Environmental-stress screening improves electronic-design reliability

V Lakshminarayanan - September 20, 2001

Environmental-stress screening (ESS) is an essential step in the design cycle of electronic systems, particularly as these systems shrink in size and increase in complexity to satisfy the growing customer need for low-power, portable, high-quality gadgets. Maintaining a high operational reliability and offering fault-free operation in all types of operating environments require careful product design, during which you must keep several factors in view. ESS is a useful process that exposes product weaknesses and allows you to make corrections in the design. Faults you detect during in-house testing are less expensive to correct than equipment failures in the field.

The following benefits accrue from a good ESS program:

- fewer warranty-period failures, which means better operational reliability of the product in the field, a better image with customers, and lower repair costs;
- help in planning for spare parts;
- better economy through fault detection and correction during the product-development cycle;
- help in making commercial decisions, such as a product's warranty period;
- improved overall quality of the process and the product;
- help in streamlining processes to weed out infant-mortality failures;
- improved productivity; and
- fewer product failures in the field.

You can achieve high operational reliability by using commercial- and industrial-grade components, by designing carefully, and by applying ESS techniques during the design-and-development phase of the product. Sometimes, safety requirements of products that must meet certain statutory guidelines make ESS mandatory. In applications such as avionics, space, defense, life-saving apparatus, and others in which the failure of a system could have serious consequences, ESS provides the necessary checks to eliminate infant-mortality failures and ensure trouble-free operation under harsh operating conditions. Products that must adhere to international standards, such as MIL, IEC, and JSS, also must meet various test specifications for parameters such as temperature, humidity, pressure, shock, vibration, dust, chemical atmosphere, and solar radiation. In such situations, ESS tests help during the product design and development.

Ultimately, the effectiveness of an ESS program depends on the effectiveness of the failure analysis and corrective-action procedure that you implement after the ESS tests. Step-by-step detection of failure modes and design flaws, followed by implementation of corrective strategies to overcome failures after each ESS step leads to a rugged system design that will operate reliably under field conditions.
What is ESS?

ESS is a technique that applies various types of stresses in a controlled manner to expose weaknesses in the design of a product. ESS tests include HALT (highly accelerated life testing), HASS (highly accelerated stress screening), and HAST (highly accelerated stress testing). The commonly applied stresses in these testing procedures are temperature, vibration, humidity, and electrical stimuli. The levels of applied stress are much greater than the stresses that the product is likely to encounter during normal operation to precipitate failures and reduce test time. ESS programs help achieve higher MTBFs and reduce the possibility of customer returns due to failures. ESS techniques can precipitate latent failures, which you cannot detect with electrical testing or visual inspection, so that you can eliminate infant-mortality cases and the product can enter the useful-life phase of the bath-tub curve at the end of the ESS testing (Figure 1). Accelerated testing exposes defects in components and manufacturing faults so that you can correct them and improve the product design to achieve higher product reliability.

You use HALT during the design phase of a product by increasing the applied stress to a product in steps and fixing the faults to improve the design. You continue the process beyond the limits of normally encountered field stresses to make the product design and manufacturing process rugged. The tests applied include temperature cycling, humidity, burn-in, voltage cycling, vibration, and overvoltage. This step-stress sequence exposes the weaknesses in the product, and the process of increasing the stress level continues until you reach the destruction limits of the material in the product. Thus, HALT can help you define the operating limits of a product. In other words, it sets the design limits of the product for successful operation. HALT is a destructive test that helps to determine a product's life. You can use HALT results to determine a product's warranty period.

HALT has many benefits. It identifies design flaws and safe-operating regions for products and helps you evaluate a product’s strengths and weaknesses. It also helps you estimate product life and evaluate component conformance to qualification standards. It estimates and predicts reliability and forms a basis for commercial decision-making, such as the length of a product’s warranty period. And it helps you plan for spare parts.

You use HASS after you know the stress-versus-destruction limits from HALT. By knowing the operating limits of a product from HALT, you use HASS to identify weak products. The screens in HASS testing are high levels of stress that reduce test time. You can perform HASS on all manufactured products, and it is a nondestructive test. It helps you verify product performance during the estimated lifetime of the product; thus, it is useful for improving the field operational reliability of a system, weeding out infant-mortality failures of components and manufacturing defects, reducing production time and cost, and comparing estimated product reliability with actual operational reliability.

Finally, HAST is a stress test you apply to electronic components in the form of high humidity and temperature to expose components that will fail during qualification testing. The test extends the standard 85°C/85% RH (relative-humidity) bias test to a temperature higher than 100°C.

Using ESS to predict failures

You can use the results of accelerated stress tests to predict the failure rate at normal operating conditions. The following example illustrates how you can use the number of failures occurring at an elevated temperature to mathematically predict the number of failures at a normal operating
temperature of 25°C.

The MTTF (mean time to failure) of a component is 1000 hours at an elevated temperature of 125°C and 600 hours at 175°C, as measured from stress tests at these temperatures. You can calculate the MTTF at a normal operating room temperature of 25°C and at an elevated ambient temperature of 50°C.

You can explain many temperature-dependent failure mechanisms in semiconductor devices using the Arrhenius Model, which is given by

$$\lambda_t = \lambda_0 e^{-\Delta E/kT},$$

where $\lambda_t$=failure rate at temperature, $t$, in degrees Celsius or, $T$, in degrees Kelvin; $\lambda_0$=constant of proportionality; $\Delta E$=activation energy of the failure mechanism; $T$=temperature in degrees Kelvin; and $k$=Boltzmann's constant=$8.61 \times 10^{-5}$ eV/°K.

Taking the ratio of failure rates at temperatures $T_1$ and $T_2$,

$$\frac{\lambda_{T_2}}{\lambda_{T_1}} = e^{(-\Delta E/k)(1/T_2 - 1/T_1)}.$$

In other words, the ratio of MTTF at the two temperatures is

$$\frac{MTTF_2}{MTTF_1} = e^{(-\Delta E/k)(1/T_2 - 1/T_1)}.$$

MTTF$_1$ is the MTTF at 125°C, and MTTF$_2$ is the MTTF at 175°C. Thus,

$$\ln(\frac{MTTF_2}{MTTF_1}) = (-\Delta E/k)(1/T_2 - 1/T_1).$$

In this case, $T_1=125+273=398°K$, $T_2=175+273=448°K$, MTTF$_1=600$, and MTTF$_2=1000$. Substituting these values in the above equation gives

$$\ln(1000/600) = (-\Delta E/k)(1/448 - 1/398).$$

Thus,

$$\Delta E/k = -\ln(10/6)/(1/448 - 1/398) = -0.5108 / -2.804 \times 10^{-4} = 1821.55,$$

and

$$\Delta E = 8.61 \times 10^{-5} \times 1821.55 = 0.157 \text{ eV}.$$

Therefore, the activation energy of the failure mechanism is 0.157 eV.

The MTTF at 25°C is given by
Similarly, the MTTF at 50°C is given by

\[
\text{MTTF}_{50} = \text{MTTF}_{75} \left( e^{(-\Delta E/k)(1/448 - 1/298)} \right) \\
= (1000)e^{-1621.55(1/448 - 1/298)} \\
= 7741.7 \text{ hours } \approx 7742 \text{ hours.}
\]

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\text{MTTF}_{50} = \text{MTTF}_{75} \left( e^{(-\Delta E/k)(1/448 - 1/323)} \right) \\
= (1000)e^{-1621.55(1/448 - 1/323)} \\
= 4823.6 \text{ hours } \approx 4824 \text{ hours.}
\]

The Arrhenius Model can be used to calculate the acceleration factors for various failure mechanisms in semiconductor devices. Acceleration factor is defined as the ratio of the time in operation to the time of the stress. Translated in terms of the ratio of temperatures, the ratio is as follows:

\[
\text{AF} = e^{(-E_A/k)(1/T_\text{stress} - 1/T_\text{use})},
\]

where AF = acceleration factor = time ∈ stress / time ∈ use; \(E_A\) = activation energy of the failure mechanism in electron volts; \(T_\text{use}\) = temperature in degrees Kelvin during use; and \(T_\text{stress}\) = elevated stress temperature in degrees Kelvin. The standard elevated stress temperature in use is generally one of the following, depending on the level of screening necessary: 85, 105, 125, 150, or 175°C.

Recommended guidelines at the system level are a temperature range of -40 to +70°C for a product using commercial devices, a rate of change of temperature of 5 to 10°C/minute, depending on the type of screen to be applied, and 20 to 40 cycles.

Semiconductor-device-failure mechanisms have activation energies of 0.1 to 1.5 eV. Table 1 gives the calculated acceleration factors corresponding to this range of activation energies based on the Arrhenius Model for various stress temperatures with reference to a usage temperature of 25°C.

### Acceleration factors

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### Calculating acceleration factors

Consider a failure mechanism with an activation energy of 0.5 eV. You can calculate the acceleration factor for this failure mechanism at an elevated temperature of 105°C with reference to device usage at 25°C.

Applying the Arrhenius Model,
In this example, \( T_1 = 298^\circ K \), \( T_2 = 378^\circ K \), \( k = 8.61 \times 10^{-5} \text{eV}^\circ K \), and \( E_A = 0.5 \). Let \( R_{25} \) and \( R_{105} \) represent the failure rates at 25°C and 105°C. Then,

\[
\frac{R_{25}}{R_{105}} = e^{-(0.5/8.61\times10^{-5})(1/298 - 1/378)} = 0.01618.
\]

That is,

\[
\frac{1}{MTTF_1} = \frac{MTTF_2}{MTTF_1} = 0.01618,
\]

and

\[
MTTF_1 = 61.8 \times MTTF_2.
\]

In other words, for a failure mechanism with \( E_A = 0.5 \text{ eV} \), one hour at 105°C is equivalent to approximately 62 hours at 25°C.

The calculations in Table 1 are similar. From Table 1, you can conclude the following:

- For a failure mechanism with an activation energy of 0.45 \text{ eV}, 19 hours at 25°C is equivalent to one hour at 85°C, 41 hours at 25°C is equivalent to one hour at 105°C, 82 hours at 25°C is equivalent to one hour at 125°C, 179 hours at 25°C is equivalent to one hour at 150°C, and 355 hours at 25°C is equivalent to one hour at 175°C.
- Every 20°C rise in temperature halves the MTTF. Suppose that you conduct a life test for 1000 hours at 150°C. Failures that occur at this temperature would occur in \( 1000 \times f \) hours at 25°C, where \( f \) is the acceleration factor for the failure mechanism. For example, consider a failure mechanism with \( E_A = 0.5 \text{ eV} \). In this case, \( f = 25/150 = 0.167, \) and \( 317 \times 1000 \) hours at 25°C are necessary for the same number of failures to occur as at 150°C. In other words, a 1000-hour life test at 150°C represents \( 317,000 \) hours of operation at 25°C. This point highlights the compression time frame that you can achieve with accelerated testing at an elevated temperature for precipitating temperature-dependent failure mechanisms.
- Failure mechanisms with lower activation energies require a shorter period of accelerated testing to fail than mechanisms with a higher activation energy at a given temperature.
- For a given failure mechanism, a higher temperature causes failure faster than a lower temperature.
- Failure mechanisms with higher activation energies happen faster for a given increase in temperature than mechanisms with lower activation energies.
- For a failure mechanism with an \( E_A \) of 0.45 \text{ eV}, the failure rate doubles for every 20°C rise in temperature.

Figure 3 depicts the variation of temperature-acceleration factors with stress temperatures.
Types of ESS tests

ESS uses the following tests to expose a product to stressful environments and obtain information about failures and design flaws.

Temperature cycling: This test subjects a product to selected temperature extremes in a cyclic manner. The rate of change of temperature determines the stress level and the acceleration factor. You must select the temperature limits to ensure that no damage occurs to the product but that enough stress is applied to the product within its withstanding capability.

Thermal shock: This test subjects a product to temperature extremes in a rapid, back-and-forth manner.

High-temperature burn-in: This test subjects a powered-up unit to a high temperature during operation for a specified time. Because temperature accelerates many failure mechanisms in semiconductor components according to the Arrhenius Model for the reaction rate of a chemical reaction, this test effectively weeds out infant-mortality failures.

Low temperature: Reduction of temperature is a "reverse" acceleration condition and is useful in accelerating some failure mechanisms. You achieve testing at low temperatures using a refrigerator or a chamber cooled by liquid nitrogen or dry ice. This test can detect moisture in a package. At low temperatures, the moisture condenses and the leakage current shows a marked increase. Hot-electron effects in n-channel MOS devices occur more often at lower temperatures due to reduced lattice scattering. You can detect such failure mechanisms at lower temperatures. The low-temperature range is generally -20 to -65°C.

Random vibration: This test verifies whether a product will survive mechanical vibrations and shocks during transportation and use and is a good simulation of the actual usage environment.

Electrical stress tests: High electric fields in a semiconductor device during operation could cause failures by breaking down the dielectric material. Higher current densities in the device structures can cause metallization damage and electromigration effects. Application of higher than normal electrical stresses can accelerate failures.

It is useful to know the failure mechanisms that that temperature, humidity, and vibration can trigger in various types of electronic-system components because these are the main stress factors in ESS tests. Table 2, Table 3, Table 4, and Table 5 summarize these factors.

A product is subjected to mechanical vibrations and shocks during transportation, handling and use. Manufacturers have to transport systems from their place of manufacture to the place of installation, and users carry around portable systems, such as mobile phones and notebook PCs, and subject them to mechanical vibrations throughout their lives. Users can also accidentally drop the products, and they must be able to withstand these mechanical stresses without damage. To qualify electronic systems against such stresses, you can conduct vibration tests of various kinds. Tests include shock, drop, random-vibration, bump, and mechanical-resonance testing. Vibration testing creates stresses in the product due to mechanical effects. Table 4 lists the effects of vibration stresses on various types of components.

Table 5 lists some of the typical stress tests that you can use to accelerate failures and screen defects and lists the defects that the various stress tests detect. This table gives broad guidelines for stimulating various failure mechanisms. It is necessary, to customize the ESS test for each product depending on the reliability requirement and cost.
The following steps are necessary for designing an effective ESS test for a product.

1. Perform stress tests on assembled units. You can carry out stress testing of an assembled card or subunit to hasten infant-mortality failures of components due to assembly defects, such as loose connections, soldering defects, and improper mounting or fixing of components. Take care not to damage any components or the assembly by causing fatigue.

2. Thoroughly study and analyze the failures of components and assemblies. Collect and record information about failures. Analyze the failures at the component and the design levels. Correlate failure modes to causes and relate ESS-test failures to field-failure data.

3. Perform changes based on failure analysis. If you conclude that overstress caused the failure, modify the ESS stress levels to eliminate overstress failures.

4. Repeat the ESS tests and collect data on failures. Compare this failure data with field-failure data and arrive at optimum ESS criteria.

A closed-loop fault detection and correction at every ESS step will lead to a robust product design. Formulate ESS tests for your requirements using the above step-by-step procedure.

References