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Long Term Thermal Reliability of Printed Circuit Board Materials

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Abstract

This paper describes the purpose, methodology, and results to date of thermal endurance testing performed at the company. The intent of this thermal aging testing is to establish long term reliability data for printed wiring board (PWB) materials for use in applications that require 20+ years (100,000+ hours) of operational life under different thermal conditions. Underwriters Laboratory (UL) testing only addresses unclad laminate (resin and glass) and not a fabricated PWB that undergoes many processing steps, includes copper and plated through holes, and has a complex mechanical structure. UL testing is based on a 5000 hour expected operation life of the electronic product. Therefore, there is a need to determine the dielectric breakdown / degradation of the composite printed circuit board material and mechanical structure over time and temperature for mission critical applications.

Thermal aging testing consisted of three phases. Phase I – A 500 hour pre-screen at four fixed temperatures following IEEE98 A.1 and UL746B 20A[1] (completed). Phase II – Short term aging for 1000 hours at four revised, fixed temperatures. Plated through hole reliability testing using IST and HATS was also completed. Phase III – Long term aging for 25,000 hours at five, revised fixed temperatures. This paper will discuss results of this testing to date.

Introduction

The objective of this testing is to establish the electrical strength-temperature Arrhenius curve (temperature life curve) for materials used in printed wiring boards (PWB) for applications that exceed the typical 5,000 hour end of life test defined in Underwriters Laboratory Standard UL746B[2]. The test methodology presented in this report generates data representing 25,000 hours of operational life. The 25,000 hour test data can then be used to extrapolate out to 100,000 hours to determine the expected electrical strength of the various laminate materials being compared. This data can be applied to the PWB design requirements by balancing the expected material degradation at 100,000 hours against the required dielectric needs throughout the service life of the printed wiring board assembly. Design elements can then be adjusted (material selection, stack up, trace size and spacing, copper weight, ground planes, heat sinks, etc.) to ensure that the PWB remains within the thermal boundaries established by the temperature life curve.

Loss of electrical strength due to thermal exposure must be a key consideration in the design of a PWB for the expected life of an application. Chemical changes within laminate are accelerated when the insulation of the PWB is exposed to elevated operating temperatures. Oxidation occurs degrading the physical and electrical properties of printed wiring board causing embrittlement, discoloration, and delamination. The thermal-aging characteristics of a laminate can be determined by measuring the changes in its properties to a predetermined level by aging at each of several elevated temperatures. In this study, dielectric strength is used to determine the relative effects of different temperatures on the end of life for a given insulating system. It is also used to compare different insulating systems at a given temperature. It is important that the design and construction of the PWB test vehicles are representative of the intended application and be consistent from laminate to laminate.

Most data available on the thermal aging of laminate materials was specifically developed on the unclad laminate composite (resin and glass). To properly determine the thermal aging characteristics of a PWB, temperature life testing must be performed on a manufactured PWB, not raw laminate. The internal structure of the board itself (amount of heat sinking capacity, density of power generating components) and the intended use environment will also affect the operational life of a PWB. In addition, manufacturing processes can be deleterious to the operational life of a fabricated PWB. Laminates will experience a number of chemical exposures, thermal excursions, and mechanical stresses during fabrication. Good process control is critical in eliminating contaminants, obtaining proper bonding surfaces and good adhesion, and preventing mechanical and thermal damage to the laminate itself. If these processes go out of control or are poorly defined, operational life can be adversely affected. These intangibles must be taken into consideration when analyzing data and predicting the operational life of a PWB.

The times to failure in thermal aging test cannot be quantitatively related to the operational life of a laminate system in actual use. However, they do provide a relative indication of a PWB's service life under the specific conditions of the test. Results of shorter time tests at higher temperatures can be extrapolated to longer times at lower temperatures. Material aging standards such as UL 746B and IEEE STD 99 limit the degree to which material life data can be extrapolated. They indicate that material thermal aging testing should be performed for at least 25% of the desired operation life of the material. In order to obtain sufficient aging data for 100,000 operational life requirements, test duration must be at least 25,000 hours.

Test Methodology

Determining the operational life of printed circuit board laminates after thermal aging consisted of a three step approach following test details and calculations outlined in IEEE98 A.1 and UL746B. Testing materials with this approach helps marry material capabilities with design requirements so proper trace spacing or other counter measures can be implemented to meet an intended design operational life of 100,000 hours. Guidance on the test methodology was provided by an outside reliability engineering company. *Phase I* - 500 hours pre-screen at four fixed temperatures following IEEE98 A.1 and UL746B 20A to estimate the high temperature test boundary for long term aging of PWB laminate material capabilities. Pre-screen data was used as an initial sort on best performing material. Criteria evaluated included highest dielectric strength, lowest overall degradation, lowest percent change in degradation, and anomalous or unexpected behavior (indicating instability)

A pre-screening test lasting 500 hours was first employed using four fixed temperatures to estimate the high-temperature test boundary for long-term aging testing of PWB laminate material capabilities. The four temperatures used varied by material with the Tg (Glass transition temperature) of the material being weighed heavily in selection of the upper temperature range. Dielectric breakdown voltage was measured at time zero and after 500 hours at elevated temperatures using a production AC Dielectric Analyzer. The %Retention of dielectric strength compared to baseline measurements was calculated for each temperature. From these results, the 50% EOL (end of life) was assigned. Due to the nature of short-term testing, it was not used to estimate low temperature boundaries as insufficient material change would be expected when testing at a low temperature for a short period of time. This test is largely based on the testing outlined in IEEE STD 98, Annex A, fixed time frame method (FTFM) of sampling.

Phase II – Short term aging for 1,000 hours at four revised, fixed temperatures was used to develop a thermal endurance graph to extrapolate and validate 500 hour degradation temperature and the 5,000 hour degradation temperature for the 25,000 life test. After performing the pre-screen analysis, this data was used to help guide selection of aging temperatures. The 1000 hour test used more aggressive temperatures as bounded by the pre-screen data and UL746A procedure. Data was first analyzed in a similar fashion to the pre-screen data to identify potential outliers or worrisome behavior. Arrhenius plots were constructed for an initial prediction on behavior and performance.

For short term aging for 1,000 hours at four revised temperatures was run next, % Retention of dielectric strength was calculated at each temperature. Next % Retention data (one curve per temperature) was plotted vs. Time (x-axis). From this data, 50% end of life was determined for each material. A thermal endurance graph was generated in order to extrapolate and validate the 500 hour degradation temperature and 5,000 hour degradation temperature to select the temperatures for the long term operational life test for 25,000 hours.

In addition to the thermal endurance testing, Interconnect Stress Testing (IST) and Highly Accelerated Thermal Shock (HATS) testing were also performed to assess mechanical robustness of plated through holes for each laminate. Two outside testing services, Company A and Company B, were used respectively.

Phase III – Long term aging for 25,000 hours at four revised fixed temperatures was used to develop a thermal endurance graph to extrapolate and validate 100,000 hour operational life temperature. Testing is approximately 40% complete at this time. Long term aging will be performed for a minimum of 25,000 hours. Arrhenius plots from the 6-week test were used to predict a certain degradation percentage in a given time frame.

Long term aging for 25,000 hours at five revised temperatures was run next. Again, % Retention of dielectric strength was calculated at each temperature. Next % Retention data (one curve per temperature) was plotted vs. Time (x-axis). From this data, 50% end of life was determined. A thermal endurance graph was generated in order to extrapolate and validate the

100,000 hour life temperature. The importance of the 25,000 hour test is based on industry practices of extrapolation of life expectancy data. In order to have any confidence of predicting material properties at 100,000 hours, the test length has to be 25% in duration.

The following materials in Table 1 were down selected from a much longer list of PWB laminates. Press fit compatibility; comparative tracking index (CTI), flammability, dielectric breakdown voltage, and glass transition temperature (Tg) were used to select five laminates for thermal aging testing.

Table 1: Materials Tested

Material	Descriptor	Descriptor 2	Tg, ^{0}C	RTI, Electrical
Laminate A	Widely Used	Standard Performance Epoxy	180	130
Laminate B	Limited Use – Application Specific	High Speed Performance - Non-Epoxy Filled	200	130
Laminate C	Limited Use – Application Specific	High Temperature Resistant – Filled	190	130
Laminate D	Limited Use – Application Specific	High Temperature Resistant – Filled	160	160
Laminate E	Specific Use (RF)	High Temperature / Microwave – Filled	>280	160

Thermal aging of printed circuit board laminates was performed on three manufactured lots of printed circuit board test vehicles. Testing a processed PWB is necessary because manufacturing processes expose the laminate to a number of thermal and chemical cycles. These exposures can have an effect on the material's properties and robustness. In Amphenol's study, the test vehicle consisted of a fourteen layer printed circuit board manufactured in accordance with IPC-6012, Class 3 meeting the workmanship standards of IPC-A-610, Class 3. Copper foil weights were 2 oz for all inner layers and 1 oz. for both outer layers to simulate actual design stack up for the specific application and intended use.

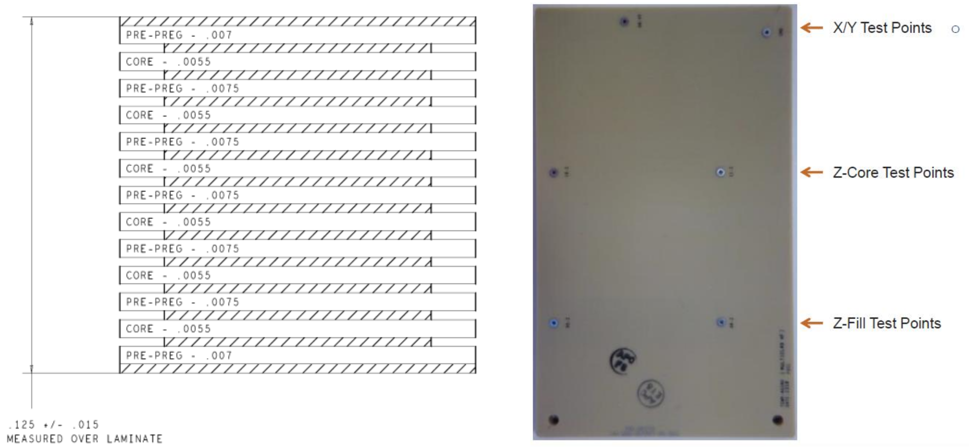


Figure 1: Test Vehicle Stack-up and Test Points on Test Vehicle

Test coupons were designed to allow separate tests to be performed at three design regions on the board. Figure 1 illustrates the stack up used as well as the test points - X/Y test point within the plane of an inner layer across a 10 mil gap, Z-Core test point between the plane of the inner layer (z-axis of a core, 5 mil span), and Z-Fill test point between the plane of the fill (z-axis through prepreg, 10mil span).

Ten (10) test specimens were used for each set for thermal end point testing. For each material the following test specimen quantities were used. Eight sets per temperature x 5 temperatures = 400 test specimens. Six spares per temperature x 5 temperatures = 30 test specimens. Materials tested include Laminate A, B, C, D and E. Twenty test specimens per material were used to establish the baseline for dielectric strength testing. For each manufacturing lot of material included in the test, there were a minimum of 5 test specimens from each manufacturing were included in the baseline dielectric strength test.

Control materials with known performance were tested in conjunction with the test materials. The control material configuration was in the form of 3” X 5” sheet (unclad) to match original testing of the control material by the supplier and UL. Control materials were selected so that at least two temperatures/data points overlapped with the materials under evaluation. Multiple test materials were used to address the range of test temperatures for the materials being tested and included Control 1, 2, and 3. Control materials were included in each oven being used for thermal aging testing. Control material data was compared to existing data from suppliers and UL to prove out the PWB test validity.

All samples (controls, baselines, and thermally aged test vehicles) were pre-conditioned following ASTM D618: Standard Practice for Conditioning Plastics for Testing - 48 hours at 25^{0}C and 50% relative humidity. Dielectric breakdown voltage was determined following ASTM D149: Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies[4]. The test was performed at a frequency of 60Hz and a voltage ramp rate of 500V/sec using a production AC Dielectric Analyzer. The fixture used for hipot testing the test vehicles is shown below in Figure 2. Each test vehicle was tested in the X-Y (PTH to PTH), Z-Core (laminate corer), and Z-Fill (pre-preg). Dielectric failure or dielectric breakdown consists of an increase in conductance, limiting the electric field that can be sustained.

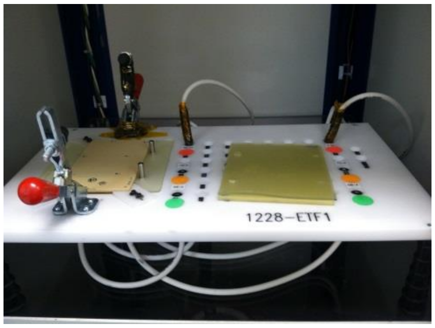
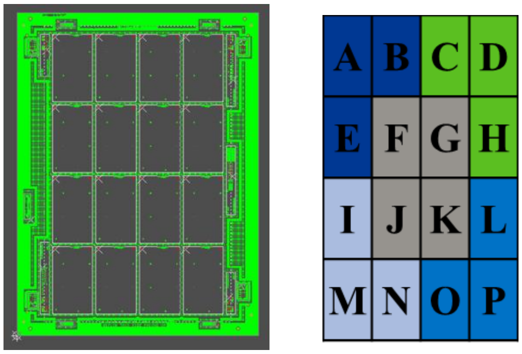


Figure 2: Hipot Test Fixture

Randomization of samples was carefully considered through all test phases. This included sample selecton based on sample ID which contained Lot #, Panel #, and Panel Position (A – P). See Figure 3. It is theorized that similar colored circuits will have reasonably similar electrical performance.



A	B	C	D
E	F	G	H
I	J	K	L
M	N	O	P

Figure 3: Circuit Location on Panel

Oven location was also planned and noted on all oven sample logs. Samples and controls were mixed within a rack (typically no more three in a row of either). Rack number and position of rack in oven were meticulously tracked. It should also be noted that bromine containing laminates were thermally aged in separate ovens than the non-bromine containing laminate systems. This was done to prevent any cross contamination that may arise due to out gassing during the thermal aging tests. A total of twelve production ovens were used for thermal aging. All ovens were continuously monitored for temperature stability using a production Data Acquisition / Switch Unit with a production 20 Channel Multiplexer equipment . All ovens had two thermocouples for redundancy. Figure 4 illustrates sample racking and sample location in oven.

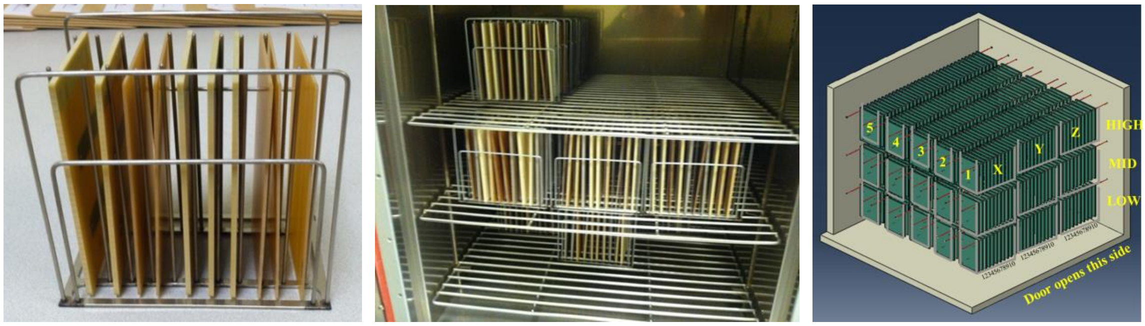


Figure 4: Sample racking, racks in oven, and sample location naming scheme.

The test plan followed is presented in the flow diagram in Figure 5. It illustrates the pre-conditioning, weighing, aging, post conditioning, final weighing, and dielectric breakdown test sequence for controls and test vehicles.

1000 Hour Sampling Schedule

Set	Remove from Oven (days)			
	T1	T2	T3	T4
1	1	1	1	1
2	3	3	3	3
3	7	7	7	7
4	14	14	14	14
5	21	21	21	21
6	28	28	28	28
7	35	35	35	35
8	42	42	42	42

Long Term Sampling Schedule
Duration (days)

Test	T5	T4	T3	T2	T1
Sets 1-5 In	3D	7D	14D	28D	42D
Set 6 In	3	7	14	28	42
Set 7 In	6	14	28	56	84
Set 8 In	9	21	42	84	126
Set 1	9	21	42	84	126
Set 2	21	49	98	196	294
Set 3	33	77	154	308	462
Set 4	45	105	210	420	630
Set 5	57	133	266	532	798
Set 6	63	147	294	588	882
Set 7	69	161	322	644	966
Set 8	75	175	350	700	1050

Figure 5: Flow diagram of testing sequence for controls and test vehicles for Phase I through III along with sample schedules for the 1000 Hour Test and 2 Year Long Term Test.

Results and Discussion

500 Hour Pre-Screen Testing - The 500 hours pre-screen at four fixed temperatures was executed following IEEE98 A.1[3] and UL746B 20A[1] to estimate the high temperature test boundary for long term aging of PWB laminate material capabilities. Pre-screen data is used as an initial sort on best performing material. Criteria evaluated include highest dielectric strength, lowest overall degradation, lowest percent change in degradation, and anomalous or unexpected behavior (indicating instability).

Table 2: Temperatures used for 500 Hour Test Based on Tg of Material and Supplier's Recommendations

Material	Tg, ^{0}C	T1, ^{0}C	T2, ^{0}C	T3, ^{0}C	T4, ^{0}C
Laminate A	180	165	175	185	195
Laminate B	200	175	185	195	205
Laminate C	190	175	185	195	205
Laminate D	160	165	175	185	195
Laminate E	>280	220	240	260	280

An outside reliability engineering company completed the first portion of testing, consisting of a 500 hours prescreen aging test of five materials at four different temperatures. Results from the 500 hours prescreen were used to adjust test parameters for the next phases of testing. Data collected included weight loss, sample thickness, dielectric breakdown voltage for baseline and sample coupons after exposure to for different temperatures for 500 hours. Five data points were collected per measurement point.

Each material was tested to collect ten baseline data points in the X-Y, Z-Core and Z-Fill areas of the test vehicle. Using the published electric strength data – the estimated dielectric withstand voltage (DWV) failure point was calculated. Average, standard deviation, and range were calculated. A summary of the baseline averages is presented below in Table 3. Laminate C and Laminate D have the highest dielectric withstand voltage values compared to the others in the test set.

Table 3: Average Breakdown Voltage Time Zero

Average Breakdown Voltage (V)	Laminate A	Laminate B	Laminate C	Laminate D	Laminate E
X-Y	17005	14758	22581	18889	13181
Std. Dev.	1841	1666	2612	2162	1413
Z-Core	9560	9523	11281	12823	8923
Std. Dev.	598	611	1541	977	585
Z-Fill	13956	19185	23893	17096	12530
Std. Dev.	1304	2075	1448	3088	1169

Results for Average % Change in Weight are illustrated in Figure 6. Weight measurements indicate a general trend of increasing weight loss as aging temperature increases in all materials. This indicates that the boards are generally degrading as expected, with oxidation accelerated at higher temperatures. All aged boards showed discoloration to various extents at the end of testing. Laminate A and Laminate E boards also exhibited delamination at higher aging temperatures. It was later discovered that temperatures selected for Laminate E were too high. Figure 7 illustrates the Average % Change in Thickness for each laminate. Laminate A had obvious delamination at T3 (185ºC) and T4 (195ºC). Laminate E showed delamination at all four temperatures tested (220ºC, 240ºC, 260ºC, and 280ºC).

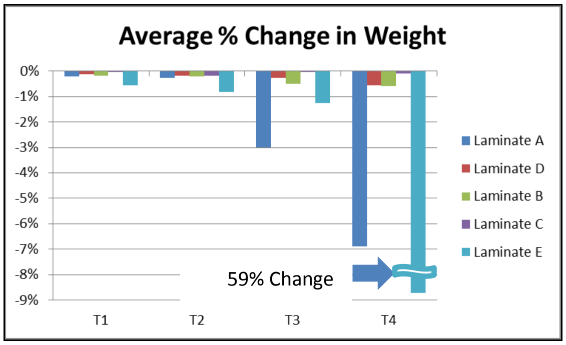


Figure 6: Average % Change in Weight for 500 Hour Test Vehicles

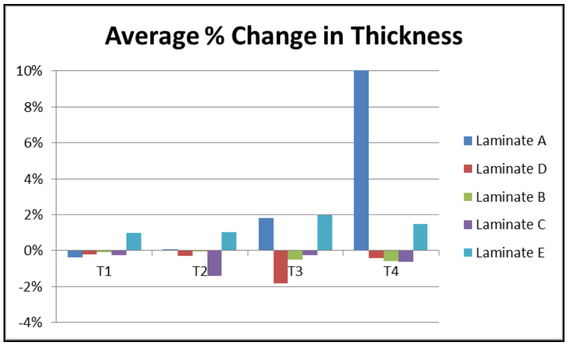


Figure 7: Average % Change in Thickness for 500 Hour Test Vehicles

Dielectric breakdown voltage varied by material and test region. Laminate A breakdown voltages remained steady up to T3 (185˚C), where the voltages in all regions sharply dropped. Laminate D breakdown voltages remained fairly steady in all aging temperatures and test regions. Laminate B breakdown voltages remained fairly steady in all aging temperatures and test regions. Laminate C breakdown voltages demonstrated a decline in strength, particularly at higher temperatures. Laminate E breakdown voltages declined steadily, but unexpectedly recovered at T4 (280˚C).

The increase in Laminate E breakdown voltages at T4 corresponds with a sharp increase in weight loss at that temperature, as well increased delamination and general degradation of the board condition. The higher breakdown voltages could be caused by a number of factors, and do not necessarily indicate a higher dielectric strength in the material at that temperature. Heavy delamination may have resulted in the copper components of the board being exposed to more air, causing formation of copper oxides and degrading the test circuit's ability to conduct electricity. The markedly increased weight loss, -9% at 280˚C compared to -1% at 260˚C, indicates the higher temperature may be causing certain compounds in the material to decompose or react in ways that aren't possible at lower temperatures. The high degree of delamination, degradation of copper components, and general changes in the physical geometry and condition of the board may have altered the way the voltage is applied during the test. It was later determined after discussions with Laminate E supplier that the temperatures selected for Laminate E were too high. This was taken into consideration when selecting temperatures for the 1000 hours test.

It was theorized here that the influence of the PWB heterogeneous stack up vs. the laminate manufacturer's homogeneous stack up will have a significant influence on the change in robustness of the materials at elevated temperatures. This difference highlights the need and value of performing thermal endurance testing on a manufactured PWB. By doing so, the possible influence of different manufacturers and process sets are also taken into account.

Dielectric strength was calculated by dividing dielectric breakdown voltage by thickness tested. %Retention was calculated using the following equation:

$$\%Retention = (1-((DS_{T0} - DS_{T552})/ DS_{T0}))*100$$

Where DS_{T0} = Dielectric Strength Time Zero and DS_{T552} = Dielectric Strength at 552 hours.

A plot was then created of % Retention (x) vs. Temperature (y) for each laminate which is presented in Figure 4a through 4e below. Data is fitted to a line or curve. In the data presented below, regression was used to determine the equation that fits the data best. % Retention value desired (y) is substituted into the equation to find the corresponding temperature (x) to predict the highest temperature to be used in the 1,000 aging test. Data can be fit multiple ways, linear, polynomial, or logarithmic. In this instance a linear and 2nd degree polynomial fits were used certain the data sets. The regression fit used for each sample's (X-Y, Z-Core, and Z-Fill %Regression vs. Temperature, ^{0}C are presented on each plot in that order. The 1,000 hours test data can be used in a similar fashion to validate this conclusion and to forecast the lowest temperature (5,000 hour failure) for the final long term aging test. These plots are produced for each material independently. Solving the equation for $y_{50\%}$ yields a temperature that becomes the T4 (highest temperature) for the 6 week test. Results for 50% Degradation for each material are presented in Table 8.

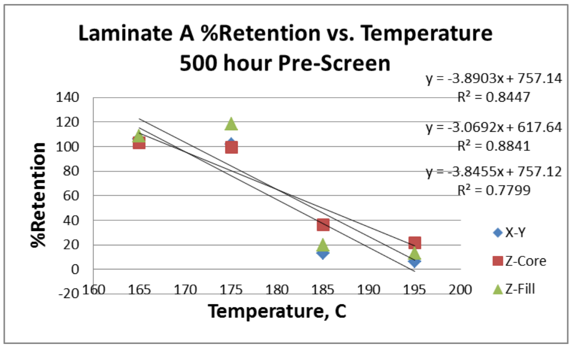


Figure 8a) Calculated T4=181^{0}C for Laminate A

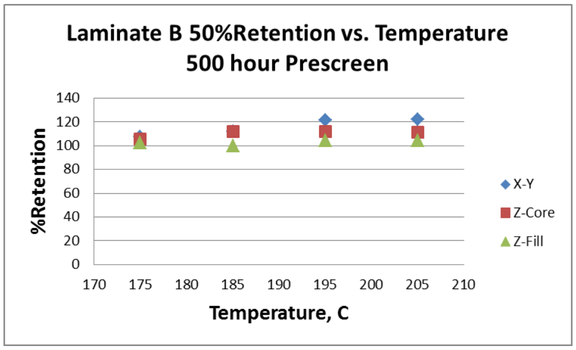


Figure 8b) Minimal to no degradation occurred for Laminate B at temperatures selected.

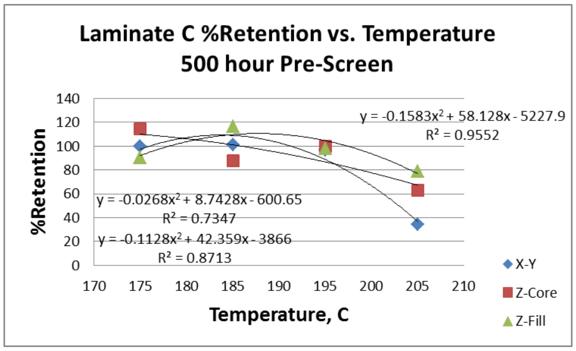


Figure 8c) Calculated T4=212^0C for Laminate C

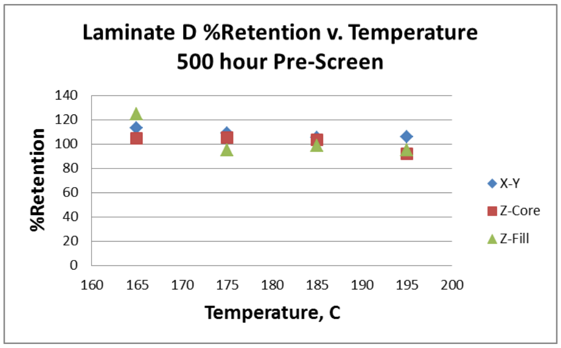


Figure 8d) Little to no degradation occurred for Laminate D at temperatures selected.

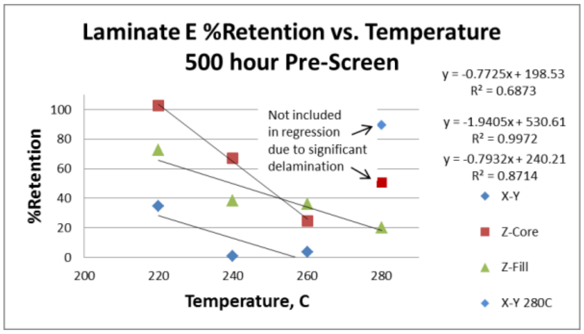


Figure 8e) Calculated T4= 226^0C for Laminate E

Figure 8: Plot of Aging Temperature vs. %Retention in 500 Hour Pre-Screen Test

Table 4: Calculated 50% Retention using regression analysis of 500 hour data. Used for guidance in T4 temperature selection for 1000 hour test.

	Calculated 50% Retention X-Y	Calculated 50% Retention Z-Core	Calculated 50% Retention Z-Fill	Average 50% Retention X-Y, Z-Core, Z-Fill
Laminate A	175	184	184	181
Laminate B	Could not calculate %Retention due to lack of degradation (100% retention) of dielectric strength at temperatures selected.			
Laminate C	203	213	219	212
Laminate D	Could not calculate %Retention due to lack of degradation (100% retention) of dielectric strength at temperatures selected.			
Laminate E	191	248	239	226

Lack of degradation in dielectric strength for Laminates B and D prohibited calculation and extrapolation of 50% Retention temperature. A test temperature 280^0C was too high for Laminate E creating severe delamination. These data points were excluded from the regression analysis.

1000 Hour Testing - Pre-screen analysis data was used to help guide selection of aging temperatures. The 1,000 test used more aggressive temperatures as bounded by the pre-screen data and UL746A procedure. Data was first analyzed in a similar fashion to the pre-screen data to identify potential outliers or worrisome behavior. Arrhenius plots were constructed for an initial prediction on behavior and performance for the 25,000 Test.

Baseline dielectric breakdown voltage data was collected for each laminate. Dielectric strength was then calculated by dividing dielectric breakdown voltage by thickness tested. Dielectric breakdown voltage (V/mil) for each laminate is summarized in Table 5. A graphical representation of dielectric strength data is presented in Figure 9.

Table 5: Baseline -Average Breakdown Strength, V/mil

Baseline	X-Y Breakdown Strength (V/mil)	Z-Core Breakdown Strength (V/mil)	Z-Fill Breakdown Strength (V/mil)
Laminate A	1854	1983	1430
Std. Dev.	157	229	159
Laminate B	2040	3095	2167
Std. Dev.	449	189	293
Laminate C	2768	2029	1772
Std. Dev.	322	210	182
Laminate D	2289	2385	2252
Std. Dev.	247	223	317
Laminate E	1227	1574	1349
Std. Dev.	135	178	94

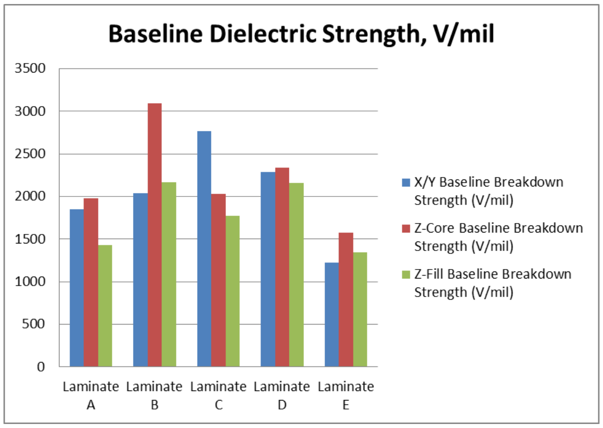


Figure 9: Graphical representation of Baseline -Average Breakdown Strength, V/mil

Table 6 provides a qualitative comparison between the five laminates. Laminates B and D have the overall highest dielectric breakdown strength before thermal aging while Laminate E has the lowest.

Table 6: Comparative Analysis Baseline Average Breakdown Strength - Laminates

Breakdown Strength (V/mil)	X/Y	Z-Fill	Z-Core
Highest	Laminate C	Laminate B	Laminate B
	Laminate D	Laminate D	Laminate D
	Laminate B	Laminate C	Laminate C
	Laminate A	Laminate A	Laminate A
Lowest	Laminate E	Laminate E	Laminate E

In general, the Z-Core was more robust with respect to dielectric breakdown. The Z-Fill (prepreg layer) was the less robust even though it thickness was almost twice that of the Z-Core. These results are summarized in Table 7.

Table 7: Comparative Analysis Baseline Average Breakdown Strength – Board Location

Dielectric Strength	Laminate A	Laminate B	Laminate C	Laminate D	Laminate E
Highest	Z-Core	Z-Core	X-Y	Z-Core	Z-Core
	X-Y	Z-Fill	Z-Core	X-Y	Z-Fill
Lowest	Z-Fill	X-Y	Z-Fill	Z-Fill	X-Y

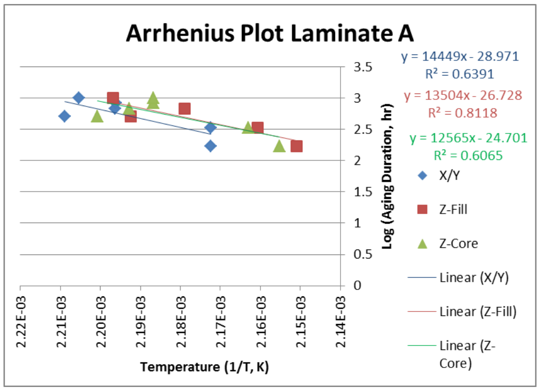
The % Retention was calculated using the same methodology that was used calculate T4 for the 1,000 hour test using the 500 hour Pre-Screening data. The 50% End of Life point was calculated for each temperature. An Arrhenius plot was generated for each material plotting 1/T (K) on the x-axis vs. Log (Aging Duration (hours)) in the y-axis. These are presented in Figure 10 for each laminate. In this instance a linear fit was used for the data sets.

Table 8: Temperatures used for 1,000 Hour Test based on 500 hour test and input from laminate suppliers

Material	T1, ^{0}C	T2, ^{0}C	T3, ^{0}C	T4, ^{0}C
Laminate A	165	175	185	195
Laminate B	185	195	205	215
Laminate C	185	195	205	215
Laminate D	185	195	205	215
Laminate E	245	255	265*	275*
Laminate E Retest	195	205	215	225

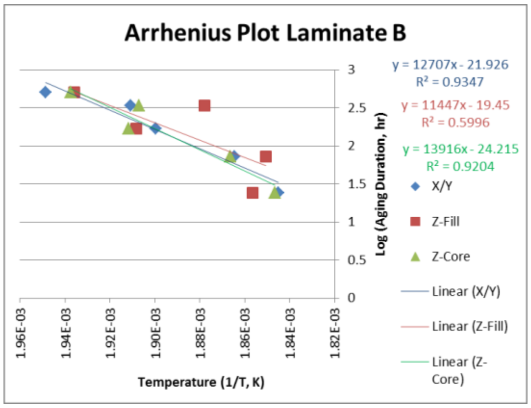
*Temperatures too high; 1,000 hour Test repeated for Laminate E

Temperatures where 50% Retention would be reached for 1368, 3192, 6384, and 12,768 hours were calculated using the linear equation generated for each laminate. For all laminates, 105^{0}C was chosen for T1. Temperatures T2, T3, T4, and T5 were selected using both the calculated (predicted) values as well as basic knowledge of material characteristics and behavior at higher operating temperatures.



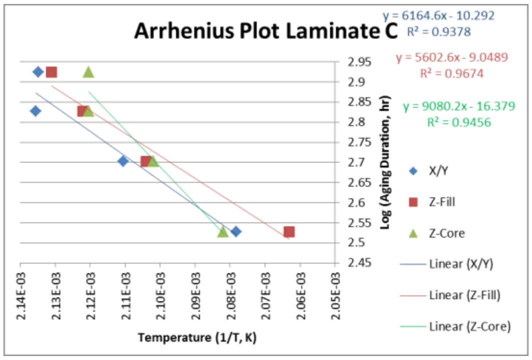
Laminate A	Failure hrs	X/Y Calculated 50% End of Life	Z-Fill Calculated 50% End of Life	Z-Core Calculate 50% End of Life	Temperature Used in 25,000 Hour Test
T5	1368	177	179	178	180
T4	3192	172	174	172	170
T3	6384	168	169	168	150
T2	12768	164	165	163	133
T1	25000	NA	NA	NA	105

Figure 10a: Arrhenius Plots 1/Temperature (K) vs Log(Aging Duration, hr) for Laminate A; Calculated 50% EOL



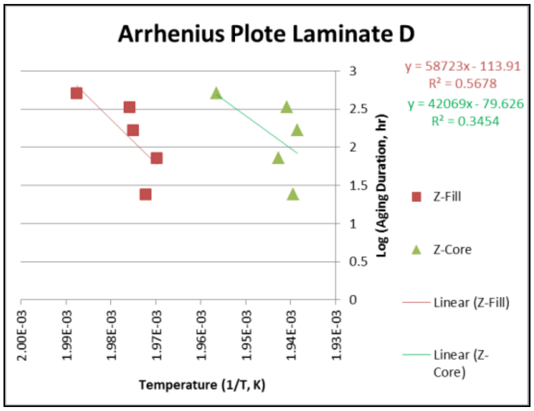
Laminate B	Failure hrs	X/Y Calculated 50% End of Life	Z-Fill Calculated 50% End of Life	Z-Core Calculate 50% End of Life	Temperature Used in 25,000 Hour Test
T5	1368	234	234	236	230
T4	3192	227	226	229	225
T3	6384	221	219	224	220
T2	12768	215	213	218	215
T1	25000	NA	NA	NA	105

Figure 10b: Arrhenius Plots 1/Temperature (K) vs Log(Aging Duration, hr) for Laminate B; Calculated 50% EOL



Laminate C	Failure hrs	X/Y Calculated 50% End of Life	Z-Fill Calculated 50% End of Life	Z-Core Calculate 50% End of Life	Temperature Used in 25,000 Hour Test
T5	1368	192	187	186	185
T4	3192	184	173	174	170
T3	6384	177	163	164	165
T2	12768	170	153	155	150
T1	25000	NA	NA	NA	105

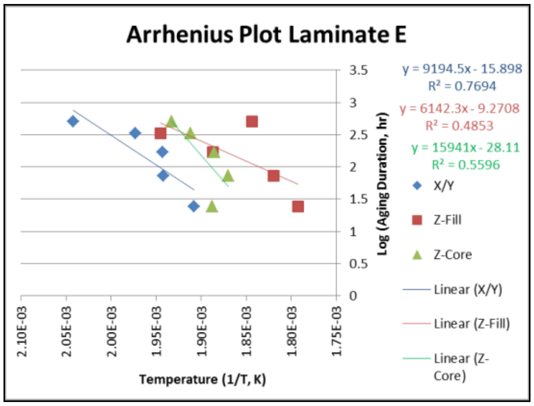
Figure 10c: Arrhenius Plots 1/Temperature (K) vs Log(Aging Duration, hr) for Laminate C; Calculated 50% EOL



Laminate D	Failure hrs	X/Y Calculated 50% End of Life	Z-Fill Calculated 50% End of Life	Z-Core Calculate 50% End of Life	Temperature Used in 25,000 Hour Test
T5	1368	NA	229	235	240
T4	3192	NA	227	233	232
T3	6384	NA	226	231	222
T2	12768	NA	225	229	195, 205, 215
T1	25000	NA	NA	NA	105

Figure 10d: Arrhenius Plots 1/Temperature (K) vs Log(Aging Duration, hr) for Laminate D; Calculated 50% EOL

e)



Laminate E	Failure hrs	X/Y Calculated 50% End of Life	Z-Fill Calculated 50% End of Life	Z-Core Calculate 50% End of Life	Temperature Used in 25,000 Hour Test
T5	1368	210	222	237	210
T4	3192	201	208	231	200
T3	6384	194	197	226	190
T2	12768	187	186	222	145, 160
T1	25000	NA	NA	NA	105

Figure 10e: Arrhenius Plots 1/Temperature (K) vs Log(Aging Duration, hr) for Laminate E; Calculated 50% EOL

Temperatures used in the Long Term Test are presented in Table 9. Temperature T2 was split into several groupings for Laminate D and Laminate E to cover additional temperatures based on early results of the T4 and T5 tests.

Table 9: Temperatures used for Long Term Test based on 1,000 hour test prediction and input from suppliers

Material	T1, ^{0}C	T2, ^{0}C	T3, ^{0}C	T4, ^{0}C	T5, ^{0}C
Laminate A	105	133	150	170	180
Laminate B	105	215	220	225	230
Laminate C	105	150	165	175	185
Laminate D	105	195, 205,215*	222	232	240
Laminate E	105	145, 160*	190	200	210

*T2 sample group was split to cover additional temperatures based on early results of the T4 and T5 tests.

Interconnect Stress Testing (IST) and Highly Accelerated Thermal Stress Testing (HATS) - In addition to thermal endurance testing, interconnect reliability was assessed using Interconnect Stress Testing (IST) and Accelerated Thermal Stress (HATS).

IST measures changes in resistance of plated-through hole barrels and internal layer connections as holes are subjected to thermal cycling. Thermal cycling is produced by the application of a current through a specific coupon configuration. In this technique, the test coupon is resistance heated by passing DC current through the internal layer connection to the barrel for three minutes to bring the temperature of the copper to a designated temperature, in this test 150^{0}C. Switching the current on and off creates thermal cycles between room temperature and the designated temperature within the sample. Thermal cycling induces cyclic fatigue strain in the plated-through hole barrels and internal layer interconnects and accelerates any latent defects. The number of cycles achieved permits quantitative assessments of the performance of the entire interconnect. A 10% Change in resistance measurement is considered a failure. Although there none of the samples developed a 10% change in resistance, Laminate B performed worse than Laminates A, D, and E. Upon cross sectioning, defects were found in the plated-through hole. Laminate C was not tested.

Table 10: IST Results

	1000 Cycles	Δ Power %	Δ Sense A %	Δ Sense B %
Laminate A	Pass	1.3 ± 0.5	1.0 ± 0.5	0.8 ± 0.4
Laminate B	Pass	1.7 ± 0.4	5.2 ± 2.7	1.3 ± 0.7
Laminate C	N/A	N/A	N/A	N/A
Laminate D	Pass	0.9 ± 0.5	0.7 ± 0.5	0.5 ± 0.4
Laminate E	Pass	1.5 ± 0.7	1.5 ± 0.8	1.0 ± 0.7

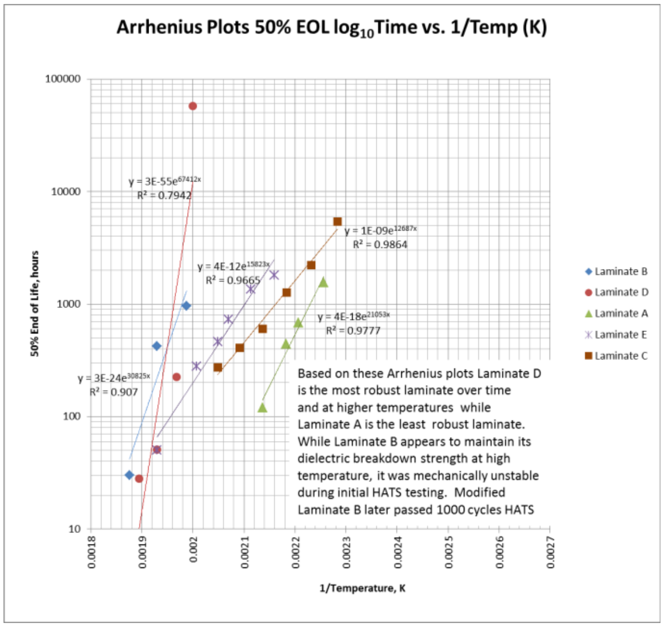
The HATS method differs from IST in that it uses high volumes of hot and cold air to rapidly heat and cool the sample coupons between -55^{0}C to +150^{0}C. This rapid thermal transition makes HATS a more stressful test than IST. A change in resistance greater than 10% is considered a failure. Samples were subjected to 500, 1000, 1500, and 2000 cycles. Each cycle took 19 minutes. Results are presented below. Laminate B again performed the worse with failures starting as early as 150 cycles. A retest of a modified formulation of Laminate B, Laminate B*, did pass 1000 cycles however, Laminate E followed by D provided the best plated through hole reliability.

Table 11: HATS Results

	500 Cycles	1,000 Cycles	1,500 Cycles	2,000 Cycles
Laminate A	Pass	Fail 3/9	Fail 1/1	N/A
Laminate B	Fail 9/9	N/A	N/A	N/A
Laminate B*	Pass	Pass	Fail 6/28	Fail 19/22
Laminate C	Pass	Pass	N/A	N/A
Laminate D	Pass	Pass	Pass	Fail 1/8
Laminate E	Pass	Pass	Pass	Fail 1/9

*Laminate B was retested using a modified formulation.

Long Term Testing - Using the 1000 hour test data and +25,000 hour test data from T3, T4, and T5, an Arrhenius plot of 50% End of Life (hours) vs. 1/Temperature (K) was generated for each laminate in Figure 11. Data is still being collected for T1 and T2 tests which will conclude in the first quarter of 2016. Based on these Arrhenius plots, Laminate D appears to be the most robust laminate over time and at higher temperatures while Laminate A is the least robust laminate. Although Laminate B appears to maintain its dielectric breakdown strength at high temperature, it was found to be mechanically unstable in HATS testing and had many plated-through hole failures before 500 cycles. A modified version of Laminate B was retested in HATS and it passed 1000 cycles.


Arrhenius Plots 50% EOL $\log_{10}$Time vs. 1/Temp (K)

Based on these Arrhenius plots Laminate D is the most robust laminate over time and at higher temperatures while Laminate A is the least robust laminate. While Laminate B appears to maintain its dielectric breakdown strength at high temperature, it was mechanically unstable during initial HATS testing. Modified Laminate B later passed 1000 cycles HATS

Figure 11: Arrhenius Plots of 50% log10 Time (hours) vs. 1/Temperature (K)

Based on these Arrhenius plots Laminate D is the most robust laminate over time and at higher temperatures while Laminate A is the least robust. While Laminate B appears to maintain its dielectric breakdown strength at high temperature, it was mechanically unstable during initial HATS testing. Modified Laminate B which is currently being tested in the 2 year test, passed 1000 cycles HATS. Maximum operating temperature obtained by extrapolating each line to 100,000 hours is presented in the Table 12 below for each laminate.

Table 12: Calculated Maximum Operating Temperatures for each Laminate based on data collected to date. Results from T1 and T2 will be incorporated once testing is completed.

Laminate A	135^{0}C
Laminate B	196^{0}C
Laminate C	130^{0}C
Laminate D	220^{0}C
Laminate E	146^{0}C

Summary

The following conclusions are based on data from 1000 hour test data and +25,000 hour test data (T3, T4, and T5) and are summarized in Table 13. Some materials that were base lined with a high dielectric strength did not maintain (hold) their advantage over other materials. Laminate E with the lowest initial dielectric strength was more capable of maintaining its performance over time and at higher temperatures than some of other laminates. Thermal aging tests showed not all materials are viable for rigorous applications where thermal excursions, high temperatures, high power, or high voltages are involved. Both Laminate A and Laminate B had delamination as time increased at temperature. Laminates C and D tended to warp as time increased with temperature. Laminates D, B, and E performed better in thermal aging tests especially at higher temperatures while Laminate E and D performed the best in PTH reliability tests.

Table 13: Summary of Results

Material	Overall Performance	Dielectric Breakdown Strength Retention	Estimated Usage in Comparison
Laminate A	Poor high temperature performance. Delamination at higher temperatures. Poor HATS* performance.	Quickly lost dielectric strength at moderately high temperatures.	Widely used
Laminate B	Second best high temperature performance. Poor performance in HATS* testing. HATS repeated on modified Laminate B - passed 1000 cycles. Some delamination at 230C.	Highest initial dielectric breakdown strength Z-Core. Second best for retention of dielectric strength at high temperature.	Limited Use – Application specific.
Laminate C	Second worst high temperature performance. Some warpage seen at all test temperatures. Passed 1000 cycles HATS*	Highest initial dielectric breakdown strength X/Y Declined in strength particularly at higher temperatures.	Limited Use – Application specific.
Laminate D	Best high temperature performance. Some warpage seen at all test temperatures. Passed 1000 cycles HATS*	Best overall initial dielectric breakdown strength. Best for retention of dielectric strength at high temperature.	Limited Use – Application specific.
Laminate E	Third best high temperature performance. Good mechanical integrity - no warpage or delamination observed. Passed 1500 cycles HATS*	Lowest initial dielectric strength. Declined slowly at higher temperatures but retain dielectric strength compared to Laminate A and E.	Specific Use (RF)

*HATS – Highly Accelerated Thermal Shock used to assess plated-through hole integrity

Some of the more commonly used materials types, such as Laminate A, are at high risk for failure over long periods of time at high temperatures, over many thermal cycles, or in high power and high voltage applications. Families of materials less commonly used are more appropriate for these applications and include B, C, D, and E laminate systems. The application demands for long term reliability needs to be considered in PWB materials selection.

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