HIGHLY ACCELERATED STRESS SCREENING FOR AIR-COOLED SWITCHING POWER SUPPLIES

PART 1

UNDERSTAND STRESS TEST METHODOLOGY

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EXECUTIVE SUMMARY

Highly Accelerated Stress Screening, or HASS, has been established as a best practice for assuring fielded electronic product reliability. HASS is especially productive in power conversion equipment, where component stress levels are typically more aggressive than found in other products. TDI has been instrumental in establishing HASS as a viable, high value-add production process.

This White Paper is the first in a series of documents outlining this process. Background information is provided regarding electronic equipment failure mechanisms and the predictive models that can be used to describe them.

ABOUT THE AUTHOR

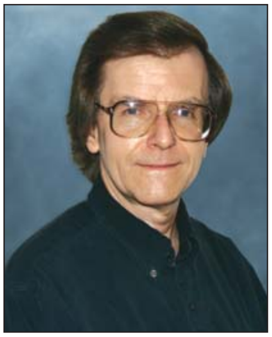

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TABLE OF CONTENTS

SECTION 1 - INTRODUCTION 4

Key Words and Acronyms 4

Overview 5

SECTION 2 - STRESS TESTING METHODOLOGY 6

Bathtub Curve 6

Part Defects 6

Arrhenius Model 7

Coffin-Manson Model 9

Norris-Landzberg Model 11

Dwell Time and Ramp Rate 13

Input Power Cycling 13

Output Power Cycling 13

SECTION 3 - PREDICTIVE FAILURE MODELS 7

SECTION 4 - APPLYING PREDICTIVE MODELS AS PART OF A PRACTIACAL PROCESS . . .14

SECTION 5 - BIBLIOGRAPHY 14

Papers and References 14

General References 15

Failure Mechanisms 15

SECTION 6 - EQUATIONS 15

Generic Inverse Power Law Model 15

Acceleration Factor for Generic Inverse Power Law Model 15

Section 1 - Introduction

Highly Accelerated Stress Screening, or HASS, is a production process that identifies product weaknesses through the application of environmental and electrical stresses. The stress levels imparted as part of the test are typically beyond what the product is specified to handle, but within the established safe operating area of the design. HASS provides the opportunity to substantially improve fielded product reliability and reduce overall cost of ownership.

Applying HASS to its best potential in a production environment requires a thorough understanding of product failure mechanisms, as well as practical methods for equipment setup, screen creation, data monitoring and product improvement realization for opportunities that result from the test. This document addresses the first of these requirements, examining product failure modes and predictive models.

HASS must be an integral part of manufacturing a switching power supply when high reliability is a requirement. It applies stress stimuli at much higher levels than exist in end-use customer environments. These stresses are intended to accelerate the time to failure for weak links in the manufactured product. HASS uncovers flaws quickly and without consuming an appreciable portion of useful product life. All failures must be scrupulously analyzed to root cause and the corrective action fed back as improvements to the manufacturing process. HASS testing is not merely used as a sieve to screen out component defects, but also, as a real-time corrective action tool to pinpoint deficiencies in the manufacturing process. If these potential problems are not found, they could surface later as a failure during normal product life in the hands of the customer.

Key Words and Acronyms

UUT → Unit Under Test
Stress → An applied stimulus
Strain → Movement of one part relative to another
End-use environment → Customer's application
HASS → Highly Accelerated Stress Screen is a manufacturing process that applies accelerated stresses to a product for the purpose of quickly precipitating latent and intermittent defects to a detectable failure
HALT → Highly Accelerated Life Testing is an engineering tool that applies ever-increasing stresses to the initial product design until failure occurs, in order to characterize and ruggedize the design
Bathtub Curve → Hazard function used in Reliability Engineering to describe the failure rates of products
Acceleration Factor → A numerical measure of how much more stressful the test environment is compared to the end-use environment
Activation Energy → Minimum energy necessary for a specific event to occur
Thermal Swing → A change in temperature between a minimum and a maximum
Thermal Cycle → A change in temperature from a minimum to a maximum and back to the minimum again, or vice versa. One thermal cycle contains two thermal swings.
Ramp Rate → Rate at which temperature changes, expressed in °C/minute
Dwell Time → Time spent at a static temperature

HASS Process Overview

There are eight fundamental steps involved in implementing an effective HASS:

Step 1: Understanding stress testing methodology

Step 2: Fixture design, fabrication and debug

Step 3: Profile design and debug

Step 4: System debug

Step 5: Proof-of-Screen

Step 6: System commissioning

Step 7: Release to Production

Step 8: Data analysis

Understanding stress testing methodology will be the topic of this technical paper.

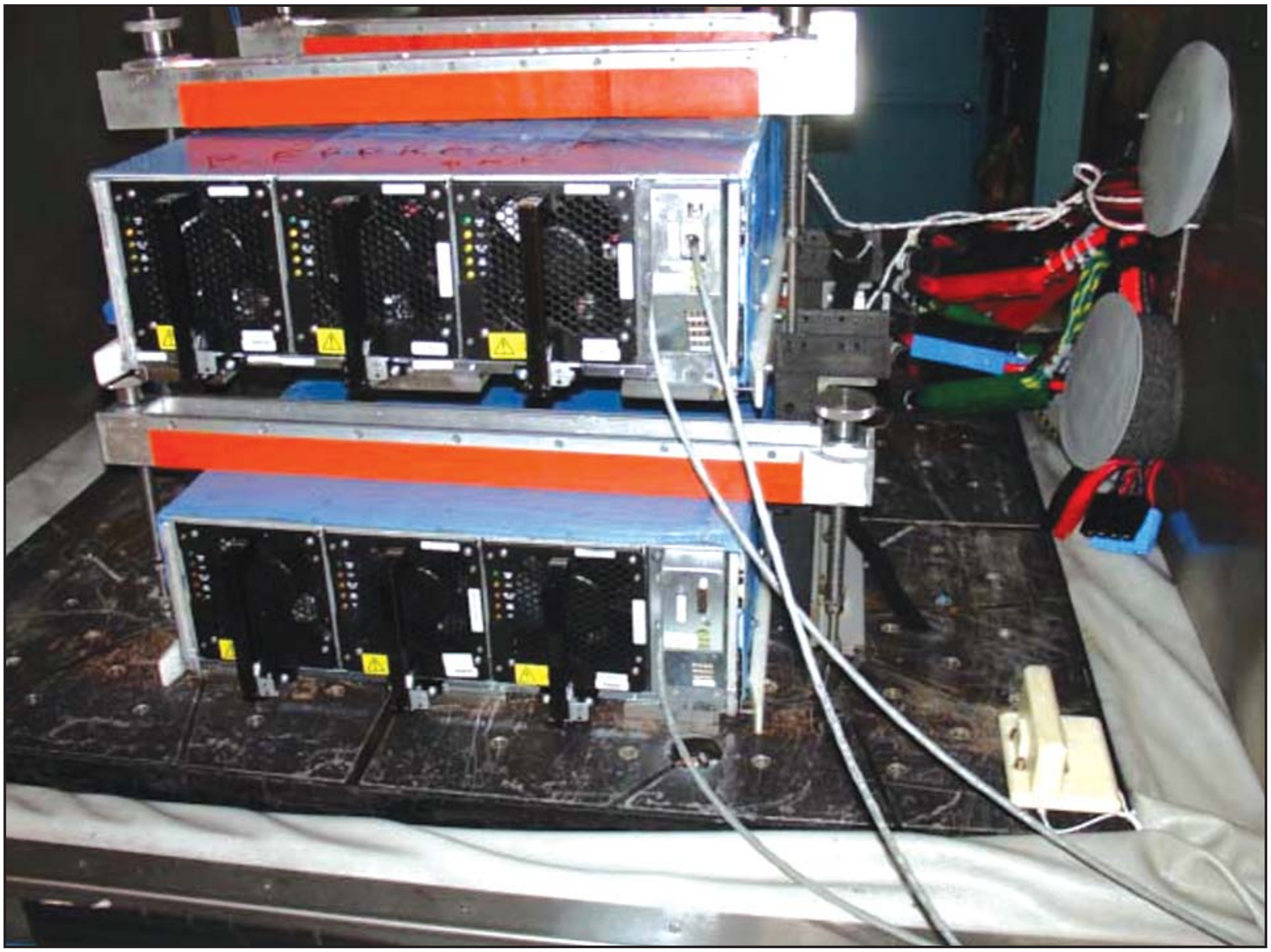

Figure 1: Typical Production units undergoing HASS Testing

SECTION 2 - STRESS TESTING METHODOLOGY

BATHTUB CURVE

The "bathtub curve" is the traditional method of graphically displaying the failure rate of an entire population of products over time. It is the mathematical superposition of three distinct functions. A typical "bathtub curve" (blue) is shown in the figure below:[1]

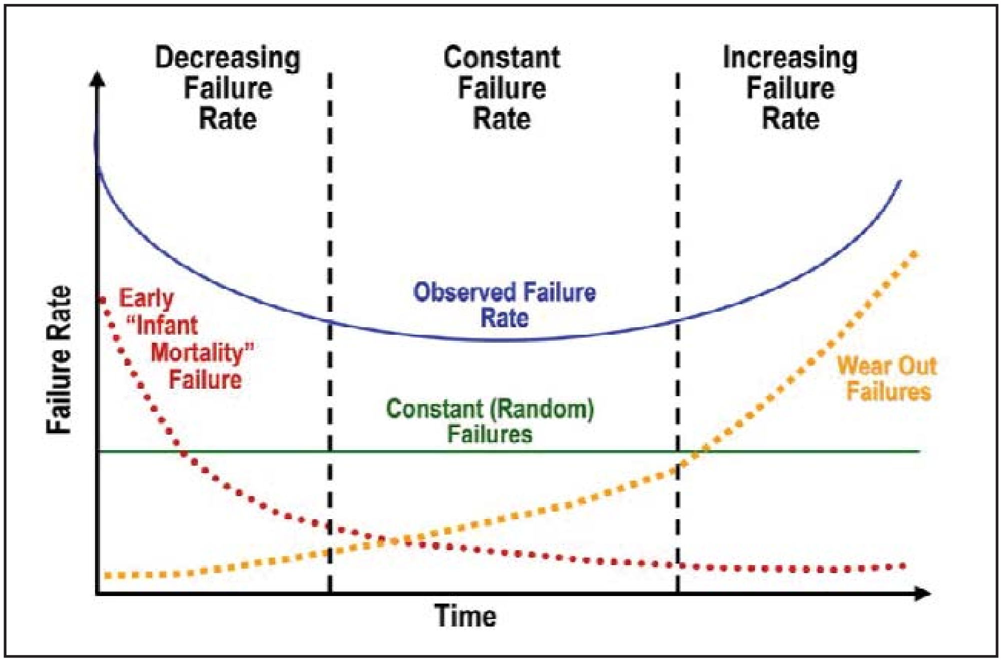

Figure 2: Bathtub Curve

The first function is the "infant mortality" function (red) that models early failures. During this period, the failure rate starts out high and rapidly decreases.

The second function is the "constant failures" function (green) that models the normal useful life of the product. During this period, the failures are random and the failure rate is low and relatively constant.

The third function is the "wear-out" function (yellow) that models the end-of-life of the product. During this period, the failure rate starts out low and rapidly increases.[2]

HASS attempts to uncover the early part defects and move the product into the "constant failures" period.

PART DEFECTS

Consider how failures occur. The process starts with a defect that occurs in a part. These part defects usually tend to concentrate applied stresses at the site of the flaw. When normal stresses are encountered in the customer's end-use environment, they eventually cause the defective part to fail at the flaw, but it may take a long time. HASS applies accelerated stresses and makes the part fail quickly at the flaw. As an example, a cold-soldered joint will quickly weaken and break loose under accelerated stress, whereas a good joint remains intact.

The guiding philosophy behind HASS must never be forgotten. That is, the implementation of an effective HASS requires an in-depth understanding of the physical processes that produce failures and the application of accurate mathematical models based on scientific principles. The key is to know the possible failures and what stresses will accelerate them.

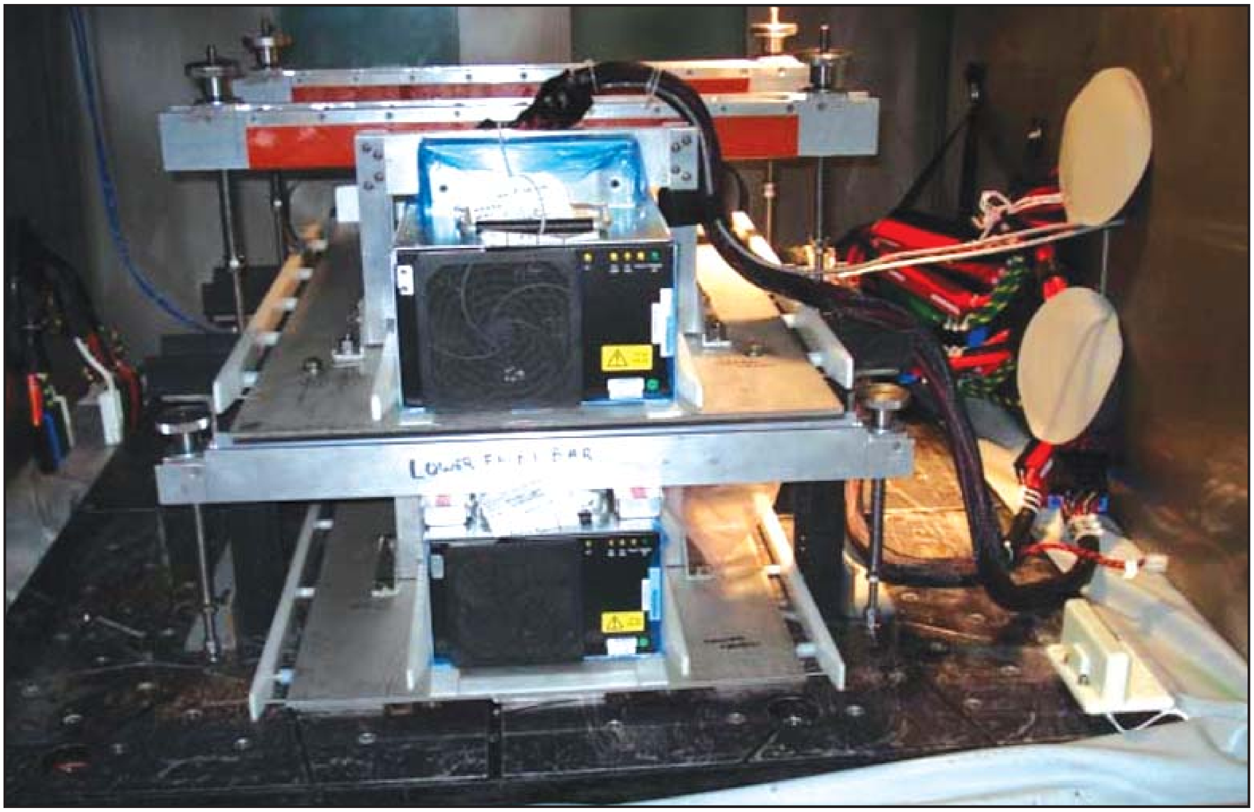

Figure 3: Production Units fixtured for Vibration

SECTION 3 – PREDICTIVE FAILURE MODELS

Failures in electronics equipment can generally be traced to long-term chemical interactions, or material fatigue caused by mechanical stress or temperature variations. These can lead to compromise of insulating properties of some materials or conductive properties of other materials. Study of these phenomena has led to the development of mathematical models that can be used to predict how long reactions will take and how severe they will be as a function of environmental factors. The models of most interest to electronic equipment are as follows.

ARRHENIUS MODEL

The Arrhenius equation was first proposed by the Dutch chemist J.H. van't Hoff in 1884 and then interpreted in 1889 by the Swedish physical chemist Svante Arrhenius. It has its roots in the molecular motion within chemical reactions, where reaction rates increase with increasing temperature and decreasing activation energy. The applicable mathematical relationships are defined in the Arrhenius equation below:[3]

$$k_A = A \times \exp\{-E_a/R \times (1/T)\}$$

Where:

k_A = Reaction rate
A = Constant
T = Absolute Temperature of the reactants (°K)
E_a = Activation energy for the particular reaction
R = Universal Gas Constant

Since many failures depend on chemical reactions, the Arrhenius equation was adapted for use in reliability testing. The concept of an "activation energy" for particular classes of failures was introduced.

Temperature is a universal stress. The Arrhenius Model is applicable when elevated temperature is the accelerating stress and potential failures depend on molecular activity. In the past, burn-in testing was a prevalent technique for improving the reliability of products. The product would be operated at a constant elevated ambient temperature for a defined time period. The Arrhenius Model for reliability applications is as follows: 4

$$L_{Tu} = C_T \ \ x \ \ \exp\{ E_a/k \ \ x \ \ (1/T_u) \}$$

Where:

L_{Tu} = Equipment (UUT) life at use temperature (hours)
T_u = Equipment temperature at use (°K)
E_a = Activation energy for the particular type of failure (eV)
k = Boltzmann's constant ($8.623 \text{x} 10^{-5}$ eV/ °K)
C_T = Thermal constant factor

The preceding form of the Arrhenius Model is seldom used as is. It is usually written in terms of an "acceleration factor", which compares the more stressful test environment at elevated temperature with the customer end-use environment. Testing at constant elevated ambient temperature can be extrapolated to estimate the equivalent time in the end-use environment. The Arrhenius Model written in terms of "acceleration factor" is as follows:

$$A_T = \exp\{ E_a/k \ \ x \ \ \{ (1/T_u)-(1/T_A) \} \} = L_{Tu} / L_{TA}$$

Where:

A_T = Thermal acceleration factor (dimensionless)
L_{Tu} = Equipment (UUT) life at use temperature (hours)
L_{TA} = Equipment (UUT) life at accelerated temperature (hours)
T_u = Maximum UUT temperature in use environment (°K)
T_A = Maximum UUT temperature in accelerated environment (°K)
E_a = Activation energy for the particular failure (eV)
k = Boltzmann's constant ($8.623 \text{x} 10^{-5}$ eV/ °K)

EXAMPLE:

Calculate the Arrhenius Model "acceleration factor" and the equivalent time in the customer end-use environment for a burn-in test conducted at an elevated ambient test temperature of 50°C.for 3 hours. It has been determined that the maximum UUT temperature in the use environment is 45°C, the maximum UUT temperature in the burn-in environment is 80°C and the targeted failure has an activation energy of 0.60eV. The nominal customer end-use ambient temperature is 25°C, the thermal rise of the UUT above ambient in the customer environment is 15°C and the fluctuation of ambient temperature in the customer environment is 5°C. The UUT is continuously powered at full load during the duration of the burn-in test.

T_u = 45°C = 318.15 °K
T_A = 80°C = 353.15 °K

$$A_T = \exp\{ 0.60/0.00008623 \text{ x } \{(1/318.15)-(1/ 353.15)\}\} = 8.74$$

That is, testing in the more stressful burn-in environment for 3 hours at 50°C ambient is equivalent to ~26 hours or ~1.1 days in the customer end-use environment of a nominal 25°C.

Various organizations and researchers have compiled comprehensive tables of activation energies for different classes of failures.[5] A good general activation energy for many classes of failures is 0.60eV. An example of how the acceleration factor varies with temperature for different activation energies is shown below:

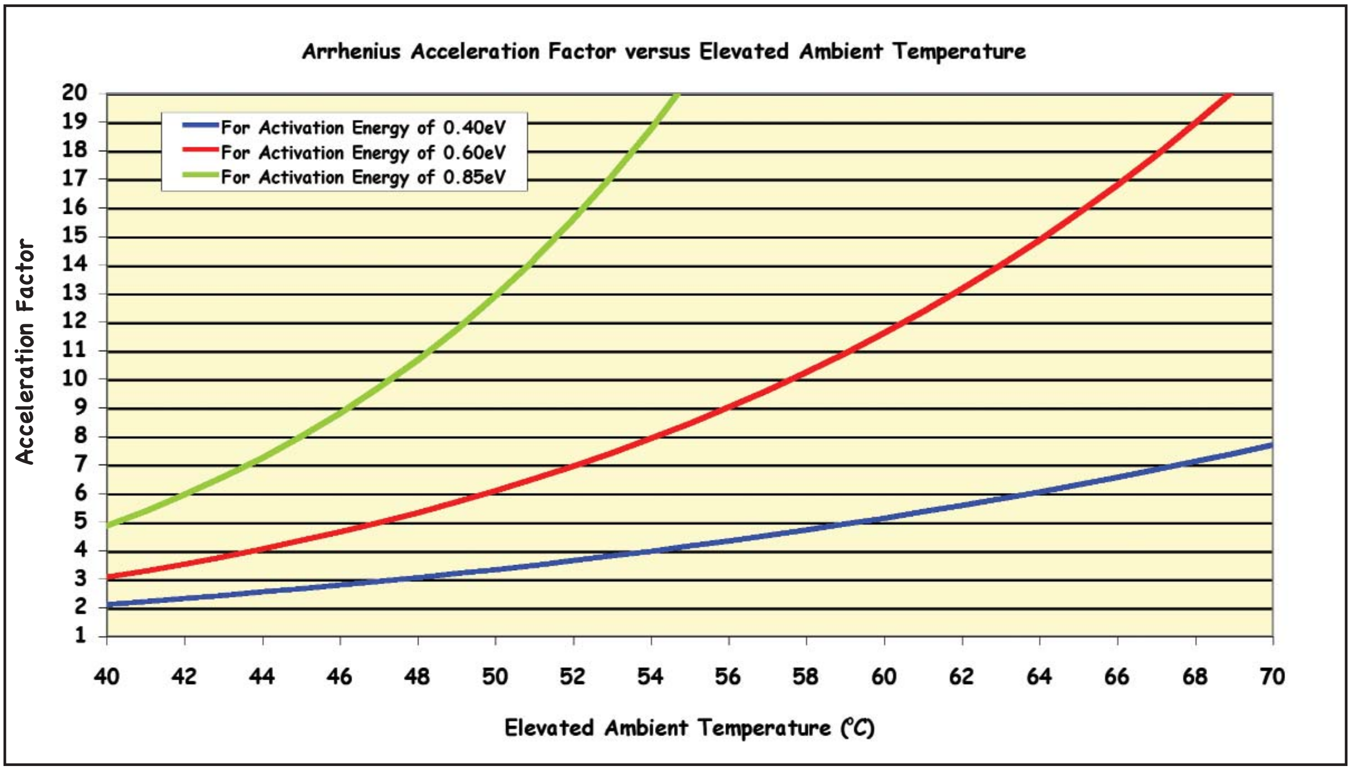

Figure 4: Arrhenius Acceleration Factor for Various Activation Energies

COFFIN-MANSON MODEL

Consider the particular physics of failure for thermal cycling. Thermal cycles induce low-cycle fatigue mechanisms in metal bonds such as solder fillets in two subsequent steps. First, a small crack will be formed at locations where high strain amplitudes occur, such as menisci, edges, corners and transition interfaces. The number of thermal cycles needed to initiate a crack is a function of the strain amplitude, which in turn depends on the magnitude of the temperature change during the thermal cycle. Second, once the crack is initiated, it propagates during subsequent thermal cycles.[6]

The Coffin-Manson equation models the effects of such low-cycle fatigue induced by thermal stressing. It follows an Inverse Power Law relationship. That is, as the magnitude of induced stress increases, the number of cycles to failure decreases by power of two. The equation developed from research done by L.F. Coffin Jr. and S.S. Manson is as follows:[7]

$$N_f \times (\Delta\varepsilon_p)^2 = C_1$$

Where:

N_f = Number of cycles to failure (cycles)
$\Delta\varepsilon_p$ = Plastic strain
C_1 = Proportionality constant for the particular material

Since the plastic strain, $\Delta\varepsilon_p$, is proportional to the magnitude of thermal cycle temperature change, ΔT , the preceding form of the Coffin-Manson equation may be rewritten in terms of the magnitude of the thermal cycle temperature change as follows:

$$\mathbf{N_f \ x \ (\Delta T)^2 = C_2}$$

Where:

N_f = Number of thermal cycles to failure (cycles)
ΔT = Magnitude of thermal cycle temperature change
C_2 = Proportionality constant for the particular material

As with the Arrhenius Model, the preceding form of the Coffin-Manson Model is seldom used as is. It is usually written in terms of an "acceleration factor", which compares thermal cycles in the more stressful test environment with thermal cycles in the customer end-use environment. Thermal cycles in the more stressful test environment can be extrapolated to estimate the equivalent thermal cycles in the end-use environment.

The Coffin-Manson Model written in terms of an "acceleration factor" for thermal cycles is as follows:

$$\mathbf{A_{CM} = (\Delta T_A / \Delta T_u)^2 = N_{fu} / N_{fA}}$$

$$\mathbf{N_{fu} = N_{fA} \ x \ (\Delta T_A / \Delta T_u)^2}$$

Where:

A_{CM} = Acceleration factor for number of cycles (dimensionless)
N_{fu} = Number of cycles to failure at use temperature change (cycles)
N_{fA} = Number of cycles to failure at accelerated temperature change (cycles)
ΔT_A = Thermal cycle temperature change in accelerated environment (°K)
ΔT_u = Thermal cycle temperature change in use environment (°K)

Each HASS test consists of a defined number of thermal cycles lasting a defined time duration. For purposes of reliability assessment, It would be desirable to express the "acceleration factor" in terms of time duration rather than thermal cycles. Consider the following definitions:

f_u = Frequency of thermal cycles in use environment (cycles/day)
f_A = Frequency of thermal cycles in accelerated environment (cycles/day)
D_u = Time duration in use environment (days)
D_A = Time duration in accelerated environment (days)

The number of thermal cycles can then be expressed in terms of the above definitions as follows:

$$\mathbf{N_{fu} = D_u \ x \ f_u}$$
$$\mathbf{N_{fA} = D_A \ x \ f_A}$$

The preceding equations for N_{fu} and N_{fA} can be substituted into the Coffin-Manson Model to yield an expression for a Coffin-Manson "time duration acceleration factor" as follows:

$$\mathbf{A_{CMD} = (\Delta T_A / \Delta T_u)^2 \ x \ (f_A / f_u) = D_u / D_A}$$

$$\mathbf{D_u = D_A \ x \ (\Delta T_A / \Delta T_u)^2 \ x \ (f_A / f_u)}$$

Where:

A_{CMD} = Acceleration factor for time duration (dimensionless)
ΔT_A = Thermal cycle temperature change in accelerated environment (°K)
ΔT_u = Thermal cycle temperature change in use environment (°K)
f_u = Frequency of thermal cycles in use environment (cycles/day)
f_A = Frequency of thermal cycles in accelerated environment (cycles/day)
D_u = Time duration in use environment (days)
D_A = Time duration in accelerated environment (days)

EXAMPLE:

Calculate the Coffin-Manson "time duration acceleration factor" and the equivalent time in the customer end-use environment for a HASS test conducted for 3 hours, cycling between a maximum HASS temperature of 50°C and a minimum HASS temperature of -10°C, for 3 complete thermal cycles. It has been determined that the maximum UUT temperature in the use environment is 45°C and the maximum UUT temperature in the HASS environment is 80°C. The nominal customer end-use ambient temperature is 25°C, the thermal rise of the UUT above ambient in the customer environment is 15°C and the fluctuation of ambient temperature in the customer environment is 5°C. The customer end-use temperature change is 20°C and the customer end-use environment classification is "computers".

$\Delta T_A = (80+273.15) - (-10+273.15) = 90\ °K$
$\Delta T_u = 20°K$
$D_A = 3 \text{ hours} \times 1 \text{ day}/ 24 \text{ hours} = 0.125 \text{ days}$
$f_A = 3 \text{ cycles}/ 3 \text{ hours} \times 24 \text{ hours/day} = 24 \text{ cycles/day}$

Numerous publications exist that estimate the number of thermal cycles for various customer end-use environments.[8, 9] The original source appears to be the Institute of Printed Circuits IPC SM 785. These sources estimate the number of thermal cycles for a "computer" classification end-use environment is 1460 cycles/year, which is equivalent to 4 cycles/day.

Therefore,

$f_u = 4 \text{ cycles/day}$
$A_{CMD} = (90 / 20)^2 \times (24 / 4) = 121.5$

That is, 3 hours in the more stressful HASS environment is equivalent to ~365 hours or ~15 days in the customer end-use environment. Thus, the real benefit of HASS compared to burn-in emerges. In a previous example, 3 hours of burn-in at 50°C was only equivalent to 1.1 days. Considering only thermal stresses, HASS is ~14 times more aggressive than burn-in.

NORRIS-LANDZBERG MODEL

Researchers have found the Coffin-Manson Model to yield somewhat conservative estimates for fatigue life. IBM researchers K.C Norris and A.H. Landzberg modified it to compensate for frequency-dependent and time-dependent anomalies. Their landmark work was presented in a paper in May 1969, as the Modified Norris-Landzberg Model as follows:

$$\mathbf{A_{NL} = (\Delta T_A / \Delta T_u)^2 \times (f_u / f_A)^{1/3} \times \exp\{ 1414 \times \{ (1/T_u)-(1/T_A) \} \}}$$

Where:

A_{NL} = Acceleration factor for number of cycles (dimensionless)
ΔT_A = Thermal cycle temperature change in accelerated environment (°K)
ΔT_u = Thermal cycle temperature change in use environment (°K)
f_u = Frequency of thermal cycles in use environment (cycles/day)
f_A = Frequency of thermal cycles in accelerated environment (cycles/day)
T_u = Maximum UUT temperature in use environment (°K)
T_A = Maximum UUT temperature in accelerated environment (°K)

Just as was done for the Coffin-Manson Model, the preceding equations for N_{fu} and N_{fA} can be substituted into the Norris-Landzberg Model to yield an expression for a Norris-Landzberg "time duration acceleration factor" as follows:

$$\mathbf{A_{NLD} = A_{NL} \ \ x \ \ (f_A / f_u) \ = D_u / D_A}$$

$$\mathbf{A_{NLD} = \ (\Delta T_A / \Delta T_u)^2 \ x \ (f_u / f_A)^{1/3} \ x \ exp\{ 1414 \ x \ \{ (1/T_u)-(1/T_A) \} \} \ x \ (f_A / f_u)}$$

$$\mathbf{D_u = D_A \ \ x \ \ (\Delta T_A / \Delta T_u)2 \ \ x \ \ (f_A / f_u)}$$

Where:

A_{NLD} = Acceleration factor for time duration (dimensionless)
ΔT_A = Thermal cycle temperature change in accelerated environment (°K)
ΔT_u = Thermal cycle temperature change in use environment (°K)
f_u = Frequency of thermal cycles in use environment (cycles/day)
f_A = Frequency of thermal cycles in accelerated environment (cycles/day)
T_u = Maximum UUT temperature in use environment (°K)
T_A = Maximum UUT temperature in accelerated environment (°K)
D_u = Time duration in use environment (days)
D_A = Time duration in accelerated environment (days)

EXAMPLE:

Calculate the Norris-Landzberg "time duration acceleration factor" and the equivalent time in the customer end-use environment for a HASS test conducted for 3 hours, cycling between a maximum HASS temperature of 50°C, minimum HASS temperature of -10°C, for 3 complete thermal cycles. It has been determined that the maximum UUT temperature in the use environment is 45°C and the maximum UUT temperature in the HASS environment is 80°C. The nominal customer end-use ambient temperature is 25°C, the thermal rise of the UUT above ambient in the customer environment is 15°C and the fluctuation of ambient temperature in the customer environment is 5°C. The customer end-use temperature change is 20°C and the customer end-use environment is "computers".

$\Delta TA = (80+273.15) - (-10+273.15) = 90$ °K
$\Delta Tu = 20$°K
D_A = 3 hours x 1 day/ 24 hours = 0.125 days
f_A = 3 cycles/ 3 hours x 24 hours/day = 24 cycles/day
f_u = 4 cycles/day
T_u = 45°C = 273.15+45 = 318.15°K
T_A = 80°C = 273.15+80 = 353.15°K

Therefore,

$$\mathbf{A_{NLD} = \ (90 / 20)^2 \ x \ (4 / 24)^{1/3} \ x \ exp\{ 1414 \ x \ \{ (1/318.15)-(1/353.15) \} \} \ x \ (24/4) = 103.8}$$

That is, 3 hours in the more stressful HASS environment is equivalent to ~311 hours or ~13 days in the customer end-use environment.

The Norris-Landzberg "time duration acceleration factor" is not as aggressive as the Coffin-Manson result, which was 121.5. But the real benefit of HASS compared to burn-in still emerges. In a previous example, 3 hours of burn-in at 50°C was only equivalent to 1.1 days. Considering only thermal cycling stresses, HASS is still ~12 times more aggressive than burn-in.

Dwell Time and Ramp Rate

A thermal cycle has an associated ramp rate and dwell time. During thermal ramp, the mismatch in coefficients of thermal expansion for the constituent materials on a printed circuit board causes stresses to develop. During thermal dwell, the stress energy gets relieved by converting to strain or relative motion. For example, if solder joints are marginal, permanent deformation or damage occurs during the thermal dwell. If the solder joints are good, no permanent deformation or damage occurs. The point is, the thermal dwell time must be sufficiently long for this stress-relaxation process to occur. If the thermal dwell time is not sufficiently long, the full benefit of HASS will not be realized.

In order to ensure that optimal thermal dwell times are achieved, the thermal inertia of the product must be estimated. The methodology involved in constructing a thermal cycling profile will be the subject of future White Papers. However, our experience indicates that ramp rates of 10°C/minute to 20°C/minute and dwell times of 15 minutes to 20 minutes are sufficient to precipitate most manufacturing and component defects. This is also supported by the work of numerous researchers. An excellent example of such work is the recent technical paper by Zhai, Sidharth and Blish II.[10]

Input Power Cycling

Consider the stresses produced by input power cycling. When the mains input power is turned on to the UUT, it produces inrush currents as capacitors charge and establish electric fields. It also causes the UUT to heat up in proportion to the UUT efficiency and delivered output power. As the mains input power is turned off, the electric fields collapse and produce voltage transients. It also causes the UUT to cool down as energy is no longer being dissipated. Our knowledge of power supplies intuitively leads us to suspect that the more the UUT is turned on and off, the greater the stress on front-end components. However, there are few definitive studies that analyze the contribution of input power cycling to acceleration factor. Therefore, it will be conservatively assumed that the acceleration factor is due entirely to the thermal effects. The non-thermal contribution due to input power cycling will be ignored. The methodology involved in designing an input power cycling profile will be the subject of future technical papers.

Output Power Cycling

Analogously, consider the stresses produced by output power cycling. When the applied load on the output of the UUT is increased, it causes the PWM circuitry to increase its duty cycle and the output power devices carry more current. Just like for input power cycling, it also causes the UUT to heat up in proportion to UUT efficiency. As the output load is decreased, the output drive components carry less current and the UUT cools down. Intuition again leads us to suspect that the greater the load, the greater the stress on output drive components. However, there are few definitive studies that analyze the contribution of output power cycling to acceleration factor. Therefore, it will be conservatively assumed that the acceleration factor is due entirely to the thermal effects. The non-thermal contribution due to output power cycling will be ignored. The methodology involved in designing an output power cycling profile will be the subject of future White Papers.

SECTION 4 – APPLYING PREDICTIVE MODELS AS PART OF A PRODUCTION PROCESS

Predictive models can be used to fine tune HASS test parameters so as to provide adequate run time to overcome infant mortality failures, but not expend a significant portion of the products' useful life. TDI's typical process is to set the HASS stress levels and duration to simulate 15 days to 60 days of operation in the product's intended environment. This will expose most failure mechanisms that would typically escape a static burn in test, while not significantly reducing the products' useful life (typically 7+ years for a power supply).

As will be shown in future papers, determination of the exact stress levels imparted to the product will be a function of the product's mass, the chamber enviroment, the product's dimensions, the types of components utilized, safety and protection circuits in the product and the design's safe operating area as established via Highly Accelerated Life Testing, or HALT.

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"If I see further, it is because I stand on the shoulders of giants", attributed to Sir Isaac Newton writing to his colleague and fellow scientist, Robert Hooke. The work, discoveries and writings of our predecessors is hereby properly acknowledged:

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SECTION 6 - EQUATIONS

GENERIC INVERSE POWER LAW MODEL

$$L_{Vu} = C_V / (V_u)^n$$

Where:

L_{Vu} = UUT life at use stress V_u (dimensionless)
V_u = UUT stress at use
C_V = Constant factor
n = Exponent for pertinent stress V_u

4.2 - ACCELERATION FACTOR FOR GENERIC INVERSE POWER LAW MODEL

$$A_V = (V_A / V_u)^n = L_{Vu} / L_{VA}$$

Where:

A_V = Acceleration factor for stress V (dimensionless)
L_{Vu} = UUT life at use stress V_u (hours)
L_{VA} = UUT life at accelerated stress V_u (hours)
V_A = UUT accelerated stress
V_u = UUT use stress
n = Exponent for particular stress V (dimensionless)

For more information

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