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Defining Accelerated Test Requirements for PWBs: A Physics-Based Approach

Kevin D. Cluff
Honeywell Air Transport
Phoenix, AZ

Michael Osterman
CALCE EPSC, University of Maryland
College Park, MD

Abstract
Typically thermal cycle test requirements for printed wiring boards (PWBs) are somewhat arbitrarily established for a particular product. Many programs simply default to a standard test without much quantitative analysis. With product reliability and cost management pressures, developing realistic accelerated test criteria is vital. The procedure described in this paper is based on substantial measured field environment data, a validated acceleration model with a generalized product definition, and statistically based test requirements. While the particular example is for commercial air transport avionics, the proposed procedure is easily extensible to other high reliability applications.

Introduction
Component qualification is an important process step in high reliability product development and validation. Often test requirements are defined without much regard to the environment and life cycle of the end application. One failure mechanism of particular interest in the air transport industry is thermal cycle fatigue of plated through holes (PTH). The interest stems not from any specific field problems, but in that PTH fatigue is a known wear out mechanism that can be potentially hazardous in air transport avionics.

The failure of a plated through hole produces an increase in electrical resistance or a complete electrical open that results in a disruption on electrical functionality due to circumferential cracking of metal plating. Failure in the PTH plating barrel results from the mismatch in the coefficient of thermal expansion (CTE) between the plating material and board material. This mismatch is primarily in the out-of-plane or thickness direction of the printed wiring board (PWB), because the out-of-plane CTE of the board is typically three to four times greater than the CTE of the plating. Due to the CTE mismatch, temperature excursion arising from electrical operation of the circuit board or exposure to ambient temperature cycling cause damage to the metal plating that eventually will lead to complete material failure (See Figure 1).

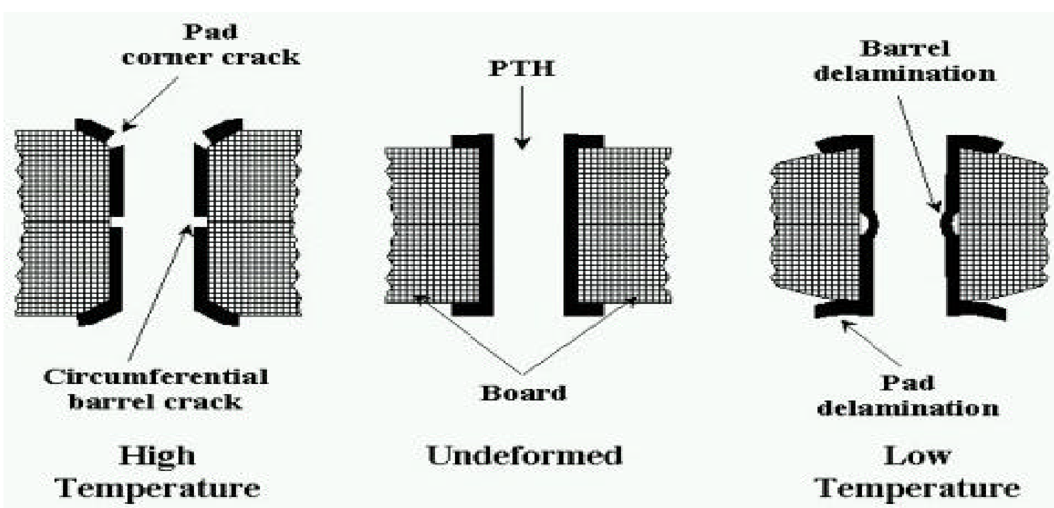

Figure 1 - Effect of Temperature Cycling on a Plated Through Hole

Printed wiring boards are exposed to airplane thermal cycles, caused by diurnal, flight-related cooling and electronics self-heating. Aircraft are parked overnight, powered up in the morning and flown on various routes. This daily routine continues for the 20-year design life -- some 60,000 flights.

The purpose of this paper is to define a process of establishing Printed Wire Board (PWB) accelerated test requirements that Honeywell's PWB suppliers, or new technology must pass in order to be preferred status. The process utilizes measured environmental data, generalizes the board geometry and design, details the assumptions and application of the acceleration model, and ultimately, defines accelerated test requirements. The number of cycles that must be passed without failure is influenced by sample size, thermal cycle definition, Weibull shape factor for the failure mechanism, confidence limits, and reliability level.

The rigor is important to give confidence to our customers (the airframe manufacturers and airlines) and the regulatory agencies. It also provides a level of credibility to our suppliers that the test requirements are not arbitrary.

Discussion of Methodology

The five steps of the methodology include

- Defining the application environment,
- Estimating the accumulated damage in application environment with a representative design,
- Calculating equivalent damage in the accelerated test,
- Applying an appropriate factor of safety, and
- Defining the test plan based on statistical parameters.

Each step in the methodology will be discussed in the context of a PWB in a commercial airplane avionics environment.

Defining the Application Environment

The process of defining the use environment can range from the very involved to the very simplistic. While avionics temperature cycles have been estimated from outside air temperatures, actually measuring the avionics environment provides a superior level of confidence. The approach involved measuring the environment on operating airplanes.

The Aircraft Environment Monitor (AEM) was developed as an engineering tool to better understand the avionics-operating environment. This stand-alone device records temperature, pressure, humidity, and sound in a timeline format. It is independent from the airplane systems and is simple to install and to recover data.[1,2]

AEMs were installed at a European airline on five commercial airplane models[3] for a period of about two years. Approximately 241,000 hours of flight data was collected through approximately 17,560 flights. Flights were identified by the sound and pressure level recorded by the AEM. In this case a "flight" was defined as the ground time prior to the flight until the landing of the flight. The difference of the maximum and minimum flight temperatures is the flight thermal cycle.

A thermal cycle was created with the AEM data. The histogram shape was very similar for the five models, one example for the electronic equipment bay is shown in Figure 2. The Weibull distribution was found to fit the data sets better than any other distribution.

The variance for the summarized data was calculated using

$$s^2 = h^2 \left\{ \Gamma\left(1+\tfrac{2}{b}\right) - \Gamma\left(1+\tfrac{1}{b}\right)^2 \right\} \qquad (1)$$

Where h is the scale factor, b is the shape factor and Γ is the gamma function.

The statistical parameters for the summarized distribution are listed in Table 1.

$$m = h\Gamma\left(1+\tfrac{1}{b}\right) \qquad (2)$$

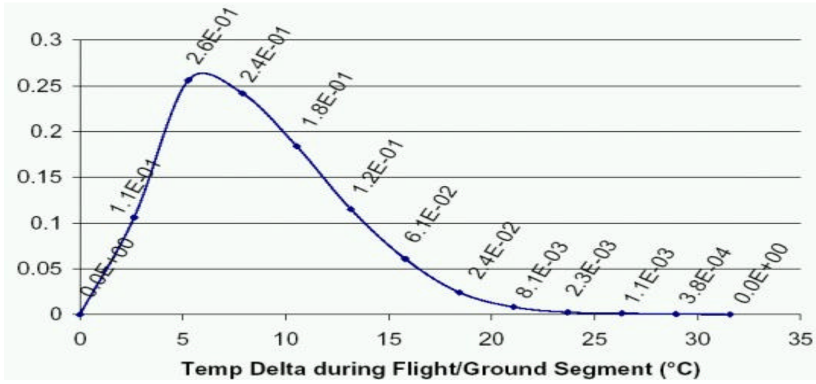

Figure 2 - Distribution of Temperature Cycles in the Electronic Equipment Bay

Table 1 - Weibull Parameters for Summarized Temperature Cycle Data

Statistical Parameters	**EE-bay**	**Shifted EE-bay**
Shape Factor	1.6	1.6
Scale Factor	11.2	24.3
Mean	10.0	22.7
Sigma	6.4	6.4
Variance	40.6	40.6

Of course the measured population is not inclusive of all routes and airlines. Two standard deviations were added to the scale factor to conservatively shift the distribution to the right. The new scale factor became 24.3°C. The measured data were shifted by 12.8°C. As more data are available, this assumption can become more quantitative.

The start-up conditions of the equipment causes a temperature cycle of the PWB that must be summed with the external cycle. A survey of thermal analyses showed a typical 21°C temperature rise for the board temperature above ambient. AEM data show that, on average, there is one equipment power cycle per day. This cycle is assumed to be 21°C and is added to those ambient power cycles (measured from the AEM distribution) that correspond to equipment start-up. (See Figure 3.)

The number of flights and the number of equipment starts per day are also important parameters of the total fatigue damage. As each commercial airplane model has different flight requirements and lifetimes, an analysis was performed to determine the worse case combination of flights and equipment starts. The worst-case damage was 60,000 flights with one equipment start-up cycle per day for 20 years.

Estimating the Accumulated Damage in Application Environment with a Representative Design

To assess PTH failure, a one-dimensional elastic-plastic model has been developed by the CALCE Electronic Products and System Center Consortium.[4] The Consortium PTH failure model simulates the stress and strain in plating material by considering the coefficients of temperature expansion (CTEs), the modulus of elasticity, and the yield strengths of the material used to construct the PTH. Alternatively, the PTH fatigue model documented in IPC-TR-579 could also be used.[5]

Finite element design of experiments was used to calibrate the stress response of the model with detailed simulation results. In developing the model and in addition to material properties, critical parameters included (See Figure 4), hole diameter, plating thickness, board thickness, pad size, spacing to adjacent PTHs, and the applied temperature excursion. Life of the PTH is estimated by using modified Manson-Coffin fatigue model to relate cyclic stress and inelastic strain to cycles to failure. The agreement between the trends predicted by the Consortium model, nonlinear finite element simulations and experimental data (when available), is quite good. A comparison of the model and experimental measurements is provided in Figure 5.[6]

To maximize the usefulness of the Consortium PTH failure model, it has been implemented as a software program that is available as a standalone failure model in the calceFAST software. A screen capture of the software tool with the Consortium PTH model loaded is depicted in Figure 6.

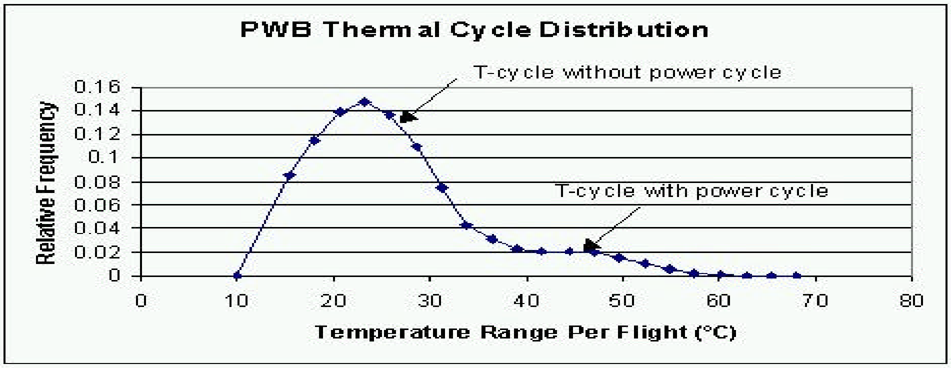

Figure 3 - Thermal Cycle Distribution by Flight of a PWB in a Commercial Avionics Application

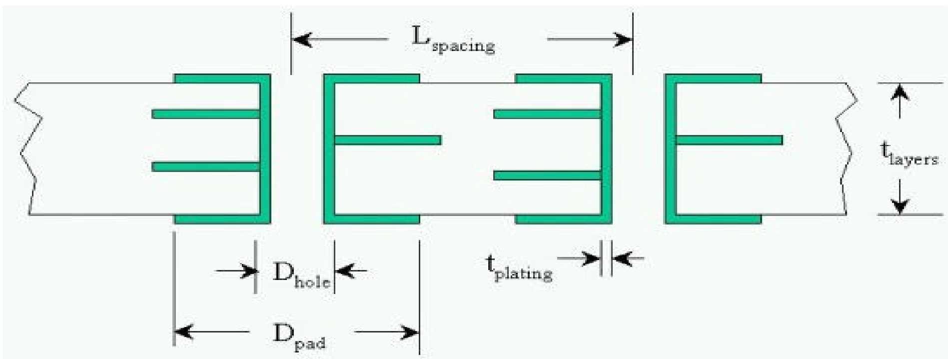

Figure 4 - Schematic of Geometric Input Parameters to the Consortium PTH Failure Model

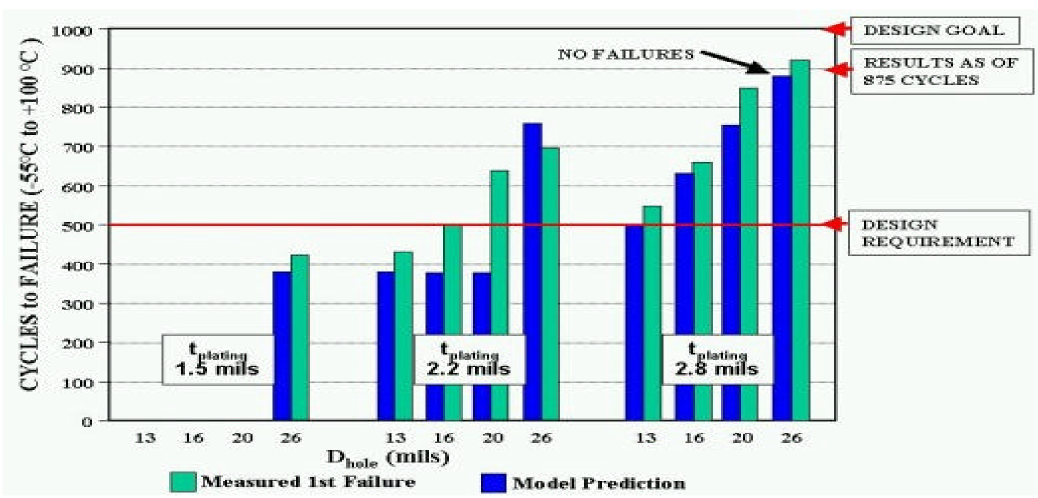

Figure 5 - Comparison of Model with Failure Data

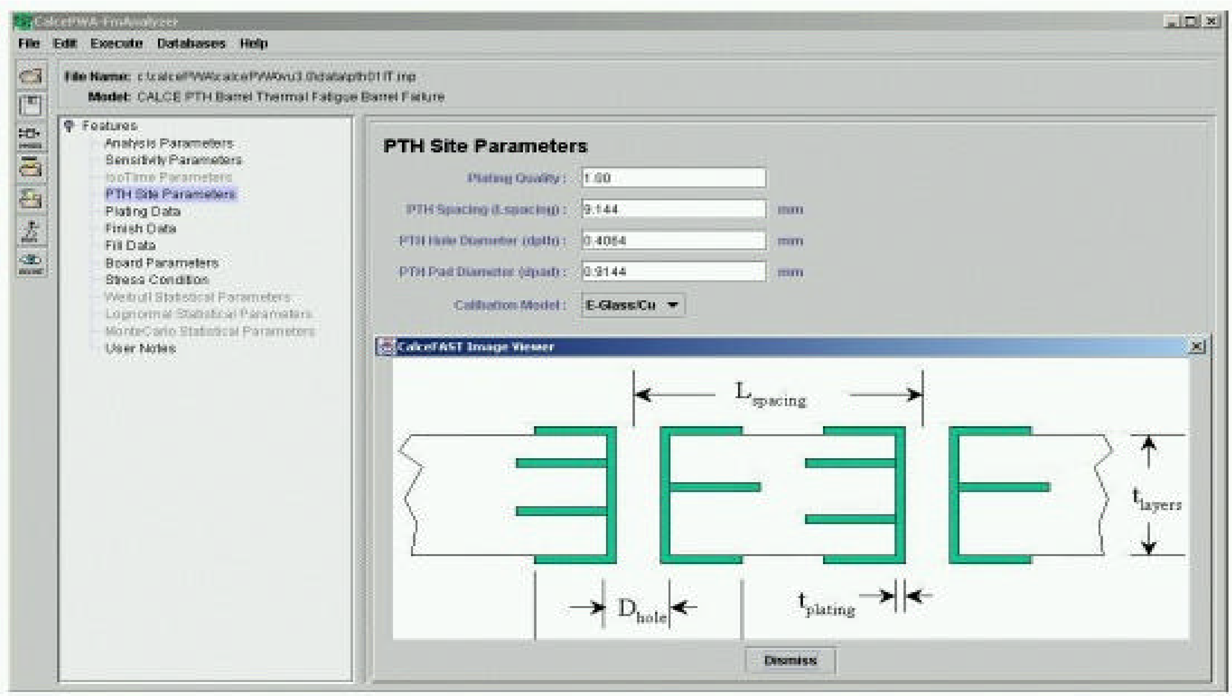

Figure 6 - Screen Capture of CalceFAST Software (Consortium PTH Failure Model Loaded)

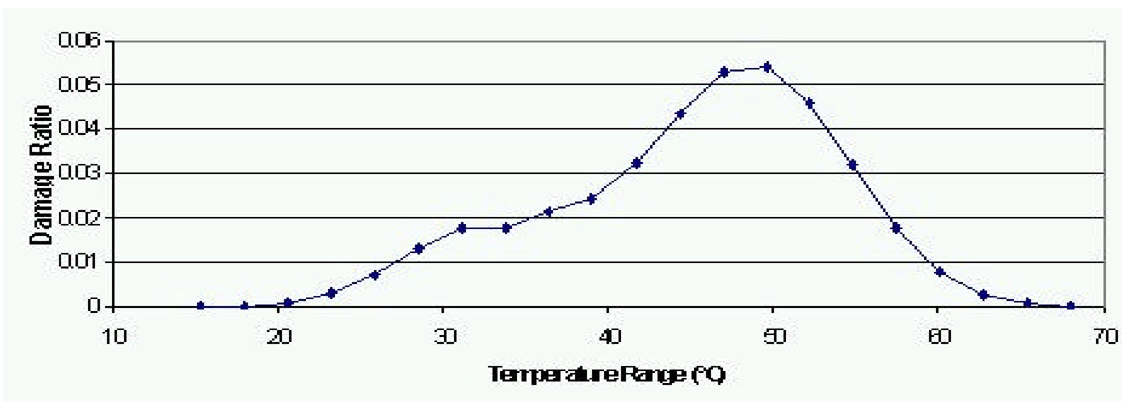

Figure 7 - Distribution of the Damage Ratio of a PWB in an Avionics Environment

The PTH failure model is used to estimate the mean cycles to failure at each thermal cycle range. The particular design variables were chosen so as to provide a conservative acceleration factor between the field and accelerated test. Analysis inputs are shown in Table 2. The model was loaded with each cycle condition to determine the predicted cycles to fail shown in Table 3. The Damage Ratio, D_R, is the number of field cycles, n_{field}, divided by the predicted cycles to fail, N_f.

$$D_R = \frac{n_{field}}{N_f} \quad (3)$$

Applying Miner's rule of damage superposition, the damage ratios can be summed to obtain the total damage accumulated over the design life. The total damage for the commercial airplane example (Table 3) is 0.395.

$$D_T = \sum D_R \quad (4)$$

The damage distribution is shown in Figure 7.

Table 2 - Consortium PTH Analysis Inputs

Consortium **PTH Parameter**	**Input Value**
Plating quality factor	0.5
PTH spacing	0.100 in
PTH hole diameter (unplated)	0.019 in
PTH pad diameter	0.034 in
Material	Eglass/Cu
Board thickness	0.096 in
Plating thickness	1.5 mil
Board z-axis CTE	65E-6/°C

Calculating Equivalent Damage in the Accelerated Test

Assuming -55 to 125°C dual chamber thermal shock test[6] for the test environment, the PTH failure model estimates the mean cycles to failure, $N_{f\text{-}test}$, to be two hundred and thirty cycles. The total damage can be converted to the number of accelerated test cycles that would cause equivalent damage. The simple relation for the Equivalent Cycles to Failure, ECTF is

$$ECTF = D_T \times N_{f-test} \quad (5)$$

Since the test coupons have been preconditioned, no additional damage needs to be added to simulate board assembly and rework.

In the commercial airplane example, ECTF is approximately ninety-one cycles a -55 to 125°C accelerated test.

Applying an Appropriate Factor of Safety

Because fatigue models are generally only accurate to within a factor of about 2X, it is important to apply this factor of safety to the test cycles. This assures that the model uncertainty will not produce an overly optimistic test result.

For the example, the number of equivalent accelerated cycles required is 91*2 = 182. This result must still be modified to account for uncertainties of the accelerated test itself.

Table 3 - Consortium PTH Stress Loads and Results

Cycle Range °C	**Frequency**	**Lifetime Cycles n_{field}**	**Predicted Cycles To Fail N_f**	**Damage Ratio D_R**
15.4	0.084866	5092	274800000	1.85E-05
18.0	0.115493	6930	47570000	0.000146
20.6	0.139044	8343	11030000	0.000756
23.3	0.147698	8862	3138000	0.002824
25.9	0.137181	8231	1159000	0.007102
28.5	0.109908	6595	510000	0.01293
31.2	0.074682	4481	252700	0.017732
33.8	0.042194	2532	143800	0.017605
36.4	0.031151	1869	87620	0.021331
39.1	0.02308	1385	56650	0.024445
41.7	0.021269	1276	39480	0.032324
44.3	0.020899	1254	28800	0.043539
47.0	0.019083	1145	21580	0.053058
49.6	0.015237	914	16840	0.05429
52.2	0.010354	621	13470	0.046119
54.8	0.00585	351	11000	0.031907
57.5	0.002688	161	9077	0.017765
60.1	0.00098	59	7659	0.007676
62.7	0.000276	17	6544	0.002532
65.4	5.86E-05	4	5624	0.000625
68.0	9.03E-06	1	4756	0.000114
Total Field Damage				0.395

Defining the Test Plan Based on Statistical Parameters

The accelerated test needs to be properly designed with a statistically based sample size. In this example, we choose a zero-failure test plan for reliability testing. This is based on the sample size, n, the Weibull shape factor for the PTH failure mechanism, b, the required reliability level, R, the desired confidence level, C, the multiplication factor, m, and the target cycles to failure ($ECTF$). The test time t_{test}, can be solved from the following relations.[8,9]

$$m = \left[\frac{\ln(1-C)}{n \ln(R)} \right]^{1/b} \quad (6)$$

$$t_{test} = m \times ECTF \quad (7)$$

This was used to determine a multiplication factor for the test time for a given confidence, Weibull shape parameter, desired reliability level, and sample size. Abernethy and Fulton[8] suggest that 0.90 is a good value for the confidence interval and that the reliability factor and confidence interval be equal.

The test multiplication factor was determined to be 0.882 based on the parameters listed in Table 4.

Thus, for the example, the requirement for printed wiring boards in commercial avionics is 0.882*182 = 160 cycles.

Table 4 Test Design Inputs

WinSMITH[9] Parameter	Input Value
Shape for PTH failures	4.0
Sample Size	36
Reliability Factor	.90
Confidence Level	.90
Allowable failures	0

Of course, if thirty-six samples are not available, equation (6) should be used to calculate a new test time multiplication factor. A smaller sample size would require a longer test for a given confidence, reliability and shape factor.

Conclusion

A methodology was described which provides a basis for establishing the limits of a PTH qualification test. As an example, the qualification limits for a PWB in the avionics bay of a commercial airplane were calculated. The analysis was based on the thermal cycle distribution of a measured field environment, a typical PWB design, and a physics-of-failure model. A factor of safety was added to account for uncertainty in the model. Finally, accepted test design techniques were applied to establish the qualification test sample size and actual test time duration for a given confidence and reliability level. The proposed procedure is easily extensible to other high reliability applications.

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