test hours (the sum of all the operation hours on test of all the components tested including those that failed) to the number of failures. For a time-terminated test in which failed components are not being replaced, the MTTF can be evaluated by

$$\mathrm{MTTF} = \frac{\sum_{i=1}^{n_\mathrm{f}} T_{\mathrm{f},i} + (n - n_\mathrm{f})T_0}{n_\mathrm{f}} \tag{12}$$

where $T_{\mathrm{f},i}$ is the component life hours of the ith failed component, n is the total number of components tested, n_f is the number of failed components, and T_0 is the terminated test time. In time-terminated tests, if a component is replaced as soon as it fails, MTTF is often estimated by

$$\mathrm{MTTF} = \frac{nT_0}{n_\mathrm{f}} \tag{13}$$

For failure-terminated tests without replacement, assuming that the test is terminated at time T_{n_f} when the n_fth failure has occurred, MTTF can be estimated by

$$\mathrm{MTTF} = \frac{\sum_{i=1}^{n_\mathrm{f}} T_{\mathrm{f},i} + (n - n_\mathrm{f})T_{n_\mathrm{f}}}{n_\mathrm{f}} \tag{14}$$

where T_{n_f} in this case is a random variable, not a constant. If a component is replaced as soon as it fails,

$$\mathrm{MTTF} = \frac{nT_{n_\mathrm{f}}}{n_\mathrm{f}} \tag{15}$$

Estimation of Life Deviation

Sample moments often are used as estimators of the corresponding life deviation, which is the expected value of $(T - \mathrm{MTTF})^2$ as shown by the following equation for a life test sample of size n, namely, $T_1, \ldots, T_n$:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(T_i - \mathrm{MTTF})^2} \tag{16}$$

where s is the estimation of life deviation, and MTTF is estimated from Eqs. (12–15).

Estimation of Confidence Interval of Mean Time to Failure

The confidence interval of MTTF can be estimated using the following equation:

$$\langle\mathrm{MTTF}\rangle_{1-\alpha} = \left(\overline{\mathrm{MTTF}} - t_{\alpha/2,n_\mathrm{f}-1}\frac{s}{\sqrt{n_\mathrm{f}}},\ \overline{\mathrm{MTTF}} + t_{\alpha/2,n_\mathrm{f}-1}\frac{s}{\sqrt{n_\mathrm{f}}}\right) \tag{17}$$

where MTTF is calculated from Eqs. (12–15), $t_{\alpha/2,n_\mathrm{f}-1}$ is the value of Student's t-distributed variable corresponding to the confidence level $(1 - \alpha)$, and s is the estimate of standard deviation expressed in Eq. (16).

Equation (17) is a general expression of confidence interval estimation. However, if the time to failure is an exponentially distributed random variable, the value $2n_\mathrm{f}\,\overline{\mathrm{MTTF}}/\mathrm{MTTF}$ has a χ^2 distribution with $(2n_\mathrm{f} + 2)$ degrees of freedom for time-terminated test data and $2n_\mathrm{f}$ degrees of freedom for failure-terminated data. Thus the confidence interval can be determined by

$$\langle\mathrm{MTTF}\rangle_{1-\alpha} = \left(\frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{1-\alpha/2,2n_\mathrm{f}+2}},\ \frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{\alpha/2,2n_\mathrm{f}}}\right) \tag{18}$$

for time-terminated data with replacement, and by

$$\langle\mathrm{MTTF}\rangle_{1-\alpha} = \left(\frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{1-\alpha/2,2n_\mathrm{f}}},\ \frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{\alpha/2,2n_\mathrm{f}}}\right) \tag{19}$$

for failure-terminated data with or without replacement.

The estimation of the lower limit of MTTF, the one-sided confidence interval of MTTF, can be determined by

$$\langle \mathrm{MTTF} \rangle_{1-\alpha} = \left(\frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{1-\alpha,2n_\mathrm{f}+2}}, \infty \right) \tag{20}$$

for time-terminated test data and

$$\langle \mathrm{MTTF} \rangle_{1-\alpha} = \left(\frac{2n_\mathrm{f}\overline{\mathrm{MTTF}}}{\chi^2_{1-\alpha,2n_\mathrm{f}}}, \infty \right) \tag{21}$$

for failure-terminated test data.

Estimation of Life Distribution

In most cases, the cumulative distribution functions are estimated from life test data. A sample of similar components from a hypothesized population of such components is tested under the operational environment. Their times to failure are recorded. Using t_i as the lifetime to failure of the $n_{\mathrm{f},i}$th component, the unreliability or the probability of failure up to time t_i, $F_\mathrm{T}(t_i)$, can be estimated by approximating $F_\mathrm{T}(t_i)$ as determined by

$$\overline{F}_\mathrm{T}(t_i) = \frac{n_{\mathrm{f},i}}{n} \tag{22}$$

where n is the total number of components under test. The reliability at time t_i is then approximately

$$\overline{R}(t_i) = 1 - \overline{F}_\mathrm{T}(t_i) = \frac{n - n_{\mathrm{f},i}}{n} \tag{23}$$

For a small sample size (say, $n < 15$), the component failure probability at time t_i can be estimated by the following equation:

$$\overline{F}_\mathrm{T}(t_i) = \frac{n_{\mathrm{f},i} - 0.3}{n + 0.4} \tag{24}$$

and the reliability at time t_i is

$$\overline{R}(t_i) = \frac{n - n_{\mathrm{f},i} + 0.7}{n + 0.4} \tag{25}$$

The calculated results are often plotted on probability paper to see if the life follows a particular common distribution, such as a Weibull distribution or log-normal distribution.

LIFE INFERENCE MODELS FOR ACCELERATED TESTING

The life of a product calculated from the accelerated test data or under normal usage conditions is a random variable. One important task of accelerated life testing is to extrapolate these statistic measures from the test data to the normal usage conditions. This requires life inference models. The models can be categorized into two groups: the acceleration models for MTTF and the acceleration models for life distribution.

Acceleration Models for Mean Time to Failure

The acceleration models for MTTF are derived mostly from empirical tests. The frequently used models are described next.

Arrhenius Reaction Model. The Arrhenius reaction model expresses the time rate of degradation of some device parameter as a function of the operating temperature. According to this model, the reaction rate, r, is

$$r = r_0 \exp\left(-\frac{E_\mathrm{A}}{kT} \right) \tag{26}$$

where r_0 is a constant, E_A is the activation energy for the failure mechanism under consideration, k is Boltzmann's constant (8.617×10^{-5} eV/K), and T is the absolute temperature. Assuming that the product of the reaction rate and MTTF is a material property, then MTTF can be determined by

$$\mathrm{MTTF} = t_0 \exp\left(\frac{E_\mathrm{A}}{kT} \right) \tag{27}$$

where t_0 is a material constant.

Power-Law Model. The power-law model is derived via considerations of kinetic theory and activation energy, which gives

$$\mathrm{MTTF} = CS^{-m} \tag{28}$$

where C and m are constants and S is applied stress. This model has found application for accelerated life tests of paper-impregnated dielectric capacitors and is also used for life modeling of fatigue initiation for most ductile materials.

Eyring Model. The Eyring model is derived from the principles of quantum mechanics and expresses the time rate of degradation of some device parameter, r, as function of the operating temperature:

$$r = r_0 T \exp\left(-\frac{E_\mathrm{A}}{kT} \right) \tag{29}$$

Application of this model can be generalized for a product subjected to two types of stress—a thermally related stress, T, and a nonthermally related stress, S:

$$r = r_0 T \exp\left(-\frac{E_\mathrm{A}}{kT} \right) \exp\left(CS + \frac{DS}{kT} \right) \tag{30}$$

where C and D are constants. Assuming that the product of reaction rate and MTTF is a material property, the MTTF can be determined by

$$\mathrm{MTTF} = t_0 \frac{1}{T} \exp\left(\frac{E_\mathrm{A}}{kT} \right) \exp\left(CS + \frac{DS}{kT} \right) \tag{31}$$

where t_0 is a material constant.

Peck Model. The Peck model separately calculates the accelerations created by temperature and humidity by modifying the Arrhenius and Eyring models:

$$\mathrm{MTTF} = t_0 \exp\left[\frac{E_A}{k}\left(\frac{1}{T_0} - \frac{1}{T}\right)\left(\frac{\mathrm{RH}_0}{\mathrm{RH}}\right)^n\right] \tag{32}$$

where $n = 2.7$ and $E_A = 0.79$ eV/K.

Acceleration Models for Life Distribution

The acceleration models for life distribution are derived mostly from the acceleration models for MTTF and the common life distributions. The frequently used models are described next.

Arrhenius–Exponential Model. This model assumes that the product life has an exponential distribution at a given stress level, and the natural logarithm of the MTTF is an inverse function:

$$\ln(\mathrm{MTTF}) = C_1 + \frac{C_2}{S} \tag{33}$$

where S is the applied accelerated stress, and C_1 and C_2 are constants determined from the test data. Therefore the cumulative distribution function is

$$F_T(t, S) = 1 - \exp\left[-t \exp\left(C_1 + \frac{C_2}{S}\right)\right]$$

Arrhenius–Log-Normal Model. The Arrhenius–log-normal model assumes that the product life has a log-normal distribution at a given stress level or, equivalently, that the natural logarithm of the life has a normal distribution. The standard deviation, σ_T, of the logarithm of life is a constant; and the logarithm of the MTTF is an inverse function of S. Therefore the cumulative distribution function is

$$F_T(t, S) = \Phi\left(\frac{\log t - \mu_T(S)}{\sigma_T}\right) \tag{34}$$

where Φ is the standard normal cumulative distribution function, and $\mu_T(S)$ is the mean of logarithm of life.

Arrhenius–Weibull Model. The Arrhenius–Weibull model combines a Weibull life distribution with an Arrhenius dependence of life on accelerated stress. The model assumes that the product life has a Weibull distribution at a given stress level, and that the shape parameter β is a constant (independent of applied accelerated stress). The natural algorithm of the characteristic life, η, is a linear function of the inverse of S:

$$\ln \eta = C_1 + \frac{C_2}{S} \tag{35}$$

Therefore the cumulative distribution function is

$$F_T(t, S) = 1 - \exp\left\{-\left[t \exp\left(C_1 + \frac{C_2}{S}\right)\right]^\beta\right\} \tag{36}$$

Power–Exponential Model. The power–exponential model assumes that the product life has an exponential distribution at any given stress level, and that the MTTF is a power law function of accelerated stress, S. Therefore the cumulative distribution function is

$$F_T(t, S) = 1 - \exp\left(-\frac{S^m t}{C}\right) \tag{37}$$

Power–Log-Normal Model. This model assumes that the product life has a log-normal distribution at any given stress level or, equivalently, that the natural logarithm of the life has a normal distribution. The standard deviation, σ_T, of the logarithm of life is a constant, and the MTTF is a power law function of accelerated stress, S. Then the cumulative distribution function is

$$F_T(t, S) = \Phi\left(\frac{\log t - CS^{-m}}{\sigma_T}\right) \tag{38}$$

where Φ is the standard normal cumulative distribution function.

Power–Weibull Model. The power–Weibull method combines a Weibull life distribution with an Arrhenius dependence of life on accelerated stress. The model assumes that the product has a Weibull distribution at a given stress level, and that the shape parameter β is a constant (independent on applied accelerated stress). The characteristic life, η, is a power law function of accelerated stress S as shown in Eq. (28). Therefore the cumulative distribution function is

$$F_T(t, S) = 1 - \exp\left[-\left(\frac{tS^m}{C}\right)^\beta\right] \tag{39}$$

More complicated models can be derived with other assumptions substituted in the life distribution and accelerated MTTF models.

Step Stress Model. The step stress model can be explained as follows. Suppose that step i runs at stress S_i, starts at time t_{i-1}, and runs to time $t_i (t_0 = 0)$, and the cumulative distribution function (CDF) of time to failure for specimens run at a particular stress level S_i is denoted by $F_i(t)$. Therefore, for step 1, we have

$$F(t) = F_1(t_1) \qquad 0 \le t \le t_1 \tag{40}$$

The equivalent start time τ_1 for step 2 would have produced the same failure fraction under stress S_2, that is, the solution of

$$F_2(\tau_1) = F_1(t_1) \tag{41}$$

The cumulative fraction of specimens failing in step 2 by total time t is

$$F(t) = F_2[(t - t_1) + \tau_1] \qquad t_1 \le t \le t_2 \tag{42}$$

Similarly, in step 3 the equivalent start time τ_2 is the solution of

$$F_3(\tau_2) = F_2[(t_2 - t_1) + \tau_1] \tag{43}$$

and the cumulative fraction of specimens failing in step 3 by total time t is

$$F(t) = F_3[(t - t_2) + \tau_2] \quad t_2 \le t \le t_3 \tag{44}$$

In general, the equivalent start time of step i, t_{i-1}, is the solution of

$$F_i(\tau_{i-1}) = F_{i-1}[(t_{i-1} - t_{i-2}) + \tau_{i-1}] \tag{45}$$

and the CDF for step stress testing is given by

$$F(t) = F_i[(t - t_{i-1}) + \tau_{i-1}] \quad t_{i-1} \le t \le t_i \tag{46}$$

As an example, let us assume that the life distribution at any stress level is Weibull:

$$F_i(t) = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{47}$$

where the shape parameter β is a constant, and the scale parameter θ is a function of applied stress level:

$$\theta = \theta_o \left(\frac{S_o}{S}\right)^{C} \tag{48}$$

The subscript o in the above equation denotes the state of operational stress condition. Therefore the distribution of time to failure is

$$F(t) = 1 - \exp\left\{-\left[\left(\frac{t - t_{i-1} + \tau_{i-1}}{\theta_o}\right)\left(\frac{S_i}{S_o}\right)^{C}\right]^{\beta}\right\} \tag{49}$$

where t_{i-1} is the solution of the following equation:

$$\tau_{i-1} = (t_{i-1} - t_{i-2} + \tau_{i-2})\left(\frac{S_{i-1}}{S_i}\right)^{C} \tag{50}$$

Thus the time to failure distribution under the step stress pattern consists of segments of a Weibull distribution.

FAILURE MECHANISMS ANALYSIS

Failure is the loss of the ability of a product to perform a required function. This definition includes catastrophic failures as well as degradation failures, whereby an important parameter drifts significantly to cause improper functioning. Failures of an electronic product can be classified by the failure site, the failure mechanism, and the failure mode. Failure site is the location or unit where failure occurs. The failure mechanism is the process by which the specific combination of physical, electrical, chemical, and mechanical stresses induces failure. Failure mode is a physically observable change caused by the failure mechanism, such as an open-circuit, a short-circuit, or a change in parameters.

A correct failure analysis in accelerated life tests should begin with an investigation of all potential failure mechanisms, followed by an identification of where and when they may occur, and their effect and criticality on the operation of the product over the required useful life. In order to most generically address failures, with the understanding that a given failure mechanism can occur at many sites, failures must be identified with respect to the failure mechanisms and the predominant mechanical, thermal, electrical, chemical, and radiation stresses which induce failure (see Table 2). The failure mechanisms should not be mixed with failure modes or defects, which serve as sources of failure. Investigations of failure mechanisms serve as pointers for design of reliability testing. It is therefore necessary to first identify the failure mechanisms that could potentially be activated in an electronic product by the applied stresses, resulting from the life cycle mission profile.

The accelerated stress may produce failure mechanisms that are different from those observed during actual service conditions. Therefore failure mechanism identification and the setting up of stress limits for all types of accelerated life tests in order to prevent shifting of the original dominant failure mechanism are necessary. If failure mechanism shifting occurs in an accelerated life test, the test data will be unrepresentative of the reliability under actual operating conditions and the test would not be a valid acceleration.

In the planning of an accelerated life test, an understanding of the change in interference pattern of various failure mechanisms as well as the acceleration stresses is critical. The selection of the proper accelerated stress should be based on the identification of failure mechanisms. Failure analysis should be conducted to validate the results of accelerated tests and correct the cause of failure.

A successful accelerated testing should meet the following conditions: (1) the failure mechanisms in the accelerated environment are the same as those observed under usage conditions; (2) the material properties under accelerated stress are not changed; (3) the shape of the failure probability density function at normal operating levels and accelerated conditions should be consistent; and (4) the quantitative extrapolation from the accelerated environment to the usage en-

Table 2. Failure Mechanisms and Accelerated Stresses

Wear-out Failure Mechanisms	Acceleration Stresses
Fatigue crack initiation	Mechanical stress/strain range, cyclic temperature range, frequency
Fatigue crack propagation	Mechanical stress range, cyclic temperature range, frequency
Creep	Mechanical stress, temperature
Wear	Contact force, relative sliding velocity
Diffusion	Temperature, concentration gradient
Interdiffusion	Temperature
Corrosion	Temperature, relative humidity
Electromigration	Current density, temperature, temperature gradient
Dendritic growth	Voltage differential
Radiation damage	Intensity of radiation
Surface charge spreading	Temperature
Slow trapping	Temperature
Stress corrosion	Mechanical stress, temperature, relative humidity

vironment must be made with some reasonable degree of confidence.

Accelerated life testing may produce significant costs for many types of equipment or sytems. To keep both costs and the uncertainties under control, accelerated life testing should be carried out in a systematic way, using all the available knowledge in the testing planning.

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