The Effects of Lead-Free Reflow on Conductive Anodic Filament (CAF) Performance of Materials

Kim Morton, Viasystems, China
Joe Smetana, Alcatel-Lucent, Plano, TX
Gordon Qin, Viasystems, China
Thilo Sack, Celestica, Toronto, Canada

Abstract

This paper details the results achieved by the High Density Packaging Users Group (HDPUG) Consortium investigating the hole-wall to hole-wall CAF performance of 20 different Pb-free printed wiring board materials in 20 layer constructions. Seven of the materials are investigated with 2 different 20 layer constructions (different glass styles and resin contents) for a total of 27 different builds. The materials are tested both as built and after Pb-free Reflow at 6x 260C. Materials in the test include high Tg, filled FR4 materials, high Tg halogen free FR4 materials, and high speed materials. Data is presented showing the impact of reflow, the impact of glass styles on the materials and some unexpected CAF results as well.

Introduction

A previous HDPUG consortium study identified significant challenges in complex multilayer applications with printed wiring board materials ability to survive multiple exposures through Pb-free assembly reflow [1-3]. This behavior was specifically related to the detrimental impact of higher temperatures on plated through hole (via) reliability [4,5] and the onset of material delamination. One of the key influences previously noted was the effect of via to via spacing on the materials ability to survive through Pb-free assembly [1]. This is also true for the CAF testing considerations which are dependent clearly on drilled hole-wall to drilled hole-wall (DHW-DHW) spacing.

The industry has recently released improved materials that better address Pb-free assembly applications and there was much interest in the Consortium to evaluate these materials not only for Pb-Free compatibility but also for CAF. The Alcatel-Lucent Material reliability test vehicle (MRT-3) used for this study contained multiple upgrades to previous versions. Major design changes to the test vehicle included;

1. Changing the 2 CAF coupon spacings to 16 and 20 mil drilled hole-wall to drilled hole-wall (DHW-DHW)
2. Adding a specific area for Dynamic Mechanical Analysis (DMA) testing
3. Implementing an innovative IST coupon that utilizes capacitance measurements to determine product construction, estimated dielectric spacing, and determines if material damage was caused during assembly
4. Consistency in the geometries and layout between the IST and air-to-air thermal cycle test vehicles
5. Expanding the focus of the IST and air-to-air thermal cycle designs to address via pitch in more detail
6. Adding custom designed IBM style WIC-20 coupons for material analysis investigations and moisture sensitivity testing.

The goals for this CAF testing were to;

- Characterize the performance of a number of recently released Pb-free compatible materials using the MRT-3 test vehicle not only for Pb-Free compatibility but also for CAF resistancy
    - Focusing on 20 layer constructions only, with some materials produced with both 58% and 69% resin content (RC) configurations and that also had 106 glass styles introduced as part of the higher RC builds
    - Identifying materials that are robust through Pb-free assembly reflow at 1mm and 0.8mm pitch via to via and simultaneously studying the CAF outcome at both 16 and 20 mil DHW-DHW spacings
    - Including strategic FR4 materials that had unique thermo-mechanical properties
    - Including new High Tg (glass transition temperature) halogen free materials
    - Including mid-level electrical performance and very high speed materials
- Focus on those FR4 and halogen free materials that are expected to be more thermally robust and have better electrical performance characteristics while remaining cost effective, and have adequate CAF resistance.. High Speed materials are included as well.

This paper reports the results of CAF testing in conjunction with material survivability through Pb-free assembly reflow and the correlation between reflow vs. no reflow for CAF resistancy. Before discussing any CAF results, it is important to have a comprehensive understanding of the TV employed, the constructions, the materials, the building process and then on to the CAF preconditioning, CAF Protocol and finally CAF Testing results.

MRT-3 Printed Circuit Board TV Design

The printed circuit board design used for this study is shown in Figures 1 and 2. In addition to the IST, ATC, DMA, WIC 20 and S1 Electrical coupons there are two CAF coupons shown in the lower right hand corner of the TV below. These consisted of two DHW-DHW spacings of 16 and 20 mils respectively. Each spacing set is separate and laid out in two arrays to cover both X and Y directions such that we are testing both the warp and fill directions of the glass weave. In addition, each spacing set is linked electrically for ease of testing both directions simultaneously. Also each set of two arrays in X+Y has effectively 190 Test Pairs due to the nature of alternating the electrical potential applied accordingly. Finally the drilled hole size (DHS) was set at 35 mils for both spacing coupons in an attempt to minimize drill splay mis-registration.

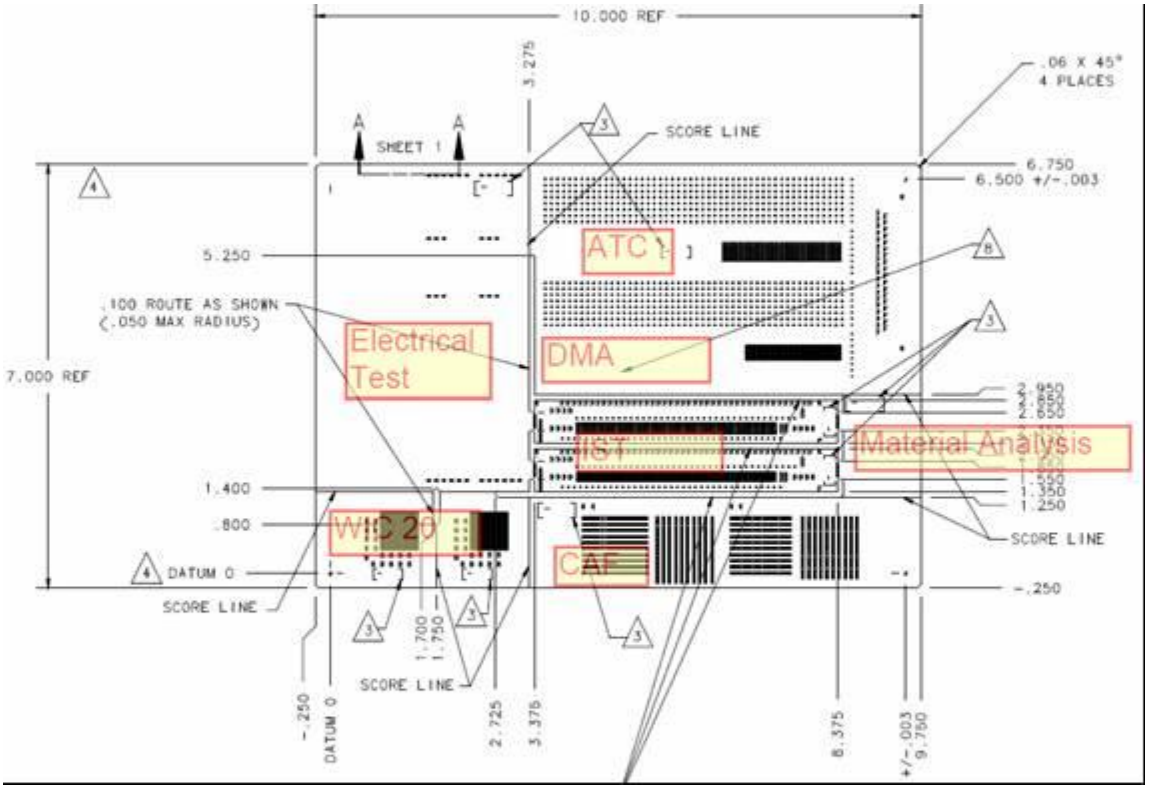


Figure 1: MRT 3 Test Board

The MRT-3 test board was stepped and repeated four times (2 by 2) onto a 24" (610mm) x 18" (457mm) production panel. See Figure 2 for production panel lay-out. For this study a minimum quantity of six production panels were produced for each material, resulting in a minimum of 24 boards of each material type. Subsequent testing was carried out on 12 non-stressed (as received) and 12 stressed (6x 260°C Reflow) boards, this effectively results in 12 "coupons" of each type for each test condition. For the purposes of increased statistical confidence a higher number of coupons (18+) is recommended, the lower quantity was determined by considering a compromise between statistical validity and containing the escalating costs associated to all types and levels of testing.

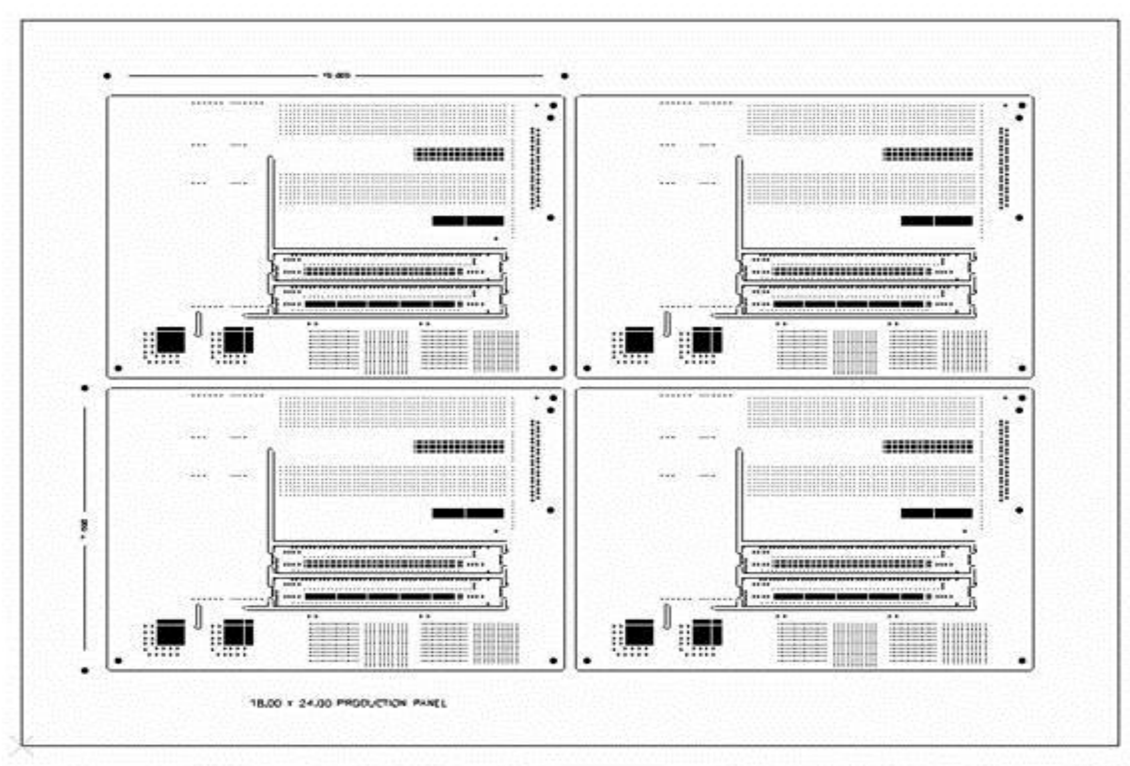


Figure 2: PWB Fabricator Production Panel

Following the production of panels for each of the 27 different material types the production panels were pre-routed and scored to enable easier removal (singulation) of certain coupon types and then profile routed into individual 254mm (10.00 inch) x 178mm (7 inch) test boards. Figure 3 shows a pre-routed and scored individual test board.

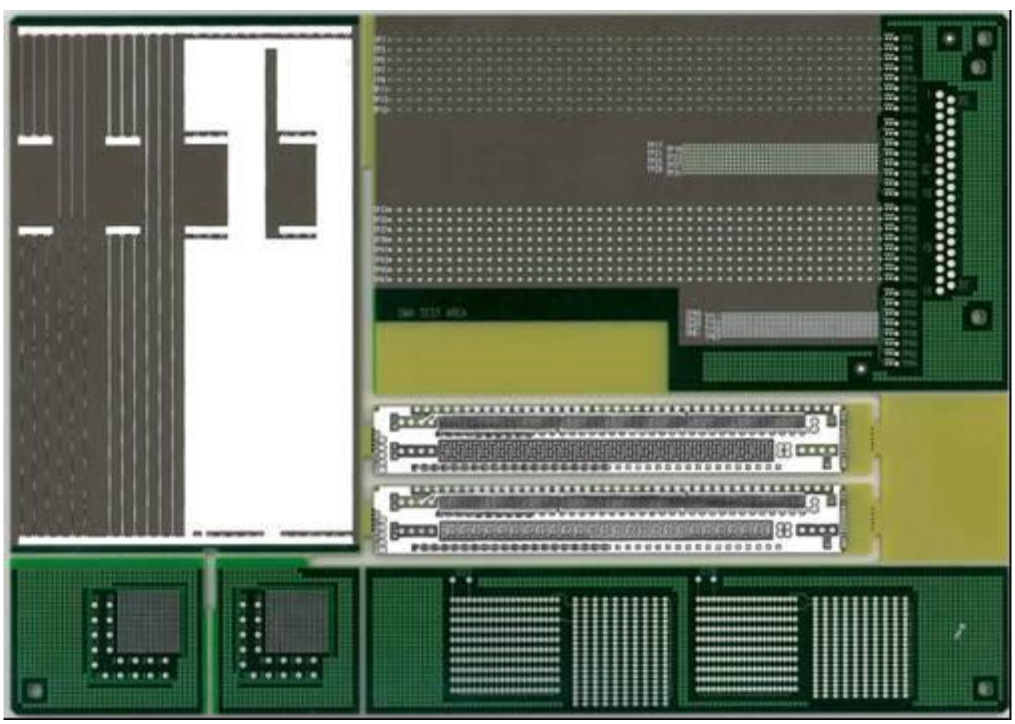


Figure 3: Picture of an actual MRT-3 test board

Material Stack-ups

All material types tested used the same material stack-ups with the same glass styles and resin contents for each given stack-up, regardless of material supplier. This enables the materials to be directly compared to one another. For the 20 layer constructions, both the standard and high resin content constructions are essentially the same in overall thickness, measuring 2.95 mm (0.116 inches) and 3.0mm (0.118 inches) thick respectively. Using similar constructions enables the ability to compare the effect of resin content independently of layer count and board thickness. In addition, for CAF testing any effects of coating finer glass such as 106 (employed for the cores of the 69% RC) can be studied. The standard 20 layer construction was designed with an overall resin content of 58% and is considered typical for a board of this thickness, as shown in Figure 4. The high resin content construction has an overall resin content of 69% and represents very complex and worst case constructions that would typically have higher layer counts (such as 26 or 28 layers) in a similar thickness. This 69% resin content stack-up is detailed in Figure 5.

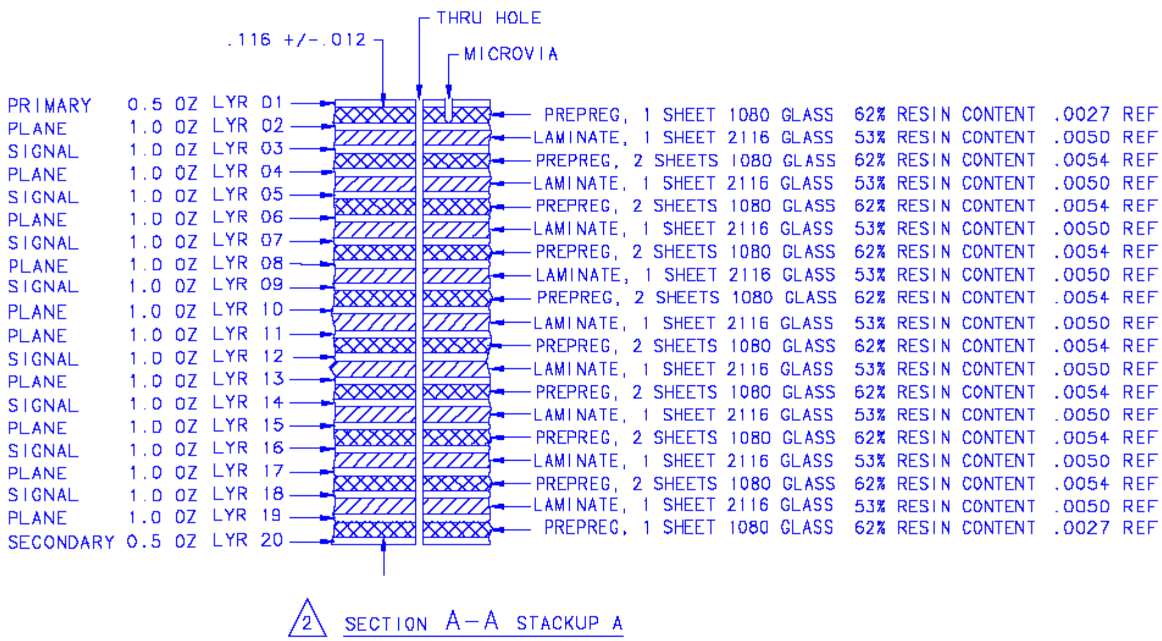


Figure 4: 20 layer standard stack-up, 58% resin content

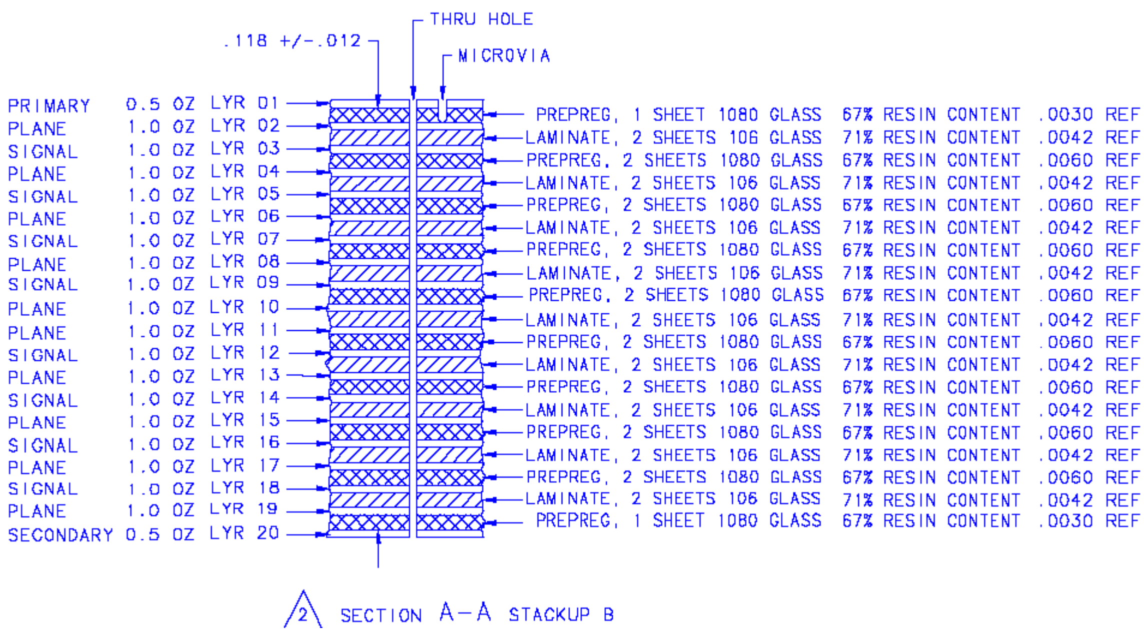


Figure 5: 20 layer high resin content stack-up, 69% resin content

PCB Surface Finish

The PCB finish chosen for this testing was immersion silver. The actual finish used was not critical, provided it remained solderable after 6X reflow at 260ºC and did not include a nickel under-layer, as a nickel underlayer could potentially affect many of the results [4, 7].

Materials

The materials selected for this study were chosen from a large group of candidates to keep the total to a manageable number, 27. Initially, FR4 materials were prioritized based on their advertised material properties and pricing. Some lower cost materials with promising properties made the first cut. After this, certain FR4 materials were further eliminated based on electrical performance and consortium team preferences. A range of material thermal properties were considered important to this effort. The halogen free and high speed selections were based on materials recently made available to the electronics industry. The choice of materials was considerably less here, and certain materials were excluded if previous testing had already been completed, or was presently in progress. All materials were fabricated using stackup “A” (Figure 4).

A subset of materials was chosen to be fabricated using a second stack-up “B” (Figure 5). The initial intention was to select the lowest and highest pre-Tg coefficient of thermal expansion (CTE) Z in each category, if it were practical. For the phenolic FR4 materials, material F and G was chosen because this material had one of the lower advertised pre-Tg CTE Z (ppm) and the lowest overall CTE Z % from 50-260°C. Material A and B was also chosen since it has the highest post Tg CTE Z (ppm) and the highest overall CTE Z% from 50-260°C in the phenolic FR4 group. In the halogen free FR4 materials, material K and L had the lowest pre-Tg CTE Z (ppm) and material M and N had the highest Pre-Tg CTE plus a lower Tg. For the high speed materials the lowest CTE Z (ppm) pre-Tg was material S and T. For the High CTE pre-Tg, two materials were selected. Material V and W and material Y and Z both have very high pre-Tg CTE Z (ppm), plus the material Y and Z has a very low overall expansion rate of 1.5%. The selected materials could be used to determine whether the pre-Tg CTE Z dominates or influences the reliability results after reflow and any effect on CAF performance. Table 1 below summarizes the conditions and configurations associated to each tested material.

Table 1: Materials Evaluated

Coding	Stackup	Resin Content (%)	Description
FR4			
A	A	58	Filled Phenolic FR4
B	B	69	Filled Phenolic FR4
C	A	58	Filled Phenolic FR4
D	A	58	Filled Phenolic FR4
E	A	58	Filled Phenolic FR4
F	A	58	Filled Phenolic FR4
G	B	69	Filled Phenolic FR4
H	A	58	Filled Phenolic FR4
I	A	58	Filled Phenolic FR4
J	A	58	Filled Phenolic FR4
Halogen Free FR4			
K	A	58	Filled Halogen Free FR4
L	B	69	Filled Halogen Free FR4
M	A	58	Filled Halogen Free FR4
N	B	69	Filled Halogen Free FR4
O	A	58	Filled Halogen Free FR4
P	A	58	Filled Halogen Free FR4
Q	A	58	Filled Halogen Free FR4
R	A	58	Filled Halogen Free FR4
High Speed Materials			
S	A	58	High Speed Material
T	B	69	High Speed Material
U	A	58	High Speed Material
V	A	58	High Speed Material
W	B	69	High Speed Material
X	A	58	High Speed Material
Y	A	58	High Speed Material
Z	B	69	High Speed Material
AA	A	58	High Speed Material

PWB Fabrication

PWB fabrication for all 27 material types was coordinated between three different manufacturing sites; Viasystems, Meadville (TTM), and Multek. All facilities are located in China. In all cases, the material suppliers were available on-site to review the critical process steps that ensured that the PWB fabricator met their specific requirements prior to product fabrication. In each case a pilot run was completed prior to the production run to resolve any potential processing issues. All subsequent testing was done only on the material used from the production runs. When possible, all material types produced at a single facility were plated as a single lot, in order to reduce potential variability of the performance critical electrolytic plating operation. This was not always possible, but in all cases efforts were made to minimize any plating variability between material types. Plated through hole wall copper thickness was targeted at 0.025 mm (.001" inch) minimum. Subsequent microsection analysis confirmed that the plating specification was achieved and the copper was evenly distributed through the barrel. Some of the low flow materials had some process related resin voiding in the areas with no or low levels of copper (low pressure areas in the stackup). Where possible these areas were avoided for any subsequent testing.

Reflow Board Preconditioning – Simulated Pb-free Assembly

All boards were preconditioned at Celestica's Suzhou China facility. A BTU Pyramax150N 10 zone forced convection oven was used for pre-conditioning.

Reflow Preconditioning Profile

The following parameters were used to create the reflow profiles.

Table 2: Target Reflow Profile Parameters

Profile Elements	***10 Zone Convection Oven Recommended***
Ramp Rate to 217°C Peak	Linear Ramp desired. Can have a small soak period. Usually 1 to 5°C/sec. No more than 2°C/sec
Pre-heat Temperature	Usually measured from 150°C to 200°C. Times within this temperature range are usually 60 to 120 seconds
TAL (Time above 217°C Liquidus)	Target 60 to 90 seconds
Time Within 5°C of Max Peak Temp.	10 to 20 seconds ok. Usually will be lower time.
Target Peak Temperature	**260°C Minimum +5°C / -0°C**
Ramp Down Rate	Target from 1.5°C/sec to 2.5°C/sec with normal oven cooling configuration
Reflow Atmosphere	Run all samples in air. (Worst case scenario)
Total Time in Oven	Usually 4 to 6 minutes
Thermocouples Attachment	Require minimum of 3 T/C's to properly profile raw card. (Leading Edge + Centre of Card +Trailing edge) are recommended locations.

One single profile card was generated for both stack-up configurations. A picture of the profile board, with three thermocouple attachment locations is shown in Figure 6 and the resulting profile is shown in Figure 7.

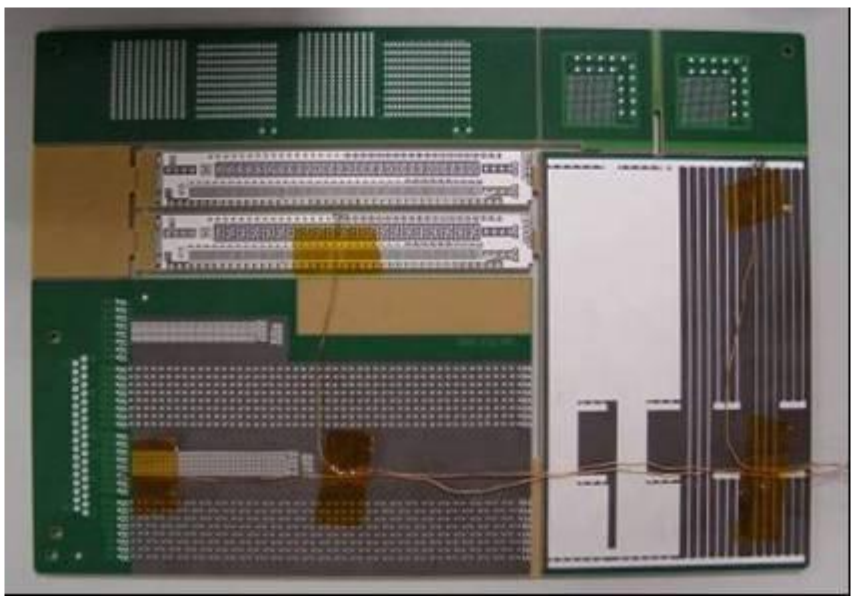


Figure 6: Reflow Oven Profile Board

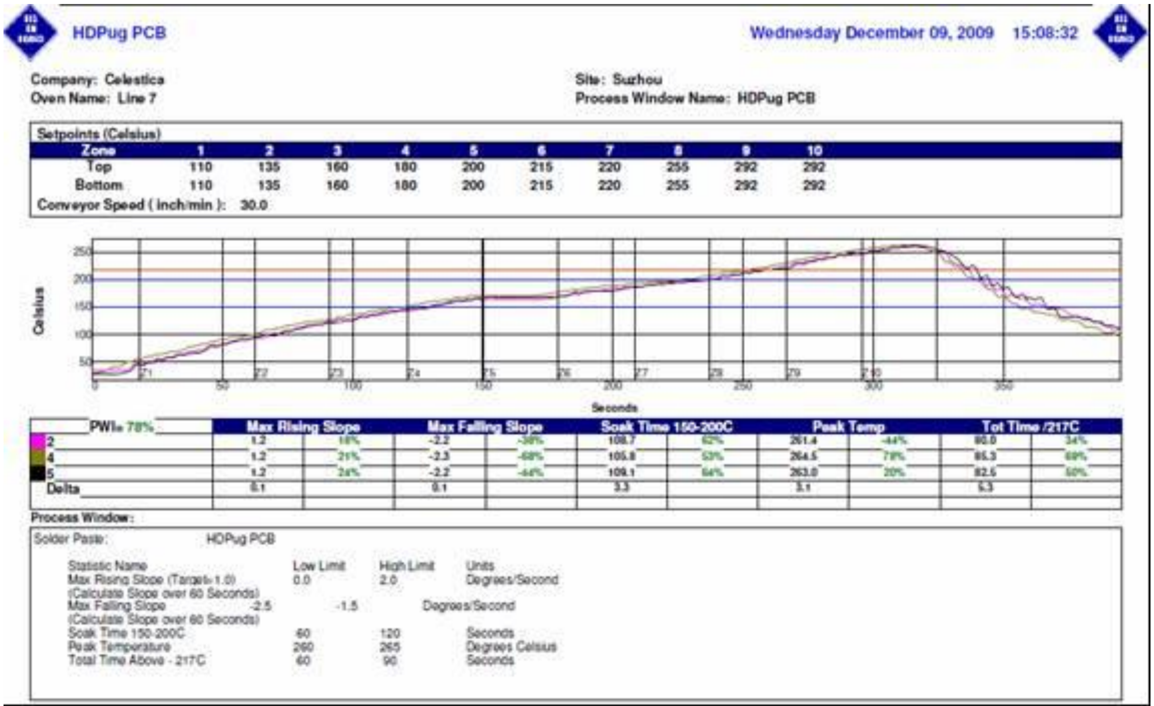


Figure 7: Profile Used for Preconditioning

Reflow Pre-conditioning Procedure

Boards were NOT baked prior to reflow. Panels (a single board including all coupon types as shown in Figure 6) were taken out of the packaging material and pre-conditioned as received. Prior to the start of each pre-conditioning run, the profiles were verified again to validate that nothing had changed between when the profiles were generated and when the actual board pre-conditioning run took place. During the actual runs, the cards were introduced into the oven to guarantee a minimum board spacing of at least two zones. This was required to ensure that there were no thermal interactions between cards. Each card was cooled to room temperature after each reflow cycle, to guarantee that each card experienced the same thermal excursion between profile runs. All “stressed” panels received six cycles of pre-conditioning. Small labels with the numbers “1 to n” were attached near each dash number box on each coupon on the panel. This was done to ensure traceability back to the original panel once all the coupons were broken out of the panel at the end of the pre-conditioning.

A tracking sheet was used to manually track and record all boards through the process.

Prior to start of the preconditioning, a photograph was taken of one panel from each dash number. After all subsequent reflow cycles the panels were inspected for any defects. All defects were recorded in the tracking sheets and photographed noting the defect location, type and run number. After the completion of 6X reflow cycles, one panel from each dash number was photographed for comparison purposes to the incoming board condition.

After each cycle through the reflow oven, each panel was visually inspected to determine if surface material delamination was present. On the majority of materials (24 out of 27) no visual delamination was found after six reflow cycles to 260°C. Material V and W exhibited severe signs of visual blistering and delamination during the pre-conditioning; it was subsequently removed from any further testing. Material Y did exhibit low level delamination on one panel, this panel was eliminated. The remaining panels were accepted for further testing. Table 3 lists the materials that exhibited material damage following pre-conditioning.

Table 3: Summary of Results after 6X Reflow Preconditioning – Showing only the Board types with Material Damage

Coding	Stackup A = (58%) B = (69%)	Comments
V	A	Major Delamination even after 1X Reflow
W	B	Major Delamination even after 1X Reflow
Y	A	Minor delamination on 1 board sample after 1X reflow

CAF Testing Protocol at Microtek Laboratories

CAF testing was carried out in two waves—first the "as received" and then the test vehicles (TVs) after Reflow preconditioning. All TV boards (both reflowed and non-reflowed) were packaged in vacuum sealed bags and shipped to Microtek Laboratories in Northern China. Upon receipt, TVs were carefully unpackaged and examined for any damage in shipment. TVs were prescreened electrically and thoroughly cleaned. Then TVs were soldered with flux-less solder, cleaned again carefully in IPA and then retested for expected resistance. Samples were then baked for six hours at 105C followed by recovery conditioning at 23°C at 50% RH for at least 24 hours. For any other aspects of CAF Testing, IPC methods (IPC-TM-650 Method 2.6.25) were followed rigorously.

Four CAF testing chambers were utilized due to the large number of TVs including both reflow (2 sets) and non-reflow samples (2 sets). The CAF Testing chambers for Relative Humidity were set at 87% and with a Temperature of 65°C and a bias and testing voltage of 100V for the duration of the test. Each TV was wired with a 1 meg-ohm current limiting resistor in series. An initial non-bias period of 96 hours was employed with testing intervals at every 48 hours including initial and employing a testing voltage of 100V for 60 seconds. The constant bias testing at 100V was then carried out for 1000 hours after the intial non-bias period of 96 hours and again utilized a testing voltage of 100V for 60 seconds. Final readings were then taken at 1000 hours, the TVs then removed from the chambers. A final recovery measurement at the prescribed time and conditions as recommended by IPC was then recorded. In addition a surface check at 10X magnification was performed for each and every coupon at both spacings to ensure that no surface ECM (Electrochemical Migration) was detected on the surfaces of the CAF coupons. There were a few samples that showed this phenomenon and these coupons were omitted from any of the CAF testing data analysis.

For a detailed description of the Microtek CAF sample preparation and testing procedure, see Appendix I.

General CAF Mechanics and Mechanisms

Before proceeding to the actual CAF Testing results and failure analysis that was performed as a result of this testing, it is important to spend some intial time discussing CAF terminology, the CAF process, important CAF elements and the Pass/Fail criteria that was ultimately chosen for the evaluation of the testing results.

CAF is an acronym for **C**onductive **A**nodic **F**ilament and is a process that results in solid copper (Cu) growth internally within the PCB that ultimately can end up as a short circuit between 2 adjacent electrical nets at different potentials. Once there is a short circuit, circuit malfunction or in the worst case, even a fire can potentially result (if circuit protection devices are not in the circuit). The CAF process follows the glass weave pathways internally and is not part of the resin system. Thus it is confined to the X and Y directions of the PCB (Warp or Fill of the glass).

CAF is a multiple step, sequential process within the PCB internally and consists of (1) Pathway formation, (2) Ionic Migration along the pathway (This is best defined an electrolyte: a conducting medium in which the flow of current is accompanied by the movement of matter in the form of ions) and (3) Growth of a solid copper filament. This process is analogous to a Copper electroplating cell in which the pathway is the open tank with water (H_2O) and a source of ions moving from anode to cathode and then plating copper in the opposite direction from the cathode surface towards the anode—just like plating a PCB.

First a pathway must be formed or present between two different nets within the PCB internally. Typically this can only occur along the glass fibers of the glass cloth weave (X or Y). It does not occur within the pure resin itself. An interfacial separation must exist between the resin and glass fiber—thus the first possible pathway. This separation can be caused by incomplete wetting of the initial coating of the resin to glass. The separation also can be caused by PCB and PCBA fabrication steps as a result of induced thermal, mechanical or chemical stresses (another type of the same pathway). A second possible pathway is a single glass filament that has a hole like a straw. This is known as a hollow fiber and can be just as detrimental as the interfacial separation of resin to glass. It is still another internal means for a Cu filament to grow. A third possible microscopic pathway can be caused by the degradation of the glass to resin bond (Silane) due to excessive temperature and humidity. This is often an irreversible process.

The second step is the migration of ions (Cu) down the pathway from anode side of the PCB net to the cathode side of an adjacent net under an applied voltage. Initially the ion concentration may be small or curtailed, but once there are enough ions, there can be a catastrophic drop in resistance between the adjacent nets within the PCB. Once this ionic pathway (electrolyte) reaches the cathode, the growth of a solid copper filament from cathode to anode begins. Once the growth is complete, a short circuit occurs - a CAF failure. However, in many or most cases we actually have a failure of the circuit before the short circuit occurs. The ions in the pathway prior to the short circuit can cause severe drops in resistance (as much as 4 decades) which in turn may cause failures in a number of electrical circuits. Thus it may not be necessary to complete the CAF process through a short circuit to have a failure. It is only necessary for sufficient ion migration (IM) to occur to cause significant reduction in resistance to create a circuit failure.. Thus this has a direct impact on how we interpret all CAF testing results. It is not necessary to have a solid Cu filament form, but rather it is only necessary to have a catastrophic drop in resistance to create a failure. For this paper we will call these CAF leakages or **Hard Leaks.**

Let's examine ionic migration (IM) more closely. This is the creation of a path of ions from anode to cathode under the influence of some applied potential, but what does this mean in reference to the PCB internally? What is the anode and cathode? What are the nets and where does the applied voltage come from? There are many different electrical nets within a PCB. Some are at the same potential, some are at different potentials and some are at a signal value with opposing nets at ground. These are the sources of different nets. In order to have Ionic Migration (IM) between nets internally, adjacent nets must be at different electrical potentials. It does not matter whether they are negative or positive just as long as the adjacent nets are at different electrical potentials. This is the driving force for IM. As we stated earlier, there must be some sort of pathway for these ions to move. This pathway comes from resin/glass separation at the interface, uncoated glass by resin, resin non-wetting between filaments, separation of glass/resin interface by thermal/mechanical/chemical means, degradation of the glass to resin Silane bond associated with temperature and humidity, or just a single hollow fiber in one glass filament. Obviously the electrical potential is supplied by the operating functions of the PCB internally. Thus IM must be between two different electrical nets at different electrical potentials with a pathway between them and a source of ions from both opposing nets. Thus one needs a source of ions, a pathway, moisture as means of the transport mechanism for the ions, and finally an applied bias voltage. This is the basic CAF process and more importantly also the IM process, which is a subset of the overall CAF process. It is not necessary to have a solid copper filament formed as a CAF short circuit to have an associated circuit failure. It is only necessary to have sufficient Ionic Migration to cause catastrophic drops in resistance between adjacent nets.

There are different modes or aspects of CAF or IM failure internally within the PCB. What are they and where are they and how do they become a problem? Remember, the pathway for CAF generally has to be along the glass cloth fibers in the X or Y direction and not through pure resin. What does this mean in terms of the internal PCB and what are the failure modes? First let's review by looking at a typical glass cloth with yarns composed of many single glass filaments running in the X and Y directions to give a proper perspective:

Woven Glass Cloth Perspective without Resin (Topographical)

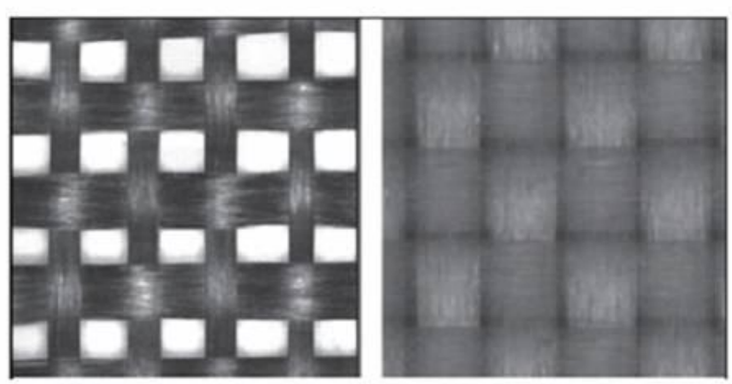


Figure 8: Topographical View of Typical Glass Fabric

Woven Glass Cloth Perspective with Resin in MLB (Vertical X-sect)

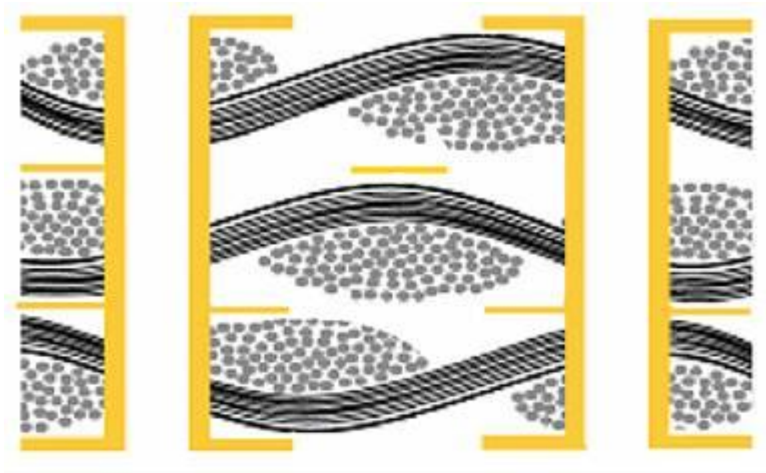


Figure 9: Vertical X-sect of Typical Glass Fabric in MLB

Having now seen the vertical X-sect above, one can now begin to understand why there are **four potential modes of CAF or (IM) failure internally within the PCB;**

1) Internal Through hole to Through hole
2) Internal Trace to Trace
3) Internal Through hole to Trace or plane
4) Internal Layer to Layer

Three potential modes of CAF can be prevented by the proper use of thick enough resin buttercoats and are depicted in Figures 11, 12 and 13. (The term buttercoat here refers to the resin coating above and below the glass.) If the buttercoats are thick enough and the pathway is following the glass, then the glass fibers cannot touch or come within close proximity of another copper feature. Migration cannot go through resin alone if it is thick enough and not damaged.

Thus as you can see from Figure 9 above and Figure 10 below , the most prevalent mode of failure would be the **Thru-hole to Thru-hole walls.** It is a direct line pathway of one copper hole to another copper hole with the potential of a single filament traversing in between them.

For this study, we concentrated only on DHW to DHW as the most prevalent failure mode and made sure that the builds had sufficient buttercoats. The four diagrams below give a more complete perspective on all four modes of CAF or IM failure:

4 Potential modes of *CAF / IM* failure

<u>Through hole to Through hole</u> Failure with CAF Cu filament shown (most prevalent failure mode)

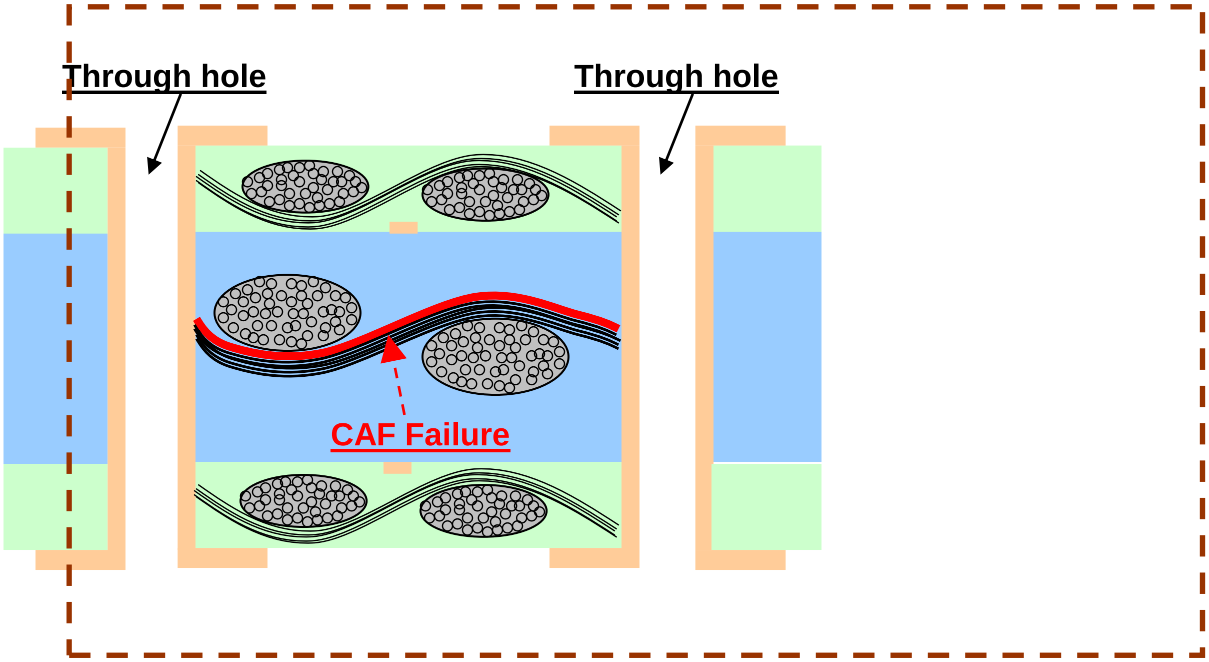


Figure 10: Through hole to Through hole

<u>Trace to Trace failure</u> with CAF Cu filament shown (*note: there is little or no buttercoat present*)

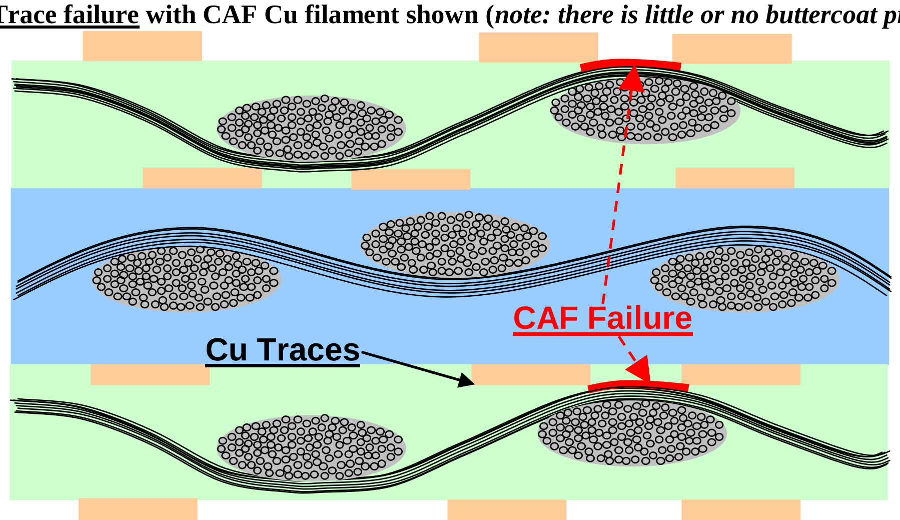


Figure 11: Trace to Trace

<u>Through hole to Trace failure</u> with CAF Cu filament shown (*note: there is little or no buttercoat present*)

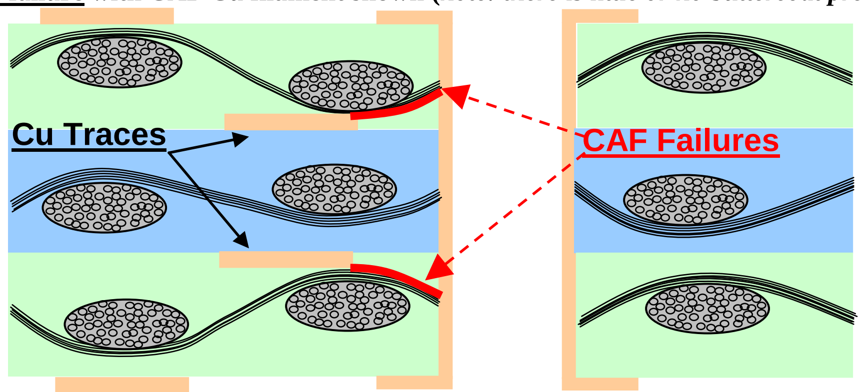


Figure 12: Hole Wall to Trace

<u>Layer to Layer failure</u> with CAF Cu filament shown (*note: there is little or no buttercoat present*)

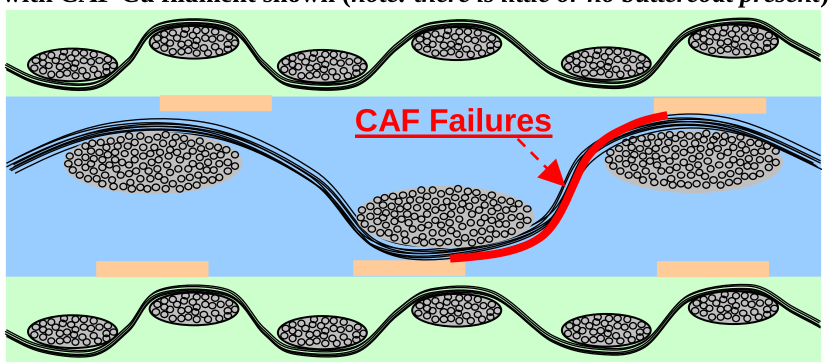


Figure 13: Layer to Layer

Graphical view of CAF / IM Testing Success vs Failure

We will now concentrate our efforts on DHW to DHW testing since that was the essence of the study at hand. The question is what is **Pass** and what is **Fail** and more importantly what is CAF failure or really IM failure as part of the CAF process vs. success? Below are depicted two figures consisting of first success (Figures 14) and then the second figure (Figure 15) of failure. CAF is a process with multiple steps and IM is part of that process where there can be catastrophic drops in resistance as a function of time. These are depicted graphically below as plots of resistance vs time

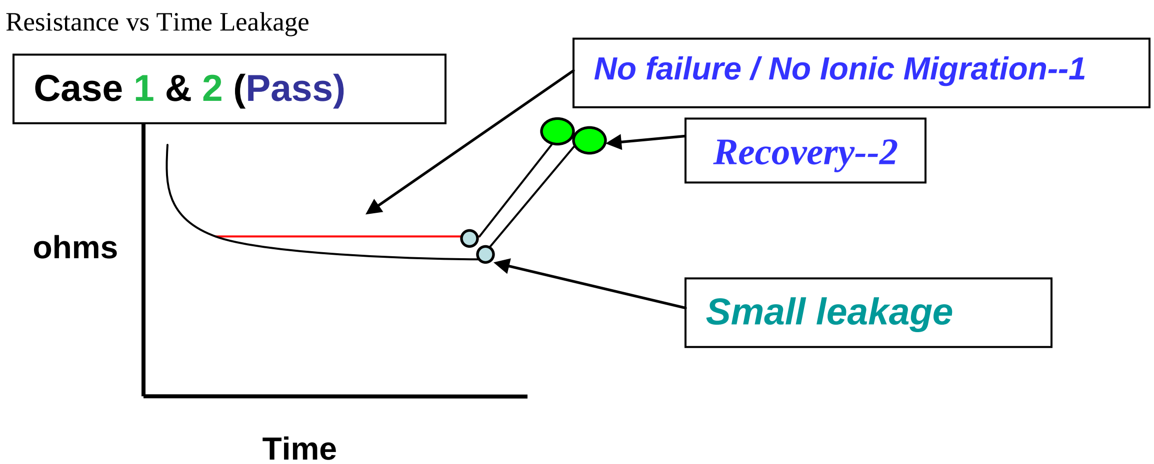


Figure 14: CAF testing Success

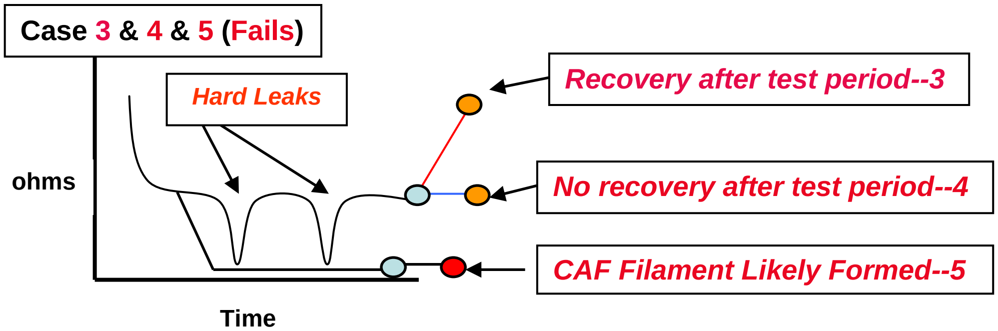


Figure 15: CAF testing Failure

In Figure 14, there are no significant drops in resistance and thus no CAF growth. More importantly there are no significant signs of the CAF process of Ionic Migration during the test period after stabilization. The first graph represents a typical passing CAF test that one would expect after the initial stabilization without any bias voltage and with no significant reductions in resistance after the bias voltage is turned on at the 96 hour mark. All materials start with an initial high resistance at time zero. As the CAF chamber doors are closed and the temperature and humidity are increased, all materials experience some drop in resistance to a stabilization point during the non-bias period. This is due to the absorption of moisture and the temperature rise. Generally this stabilization resistance equilibrates in the 10E10 to 10E11 ohms range. The bias voltage is turned on at the 96 hour mark. The perfect material has zero drop in resistance from the stabilization point and fully recovers back to the initial starting resistance after the test is over and the samples are removed from the CAF test chamber. Some materials experience a small drop in resistance from the stabilization point, but as long as the drop is not more than a decade, this is considered a success. Note that it is not necessary for the material to recover to the initial resistance to be a success, just as long as any drop in resistance is not more than one decade. A sufficient ion pathway is not in place to cause a problem.

Interpretation of a failure is more difficult. In Figure 15 we see the same initial starting resistance with a drop to the stabilization resistance during the non-bias period. However, we now see catastrophic drops of approximately four decades in resistance during the bias period. Sometimes there is a mild recovery back to the stabilization resistance and then another catastrophic drop in resistance and this cycle may repeat. In this case, we call these the **Hard Leaks** and it is a sign of an ionic path or Ionic Migration between anode and cathode in the presence of moisture. Note also that the material at the end of the bias period may or may not recover to the initial starting resistance (case 3 and 4 above) and this really does not matter. What does this all mean relative to determining a failure? As moisture is added, and a path exists, the ions develop a low resistance path for electron flow in the presence of the bias, limited only by the resistance of the pathway. As the concentration of ions increases the resistance decreases. Since this is a fluid system, driven by the presence of moisture, the resistance will vary as a function of the amount of ions present and the size of the path. Thus the pathway resistance varies until we get another catastrophic drop in resistance. This process may repeat multiple times until a permanent pathway of sufficient size is developed at which point the resistance remains at the limiting current resistor and the copper CAF filament grows. For case 5, the process is the same from the initial starting point and including the resistance drop during the stabilization period of non-bias. However, as soon as we turn on the bias voltage, the resistance drops four decades to the limiting current resistor and stays there until the end of the bias testing period. This is generally a clear sign that the pathway is already present at the start of the test and is of sufficient size that electrons can move freely down the ionic pathway and now permit the CAF filament growth to proceed. Lastly for case 5, the lack of any recovery from the current limiting resistor value is a sure sign that a solid Cu CAF filament has formed.

These are graphically illustrated examples of what is seen for this study with different CAF quality materials and will be shown later in this paper as actual examples of this recent testing with the 27 different builds.

Failure Focus

Now that we have established a reasonable perspective of what resistance drops mean during the CAF testing as a function of time, we can now proceed to define or focus on how to define a CAF or IM failure. We actually will focus on Ionic Migration or the **Hard** and **Soft** resistance Leaks that we see instead of just a completed CAF process which results in a solid copper filament growth. First needed are some definitions clarified for resistance Leaks as follows:

Hard Leak ➔ Resistance Drop to < 10 meg-ohms or approximately a four decade drop from the Stabilization Resistance (IR1 per IPC) as measured just before the bias voltage is turned and for > 1 Time Interval of measurement. Measurements are taken every 48 hrs for this study.

Soft Leak ➔ Resistance Drop > 1-2 decades from the Stabilization Resistance (IR1 per IPC) as measured just before the bias voltage is turned on for > 1 Time Interval of measurement.

Passing Protocol

For this study, no **Hard** or **Soft** Leaks were allowed for 500 hrs of the initial monitoring period at 100V Bias to be considered a passing material build. Note that this is independent of what the material did at the end of the 1000 hr bias at 100V, that is whether it recovered fully or not at the end of the test. Sometimes there is a judgment call as to the severity of a **Soft Leak** that occurs very close to the resistance drop allowed and how many of the time intervals are seen with the **Soft Leak(s)**. Thus if the material being tested during the initial 500 hrs of bias voltage has no **Hard** and no **Soft** Leaks, then it is considered a pass. That material is then estimated to have a Mean Time to Failure (MTF) or Life Time of ~ 7-13 years in the Field for typical applications of 10 to 5 Volts. This is very subjective matter and depends on the particular application with many influencing factors. For some customers, absolutely no Leaks (**Hard** or **Soft**) whatsoever are allowed during the 500 hrs of bias and for other customers absolutely no Leaks are allowed during 1000 hrs of Bias test period. It is dependent on the desired lifetime and application conditions. If one really wants to make accurate predictions, more samples are needed (like >30) but with this study one can derive a reasonable estimate of what is going on. Additionally, better acceleration models would also be required that take into account for the two step CAF [8] process and the kinetics of pathway formation.

Applications Susceptible to IM Failure

Let's clarify why we are focusing on IM failures and not just the CAF failure end result with the formation of the solid copper filament. There are many Industries that have applications that are totally susceptible to catastrophic drops in resistance or **Hard Leaks** for even short periods of time as we have defined them (four decade drops). If these applications see this type of resistance drop for any period of time, they may and will cease to function as their original intent. Examples are listed below as follows:

Automotive Industry
- a) Brake Controllers
- b) Other Controllers

Telecommunications Industry
- a) Any circuit with high impedance ➔ radically affected
- b) Phase Locked Loops (control of system clocks)
- c) Analog and RF circuits

Other Industries
- A-D and D-A converters

The important thing to remember here is that it is not necessary to have a direct short to cause failures. Large drops in resistance can cause failures. Thus we have defined failure to be associated with severe and mild resistance drops and thus Ionic Migration (IM) is the focus and not just the short circuit at end of the CAF process. Now armed with all these definitions and understandings, the actual results obtained will be presented and discussed accordingly. For the purpose of this study a CAF failure is defined as any **Hard** or **Soft Leak** that occurs during the first 500 hrs of the stabilized bias period at 100V.

Actual CAF Testing Results for this Study

CAF or IM failures for 500 and 1000 hrs for the 27 Builds

Table 4 summarizes the failures associated with all of the builds. A brief summary and some typical examples of the actual data to emphasize the various points will follow.

Table 4: CAF failures at 500 and 1000 hours

Tes Vehicle information			Visual Delam after 6X Reflow	Failures Before 500 Hours				Failures Before 1000 Hours			
APEX Coding	Stackup	Resin Content (%)		16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R	16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R
A	A	58	No	1_480	2	1_480	No	Many	Many	2	2
B	B	69	No	1_432	No	1_432	No	Many	Many	Many	No
C	A	58	No	Many	1_240	Many	No	Many	Many	Many	1_864
D	A	58	No	1_336	Many	Many	No	Many	Many	Many	Many
E	A	58	No	Many	Many	Many	Many	Many	Many	Many	Many
F	A	58	No	2	1_480	No	1_336	2	2	No	Few
G	B	69	No	1_192	No	2	No	3	1_624	3	No
H	A	58	No	Many	Many	Many	1_288	Many	Many	Many	Many
I	A	58	No	Many	Many	Many	2	Many	Many	Many	3
J	A	58	No	3	2	No	No	4	3	1_816	3
K	A	58	No	2	1_384	Many	No	Many	2	Many	1_1000
L	B	69	No	2	No	1_336	No	Many	No	1_336	No
M	A	58	No	Many	No	Many	No	Many	Many	Many	2
N	B	69	No	Many	2	Many	No	Many	Many	Many	No
O	A	58	No	1--> 10E8	1-->10E9	No	1_192	1--> 10E8	1-->10E9	No	1_192
P	A	58	No	Many	Many	Many	Many	Many	Many	Many	Many
Q	A	58	No	No	1_48	No	_144(10E8-	Many	2	2	2 (10E8+)
R	A	58	No	Many	Many	Many	Many(10E9	Many	Many	Many	3
S	A	58	No	1_432	No	1_480	No	1	No	1_480	1_672
T	B	69	No	Many	Many	Many	Many	Many	Many	Many	Many
U	A	58	No	Many	Low R	Many	Low R	Many	Low R	Many	Low R
V	A	58	Yes	No	Many	No	1_480	Many	Many	No	Many
W	B	69	Yes	Many	Many	No	Many	Many	Many	No	Many
X	A	58	No	Many	Many	2	Many	Many	Many	Many	Many
Y	A	58	No	Many	Many	Many	No	Many	Many	Many	2
Z	B	69	No	Many	Many	Many	Many	Many	Many	Many	Many
AA	A	58	No	Many	Many	2	2	Many	Many	3	2

Expanded Summary of Failure Results for all 27 builds

Table 5 below summarizes the results detailed in Table 4. In this table 5;

2/27 means that 2 material builds of 27 passed at this condition

Likewise 0/27 means that none passed

Material Types are listed in parentheses at the right

Table 5: Expanded Summary Table of CAF Testing Results

Before Reflow (500 hrs)

2/27 **Builds passes 16 mils (1 HF, 1 HiSpd)**

6/27 **Builds passes 20 mils (2 FR4, 2 HF, 2 HiSpd)**

7/8 above fail 20 mils After Reflow at 500 hrs (Material Damage)

8/8 above fail 20 mils After Reflow at 1000 hrs (Material Damage)

Before Reflow (1000 hrs)

0/27 **Builds pass 16 mils**

4 of same 6/27 **Builds above pass 20 mils (1 FR4, 1 HF, 2 HiSpd)**

All 4 above fail 20 mils After Reflow at 1000 hrs (Material Damage)

After Reflow (500 hrs)

5/27 **Builds passes 16 mils (2 FR4, 2 HF, 1 HiSpd)**

11/27 **Builds passes 20 mils (6 FR4, 4 HF, 1 HiSpd)**

After Reflow (1000 hrs)

2/27 **Builds passes 16 mils (1 HF, 1 HiSpd)**

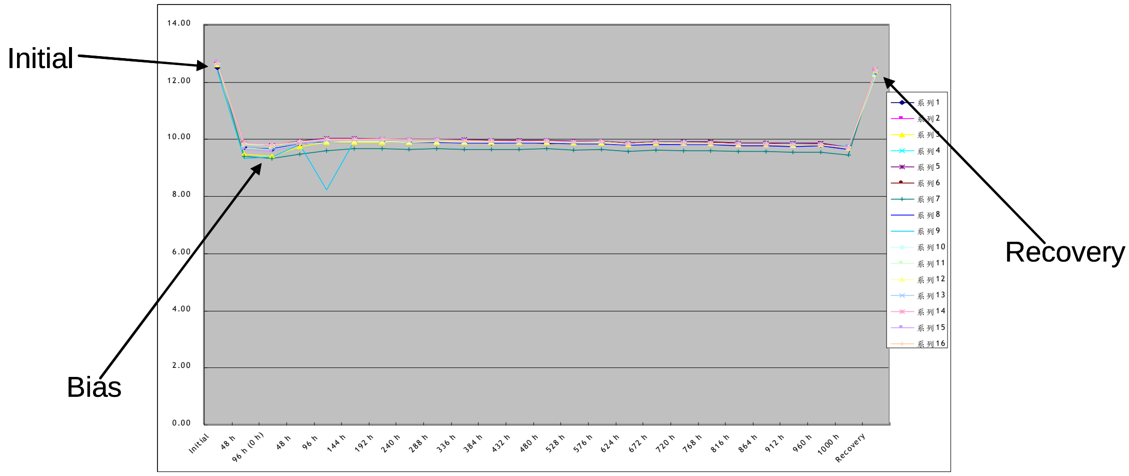
4/27 **Builds passes 20 mils (2 FR4, 2 HF)**

Comments for Table 4 and 5

1. It is clear that from both tables, there are not many passing materials Before Reflow and especially at the 16 mil spacing whether it is at 500 or 1000 hour testing periods.
2. The limited number of passing materials at the 20 mil spacing Before Reflow at the 500 hour mark is a definite concern for Backpanels since this specific application is likely to be assembled with no thermal transients, generally utilizing entirely compliant pin technology.
3. Almost all the material builds that do pass Before Reflow fail After Reflow at 20 mil spacing at both the 500 and 1000 hour marks.
4. As expected, more material builds pass at the 20 mil spacing than at the 16 mil spacing.
5. After Reflow after 500 hours many different material builds now pass when they originally failed before Reflow. This is true for the 16 mil spacing and especially true for the 20 mil spacing. This is unique and unexpected. It will be discussed in more detail later.
6. There would appear to be an equal spread of similar results between the FR4, Halogen Free (HF) and High Speed materials. However other results to be shown later will pin point the High Speed materials as having more problems then either the FR4 or HF materials. This might be expected if one considers that both the FR4 and HF materials are more mature whereas the High Speed materials are relatively newer materials and probably need more development.
7. Material Damage as the result of Reflow will be discussed in a subsequent section, but is noted in Table 5 above as one of the potential reasons for IM failure. Material Damage consists of Delamination, Eyepbrow Cracking, Cigar Voids, Snake Voids and Hole Wall Separation—these also will discussed later with visual examples.

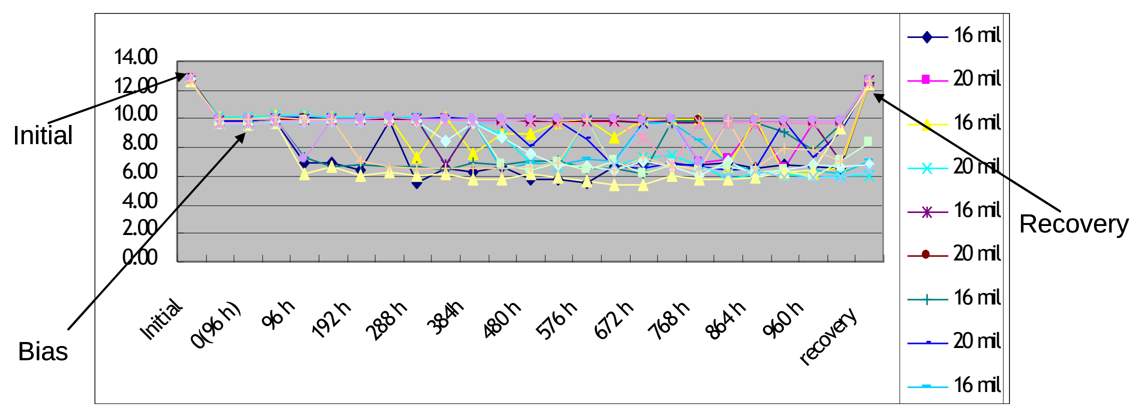
Example Raw Data that is typical for <u>Before Reflow</u> and <u>After Reflow</u>

In figures 16 through 21, data is first plotted as Log Resistance on the Y-axis and Time in hours on the X-axis. Initial, Start of Bias and Recovery is shown. In addition, a Table of the raw data is shown directly under each plot of this respective data. Yellow highlights indicate **Hard Leaks** and the Light Brown highlight indicates **Soft Leaks** for the actual resistance data. Light green is the CAF spacing; darker green is the time in hours and violet is the last measurement of the non-bias period. Blue is the 528 hour mark and the grey is the end of test at 1000 hours of bias after the final Recovery measurement. This color highlighting will be consistent for all resistance vs. time Tables shown in this paper and that depict Log Resistance vs Time in hours for CAF Testing.



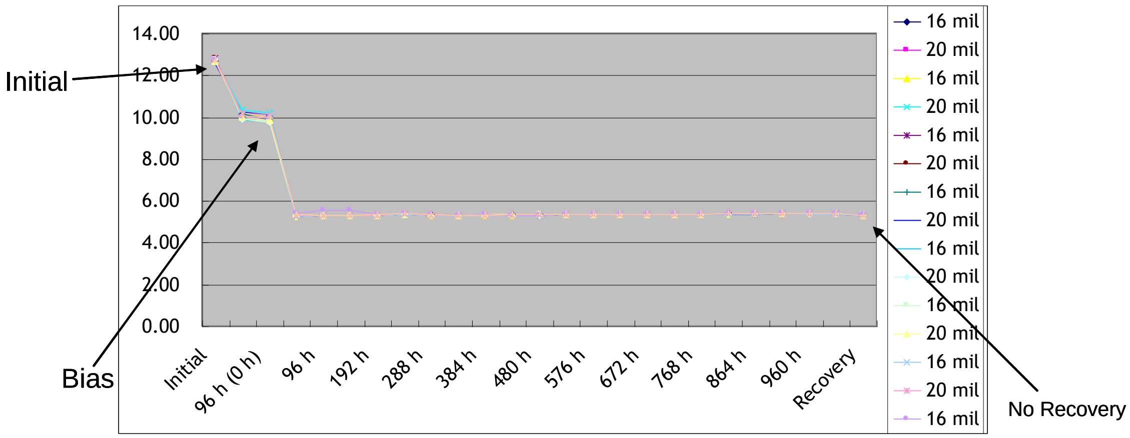
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.49	9.70	9.62	9.78	9.86	9.87	9.88	9.86	9.86	9.86	9.85	9.86	9.88	9.84	9.86	9.79	9.84	9.84	9.81	9.78	9.79	9.77	9.77	9.66	12.32
20 mil	12.64	9.85	9.75	9.87	9.93	9.93	9.93	9.90	9.92	9.90	9.90	9.91	9.92	9.87	9.88	9.82	9.87	9.86	9.85	9.82	9.81	9.79	9.80	9.70	12.33
16 mil	12.58	9.45	9.38	9.71	9.87	9.87	9.87	9.86	9.87	9.86	9.86	9.87	9.87	9.84	9.85	9.79	9.84	9.83	9.82	9.80	9.79	9.78	9.79	9.67	12.36
20 mil	12.61	9.81	9.71	9.87	9.95	9.94	9.93	9.91	9.92	9.91	9.90	9.91	9.91	9.88	9.89	9.83	9.88	9.87	9.86	9.83	9.83	9.81	9.82	9.71	12.32
16 mil	12.64	9.84	9.77	9.92	10.00	10.00	9.99	9.97	9.97	9.95	9.93	9.94	9.94	9.91	9.92	9.85	9.90	9.89	9.89	9.85	9.84	9.83	9.83	9.70	12.41
20 mil	12.63	9.69	9.64	9.83	9.92	9.93	9.94	9.92	9.93	9.91	9.90	9.91	9.81	9.87	9.88	9.82	9.87	9.87	9.86	9.83	9.83	9.80	9.81	9.68	12.37
16 mil	12.63	9.38	9.30	9.44	9.58	9.64	9.64	9.63	9.64	9.63	9.63	9.63	9.64	9.60	9.61	9.55	9.60	9.58	9.57	9.54	9.54	9.52	9.53	9.42	12.39
20 mil	12.66	9.70	9.64	9.80	9.89	9.90	9.89	9.86	9.87	9.85	9.84	9.84	9.85	9.81	9.82	9.76	9.80	9.79	9.78	9.75	9.74	9.72	9.73	9.61	12.39
16 mil	12.36	9.31	9.34	9.78	8.21	9.91	9.92	9.92	9.91	9.91	9.90	9.89	9.90	9.86	9.88	9.81	9.86	9.85	9.84	9.81	9.81	9.79	9.79	9.67	12.34
20 mil	12.62	9.82	9.76	9.90	9.95	9.96	9.95	9.93	9.94	9.92	9.91	9.90	9.92	9.87	9.89	9.82	9.87	9.86	9.85	9.82	9.81	9.79	9.79	9.69	12.39
16 mil	12.54	9.67	9.61	9.79	9.86	9.88	9.88	9.87	9.88	9.87	9.86	9.86	9.86	9.84	9.85	9.78	9.83	9.82	9.82	9.79	9.78	9.76	9.77	9.66	12.16
20 mil	12.64	9.84	9.76	9.86	9.91	9.91	9.91	9.89	9.90	9.89	9.88	9.88	9.89	9.86	9.87	9.81	9.86	9.84	9.83	9.80	9.80	9.77	9.78	9.67	12.40
16 mil	12.64	9.70	9.66	9.83	9.93	9.95	9.94	9.92	9.93	9.91	9.91	9.90	9.91	9.87	9.89	9.81	9.87	9.86	9.85	9.81	9.80	9.78	9.79	9.67	12.32
20 mil	12.63	9.83	9.78	9.90	9.98	9.99	9.98	9.96	9.96	9.93	9.92	9.91	9.92	9.88	9.89	9.82	9.87	9.85	9.85	9.82	9.80	9.78	9.79	9.68	12.42
16 mil	12.67	9.62	9.55	9.80	9.93	9.94	9.94	9.92	9.93	9.91	9.91	9.90	9.91	9.87	9.88	9.81	9.87	9.85	9.85	9.81	9.81	9.78	9.80	9.68	12.37
20 mil	12.63	9.78	9.71	9.88	9.96	9.97	9.96	9.94	9.94	9.92	9.91	9.90	9.91	9.87	9.88	9.81	9.86	9.85	9.84	9.80	9.80	9.78	9.79	9.67	12.34

Figure 16: *No Hard Leaks* at 1000 hrs - Before Reflow – (HF Material-O)



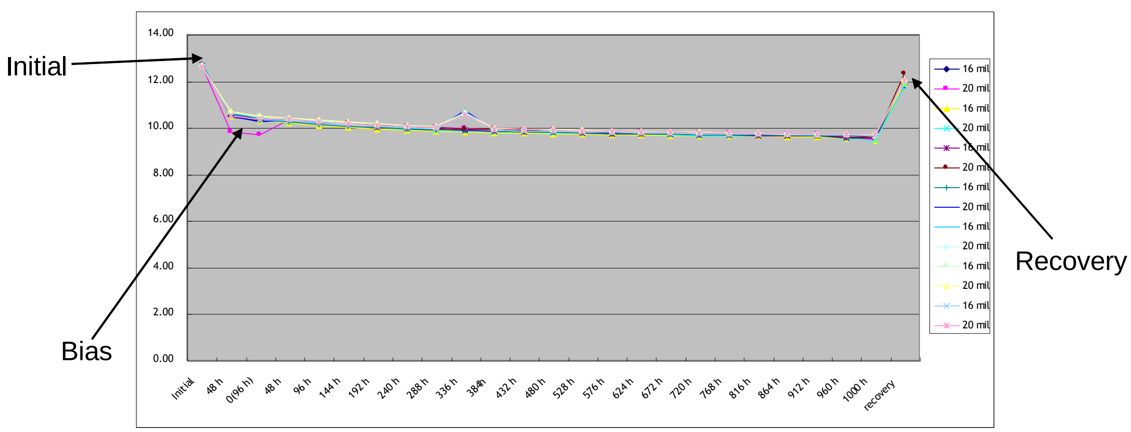
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.64	9.67	9.68	9.82	6.89	6.93	6.31	9.81	5.52	6.52	6.29	6.60	5.75	5.70	5.50	6.66	6.89	6.77	6.73	6.91	6.47	6.74	6.68	6.47	12.41
20 mil	12.72	9.84	9.78	9.91	9.90	9.89	9.90	9.91	9.90	9.87	9.70	9.67	9.79	9.68	9.79	9.80	9.74	9.75	6.88	7.14	9.69	6.52	9.70	9.70	12.49
16 mil	12.64	10.02	9.96	10.12	10.11	10.10	10.09	10.11	7.29	10.02	7.48	8.97	8.96	9.66	9.94	8.71	9.94	9.95	9.91	6.59	9.92	6.10	6.12	6.68	12.47
20 mil	12.67	10.09	10.01	10.15	10.13	10.11	10.11	10.11	10.09	6.78	9.83	8.78	6.91	6.57	9.95	6.60	7.20	7.42	6.77	5.73	6.07	6.06	5.90	5.94	6.02
16 mil	12.64	9.79	9.74	9.88	9.87	9.87	9.87	9.88	9.87	6.77	9.70	9.66	9.78	9.67	9.77	9.77	9.72	9.72	9.70	9.72	9.70	9.68	9.66	7.06	12.60
20 mil	12.72	9.88	9.83	9.97	9.96	9.96	9.93	9.95	9.93	9.88	9.75	9.73	9.83	9.73	9.81	9.82	9.77	9.77	9.74	9.75	9.74	9.72	9.70	9.72	12.54
16 mil	12.63	9.80	9.77	9.93	7.28	6.59	6.76	6.67	6.66	6.31	6.87	6.78	7.01	7.06	6.53	6.52	6.14	9.75	9.77	9.75	9.73	9.02	7.73	9.56	12.46
20 mil	12.63	9.82	9.80	10.01	10.00	9.98	9.99	10.03	9.94	10.00	9.87	9.80	7.99	9.78	8.50	6.67	6.46	6.91	6.62	6.36	6.52	9.78	7.29	9.05	12.56
16 mil	12.64	9.71	9.68	9.85	9.85	9.85	9.84	9.85	9.84	9.82	9.79	6.38	6.81	6.69	7.18	6.94	9.66	9.69	8.34	6.85	6.18	6.20	6.40	6.14	6.95
20 mil	12.67	9.62	9.60	9.81	9.81	9.82	9.81	9.82	9.81	8.42	9.65	8.67	7.57	6.73	6.56	6.35	7.02	6.64	5.98	7.05	6.03	6.36	6.77	6.60	6.72
16 mil	12.58	9.68	9.65	9.79	9.80	9.77	9.77	9.80	9.79	9.76	9.74	6.69	6.37	6.91	6.42	6.97	6.07	6.77	6.38	6.63	6.21	6.31	5.90	7.01	8.25
20 mil	12.64	9.63	9.59	9.73	6.10	6.60	5.96	6.26	5.96	6.12	5.70	5.69	6.09	5.81	5.57	5.35	5.32	5.95	5.73	5.79	5.84	6.18	6.35	9.28	12.35
16 mil	12.67	9.59	9.56	9.72	9.73	9.73	9.73	9.75	9.74	9.73	9.70	9.68	9.67	9.67	9.66	6.77	9.39	9.62	6.62	6.12	6.35	5.91	5.85	5.91	6.37
20 mil	12.72	9.68	9.65	9.79	9.79	9.81	9.80	9.81	9.81	9.79	9.77	9.75	9.72	9.73	9.73	9.66	8.61	6.69	9.66	9.68	9.67	9.63	9.64	9.64	12.51
16 mil	12.58	9.92	9.87	9.99	7.19	9.98	9.97	10.00	9.96	9.98	9.96	9.89	9.90	9.91	9.90	9.88	9.85	9.91	6.85	9.85	9.83	9.82	9.80	9.80	12.60
20 mil	12.66	9.95	9.91	10.01	9.99	9.99	7.06	6.56	6.45	6.46	6.52	6.55	6.57	6.83	9.88	6.38	7.20	6.56	6.32	9.78	6.43	7.87	7.82	6.95	12.60

Figure 17: *A lot of Hard Leaks* at 1000 hrs - Before Reflow – (FR4 Material-C)



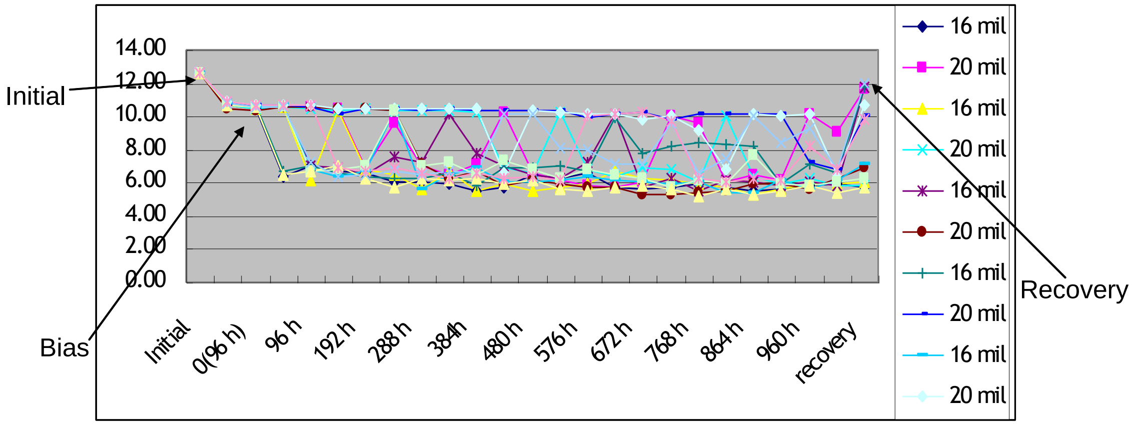
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.69	10.03	9.82	5.24	5.28	5.28	5.30	5.35	5.32	5.30	5.30	5.32	5.32	5.33	5.33	5.34	5.34	5.34	5.34	5.37	5.37	5.38	5.38	5.37	5.29
20 mil	12.70	9.99	9.93	5.25	5.26	5.26	5.29	5.35	5.30	5.29	5.29	5.30	5.30	5.32	5.32	5.33	5.34	5.34	5.33	5.35	5.37	5.38	5.37	5.37	5.29
16 mil	12.69	10.18	9.99	5.24	5.26	5.26	5.28	5.35	5.30	5.29	5.30	5.30	5.32	5.32	5.33	5.33	5.33	5.34	5.33	5.35	5.37	5.38	5.37	5.37	5.29
20 mil	12.71	10.32	10.16	5.25	5.28	5.28	5.29	5.35	5.30	5.29	5.30	5.30	5.32	5.32	5.32	5.33	5.34	5.34	5.33	5.35	5.37	5.38	5.37	5.37	5.29
16 mil	12.77	9.98	9.90	5.24	5.26	5.26	5.29	5.35	5.30	5.29	5.30	5.30	5.30	5.32	5.32	5.33	5.34	5.33	5.33	5.35	5.35	5.37	5.37	5.37	5.29
20 mil	12.77	10.05	10.00	5.24	5.26	5.26	5.28	5.35	5.30	5.29	5.29	5.30	5.30	5.32	5.32	5.33	5.33	5.33	5.33	5.35	5.35	5.37	5.37	5.35	5.29
16 mil	12.72	10.14	9.90	5.24	5.26	5.26	5.29	5.35	5.30	5.29	5.30	5.29	5.30	5.32	5.32	5.33	5.33	5.33	5.33	5.35	5.37	5.37	5.37	5.37	5.29
20 mil	12.56	10.22	10.10	5.25	5.26	5.26	5.29	5.35	5.30	5.29	5.29	5.30	5.30	5.32	5.32	5.33	5.33	5.33	5.33	5.35	5.37	5.37	5.37	5.37	5.29
16 mil	12.74	9.83	9.77	5.24	5.26	5.26	5.28	5.34	5.30	5.29	5.30	5.30	5.30	5.32	5.32	5.32	5.33	5.33	5.33	5.35	5.35	5.37	5.37	5.35	5.29
20 mil	12.76	9.88	9.73	5.24	5.26	5.26	5.29	5.35	5.30	5.29	5.30	5.30	5.30	5.32	5.32	5.33	5.34	5.34	5.33	5.35	5.37	5.37	5.37	5.37	5.29
16 mil	12.74	9.89	9.80	5.24	5.26	5.26	5.29	5.35	5.30	5.29	5.30	5.30	5.32	5.32	5.32	5.33	5.33	5.33	5.33	5.35	5.37	5.37	5.37	5.37	5.32
20 mil	12.63	9.97	9.84	5.35	5.28	5.28	5.29	5.35	5.32	5.29	5.32	5.32	5.32	5.32	5.33	5.33	5.34	5.34	5.33	5.37	5.37	5.38	5.38	5.37	5.29
16 mil	12.74	10.15	10.02	5.25	5.26	5.26	5.29	5.34	5.30	5.29	5.30	5.30	5.30	5.32	5.32	5.33	5.33	5.33	5.33	5.35	5.35	5.37	5.35	5.35	5.29
20 mil	12.73	10.19	10.09	5.26	5.29	5.26	5.30	5.37	5.30	5.30	5.30	5.30	5.32	5.33	5.32	5.33	5.33	5.34	5.33	5.37	5.37	5.37	5.37	5.37	5.29
16 mil	12.69	10.00	9.95	5.38	5.51	5.52	5.32	5.37	5.32	5.29	5.32	5.30	5.30	5.33	5.32	5.33	5.34	5.34	5.33	5.35	5.37	5.37	5.37	5.37	5.33
20 mil	12.71	10.04	9.98	5.32	5.28	5.28	5.34	5.37	5.32	5.30	5.30	5.32	5.32	5.33	5.33	5.33	5.34	5.34	5.33	5.37	5.37	5.37	5.37	5.37	5.29

Figure 18: *All Hard Leaks* at 1000 hrs – Before Reflow – (FR4 Material-E)



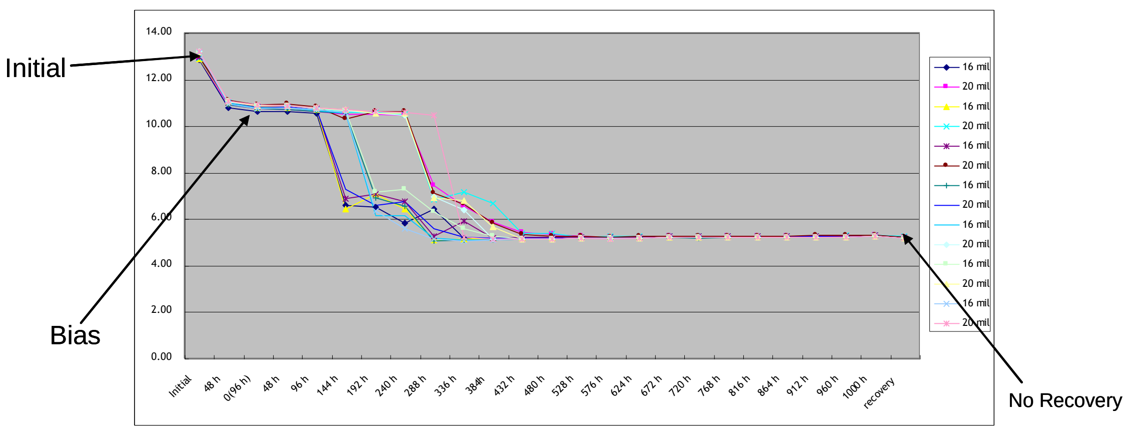
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.63	10.54	10.34	10.27	10.17	10.08	10.03	9.97	9.93	9.89	9.86	9.84	9.81	9.79	9.76	9.75	9.74	9.70	9.70	9.70	9.69	9.69	9.58	9.57	11.81
20 mil	12.66	9.80	9.69	10.33	10.23	10.16	10.09	10.03	9.99	9.95	9.92	9.89	9.87	9.84	9.82	9.80	9.78	9.76	9.75	9.74	9.73	9.72	9.62	9.50	11.78
16 mil	12.64	10.49	10.27	10.19	10.08	10.01	9.94	9.89	9.85	9.81	9.78	9.76	9.74	9.72	9.70	9.68	9.66	9.65	9.64	9.63	9.62	9.61	9.51	9.44	11.89
20 mil	12.65	10.49	10.30	10.25	10.15	10.07	10.01	9.94	9.90	9.86	9.82	9.80	9.78	9.75	9.72	9.71	9.68	9.66	9.65	9.64	9.63	9.63	9.51	9.44	11.77
16 mil	12.65	10.57	10.36	10.28	10.17	10.09	10.02	9.96	9.91	9.88	9.84	9.82	9.80	9.77	9.73	9.73	9.71	9.67	9.67	9.66	9.66	9.65	9.55	9.66	12.03
20 mil	12.67	10.43	10.30	10.32	10.23	10.15	10.08	10.04	9.99	9.94	9.91	9.88	9.86	9.82	9.80	9.77	9.74	9.73	9.70	9.69	9.68	9.67	9.57	9.57	12.29
16 mil	12.76	10.53	10.32	10.24	10.13	10.05	9.99	9.93	9.89	10.68	9.83	9.81	9.79	9.77	9.74	9.73	9.71	9.70	9.68	9.67	9.67	9.66	9.65	9.66	11.99
20 mil	12.63	10.51	10.26	10.33	10.23	10.14	10.07	10.01	9.96	10.73	9.90	9.86	9.84	9.81	9.79	9.78	9.76	9.75	9.73	9.72	9.72	9.71	9.70	9.68	12.01
16 mil	12.65	10.60	10.39	10.30	10.19	10.11	10.04	9.98	9.95	10.54	9.88	9.86	9.84	9.82	9.79	9.77	9.75	9.74	9.72	9.72	9.71	9.70	9.69	9.68	12.01
20 mil	12.67	10.67	10.48	10.40	10.30	10.22	10.15	10.08	10.03	10.67	9.96	9.93	9.90	9.87	9.85	9.82	9.80	9.79	9.77	9.76	9.74	9.74	9.73	9.71	12.03
16 mil	12.62	10.64	10.43	10.34	10.23	10.14	10.07	10.01	9.96	10.53	9.89	9.86	9.85	9.82	9.80	9.77	9.75	9.74	9.72	9.71	9.70	9.69	9.69	9.67	11.95
20 mil	12.64	10.69	10.49	10.42	10.31	10.23	10.16	10.10	10.06	10.59	9.97	9.94	9.92	9.89	9.86	9.83	9.81	9.79	9.77	9.76	9.75	9.74	9.72	9.70	12.05
16 mil	12.64	10.52	10.33	10.28	10.17	10.10	10.04	9.99	9.94	10.59	9.88	9.85	9.84	9.81	9.79	9.77	9.75	9.74	9.72	9.71	9.71	9.70	9.68	9.65	12.02
20 mil	12.60	10.51	10.36	10.35	10.24	10.17	10.10	10.05	10.01	10.52	9.94	9.91	9.89	9.86	9.84	9.81	9.80	9.78	9.76	9.76	9.75	9.74	9.73	9.71	12.03

Figure 19: *No Hard Leaks* at 1000 hrs – After Reflow – (HF Material-L)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.59	10.67	10.40	6.38	6.96	6.73	6.53	6.00	6.04	5.88	5.46	5.72	6.46	6.22	6.62	5.68	5.58	5.70	5.93	5.73	5.52	5.58	5.81	5.89	5.73
20 mil	12.59	10.69	10.53	10.55	10.58	10.48	6.94	9.62	6.96	6.47	7.12	10.26	6.59	6.15	5.79	5.72	6.06	9.99	9.62	5.99	6.43	6.12	10.07	9.05	11.64
16 mil	12.57	10.68	10.47	10.52	6.19	10.39	6.78	6.41	5.59	6.66	5.49	5.88	5.50	5.74	5.91	6.65	6.30	6.16	5.88	5.67	5.33	5.65	5.93	5.90	6.01
20 mil	12.63	10.65	10.45	10.56	10.41	10.38	10.40	10.35	10.32	10.33	10.28	6.89	6.58	10.21	6.79	6.39	6.87	6.81	5.98	10.00	6.33	5.94	6.27	5.78	5.78
16 mil	12.62	10.73	10.52	10.54	7.03	6.85	6.48	7.50	7.20	10.11	7.72	6.98	6.50	6.21	7.25	10.10	5.76	6.23	5.48	6.16	6.01	5.84	6.03	5.77	11.79
20 mil	12.63	10.47	10.34	10.57	10.51	10.45	10.41	10.39	7.14	6.28	6.69	5.77	6.09	5.97	5.72	5.72	5.30	5.33	5.34	5.46	5.88	5.90	5.55	6.24	6.89
16 mil	12.59	10.78	10.61	6.70	6.99	6.60	6.39	6.29	6.29	6.56	5.81	6.93	6.87	7.01	6.63	9.91	7.70	8.20	8.37	8.27	8.17	5.90	7.07	6.52	11.70
20 mil	12.60	10.81	10.63	10.64	10.57	10.13	10.41	10.41	10.39	10.40	10.35	10.34	10.34	10.32	9.87	10.13	10.23	9.80	10.11	10.15	10.16	10.17	7.25	6.74	10.04
16 mil	12.58	10.78	10.59	10.61	6.79	6.35	6.63	10.29	5.65	6.49	6.92	6.04	6.01	6.10	6.38	6.12	6.02	5.95	6.00	5.34	5.42	6.17	5.55	6.18	7.06
20 mil	12.63	10.88	10.66	10.70	10.65	10.45	10.44	10.49	10.43	10.46	10.41	6.62	10.30	10.21	10.16	10.12	9.85	10.05	9.15	6.82	10.15	10.00	10.12	6.49	10.65
16 mil	12.63	10.70	10.54	10.53	6.69	6.75	6.95	10.35	6.98	7.18	6.46	7.30	6.80	6.22	6.74	6.47	6.21	5.76	6.12	5.94	7.64	5.97	5.80	5.99	6.22
20 mil	12.65	10.66	10.53	6.44	6.73	6.99	6.22	5.71	6.20	6.10	6.22	5.90	6.15	5.63	5.53	5.66	5.79	5.60	5.21	5.65	5.30	5.46	5.85	5.35	5.70
16 mil	12.56	10.74	10.50	10.59	7.25	6.39	6.49	6.69	6.43	6.67	6.52	10.16	10.16	8.12	7.97	7.10	7.06	9.57	6.56	7.40	10.01	8.36	9.26	6.80	11.97
20 mil	12.59	10.85	10.68	10.66	10.61	6.85	6.69	6.84	6.60	6.24	6.57	6.24	6.38	6.10	10.01	10.11	10.19	9.64	6.22	6.07	6.29	6.14	8.18	6.74	9.75

Figure 20: A lot of Hard Leaks at 1000 hrs - After Reflow – (HF Material-P)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.83	10.78	10.60	10.61	10.54	6.58	6.49	5.80	6.41	5.16	5.16	5.17	5.19	5.21	5.21	5.22	5.24	5.24	5.24	5.25	5.25	5.26	5.26	5.28	5.21
20 mil	12.86	10.89	10.73	10.71	10.62	10.49	10.47	10.43	7.42	6.52	5.84	5.39	5.32	5.24	5.21	5.21	5.24	5.22	5.24	5.25	5.25	5.26	5.26	5.28	5.21
16 mil	12.89	10.96	10.77	10.79	10.70	6.43	7.06	6.40	5.10	5.14	5.16	5.17	5.17	5.21	5.21	5.21	5.22	5.22	5.24	5.24	5.25	5.26	5.26	5.28	5.21
20 mil	12.92	11.00	10.78	10.82	10.72	10.56	10.56	10.51	6.83	7.13	6.67	5.38	5.37	5.22	5.24	5.24	5.24	5.24	5.25	5.25	5.25	5.26	5.28	5.29	5.24
16 mil	12.95	10.99	10.80	10.83	10.73	6.86	7.06	6.74	5.26	5.90	5.17	5.19	5.21	5.22	5.21	5.22	5.24	5.24	5.24	5.25	5.25	5.26	5.26	5.28	5.21
20 mil	12.97	11.08	10.91	10.92	10.82	10.29	10.60	10.63	7.09	6.61	5.79	5.33	5.25	5.24	5.22	5.24	5.25	5.25	5.25	5.25	5.26	5.28	5.28	5.29	5.22
16 mil	13.19	10.91	10.74	10.71	10.62	10.52	6.90	6.54	5.06	5.08	5.10	5.12	5.14	5.16	5.16	5.16	5.19	5.17	5.19	5.21	5.21	5.22	5.21	5.24	5.16
20 mil	13.18	10.92	10.75	10.80	10.71	7.28	6.58	6.73	5.58	5.19	5.17	5.17	5.16	5.17	5.16	5.17	5.21	5.19	5.22	5.21	5.22	5.24	5.22	5.24	5.17
16 mil	13.18	10.97	10.78	10.78	10.67	10.55	6.15	6.12	5.17	5.08	5.10	5.12	5.14	5.16	5.16	5.17	5.19	5.19	5.19	5.21	5.22	5.22	5.21	5.24	5.16
20 mil	13.18	11.01	10.84	10.84	10.72	10.66	10.53	10.44	6.95	6.37	5.12	5.12	5.14	5.16	5.16	5.17	5.19	5.19	5.21	5.21	5.21	5.22	5.22	5.24	5.16
16 mil	13.17	11.05	10.86	10.86	10.75	10.65	7.13	7.27	6.29	5.56	5.24	5.14	5.14	5.16	5.16	5.17	5.19	5.19	5.19	5.21	5.21	5.22	5.22	5.24	5.16
20 mil	13.17	11.05	10.87	10.86	10.77	10.70	10.53	10.55	6.90	6.77	5.64	5.14	5.14	5.16	5.16	5.17	5.19	5.19	5.21	5.21	5.21	5.22	5.22	5.25	5.16
16 mil	13.17	10.93	10.75	10.76	10.68	10.59	6.32	5.55	5.14	5.06	5.10	5.12	5.14	5.16	5.16	5.17	5.19	5.19	5.19	5.19	5.21	5.22	5.22	5.24	5.16
20 mil	13.18	11.04	10.88	10.87	10.77	10.70	10.60	10.57	10.45	5.21	5.12	5.12	5.12	5.16	5.14	5.16	5.19	5.19	5.19	5.21	5.21	5.22	5.22	5.24	5.16

Figure 21: All Hard leaks at 1000 hrs - After Reflow – (HiSpd Material-T)

Observations about the raw CAF Data Shown in Figures 16 through 21

1) Figure 16 is a good example of a single Soft Leak (both graphically and tabular form as 10E8).

2) Figure 18 is an excellent example of immediate failure just after the bias voltage is turned on. This is indicative of a material build that already has the full pathway present and ions are moving freely as Ionic Migration immediately with enough moisture present for the ion movement. The CAF solid Cu filament is most likely not formed at this point. However, this is a good example of an immediate failure that can knock out controllers and electrical circuits. Note that you do not need reflow to have catastrophic failure. Thus there is definite concern for any PCB that does not see any thermal transients in assembly such as Backpanels. Material choices may be severely limited unless improvements can be made.

3) Conversely, Figure 21 is a good example of failure that takes a while to develop indicating development of the Pathway and the introduction of moisture down the entire pathway. This is not an immediate failure, but rather one that is delayed until ions can get moving freely.

4) Figures 17 and 19 are examples of where Ion Migration is both delayed and short term, but also shows the rising and falling of resistance multiple times previously discussed. This is the phenomena where ionic path resistance is changing over time. This process can repeat multiple times. It is again important to emphasize that each one of these swings can cause catastrophic failure and recovery of an electrical circuit depending on how the circuit is designed. Often the actual failing part of the circuit cannot be found since there is recovery when the part is taken out of service and returned to a RT equilibrium state and then examined for problems. This may be a reason why some CAF failures are not reported as CAF because the resistivity of the circuit has recovered. However the pathway is still there and Ionic Migration can still occur again. It is only when the solid CAF has grown with sufficient time that these failures can be found and not when only Ionic Migration has occurred. Both CAF filaments and IM as part of the CAF process can be devastating.

FMA Investigations for CAF/IM Pathway Detection

Seeing the CAF resistant failures that have been presented, failure analysis was performed to determine the nature of the failure. Was a pathway already there before reflow and, if so where was it? Was a resin void or a hollow fiber present? We already suspect that pathways are present ahead of the CAF testing when immediate failures are seen at the start of the CAF test. Thus a number of samples were selected Before Reflow that had detectable resistance failure at the end of the CAF test. These were vertically X-sectioned in between the opposing failed hole pairs and prepared for SEM analysis including EDAX as well. The following Scanning Electron Microscope (SEM) photos, Figures 22 through 26, will give the reader a good perspective of the problem.

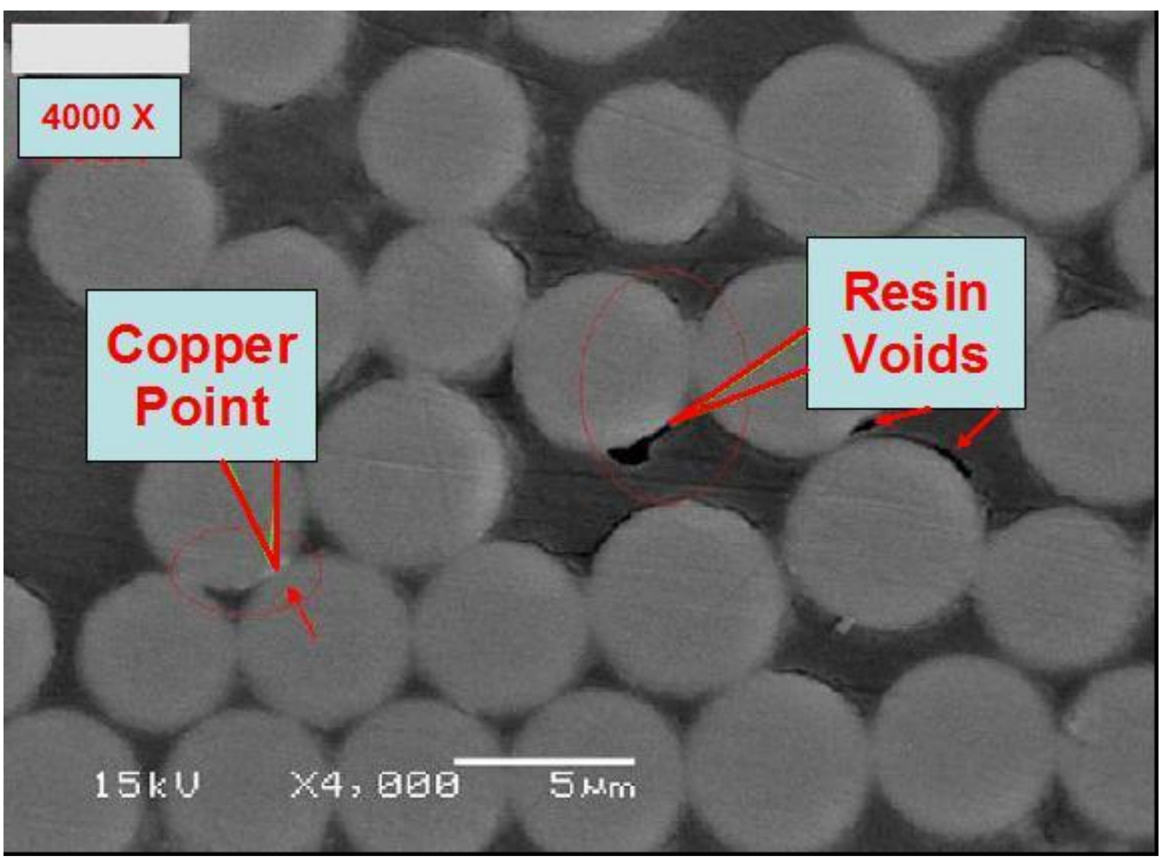


Figure 22: CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM - (HiSpd Material-U)

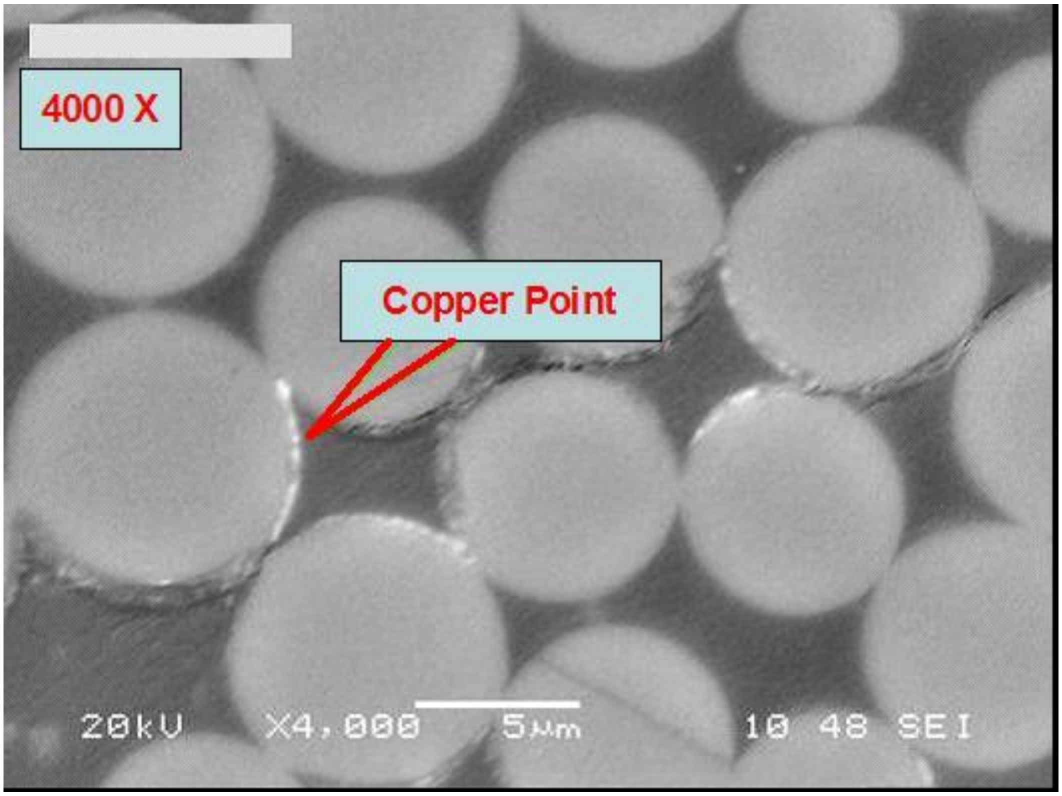


Figure 23 : CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM - (FR4 Material-I)

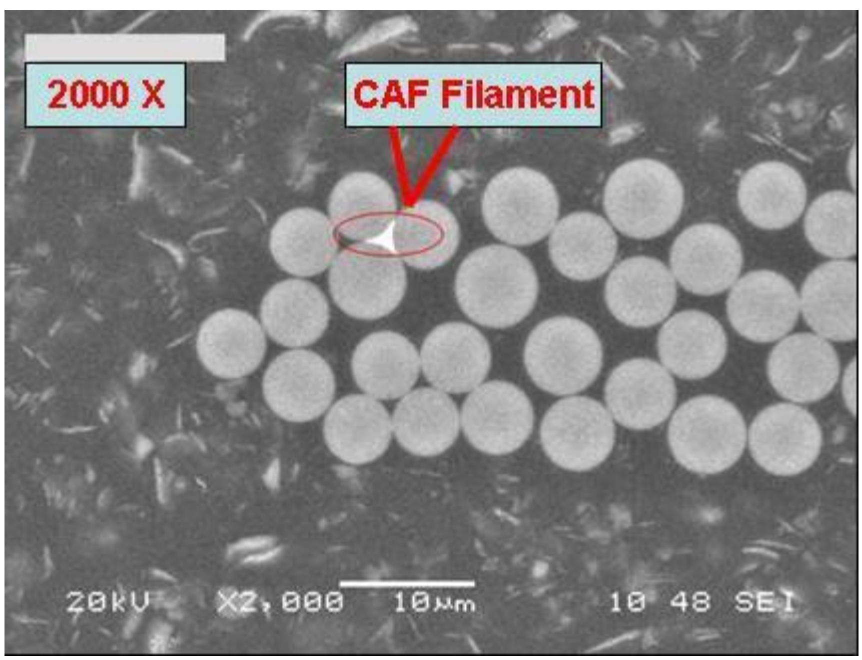


Figure 24 : CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM - (FR4 Material-I)

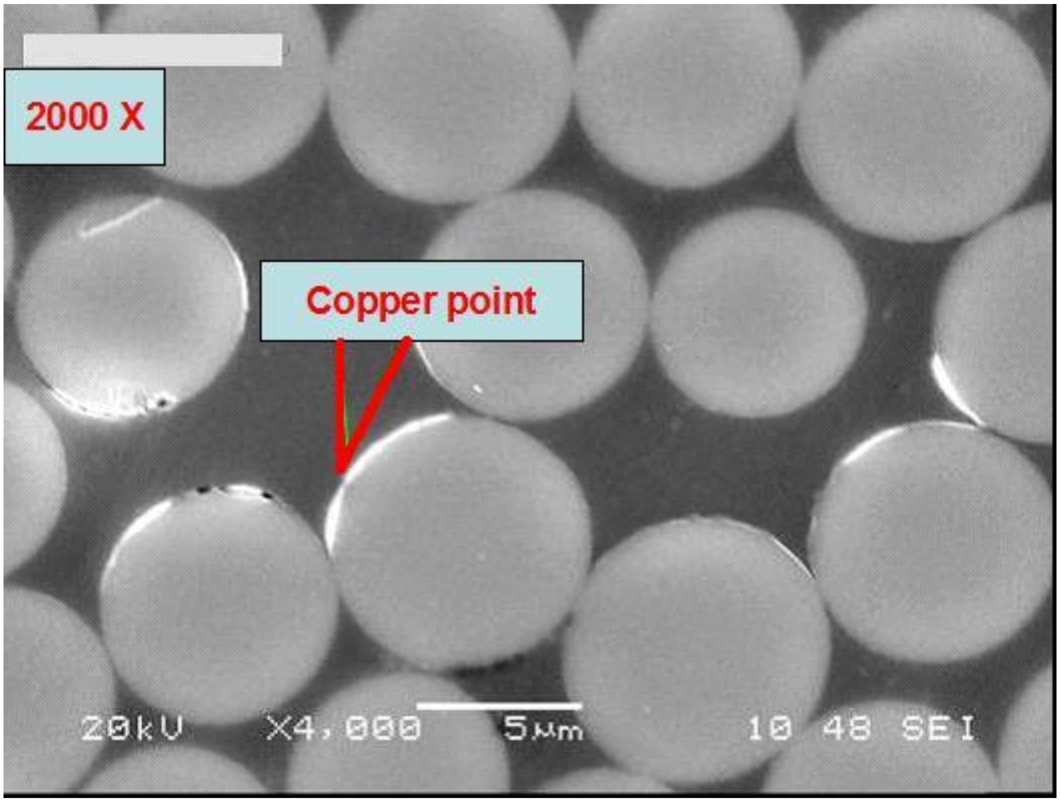


Figure 25 : CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM - (HF Material-N)

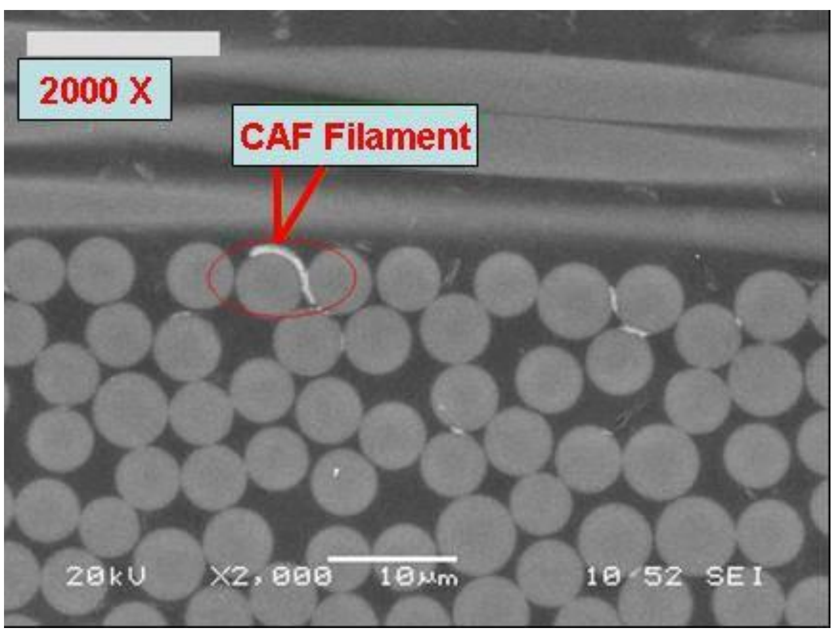


Figure 26 : CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM - (HF Material-N)

Discussion of Failure for CAF Failures by SEM vertical X-Section

SEM analysis is very good for detecting microscopic pathways and voids. It also clearly identifies copper which generally shows up as white background in the SEM picture. One FR4, one HF, and High Speed material were selected for these examples.

1. It is clear that there is indeed a very visible pathway prior to Reflow and it does not take Reflow to create one
2. It is also clear from Figures 22, 23, 24 and 26 that the pathway is an interfacial separation of resin to glass
3. The pathway is not hollow fibers and for all remaining SEM failure analysis that will be shown, this was also true
4. Typically resin voids as shown above can be found in both core and prepreg.
5. Figure 25 is one of the more revealing pictures in that the CAF Cu filament that was formed is in between three glass fibers and is known classically as a triple point failure. This is the likely spot where there is a resin void and should be indicative of problems of originally coating the resin to the glass fiber. Although resin can shrink away from the glass interface for some materials due to a high temp thermal transient such as drilling, it is unlikely in this case and certainly is exemplified by Figure 25 showing the triple point. There will more examples forthcoming on this type of insufficient resin coating of the glass.

Material Damage after Reflow and Effect on CAF Results

Laminate Integrity using 6X Thermal Stress (Solder Float) Methodology

Table 6 below summarizes the laminate integrity results by material and construction as determined by both visual and internal X-sect inspection after 6X reflow cycles at 260°C for the CAF coupons. Entries color coded red confirm a condition (damage) that is rejectable per IPC 6012C (class 3) criteria. The magnitude of the damage was separated into two categories; major ("MAJ") and medium ("MED"). The typical failure mode was material delamination as shown in Figures 27 and 28 for major delamination and Figure 28 for medium delamination. Cross sections that showed "eye-browing" without other major defects present as shown in Figure 29 are specifically highlighted as "EB" in the table. As there is no clear industry agreement as to whether this is a real defect, the decision whether or not to consider this a valid failure mode rests with the product's customer.

The authors of this paper believe that, at least in the specific cross-sections examined, eye-browing is an actual separation of the glass to resin bond and is not caused by the pulling out of a glass fiber during sample preparation. Other damage identified, highlighted as yellow, is significant material degradation that may or may not be rejectable per IPC criteria. Examples of this include medium "cigar" voids as shown in Figure 30 or other zone "A" degradation or damage. Hole wall separation that exceeds 20%, though not an IPC defect, is also highlighted as yellow and specifically noted as "HWS", when no other defects or degradation are noted in the cross sections.

Table 6: Material Damage after Reflow or Thermal Shock for CAF Coupons

Tes Vehicle information			Visual Delam after 6X Reflow	Internal Material Damage after 6X 260C reflow		Internal Material Damage after 6X 288C thermal shock	
APEX Coding	Stackup A=LR B=HR	Resin Content (%)		CAF - 16 mil HW-HW	CAF - 20 mil HW-HW	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW
A	A	58	No	HWS	HWS	No	No
B	B	69	No	HWS	HWS	No	No
C	A	58	No	MAJ	No	No	No
D	A	58	No	HWS	EB	No	No
E	A	58	No	No	HWS	No	No
F	A	58	No	EB	No	MAJ	MAJ
G	B	69	No	No	No	No	No
H	A	58	No	No	HWS	No	No
I	A	58	No	No	HWS	No	No
J	A	58	No	MED	No	No	No
K	A	58	No	HWS	HWS	HWS	No
L	B	69	No	HWS	HWS	HWS	No
M	A	58	No	MAJ	MAJ	MAJ	MAJ
N	B	69	No	MAJ	MAJ	MAJ	MAJ
O	A	58	No	MAJ	MAJ	MAJ	MAJ
P	A	58	No	No	No	No	No
Q	A	58	No	HWS	HWS	HWS	No
R	A	58	No	HWS	No	No	No
S	A	58	No	No	No	No	No
T	B	69	No	No	No	No	No
U	A	58	No	EB	EB	EB	EB
V	A	58	Yes	MAJ	MAJ	MAJ	MAJ
W	B	69	Yes	MAJ	MAJ	MAJ	MAJ
X	A	58	No	EB	No	HWS	No
Y	A	58	No	EB	No	EB	EB
Z	B	69	No	No	No	EB	No
AA	A	58	No	No	No	MAJ	No

HWS:
Hole Wall Separation > 20%

MAJ:
Delamination or Cigar voids beyond zone A

MED:
Medium damage - May or may not be rejectable (example - medium cigar void)

EB:
Eye-browing beyond Zone A

Damage in Zone A only = not listed

LR: **Low Resin Content**
HR: **High Resin Content**

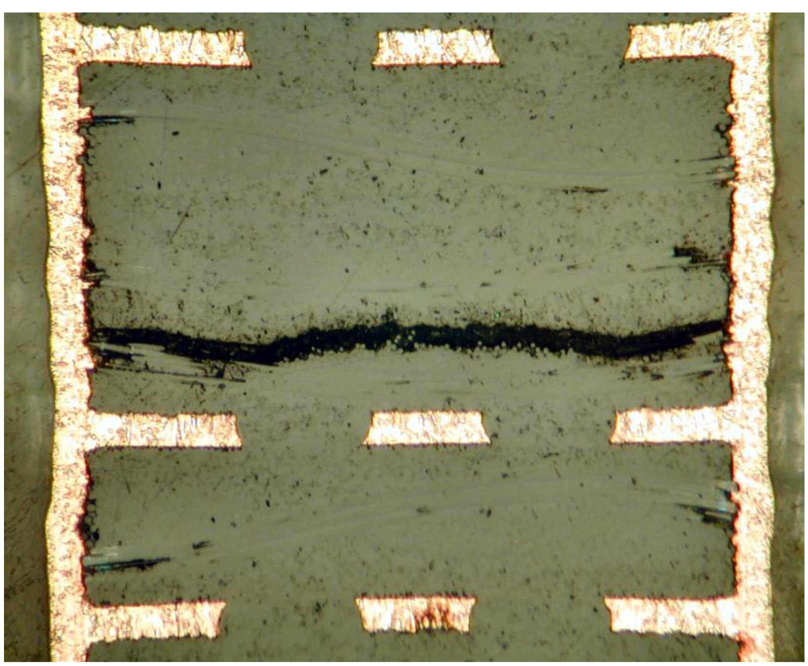


Figure 27: Example internal longtitudinal cohesive delamination

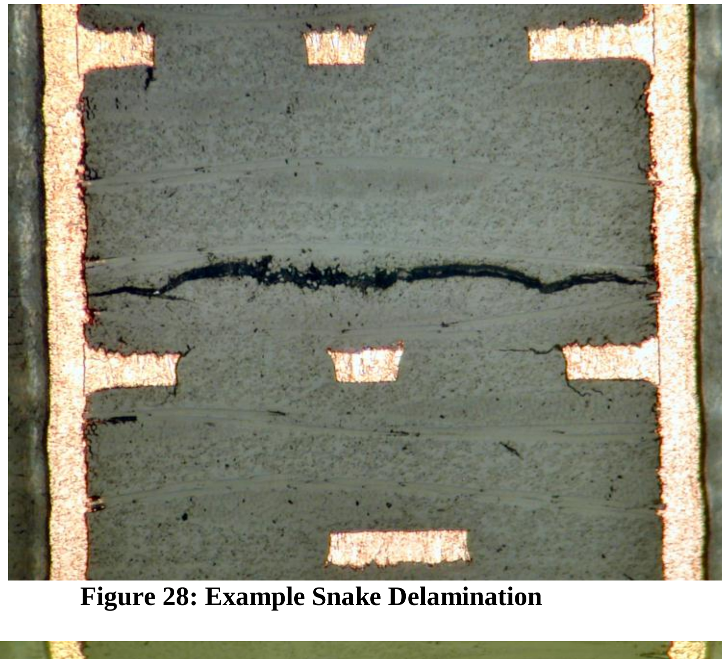


Figure 28: Example Snake Delamination

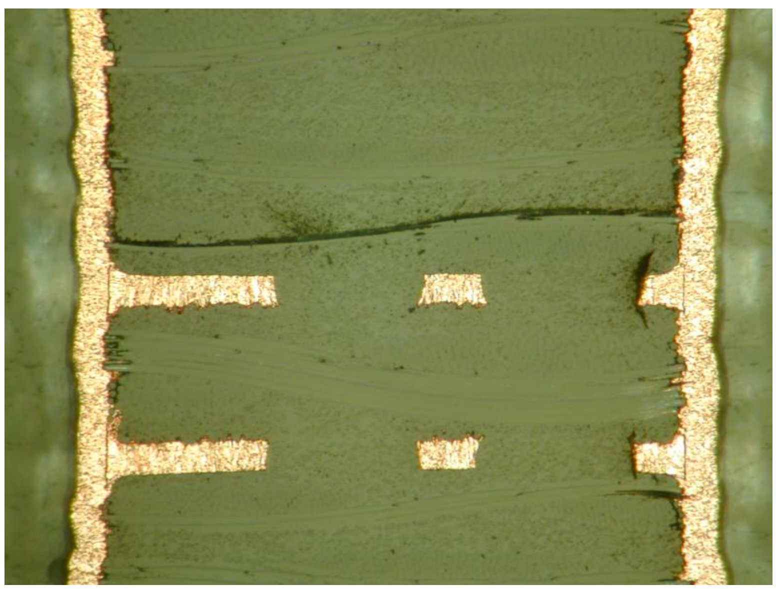


Figure 29: Example of Eye-Browing

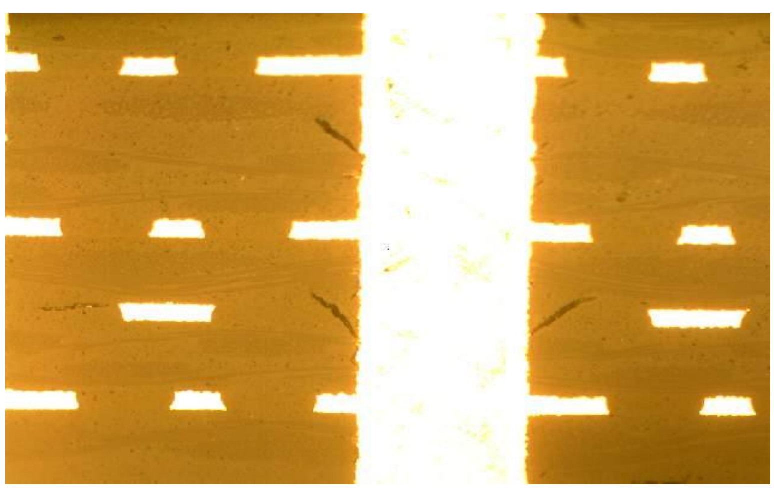


Figure 30: Example of cigar voids

1) Many materials had multiple levels of rejectable internal damage not detectable in surface visual inspection. This issue was identified and previously discussed in detail in reference 1 for a previous series of similar tests. This specific subject will be detailed in the work completed with the IST MAT (material damage) test vehicle, covered in a separate paper [6].
2) In the majority of cases, the 6X thermal shock at 288°C test condition for IST and ATC coupons was more severe than the 6X reflow cycles at 260°C. Considering the complexity of the product (20 layers, 0.115” thick, 11.5:1 aspect ratio) it is accepted that the six solder float thermal excursions is a very challenging requirement. Despite this situation, the 288°C thermal stress methodology is both easy to implement at the PWB fabricator and a valuable tool for looking at first article, or as a production check on an actual design. It is recommended to use both the combination of reflow testing and solder float testing when material and product qualification is important.
3) In Table 6, hole wall separation (HWS) was caused much more often after 6X reflow at 260°C especially for the CAF coupons. This is believed to be a function of the longer time at temperature associated with the reflow oven compared to the very short duration of the thermal stress test. The presence of hole wall separation indicates that plastic deformation of copper occurred during the reflow cycles, confirming that the tensile strength of the copper was exceeded. The resulting shear stress separates the interface between the copper plating and the resin/glass sidewall of the barrel and the resulting separation would potentially affect the levels of strain being applied to the copper barrel. The influence of hole wall separation on product reliability is not fully understood, but a hypothesis is as follows: If structural damage (copper crack initiation) was caused during the 260°C reflow cycles, this could propagate during the subsequent thermal cycling and lead to premature (earlier) cycles to failure. If no structural damage was caused, the copper barrel could experience lower levels of strain (stress relieving) and would perform with extended cycles.
4) Hole wall separation was noted more often in the CAF sections compared to the 1mm and 0.8mm pitch IST and air to air test vehicles (not shown, see reference 9). An important consideration is that the non functional lands had been removed in many cases from the CAF test vehicles; this could potentially reduce the number of “anchor points” for the attachment between the plated copper and the materials. However, the CAF sections also have larger drilled hole sizes and have increased volumes of copper compared to the smaller holes in the reliability test vehicles. The stronger barrels could re-distribute more of the stress toward the surface layers and subsequently increase the shear at the sidewall. The added copper could also maintain the material temperatures higher (through thermal conduction) for a longer period of time compared to the small hole size vias.

Table 7: Combining Reflow Material Damage with General CAF Results

Tes Vehicle information			Internal Material Damage after 6X 260C reflow		Failures Before 500 Hours				Failures Before 1000 Hours			
APEX Coding	Stackup	Resin Content (%)	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW	16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R	16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R
A	A	58	HWS	HWS	1_480	2	1_480	No	Many	Many	2	2
B	B	69	HWS	HWS	1_432	No	1_432	No	Many	Many	Many	No
C	A	58	MAJ	No	Many	1_240	Many	No	Many	Many	Many	1_864
D	A	58	HWS	EB	1_336	Many	Many	No	Many	Many	Many	Many
E	A	58	No	HWS	Many	Many	Many	Many	Many	Many	Many	Many
F	A	58	EB	No	2	1_480	No	1_336	2	2	No	Few
G	B	69	No	No	1_192	No	2	No	3	1_624	3	No
H	A	58	No	HWS	Many	Many	Many	1_288	Many	Many	Many	Many
I	A	58	No	HWS	Many	Many	Many	2	Many	Many	Many	3
J	A	58	MED	No	3	2	No	No	4	3	1_816	3
K	A	58	HWS	HWS	2	1_384	Many	No	Many	2	Many	1_1000
L	B	69	HWS	HWS	2	No	1_336	No	Many	No	1_336	No
M	A	58	MAJ	MAJ	Many	No	Many	No	Many	Many	Many	2
N	B	69	MAJ	MAJ	Many	2	Many	No	Many	Many	Many	No
O	A	58	MAJ	MAJ	1--> 10E8	1-->10E9	No	1_192	1--> 10E8	1-->10E9	No	1_192
P	A	58	No	No	Many	Many	Many	Many	Many	Many	Many	Many
Q	A	58	HWS	HWS	No	1_48	No	1_144(10E8+)	Many	2	2	2 (10E8+)
R	A	58	HWS	No	Many	Many	Many	Many(10E9)	Many	Many	Many	3
S	A	58	No	No	1_432	No	1_480	No	1	No	1_480	1_672
T	B	69	No	No	Many	Many	Many	Many	Many	Many	Many	Many
U	A	58	EB	EB	Many	Low R	Many	Low R	Many	Low R	Many	Low R
V	A	58	MAJ	MAJ	No	Many	No	1_480	Many	Many	No	Many
W	B	69	MAJ	MAJ	Many	Many	No	Many	Many	Many	No	Many
X	A	58	EB	No	Many	Many	2	Many	Many	Many	Many	Many
Y	A	58	EB	No	Many	Many	Many	No	Many	Many	Many	2
Z	B	69	No	No	Many	Many	Many	Many	Many	Many	Many	Many
AA	A	58	No	No	Many	Many	2	2	Many	Many	3	2

It is clear that 6X Reflow at 260C is creating damage in the CAF coupons and with more of a prevalence for hole wall separation as well. What the exact role that delamination, eye-browing, voiding and HWS is playing either collectively or individually towards CAF failure at this time is unclear and much more work is needed in this area. However from Table 7 above, almost every coupon that passed before Reflow and then fails after Reflow has some sort of reflow damage. One could simply postulate that the reflow damage is creating a shorter pathway for Ionic Migration or for the full CAF process to proceed. Clearly delamination and eye-browing are evidence of separation and thus pathway creation that may not have existed prior to the thermal transients. On the other hand, we see many coupons that failed prior to reflow and once reflow was performed, the pathway was altered in some way that halted the Ionic Migration for at least the 500 hour testing period. There are at least 11 of these examples where the detected CAF failures were at 0 and a number where there was improvement with Reflow. With 1000 hr testing, this is far less prevalent, but still one can see some benefit. There are at least four instances where Reflow improved the CAF performance in the 1000 hour testing.. Even with major damage created, the data shows CAF failures disappearing after Reflow for the 500 hr testing period.

From the previous SEM work shown in this paper, it is clear that we do indeed have pathways already present before we even subject the coupons to reflow and then start the CAF testing. It is also clear that other pathways are created which may or may not be extensions of the pathways that were already present beforehand. It is almost impossible to find pathways that are resin voids at the glass/resin interface directly after fabrication. It is much easier to find these pathways once the CAF test is complete since the coupon can be probed for resistance abnormalities to get to the exact hole pair that failed. Thus to determine whether Reflow is contributing new pathways or adding to or expanding old ones already present is a extremely difficult task. Much more work is needed to really understand this aspect of the results. Clearly the major defects seen after reflow are certainly not good for the long term reliability of the product. However it is not understood how much these defects contribute to the overall CAF failure mechanism.

The exact inter-relationship between these pathways is unknown at the moment, but what is important is that reflow does help the problem immensely.
This was a totally unexpected result. Subsequent data in this paper will show that this is not a moisture removal effect, but more likely with reflow, temporary elimination of the pathway for CAF. This is clearly visible at the 500 hour test mark and still has an impact, though less, at the 1000 hr mark. Unfortunately the small number of materials that passed at 1000 hours is a concern for very long term CAF reliability in the field. What is clear is that there are improvements in CAF performance after reflow for those materials that are robust enough to pass through assembly reflow without internal damage. A number of materials will now pass the CAF criteria even though they may not pass CAF without it.

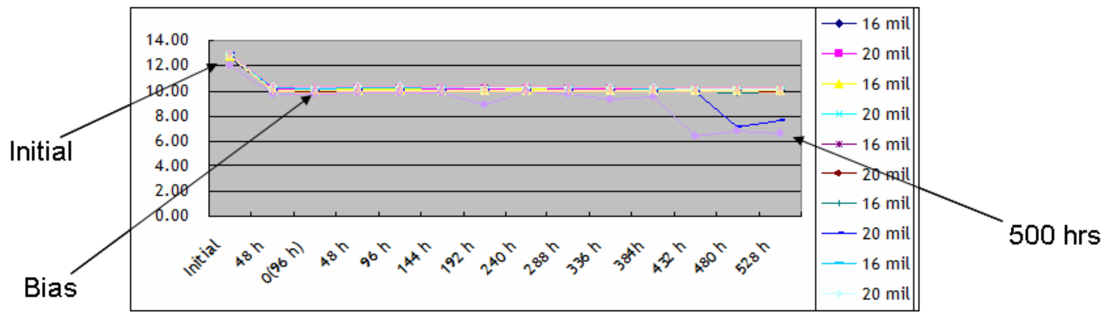
Since reflow can be beneficial for improved CAF performance and actually necessary in some materials for acceptable performance, what can be done for Backpanels that have NO thermal transients associated with their respective assembly, where all the assembly is compliant pin? A method is needed to deal with this situation such that acceptable CAF performance is achieved at the 500 hr mark at 100V testing to ensure that we have some degree of field lifetime for these type applications. Backpanels assembled with compliant pin connectors can be more challenging for CAF since the insertion of the compliant pin into the plated through holes expands the hole slightly, typically increasing the localized separation of the glass and resin in the localized area of the drill. This requires that either the holes be farther apart, or the material be more CAF resistant to ensure adequate CAF performance. On the other hand, most compliant pitch connectors have a relatively large distance from DHW to DHW. However, there are some connectors that provide significant challenges in this area with DHW to DHW spacing as close as 0.55 mm.

The next section(s) will deal with other unexpected results for this latest round of CAF testing as well as examples of the Reflow Pathway Elimination Effect discussed above. Some of these are not obvious without careful evaluation of all the data.

Unexpected Results from CAF/IM Testing
Three unexpected results were encountered during this CAF testing including the Reflow Pathway Elimination Effect discussed above.

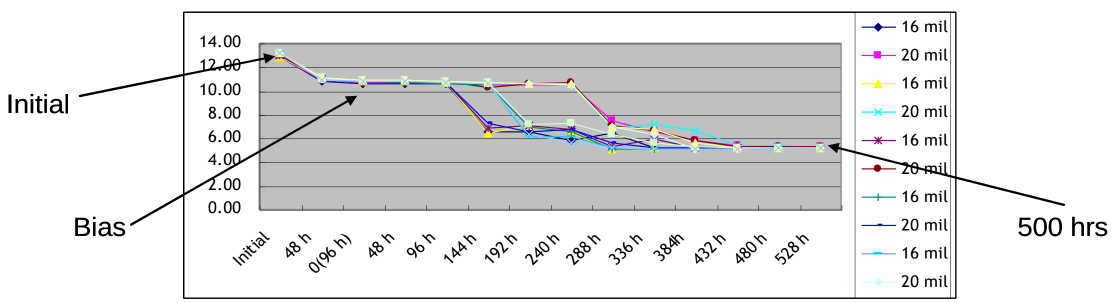
I – The 106 glass Effect
It became quickly apparent that two Hi-speed materials could pass CAF testing for the Low Resin content builds, but were catastrophically failing with the High Resin content builds. This was true for both before and after reflow. This turned out not to be related to the resin content at all and was traced to the cores which were constructed with 1x106 glass and bonded with 1080 prepreg whereas the Low Resin content builds were fabricated only with 1x2116 cores and bonded also with 1080 prepreg. It is known that 106 glass is more difficult to wet with resin and particularly with viscous resin systems as often the Hi-speed materials are, but the extent of this effect had never been quantified as an important contributor to CAF.. The subsequent CAF resistance data (Figures 31-34) will show the magnitude of the effect and the SEM FMA X-sections (Figures 35-36) will clearly show where the pathways are. The most important point is the failure pathways are around the

exterior glass fiber surface as well as resin voids for both materials and **only** in the **cores** which were received as ready to build product. It is also interesting that both of the materials are known to have viscous resin systems and that other 106 constructed core materials (5 other builds out of the 7 total) did not show this phenomena. This result was the same for both the 500 and 1000 hour testing. It is important to test for CAF both with and without 106 glass in order to determine if this is an issue for any given material..



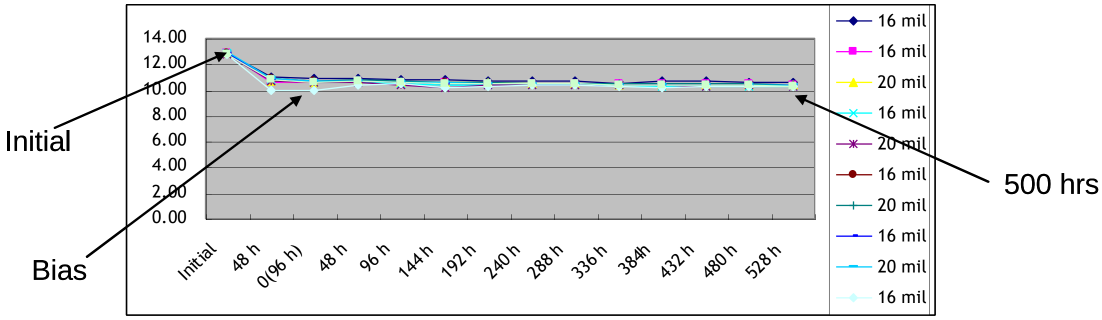
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h
16 mil	12.67	10.05	10.07	10.18	10.15	10.13	10.14	10.15	10.14	10.11	10.09	10.08	10.07	10.06
20 mil	12.73	10.12	10.05	10.18	10.16	10.14	10.15	10.16	10.15	10.12	10.09	10.08	10.07	10.06
16 mil	12.78	10.07	10.02	10.14	10.12	10.10	10.11	10.13	10.11	10.09	10.06	10.06	10.04	10.04
20 mil	12.83	10.39	10.31	10.41	10.38	10.35	10.35	10.35	10.33	10.31	10.28	10.26	10.24	10.24
16 mil	12.86	10.37	10.29	10.37	10.34	10.31	10.31	10.33	10.31	10.28	10.25	10.24	10.22	10.22
20 mil	12.90	9.98	9.92	10.05	10.03	10.01	10.03	10.04	10.03	10.01	9.98	9.97	9.96	9.97
16 mil	12.93	9.93	9.88	9.98	9.97	9.93	9.96	9.98	9.96	9.94	9.92	9.91	9.89	9.90
20 mil	12.96	10.06	10.01	10.10	10.07	10.05	10.06	10.07	10.06	10.04	10.00	9.99	7.20	7.69
16 mil	12.77	10.29	10.20	10.30	10.28	10.25	10.26	10.26	10.24	10.22	10.19	10.19	10.17	10.17
20 mil	12.82	10.36	10.27	10.35	10.32	10.29	10.30	10.30	10.28	10.26	10.23	10.20	10.19	10.19
16 mil	12.85	10.11	10.04	10.11	10.09	10.06	10.09	10.10	10.09	10.07	10.04	10.03	10.02	10.02
20 mil	12.89	10.07	10.03	10.11	10.09	10.07	10.09	10.10	10.09	10.07	10.04	10.03	10.01	10.02
16 mil	12.89	10.35	10.29	10.36	10.34	10.30	10.32	10.32	10.30	10.28	10.25	10.24	10.22	10.22
20 mil	12.93	10.41	10.33	10.41	10.37	10.34	10.35	10.35	10.34	10.31	10.28	10.26	10.24	10.24
16 mil	12.04	9.77	9.77	9.87	9.86	9.86	8.90	9.91	9.80	9.29	9.55	6.40	6.83	6.61
20 mil	12.75	9.91	9.87	9.95	9.94	9.93	9.96	9.97	9.97	9.96	9.93	9.92	9.91	9.90

Figure 31: Low resin content (No 106 glass) at 500 hrs – Before Reflow– (HiSpd Build-S)



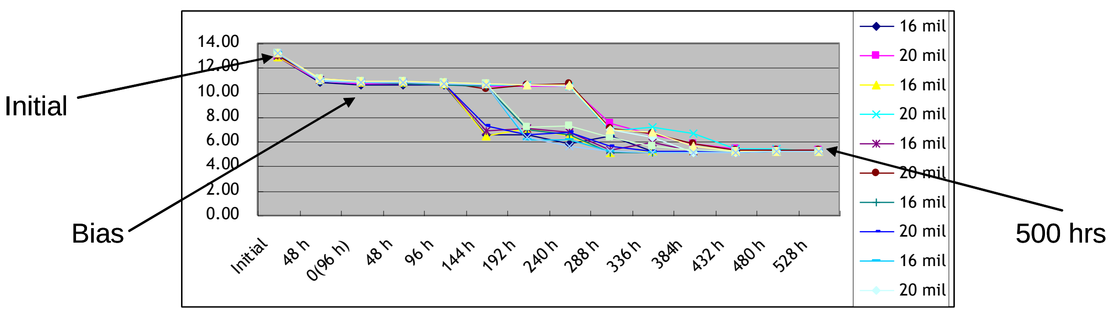
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h
16 mil	12.83	10.78	10.60	10.61	10.54	6.58	6.49	5.80	6.41	5.16	5.16	5.17	5.19	5.21
20 mil	12.86	10.89	10.73	10.71	10.62	10.49	10.47	10.43	7.42	6.52	5.84	5.39	5.32	5.24
16 mil	12.89	10.96	10.77	10.79	10.70	6.43	7.06	6.40	5.10	5.14	5.16	5.17	5.17	5.21
20 mil	12.92	11.00	10.78	10.82	10.72	10.56	10.56	10.51	6.83	7.13	6.67	5.38	5.37	5.22
16 mil	12.95	10.99	10.80	10.83	10.73	6.86	7.06	6.74	5.26	5.90	5.17	5.19	5.21	5.22
20 mil	12.97	11.08	10.91	10.92	10.82	10.29	10.60	10.63	7.09	6.61	5.79	5.33	5.25	5.24
16 mil	13.19	10.91	10.74	10.71	10.62	10.52	6.90	6.54	5.06	5.08	5.10	5.12	5.14	5.16
20 mil	13.18	10.92	10.75	10.80	10.71	7.28	6.58	6.73	5.58	5.19	5.17	5.17	5.16	5.17
16 mil	13.18	10.97	10.78	10.78	10.67	10.55	6.15	6.12	5.17	5.08	5.10	5.12	5.14	5.16
20 mil	13.18	11.01	10.84	10.84	10.72	10.66	10.53	10.44	6.95	6.37	5.12	5.12	5.14	5.16
16 mil	13.17	11.05	10.86	10.86	10.75	10.65	7.13	7.27	6.29	5.56	5.24	5.14	5.14	5.16
20 mil	13.17	11.05	10.87	10.86	10.77	10.70	10.53	10.55	6.90	6.77	5.64	5.14	5.14	5.16
16 mil	13.17	10.93	10.75	10.76	10.68	10.59	6.32	5.55	5.14	5.06	5.10	5.12	5.14	5.16

Figure 32: High resin content (Same Material as Figure 31 with 106 glass) at 500 hrs – Before Reflow (HiSpd Build-T)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h
16 mil	12.85	10.99	10.87	10.90	10.83	10.77	10.73	10.71	10.68	10.50	10.64	10.63	10.58	10.57
16 mil	12.82	10.59	10.61	10.66	10.60	10.55	10.51	10.51	10.50	10.49	10.44	10.48	10.43	10.38
20 mil	12.88	10.64	10.60	10.68	10.61	10.56	10.53	10.49	10.48	10.42	10.40	10.39	10.39	10.34
16 mil	12.89	10.75	10.57	10.55	10.48	10.42	10.38	10.35	10.32	10.32	10.30	10.29	10.26	10.22
20 mil	12.79	10.69	10.55	10.61	10.40	10.17	10.42	10.40	10.37	10.35	10.32	10.30	10.32	10.27
16 mil	12.84	10.85	10.68	10.71	10.62	10.53	10.50	10.48	10.44	10.42	10.39	10.39	10.35	10.30
20 mil	12.88	10.86	10.69	10.74	10.65	10.58	10.54	10.51	10.48	10.46	10.43	10.43	10.43	10.38
16 mil	12.91	10.81	10.64	10.67	10.59	10.49	10.46	10.44	10.42	10.39	10.35	10.36	10.37	10.32
20 mil	12.94	10.84	10.69	10.69	10.61	10.54	10.49	10.47	10.46	10.42	10.39	10.39	10.39	10.34
16 mil	12.76	9.94	9.96	10.33	10.44	10.20	10.31	10.34	10.34	10.23	10.19	10.30	10.29	10.26
20 mil	12.80	10.75	10.61	10.67	10.60	10.51	10.50	10.48	10.46	10.41	10.37	10.41	10.39	10.30

Figure 33: Low resin content (No 106 glass) at 500 hrs – After Reflow– (HiSpd Build-S)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h
16 mil	12.83	10.78	10.60	10.61	10.54	6.58	6.49	5.80	6.41	5.16	5.16	5.17	5.19	5.21
20 mil	12.86	10.89	10.73	10.71	10.62	10.49	10.47	10.43	7.42	6.52	5.84	5.39	5.32	5.24
16 mil	12.89	10.96	10.77	10.79	10.70	6.43	7.06	6.40	5.10	5.14	5.16	5.17	5.17	5.21
20 mil	12.92	11.00	10.78	10.82	10.72	10.56	10.56	10.51	6.83	7.13	6.67	5.38	5.37	5.22
16 mil	12.95	10.99	10.80	10.83	10.73	6.86	7.06	6.74	5.26	5.90	5.17	5.19	5.21	5.22
20 mil	12.97	11.08	10.91	10.92	10.82	10.29	10.60	10.63	7.09	6.61	5.79	5.33	5.25	5.24
16 mil	13.19	10.91	10.74	10.71	10.62	10.52	6.90	6.54	5.06	5.08	5.10	5.12	5.14	5.16
20 mil	13.18	10.92	10.75	10.80	10.71	7.28	6.58	6.73	5.58	5.19	5.17	5.17	5.16	5.17
16 mil	13.18	10.97	10.78	10.78	10.67	10.55	6.15	6.12	5.17	5.08	5.10	5.12	5.14	5.16
20 mil	13.18	11.01	10.84	10.84	10.72	10.66	10.53	10.44	6.95	6.37	5.12	5.12	5.14	5.16
16 mil	13.17	11.05	10.86	10.86	10.75	10.65	7.13	7.27	6.29	5.56	5.24	5.14	5.14	5.16
20 mil	13.17	11.05	10.87	10.86	10.77	10.70	10.53	10.55	6.90	6.77	5.64	5.14	5.14	5.16
16 mil	13.17	10.93	10.75	10.76	10.68	10.59	6.32	5.55	5.14	5.06	5.10	5.12	5.14	5.16

Figure 34: High resin content (Same Material as Figure 33 with 106 glass) at 500 hrs – After Reflow– (HiSpd Build-T)

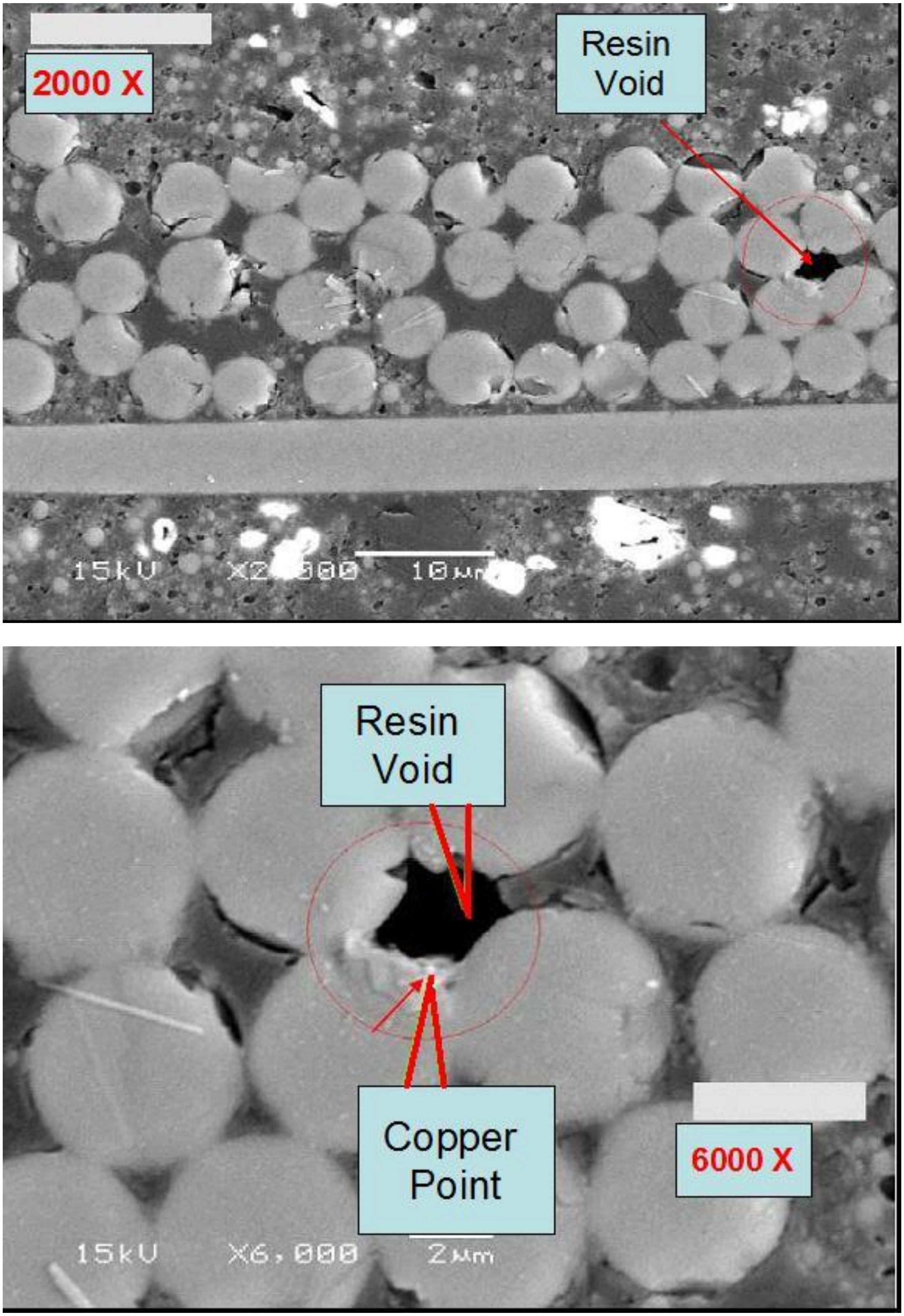


Figure 35a (top) 2000X and 35b (bottom) 6000X (The 106 Glass Effect)
CAF Failure (with 106 glass core) After Reflow - FMA vertical X-sect Picture by SEM - (HiSpd Material-T)

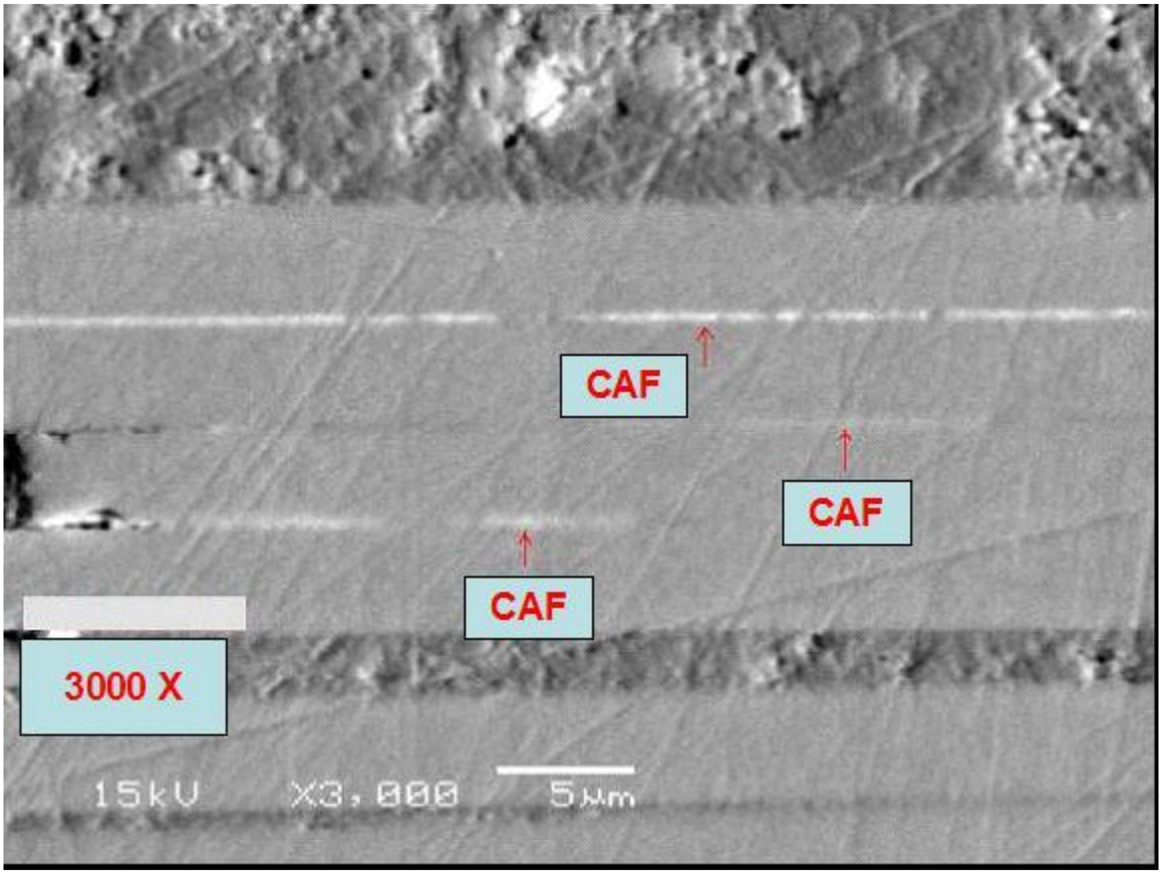
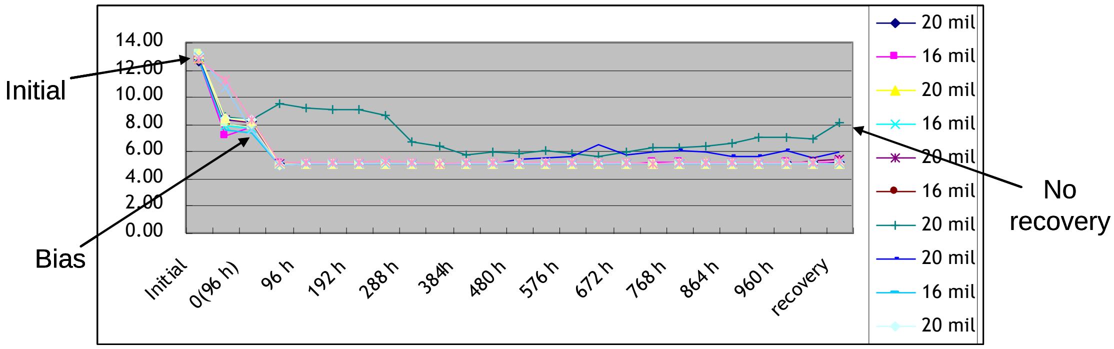


Figure 36 (The 106 Glass Effect)
CAF Failure (with 106 glass core) After Reflow - FMA vertical X-sect Picture by SEM - (HiSpd Material-Z)

II – The Low Bulk Resistivity Effect
The phenomena of observing lower resitivity during the CAF Test at a particular time is not as obvious as other anomalies. It takes careful examination of the resistance data as a function of time along with substantial historical CAF testing data. Most materials start off with an initial high resistance value of 10E13 before the CAF chamber doors are closed and the temperature and humidity are raised to the test conditions. Then, with no bias voltage and the samples equilibrating under the CAF Chamber test temperature and humidity settings, the resistance values will fall from their initial resistance values to some lower resistance stabilization. This typically and historically has been (for FR4, HF and Hi-Speed materials) ~ 10E10 to 10E11 as a stabilized resistance before the bias voltage is turned on at the 96 hour mark of non-bias stabilization. For the perfect material during the bias period, it will remain at stabilized resistance of 10E10 for the duration of the 500 or 1000 hour test and then recover back to the original starting resistance of 10E13. Some materials that are not perfect -- but still these passing materials will have a small leakage from the stabilization resistance of not more than 1 decade at ~10E9 to 10E10.

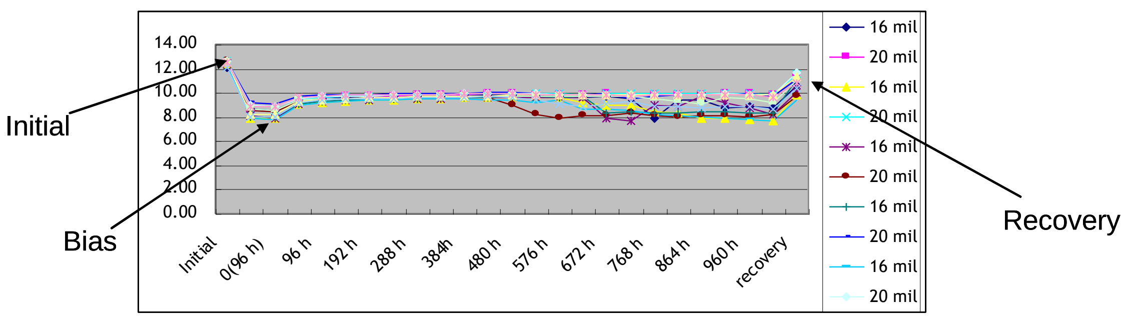
For this study, we observed two different Hi-Speed materials to have a very unusual behavior of resistance during the CAF test. First both would start with an initial high resistance value of 10E13, but when the CAF chamber doors were closed and the Temperature and Humidity raised, both materials would drop to a much lower stabilization resistance of typically 10E8 for one and 10E8.8 for the other. For the before reflow samples and when the bias voltage was turned on at the 96 hour mark, one material failed all samples immediately to limiting current resistor of 10E6 and the other failed many samples ~ 100 hours into the test especially at the closer spacing. Both materials did not recover at all at the end of the 1000 hour testing period. This is a sure sign that not only has a CAF filament grown, but also that there is probably a very large pathway before the CAF test even started. After reflow, one of the materials dropped as it did before, but remained at the low resistance level of 10E9 for the remainder of the bias period and only recovered slightly at the end of the 1000 hours. Again we are seeing a mild form of Reflow Pathway Elimination effect, but not enough to overcome a low resistance performance. For the purpose of long-term reliability, it is not recommended to use materials that portray this phenomenon as this type of performance could lead in micro-shorts or eventual CAF failures.

For the 2nd material, it did not demonstrate high resistivity during the bias period either and also as stated above did not recover fully but more than the first Hi-Speed material. The next set of figures for one Hi-Speed material will give a clearer picture of this phenomena as well as the X-sect SEM work that went along with it. Essentially for the one material, the pathway is present prior to Reflow and is very large.



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
20 mil	12.58	8.29	8.14	5.02	5.04	5.06	5.06	5.06	5.08	5.06	5.08	5.08	5.10	5.08	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.10	5.16	5.12	5.16
16 mil	12.68	7.11	7.79	5.02	5.04	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.10	5.10	5.10	5.12	5.12	5.10	5.10	5.10	5.12	5.10	5.28
20 mil	12.78	8.26	8.03	5.02	5.04	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.10	5.10	5.10	5.10	5.08	5.12	5.10	5.10	5.12	5.10	5.10
16 mil	12.76	7.89	7.67	5.02	5.06	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.08	5.10	5.08	5.10	5.08	5.12	5.10	5.10	5.10	5.10	5.08
20 mil	12.68	8.32	8.12	5.02	5.04	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.10	5.10	5.08	5.10	5.10	5.10	5.10	5.17	5.10	5.10	5.24	5.34
16 mil	12.76	7.93	7.71	5.00	5.04	5.04	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.08	5.08	5.10	5.08	5.08	5.10	5.10	5.10	5.10	5.10	5.08
20 mil	12.72	8.47	8.31	9.45	9.15	9.10	9.04	8.64	6.63	6.37	5.68	5.92	5.81	6.00	5.81	5.64	5.90	6.24	6.22	6.31	6.54	6.98	7.02	6.88	8.13
20 mil	12.68	8.31	8.29	5.02	5.04	5.04	5.06	5.06	5.08	5.08	5.08	5.08	5.43	5.47	5.65	6.44	5.67	5.97	6.01	5.97	5.59	5.62	6.08	5.52	5.90
16 mil	12.67	7.55	7.30	5.00	5.02	5.04	5.06	5.06	5.06	5.06	5.08	5.08	5.10	5.08	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.10	5.10	5.10	5.06
20 mil	13.16	8.41	8.28	5.00	5.04	5.04	5.06	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.08	5.10	5.08	5.10	5.10	5.10	5.10	5.10	5.10	5.10	5.08
16 mil	13.15	7.94	7.78	5.00	5.02	5.04	5.06	5.06	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.10	5.10	5.10	5.10	5.10	5.08
20 mil	13.16	8.43	8.22	5.02	5.02	5.04	5.06	5.06	5.06	5.06	5.08	5.08	5.10	5.08	5.08	5.08	5.08	5.08	5.08	5.10	5.10	5.10	5.10	5.08	5.06
16 mil	12.91	10.68	7.55	5.00	5.02	5.02	5.04	5.06	5.06	5.06	5.06	5.06	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.10	5.08	5.08
20 mil	12.69	11.19	8.27	5.19	5.14	5.22	5.17	5.24	5.17	5.10	5.12	5.16	5.22	5.17	5.19	5.14	5.12	5.10	5.14	5.12	5.14	5.16	5.17	5.22	5.24

Figure 37: The Low Bulk Resistivity Effect – Before Reflow–1000 hrs -- (HiSpd Material-U)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.07	8.64	8.54	9.40	9.48	9.58	9.61	9.67	9.70	9.72	9.76	9.77	9.78	9.73	9.65	9.63	9.72	9.45	7.85	9.36	9.37	8.72	8.86	8.70	**10.54**
20 mil	12.54	8.56	8.51	9.38	9.54	9.64	9.69	9.74	9.79	9.82	9.85	9.87	9.87	9.85	9.83	9.83	9.86	9.74	9.81	9.84	9.84	9.87	9.87	9.80	**11.27**
16 mil	12.36	7.89	7.81	9.01	9.18	9.29	9.36	9.42	9.48	9.52	9.56	9.59	9.60	9.60	9.59	9.13	8.99	8.92	8.38	8.24	7.90	7.83	7.78	7.68	**9.80**
20 mil	12.58	8.60	8.55	9.42	9.58	9.67	9.72	9.76	9.81	9.85	9.88	9.90	9.90	9.86	9.86	9.85	9.86	9.86	9.86	9.86	9.87	9.88	9.86	9.81	**11.53**
16 mil	12.40	8.08	7.83	9.08	9.24	9.34	9.40	9.45	9.50	9.53	9.57	9.60	9.59	9.60	9.59	9.59	7.89	7.61	8.99	8.80	9.64	9.18	8.70	8.16	**9.97**
20 mil	12.59	8.47	8.37	9.23	9.40	9.51	9.58	9.63	9.68	9.72	9.73	9.61	8.94	8.21	7.82	8.12	8.05	8.28	8.06	7.99	8.05	8.10	8.02	8.16	**9.74**
16 mil	12.29	7.97	7.92	9.06	9.23	9.33	9.40	9.46	9.52	9.56	9.60	9.63	9.64	9.64	9.63	9.64	8.32	8.41	8.28	8.33	8.40	8.38	8.25	8.28	**11.11**
20 mil	12.63	9.12	9.02	9.67	9.76	9.82	9.84	9.87	9.91	9.93	9.95	9.97	9.97	9.92	9.84	9.80	9.89	9.46	9.74	9.83	9.80	9.85	9.87	9.69	**11.08**
16 mil	12.41	7.86	7.77	8.97	9.15	9.27	9.33	9.39	9.45	9.48	9.52	9.35	9.32	9.20	9.33	8.60	8.59	8.47	8.14	8.04	7.99	7.91	7.78	7.67	**9.42**
20 mil	12.63	8.91	8.84	9.52	9.64	9.71	9.74	9.78	9.81	9.84	9.86	9.88	9.90	9.86	9.85	9.85	9.85	9.84	9.84	9.84	9.85	9.86	9.85	9.84	**11.64**
16 mil	12.49	8.57	8.51	9.32	9.43	9.51	9.54	9.58	9.61	9.65	9.67	9.69	9.71	9.67	9.66	9.66	9.67	9.66	9.52	9.29	9.00	9.55	9.43	9.19	**11.00**
20 mil	12.54	8.23	8.18	9.21	9.38	9.49	9.55	9.60	9.65	9.68	9.72	9.74	9.76	9.77	9.77	9.78	9.79	9.78	9.80	9.80	9.81	9.83	9.82	9.81	**11.36**
16 mil	12.05	7.99	7.92	9.17	9.34	9.44	9.48	9.52	9.56	9.60	9.62	9.64	9.58	9.38	9.00	8.87	9.01	9.25	8.84	8.84	8.69	8.78	8.83	8.63	**10.36**
20 mil	12.50	8.85	8.78	9.57	9.67	9.75	9.76	9.79	9.81	9.84	9.86	9.86	9.87	9.84	9.81	9.80	9.82	9.74	9.80	9.80	9.80	9.82	9.81	9.58	**10.73**

Figure 38: The Low Bulk Resistivity Effect – After Reflow–1000 hrs -- (HiSpd Material-U)

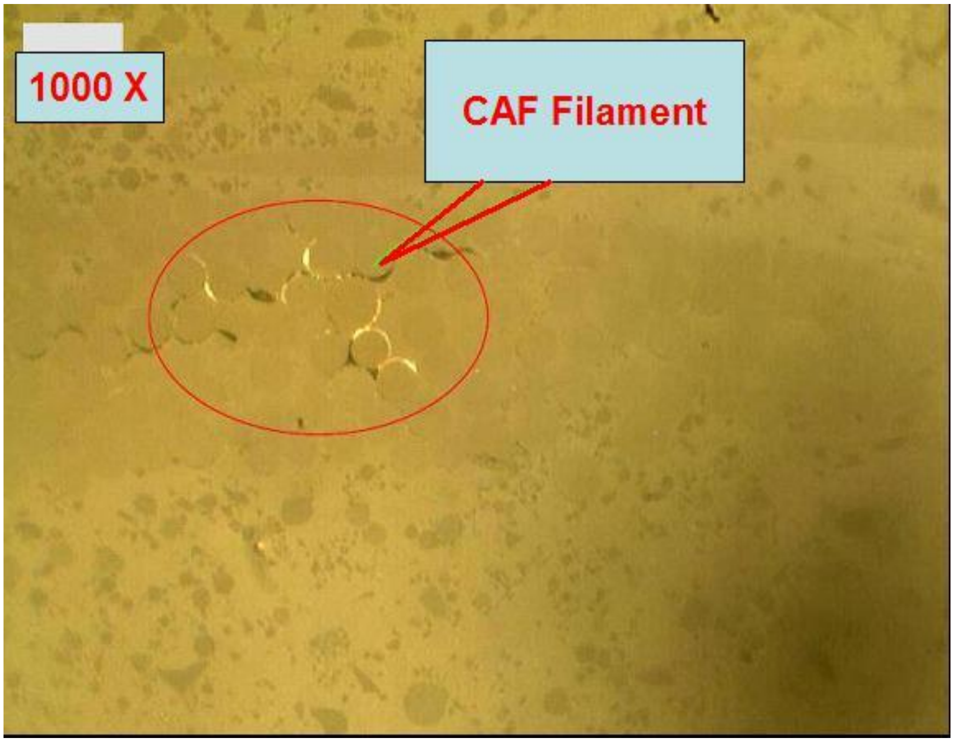


Figure 39 (The Low Bulk Resistivity Effect)
CAF Failure Before Reflow - FMA vertical X-sect Picture by Microscope – (HiSpd Material-U)

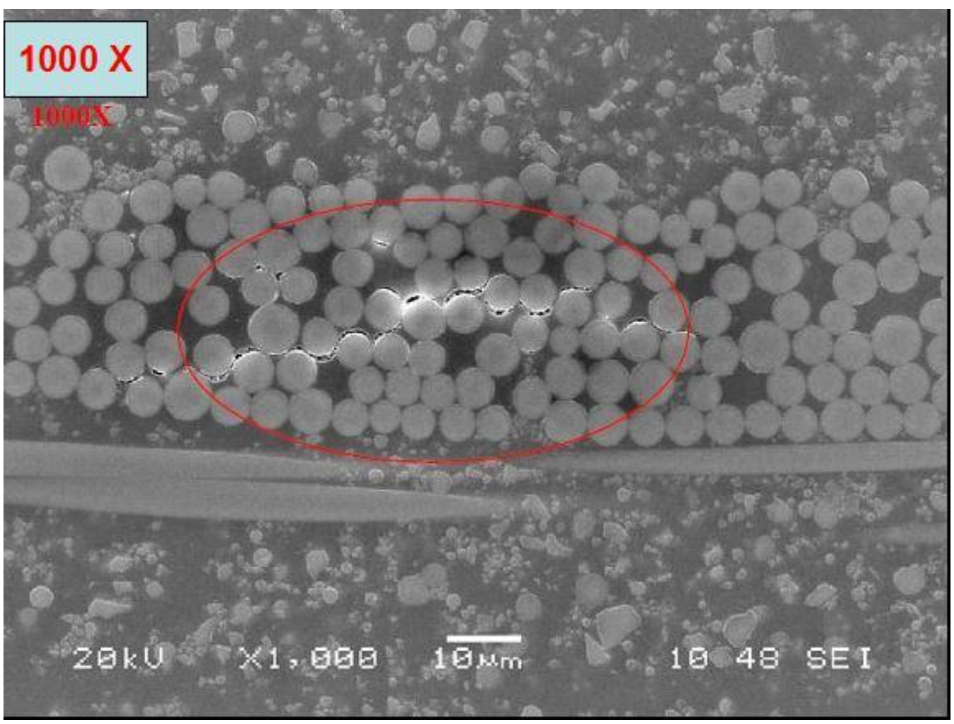
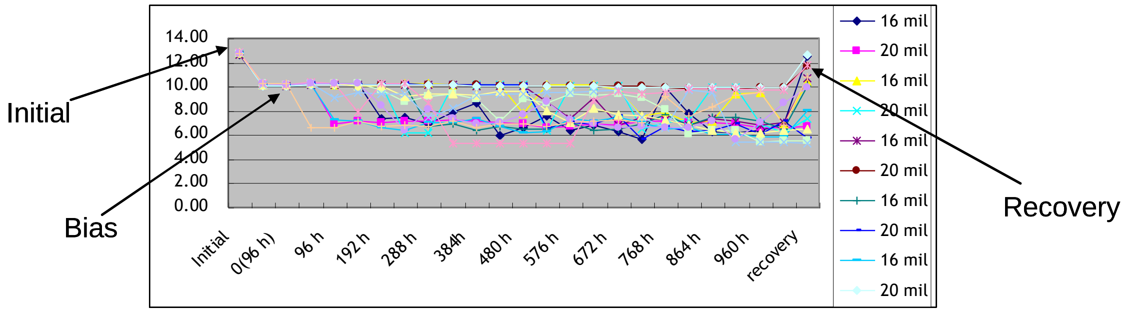


Figure 40 (The Low Bulk Resistivity Effect)
CAF Failure Before Reflow - FMA vertical X-sect Picture by SEM – (HiSpd Material-U)
Note: Evidence of a very Large Pathway present Before Reflow ➔
Can lead to overall resistivity problems besides CAF/IM failures

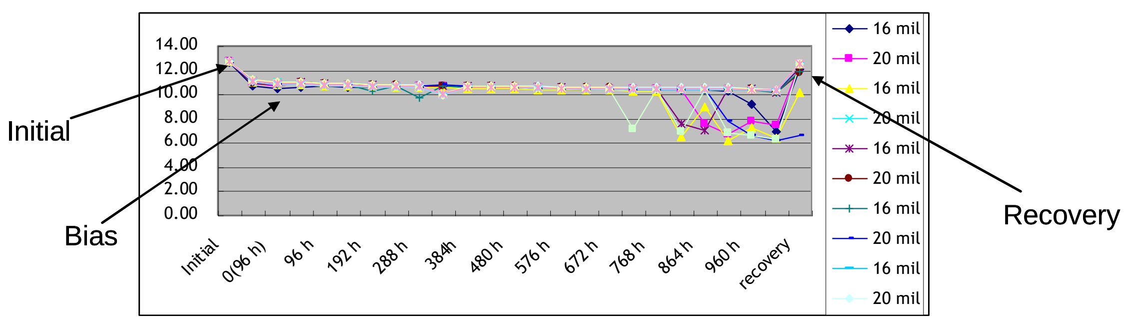
III – The Reflow Pathway Elimination Effect (Before / After Reflow)
This was discussed extensively under the Material Damage section with the effects of Reflow. There are 11 materials that show significant improvement after Reflow at the 500 hour mark (4 FR4, 4 HF, 3 Hi-Speed). For these materials, it does not appear to be any kind of a moisture effect for 9 of the 11 material builds as the average level of volatiles was measured at ~0.2 to 0.4% by TGA before and after reflow. The same effect, but much smaller in number (only 4 material builds of 2FR4, 2HF) is seen for the 1000 hour testing mark. Therefore in some cases, reflow can be advantageous. The question remains: what is one to do about Backpanels which have no Thermal Transients for Assembly?

The next set of figures will give the flavor of the Pathway Elimination Effect for typical CAF Testing for 4 of 11 materials before and after reflow at the low moisture level. Remember those coded yellow are **Hard Leaks** and those coded light brown are **Soft Leaks.**



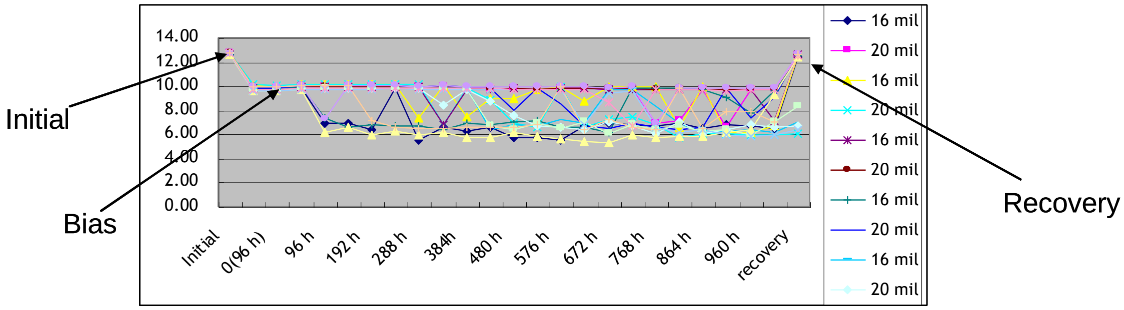
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.60	10.16	10.11	10.19	10.18	10.18	7.30	7.40	6.86	7.82	8.66	5.89	6.62	7.53	6.37	6.74	6.24	5.56	9.90	7.80	6.22	6.15	6.36	6.92	12.50
20 mil	12.67	10.20	10.17	10.27	6.88	7.09	7.03	7.07	7.15	7.18	7.14	6.99	6.87	6.52	6.67	6.86	6.80	7.09	7.12	7.02	7.01	6.85	6.52	6.58	6.72
16 mil	12.69	10.12	10.09	10.18	10.17	10.17	10.17	10.18	10.18	10.16	10.14	10.12	7.73	10.11	10.11	10.11	9.68	7.57	7.91	7.00	7.12	9.38	9.44	6.94	10.30
20 mil	12.74	10.07	10.06	10.12	10.12	10.12	10.13	6.16	6.09	10.11	10.09	10.07	10.07	6.39	10.06	10.06	9.98	6.48	7.04	7.25	9.95	9.93	6.91	6.12	7.32
16 mil	12.62	10.12	10.06	10.12	10.11	10.10	10.09	10.11	10.10	10.07	10.04	10.02	10.01	8.69	7.27	9.01	6.77	7.47	7.18	6.75	7.37	7.10	6.80	6.99	10.69
20 mil	12.68	10.16	10.10	10.17	10.16	10.14	10.13	10.15	10.14	10.11	10.09	10.06	10.05	10.05	10.06	10.04	9.99	9.97	9.95	9.79	9.84	9.84	9.89	9.88	11.60
16 mil	12.66	10.11	10.06	10.19	10.18	10.16	10.16	10.17	6.70	6.93	6.37	6.70	6.49	6.51	7.01	6.39	6.48	6.89	7.62	6.75	7.45	7.46	7.09	6.47	10.05
20 mil	12.71	10.12	10.07	10.18	10.17	10.17	10.17	10.18	10.17	10.16	10.12	10.11	10.08	6.59	6.97	6.87	7.52	5.62	6.64	6.28	6.36	6.84	6.08	7.11	5.70
16 mil	12.70	10.04	9.99	10.08	7.26	7.16	6.53	6.37	6.95	7.03	7.30	6.67	6.17	6.20	7.30	7.16	7.43	7.05	6.48	6.52	6.06	6.02	5.81	5.84	7.94
20 mil	12.75	10.05	10.03	10.10	10.10	10.09	10.10	10.09	10.10	10.09	10.05	10.02	10.01	10.06	10.02	10.02	9.94	9.93	9.93	9.93	9.92	9.90	9.86	9.86	12.58
16 mil	12.75	10.20	10.16	10.25	10.25	10.23	9.72	8.68	9.19	9.37	8.94	7.11	8.90	8.63	9.42	9.31	9.34	9.09	8.07	6.06	6.32	6.38	5.34	5.47	5.47
20 mil	12.80	10.14	10.11	10.22	10.22	9.99	10.04	9.12	9.34	9.36	9.31	9.55	9.56	8.00	7.02	8.22	7.69	7.55	7.19	6.74	6.35	6.18	6.09	6.38	6.42
16 mil	12.81	10.16	10.12	10.25	9.01	9.45	9.39	9.40	7.39	8.21	9.30	9.37	9.42	9.46	9.52	9.55	9.65	7.46	6.53	9.64	9.50	5.37	5.35	5.37	5.30
20 mil	12.83	10.27	10.11	10.29	10.27	7.90	10.25	10.26	8.58	5.26	5.26	5.28	5.29	5.29	5.29	8.78	9.54	9.34	9.47	9.75	9.79	9.77	9.74	9.74	11.69
16 mil	12.74	10.22	10.16	10.25	10.25	10.22	8.45	6.39	8.10	7.27	6.87	6.97	7.67	8.70	7.18	6.85	6.54	6.63	6.59	6.60	7.07	5.57	7.01	8.66	9.95
20 mil	12.73	10.24	10.18	6.61	6.55	7.07	6.63	6.81	6.68	7.06	6.54	6.89	6.89	6.64	6.99	7.15	7.19	7.01	9.19	7.53	8.30	9.31	9.44	6.81	10.75

Figure 41: The Reflow Pathway Elimination Effect – Before Reflow–1000 hrs -- (HF Material-M)



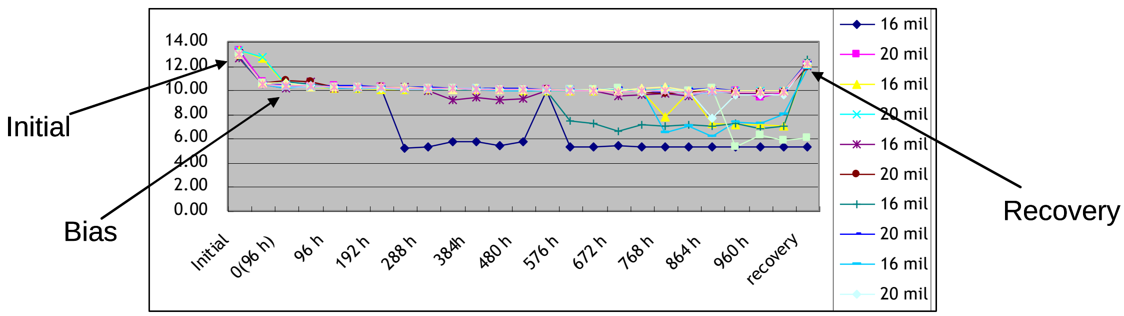
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.56	10.65	10.42	10.56	10.70	10.60	10.60	10.55	10.55	10.64	10.51	10.47	10.48	10.40	10.33	10.33	10.35	10.30	10.32	10.31	10.32	10.28	9.19	6.86	12.07
20 mil	12.66	10.86	10.67	10.84	10.77	10.71	10.68	10.65	10.63	10.69	10.59	10.58	10.57	10.52	10.47	10.46	10.45	10.40	10.41	10.39	7.51	6.72	7.75	7.44	12.49
16 mil	12.69	11.02	10.72	10.80	10.69	10.63	10.58	10.53	10.51	10.57	10.47	10.45	10.43	10.38	10.33	10.32	10.32	10.28	10.28	6.50	8.95	6.13	7.19	6.36	10.15
20 mil	12.70	11.14	10.96	10.93	10.82	10.76	10.72	10.67	10.66	10.68	10.60	10.58	10.57	10.52	10.47	10.47	10.47	10.40	10.41	10.33	10.39	10.31	10.41	10.24	12.18
16 mil	12.66	11.10	10.90	10.96	10.86	10.78	10.74	10.69	10.68	10.62	10.63	10.61	10.60	10.55	10.51	10.49	10.49	10.44	10.44	7.57	7.01	10.42	10.42	10.13	12.16
20 mil	12.62	10.93	10.72	10.98	10.88	10.82	10.77	10.73	10.71	10.64	10.66	10.64	10.63	10.57	10.53	10.51	10.51	10.46	10.47	10.46	10.42	10.46	10.44	10.11	11.69
16 mil	12.70	10.94	10.76	10.88	10.77	10.74	10.23	10.61	9.74	10.67	10.55	10.53	10.53	10.48	10.44	10.44	10.43	10.40	10.39	10.38	10.38	10.38	10.36	10.17	11.87
20 mil	12.65	11.00	10.79	10.92	10.83	10.78	10.72	10.68	10.66	10.74	10.61	10.60	10.59	10.54	10.51	10.49	10.47	10.45	10.44	10.43	10.43	7.72	6.55	6.18	6.61
16 mil	12.66	11.19	11.02	11.00	10.89	10.83	10.78	10.73	10.70	9.86	10.65	10.64	10.63	10.58	10.54	10.53	10.51	10.49	10.48	10.46	10.47	10.46	10.44	10.33	12.46
20 mil	12.67	11.06	10.96	11.03	10.93	10.88	10.81	10.77	10.74	9.93	10.70	10.69	10.68	10.62	10.59	10.57	10.56	10.52	10.52	10.50	10.51	10.51	10.48	10.39	12.53
16 mil	12.65	11.05	10.88	10.84	10.75	10.69	10.63	10.59	10.57	9.92	10.52	10.52	10.51	10.46	10.43	10.41	10.38	7.13	10.36	6.92	10.35	6.75	6.54	6.24	12.46
20 mil	12.71	11.21	11.03	11.00	10.89	10.84	10.78	10.73	10.71	10.00	10.66	10.65	10.63	10.59	10.56	10.54	10.52	10.49	10.49	10.48	10.48	10.47	10.48	10.31	12.48
16 mil	12.69	10.96	10.80	10.78	10.69	10.65	10.60	10.57	10.55	9.93	10.51	10.50	10.50	10.45	10.42	10.39	10.38	10.37	10.35	10.34	10.35	10.35	10.31	10.27	12.50
20 mil	12.67	11.05	10.86	10.88	10.79	10.74	10.69	10.64	10.62	10.02	10.58	10.57	10.57	10.51	10.48	10.46	10.45	10.43	10.42	10.40	10.41	10.40	10.38	10.32	12.51

Figure 42: The Reflow Pathway Elimination Effect – After Reflow–1000 hrs -- (HF Material-M)



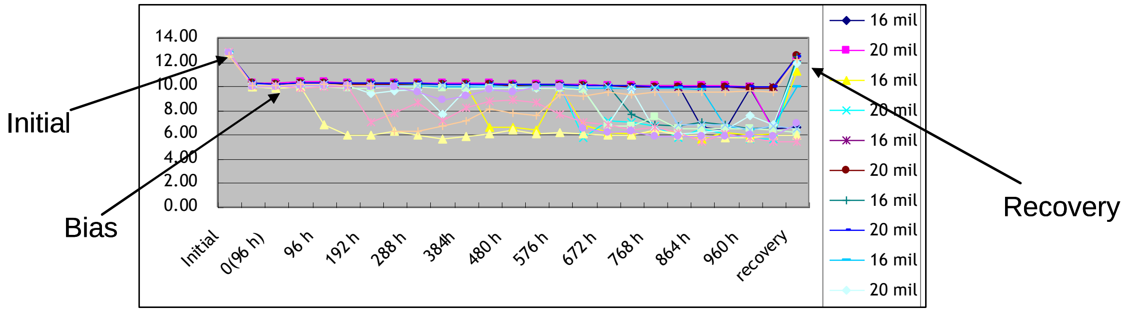
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.64	9.67	9.68	9.82	6.89	6.93	6.31	9.81	5.52	6.52	6.29	6.60	5.75	5.70	5.50	6.66	6.89	6.77	6.73	6.91	6.47	6.74	6.68	6.47	12.41
20 mil	12.72	9.84	9.78	9.91	9.90	9.89	9.90	9.91	9.90	9.87	9.70	9.67	9.79	9.68	9.79	9.80	9.74	9.75	6.88	7.14	9.69	6.52	9.70	9.70	12.49
16 mil	12.64	10.02	9.96	10.12	10.11	10.10	10.09	10.11	7.29	10.02	7.48	8.97	8.96	9.66	9.94	8.71	9.94	9.95	9.91	6.59	9.92	6.10	6.12	6.68	12.47
20 mil	12.67	10.09	10.01	10.15	10.13	10.11	10.11	10.11	10.09	6.78	9.83	8.78	6.91	6.57	9.95	6.60	7.20	7.42	6.77	5.73	6.07	6.06	5.90	5.94	6.02
16 mil	12.64	9.79	9.74	9.88	9.87	9.87	9.87	9.88	9.87	6.77	9.70	9.66	9.78	9.67	9.77	9.77	9.72	9.72	9.70	9.72	9.70	9.68	9.66	7.06	12.60
20 mil	12.72	9.88	9.83	9.97	9.96	9.96	9.93	9.95	9.93	9.88	9.75	9.73	9.83	9.73	9.81	9.82	9.77	9.77	9.74	9.75	9.74	9.72	9.70	9.72	12.54
16 mil	12.63	9.80	9.77	9.93	7.28	6.59	6.76	6.67	6.66	6.31	6.87	6.78	7.01	7.06	6.53	6.52	6.14	9.75	9.77	9.75	9.73	9.02	7.73	9.56	12.46
20 mil	12.63	9.82	9.80	10.01	10.00	9.98	9.99	10.03	9.94	10.00	9.87	9.80	7.99	9.78	8.50	6.67	6.46	6.91	6.62	6.36	6.52	9.78	7.29	9.05	12.56
16 mil	12.64	9.71	9.68	9.85	9.85	9.85	9.84	9.85	9.84	9.82	9.79	6.38	6.81	6.69	7.18	6.94	9.66	9.69	8.34	6.85	6.18	6.20	6.40	6.14	6.95
20 mil	12.67	9.62	9.60	9.81	9.81	9.82	9.81	9.82	9.81	8.42	9.65	8.67	7.57	6.73	6.56	6.35	7.02	6.64	5.98	7.05	6.03	6.36	6.77	6.60	6.72
16 mil	12.58	9.68	9.65	9.79	9.80	9.77	9.77	9.80	9.79	9.76	9.74	6.69	6.37	6.91	6.42	6.97	6.07	6.77	6.38	6.63	6.21	6.31	5.90	7.01	8.25
20 mil	12.64	9.63	9.59	9.73	6.10	6.60	5.96	6.26	5.96	6.12	5.70	5.69	6.09	5.81	5.57	5.35	5.32	5.95	5.73	5.79	5.84	6.18	6.35	9.28	12.35
16 mil	12.67	9.59	9.56	9.72	9.73	9.73	9.73	9.75	9.74	9.73	9.70	9.68	9.67	9.67	9.66	6.77	9.39	9.62	6.62	6.12	6.35	5.91	5.85	5.91	6.37
20 mil	12.72	9.68	9.65	9.79	9.79	9.81	9.80	9.81	9.81	9.79	9.77	9.75	9.72	9.73	9.73	9.66	8.61	6.69	9.66	9.68	9.67	9.63	9.64	9.64	12.51
16 mil	12.58	9.92	9.87	9.99	7.19	9.98	9.97	10.00	9.96	9.98	9.96	9.89	9.90	9.91	9.90	9.88	9.85	9.91	6.85	9.85	9.83	9.82	9.80	9.80	12.60
20 mil	12.66	9.95	9.91	10.01	9.99	9.99	7.06	6.56	6.45	6.46	6.52	6.55	6.57	6.83	9.88	6.38	7.20	6.56	6.32	9.78	6.43	7.87	7.82	6.95	12.60

Figure 43: The Reflow Pathway Elimination Effect – Before Reflow–1000 hrs -- (FR4 Material-C)



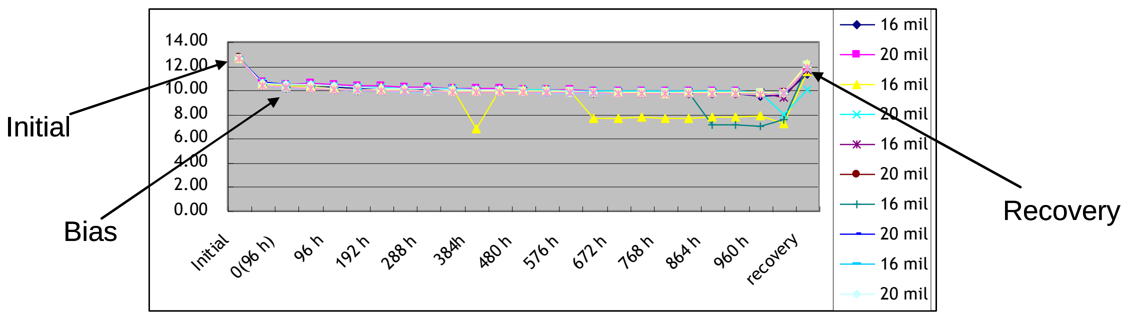
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	13.21	10.57	10.45	10.30	10.24	10.19	10.12	5.17	5.33	5.75	5.71	5.39	5.73	9.96	5.26	5.28	5.41	5.30	5.26	5.30	5.29	5.29	5.30	5.30	5.33
20 mil	13.21	10.61	10.46	10.38	10.29	10.23	10.18	10.06	10.13	10.00	10.07	10.05	9.98	10.00	9.94	9.95	9.88	9.93	9.86	9.63	9.91	9.87	9.32	9.85	12.07
16 mil	13.21	12.64	10.35	10.21	10.10	10.07	10.02	10.00	10.04	9.99	9.99	9.97	9.96	9.96	9.96	9.92	9.87	9.87	7.75	9.84	7.26	7.12	7.07	7.02	12.24
20 mil	13.21	12.71	10.43	10.34	10.24	10.19	10.16	10.08	10.11	10.02	10.06	10.03	10.01	10.00	9.97	9.93	9.93	9.91	9.97	9.91	9.92	9.90	9.96	9.88	12.12
16 mil	12.58	10.44	10.09	10.70	10.16	10.11	10.23	10.18	9.92	9.15	9.34	9.12	9.24	9.96	9.98	9.88	9.52	9.58	9.71	9.48	9.91	9.71	9.68	9.78	11.92
20 mil	12.71	10.54	10.75	10.71	10.26	10.22	10.23	10.11	10.06	10.14	10.13	10.03	10.02	10.00	9.94	9.97	9.94	9.84	9.69	9.80	10.03	9.84	9.85	9.85	11.80
16 mil	12.76	10.47	10.63	10.47	10.18	10.12	10.14	10.11	10.09	10.03	9.97	9.97	9.94	9.96	7.43	7.24	6.59	7.10	6.96	7.09	6.96	7.22	6.83	7.04	12.45
20 mil	12.83	10.62	10.32	10.25	10.34	10.29	10.26	10.23	10.22	10.11	10.17	10.10	10.09	10.00	10.05	10.03	10.15	9.94	9.78	10.00	10.16	9.95	9.95	9.94	12.33
16 mil	12.89	10.40	10.13	10.32	10.15	10.10	10.10	10.02	10.02	10.01	9.99	9.94	9.93	9.96	9.88	9.87	9.98	10.01	6.42	6.97	6.15	7.32	7.17	7.92	11.70
20 mil	12.91	10.52	10.55	10.33	10.23	10.18	10.17	10.09	10.10	10.07	10.01	10.00	9.99	10.00	9.95	9.90	9.87	9.81	10.02	9.87	7.68	9.59	9.57	9.57	12.13
16 mil	12.92	10.52	10.23	10.24	10.25	10.20	10.14	10.10	10.12	10.10	10.10	10.04	10.03	9.96	10.02	10.00	10.10	9.87	9.86	9.93	10.10	5.26	6.30	5.81	6.00
20 mil	12.95	10.53	10.55	10.22	10.28	10.22	10.19	10.18	10.15	10.06	10.11	10.05	10.04	10.00	10.04	9.99	9.89	10.10	10.18	9.93	10.02	9.91	9.87	9.91	12.12
16 mil	12.94	10.48	10.25	10.28	10.19	10.14	10.11	10.05	10.04	10.10	10.07	9.98	9.97	9.96	9.98	9.87	9.79	9.88	9.95	9.60	9.80	9.79	9.81	9.80	12.14
20 mil	12.89	10.48	10.34	10.30	10.26	10.20	10.19	10.14	10.11	10.09	10.05	10.03	10.00	10.00	9.96	9.92	9.81	9.88	9.90	9.66	9.90	9.84	9.85	9.85	12.13

Figure 44: The Reflow Pathway Elimination Effect – After Reflow–1000 hrs -- (FR4 Material-C)



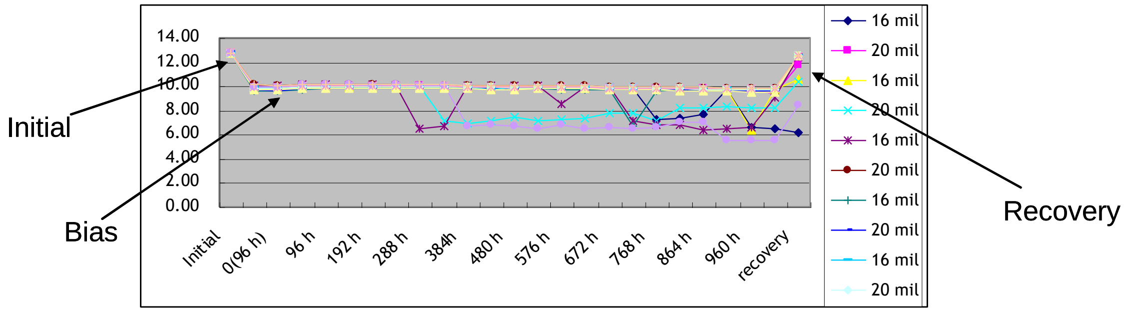
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.71	10.16	10.12	10.26	10.24	10.22	10.22	10.22	10.19	10.17	10.14	10.13	10.12	10.11	10.10	10.09	10.01	10.00	9.98	9.98	6.57	6.39	9.83	6.41	6.53
20 mil	12.74	10.24	10.19	10.31	10.29	10.28	10.26	10.26	10.24	10.21	10.19	10.18	10.16	10.14	10.14	10.13	10.05	10.04	10.01	10.01	10.01	9.97	9.96	6.35	12.42
16 mil	12.73	10.01	9.97	10.10	10.09	10.08	10.08	10.08	10.07	10.05	10.02	6.55	6.61	6.36	9.96	6.81	6.16	6.00	6.20	6.18	5.55	6.10	5.97	6.05	11.20
20 mil	12.74	9.95	9.98	10.12	10.11	10.10	10.10	10.10	10.09	10.07	10.04	10.05	10.01	9.98	10.01	5.67	7.09	7.02	6.73	5.67	6.45	6.05	5.61	5.65	12.28
16 mil	12.74	10.16	10.10	10.21	10.19	10.17	10.16	10.16	10.14	10.11	10.09	10.07	10.06	10.05	10.04	10.03	9.96	9.95	9.93	9.93	9.91	9.90	9.89	9.88	12.42
20 mil	12.74	10.19	10.12	10.22	10.19	10.17	10.17	10.16	10.14	10.12	10.09	10.07	10.05	10.04	10.03	10.02	9.94	9.93	9.91	9.90	9.89	9.88	9.85	9.85	12.47
16 mil	12.73	10.20	10.13	10.24	10.22	10.20	10.18	10.18	10.15	10.13	10.10	10.09	10.07	10.06	10.05	10.04	9.97	7.63	6.74	6.65	6.96	6.75	6.47	6.58	12.43
20 mil	12.75	10.20	10.15	10.25	10.23	10.22	10.20	10.20	10.18	10.15	10.12	10.11	10.09	10.08	10.07	10.06	9.99	9.97	9.93	9.94	9.93	9.91	9.87	9.88	12.42
16 mil	12.72	9.89	9.86	9.99	9.98	9.97	9.96	9.97	9.95	9.94	9.91	9.90	9.88	9.87	9.86	9.85	9.81	9.81	9.78	9.79	9.74	6.67	6.37	6.72	9.90
20 mil	12.70	9.93	9.89	10.00	10.00	9.99	9.39	9.63	9.64	7.61	9.66	9.75	9.75	9.76	9.75	9.74	6.82	9.71	6.38	6.01	6.13	6.35	7.52	6.80	11.86
16 mil	12.75	9.86	9.81	9.89	9.91	9.83	9.85	9.86	9.86	9.80	9.80	9.79	9.79	9.77	9.75	9.70	6.64	6.70	7.47	6.49	6.48	6.49	6.49	6.39	6.16
20 mil	12.73	9.90	9.85	9.93	6.74	5.91	5.92	6.24	5.97	5.55	5.83	6.05	6.33	6.06	6.09	6.08	5.96	5.90	6.31	5.97	5.90	5.76	5.71	5.94	5.93
16 mil	12.76	10.07	10.00	10.09	10.07	10.05	10.03	10.05	10.02	9.99	9.97	9.95	9.93	9.92	9.91	9.89	9.86	9.84	9.83	6.82	6.74	6.76	6.31	6.68	6.43
20 mil	12.81	10.05	9.98	9.80	9.92	9.96	7.03	7.77	8.59	7.09	8.16	8.69	8.81	8.60	7.67	7.02	6.81	6.38	6.59	6.18	5.41	6.01	5.66	5.43	5.43
16 mil	12.69	9.92	9.87	10.02	10.01	9.98	9.95	9.96	9.48	8.85	9.14	9.68	9.53	9.86	9.86	6.51	6.12	6.25	5.85	5.85	5.85	5.81	5.91	5.85	6.84
20 mil	12.51	10.03	9.98	10.09	10.08	10.06	10.04	6.22	6.24	6.68	7.10	8.12	7.73	7.56	9.23	9.20	9.46	9.27	9.45	9.48	9.48	9.53	9.54	9.51	12.13

Figure 45: The Reflow Pathway Elimination Effect – Before Reflow–1000 hrs -- (HF Material-K)



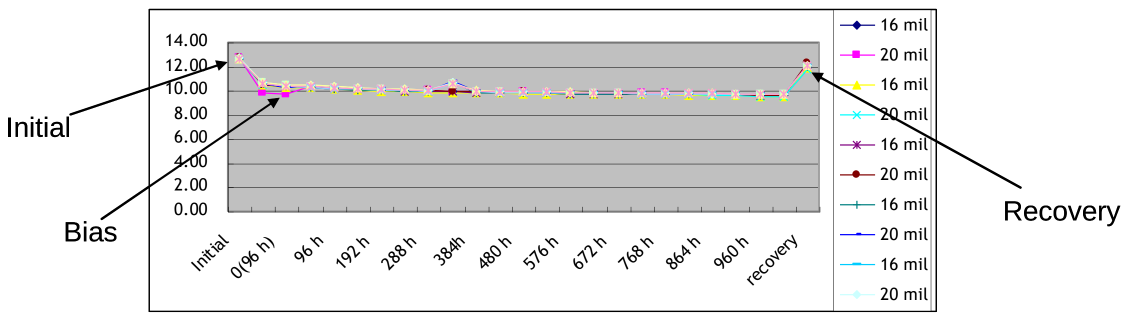
Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.65	10.47	10.21	10.31	10.23	10.16	10.12	10.08	10.05	10.01	9.98	9.97	9.94	9.86	9.87	9.88	9.79	9.79	9.68	9.69	9.71	9.68	9.53	9.61	11.36
20 mil	12.63	10.66	10.47	10.50	10.41	10.33	10.29	10.23	10.18	10.14	10.11	10.08	10.05	10.01	9.98	9.96	9.93	9.91	9.89	9.88	9.87	9.87	9.85	9.79	11.71
16 mil	12.58	10.52	10.36	10.38	10.29	10.23	10.18	10.15	10.10	10.07	6.77	10.03	10.01	9.97	9.95	7.65	7.65	7.70	7.69	7.67	7.76	7.79	7.81	7.18	11.47
20 mil	12.58	10.64	10.46	10.41	10.32	10.25	10.19	10.14	10.11	10.07	10.02	10.03	10.00	9.97	9.94	9.92	9.90	9.88	9.87	9.86	9.86	9.86	9.84	7.96	10.05
16 mil	12.59	10.33	10.15	10.10	10.03	9.95	9.94	9.92	9.90	9.88	9.87	9.86	9.87	9.85	9.75	9.71	9.80	9.72	9.69	9.77	9.78	9.79	9.78	9.36	11.65
20 mil	12.67	10.39	10.20	10.15	10.07	10.01	9.97	9.94	9.91	9.89	9.88	9.88	9.87	9.85	9.83	9.74	9.81	9.80	9.74	9.78	9.79	9.79	9.78	9.76	12.00
16 mil	12.68	10.40	10.22	10.19	10.11	10.06	10.02	9.98	9.96	9.93	9.92	9.90	9.90	9.88	9.86	9.77	9.82	9.82	9.75	9.79	7.14	7.09	7.04	7.50	11.90
20 mil	12.65	10.64	10.46	10.41	10.31	10.24	10.17	10.12	10.07	10.03	9.99	9.97	9.95	9.92	9.89	9.79	9.85	9.83	9.75	9.79	9.80	9.77	9.79	9.74	12.03
16 mil	12.63	10.39	10.22	10.18	10.09	10.05	10.02	9.97	9.95	9.93	9.91	9.90	9.90	9.88	9.85	9.76	9.82	9.80	9.74	9.78	9.79	9.79	9.78	9.75	12.03
20 mil	12.62	10.59	10.44	10.41	10.31	10.23	10.17	10.12	10.07	10.03	9.99	9.97	9.95	9.92	9.89	9.80	9.84	9.83	9.76	9.79	9.80	9.79	9.78	9.72	12.01
16 mil	12.64	10.30	10.12	10.09	10.03	9.99	9.96	9.94	9.93	9.91	9.91	9.90	9.90	9.88	9.87	9.78	9.85	9.84	9.77	9.81	9.83	9.83	9.82	9.74	12.04
20 mil	12.65	10.41	10.24	10.20	10.12	10.06	10.01	9.97	9.94	9.92	9.90	9.89	9.88	9.86	9.85	9.75	9.82	9.81	9.74	9.78	9.80	9.79	9.78	9.76	12.12
16 mil	12.63	10.35	10.14	10.08	9.99	9.94	9.89	9.85	9.83	9.80	9.79	9.77	9.77	9.74	9.73	9.72	9.71	9.69	9.69	9.68	9.68	9.68	9.60	9.82	11.72
20 mil	12.61	10.39	10.19	10.14	10.06	9.99	9.94	9.90	9.87	9.84	9.82	9.80	9.80	9.78	9.75	9.75	9.73	9.72	9.71	9.71	9.71	9.70	9.61	9.72	11.85

Figure 46: The Reflow Pathway Elimination Effect – After Reflow–1000 hrs -- (HF Material-K)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.68	9.89	9.84	9.94	9.94	9.94	9.94	9.95	9.94	9.92	9.90	9.89	9.88	9.87	9.87	9.86	9.81	9.80	7.23	7.32	7.65	9.74	6.54	6.50	6.10
20 mil	12.74	9.95	9.89	9.99	9.98	9.98	9.97	9.98	9.97	9.94	9.92	9.92	9.90	9.89	9.89	9.88	9.83	9.81	9.79	9.81	9.78	9.69	9.73	9.39	11.74
16 mil	12.73	9.96	9.90	9.99	9.98	9.96	9.95	9.96	9.95	9.89	9.89	9.89	9.87	9.86	9.85	9.84	9.79	9.78	9.76	9.76	9.74	9.72	6.33	9.66	10.55
20 mil	12.76	10.00	9.94	10.04	10.03	10.01	10.00	10.01	9.99	7.14	6.84	7.09	7.42	7.06	7.26	7.27	7.79	7.80	7.15	8.16	8.21	8.29	8.17	8.18	10.38
16 mil	12.75	10.04	9.99	10.08	10.07	10.06	10.07	10.06	6.46	6.68	10.00	9.98	9.98	9.97	8.51	9.96	9.90	7.11	6.81	6.82	6.39	6.41	6.55	9.09	12.40
20 mil	12.75	10.08	10.03	10.12	10.10	10.09	10.09	10.09	10.06	10.06	10.03	10.01	10.00	9.99	9.98	9.98	9.92	9.89	9.89	9.88	9.85	9.84	9.83	9.83	12.51
16 mil	12.69	9.60	9.59	9.73	9.75	9.76	9.77	9.80	9.79	9.78	9.76	9.75	9.75	9.75	9.74	9.74	9.67	6.63	9.63	9.64	9.61	9.61	9.59	9.59	12.46
20 mil	12.77	9.65	9.63	9.77	9.79	9.79	9.80	9.82	9.82	9.80	9.79	9.78	9.77	9.77	9.77	9.77	9.70	9.66	9.66	9.66	9.64	9.62	9.60	9.60	12.49
16 mil	12.75	9.88	9.85	9.95	9.96	9.95	9.95	9.97	9.96	9.94	9.92	9.70	9.90	9.89	9.88	9.88	9.82	9.80	9.78	9.78	9.77	9.75	9.73	9.73	12.47
20 mil	12.74	9.81	9.78	9.90	9.92	9.92	9.92	9.94	9.93	9.91	9.89	9.88	9.87	9.87	9.86	9.85	9.79	9.78	9.75	9.76	9.73	9.72	9.70	9.69	12.47
16 mil	12.72	9.69	9.75	9.85	9.89	9.89	9.90	9.92	9.91	9.89	9.87	9.86	9.85	9.85	9.85	9.84	9.78	9.77	9.74	9.75	9.73	9.71	9.69	9.68	12.44
20 mil	12.73	9.68	9.67	9.79	9.80	9.81	9.82	9.84	9.84	9.81	9.77	9.73	9.73	9.77	9.76	9.75	9.65	9.68	9.65	9.61	9.58	9.62	9.53	9.53	12.52
16 mil	12.66	9.93	9.90	10.00	10.00	10.00	10.00	10.02	10.01	9.99	9.96	9.94	9.91	9.91	9.91	9.91	9.87	9.86	9.84	9.84	9.82	9.80	9.79	9.79	12.47
20 mil	12.77	9.90	9.88	9.97	9.98	9.98	9.98	10.00	9.99	9.97	9.95	9.94	9.93	9.93	9.92	9.92	9.85	9.84	9.82	9.83	9.81	9.80	9.78	9.78	12.50
16 mil	12.70	9.91	9.92	10.08	10.08	10.07	10.06	10.07	10.05	10.05	6.68	6.80	6.70	6.41	6.78	6.51	6.56	6.41	6.57	6.96	6.99	5.53	5.53	5.47	8.40
20 mil	12.75	10.12	10.06	10.16	10.15	10.13	10.12	10.13	10.12	10.09	10.04	10.05	10.03	10.02	10.02	9.99	9.87	9.91	9.90	9.92	9.89	9.83	9.80	9.80	12.50

Figure 47: The Reflow Pathway Elimination Effect – Before Reflow–1000 hrs -- (HF Material-L)



Hole Spacing	Initial	48 h	0(96 h)	48 h	96 h	144 h	192 h	240 h	288 h	336 h	384h	432 h	480 h	528 h	576 h	624 h	672 h	720 h	768 h	816 h	864 h	912 h	960 h	1000 h	recovery
16 mil	12.63	10.54	10.34	10.27	10.17	10.08	10.03	9.97	9.93	9.89	9.86	9.84	9.81	9.79	9.76	9.75	9.74	9.70	9.70	9.70	9.69	9.69	9.58	9.57	11.81
20 mil	12.66	9.80	9.69	10.33	10.23	10.16	10.09	10.03	9.99	9.95	9.92	9.89	9.87	9.84	9.82	9.80	9.78	9.76	9.75	9.74	9.73	9.72	9.62	9.50	11.78
16 mil	12.64	10.49	10.27	10.19	10.08	10.01	9.94	9.89	9.85	9.81	9.78	9.76	9.74	9.72	9.70	9.68	9.66	9.65	9.64	9.63	9.62	9.61	9.51	9.44	11.89
20 mil	12.65	10.49	10.30	10.25	10.15	10.07	10.01	9.94	9.90	9.86	9.82	9.80	9.78	9.75	9.72	9.71	9.68	9.66	9.65	9.64	9.63	9.63	9.51	9.44	11.77
16 mil	12.65	10.57	10.36	10.28	10.17	10.09	10.02	9.96	9.91	9.88	9.84	9.82	9.80	9.77	9.73	9.73	9.71	9.67	9.67	9.66	9.66	9.65	9.55	9.66	12.03
20 mil	12.67	10.43	10.30	10.32	10.23	10.15	10.08	10.04	9.99	9.94	9.91	9.88	9.86	9.82	9.80	9.77	9.74	9.73	9.70	9.69	9.68	9.67	9.57	9.57	12.29
16 mil	12.76	10.53	10.32	10.24	10.13	10.05	9.99	9.93	9.89	10.68	9.83	9.81	9.79	9.77	9.74	9.73	9.71	9.70	9.68	9.67	9.67	9.66	9.65	9.66	11.99
20 mil	12.63	10.51	10.26	10.33	10.23	10.14	10.07	10.01	9.96	10.73	9.90	9.86	9.84	9.81	9.79	9.78	9.76	9.75	9.73	9.72	9.72	9.71	9.70	9.68	12.01
16 mil	12.65	10.60	10.39	10.30	10.19	10.11	10.04	9.98	9.95	10.54	9.88	9.86	9.84	9.82	9.79	9.77	9.75	9.74	9.72	9.72	9.71	9.70	9.69	9.68	12.01
20 mil	12.67	10.67	10.48	10.40	10.30	10.22	10.15	10.08	10.03	10.67	9.96	9.93	9.90	9.87	9.85	9.82	9.80	9.79	9.77	9.76	9.74	9.74	9.73	9.71	12.03
16 mil	12.62	10.64	10.43	10.34	10.23	10.14	10.07	10.01	9.96	10.53	9.89	9.86	9.85	9.82	9.80	9.77	9.75	9.74	9.72	9.71	9.70	9.69	9.69	9.67	11.95
20 mil	12.64	10.69	10.49	10.42	10.31	10.23	10.16	10.10	10.06	10.59	9.97	9.94	9.92	9.89	9.86	9.83	9.81	9.79	9.77	9.76	9.75	9.74	9.72	9.70	12.05
16 mil	12.64	10.52	10.33	10.28	10.17	10.10	10.04	9.99	9.94	10.59	9.88	9.85	9.84	9.81	9.79	9.77	9.75	9.74	9.72	9.71	9.71	9.70	9.68	9.65	12.02
20 mil	12.60	10.51	10.36	10.35	10.24	10.17	10.10	10.05	10.01	10.52	9.94	9.91	9.89	9.86	9.84	9.81	9.80	9.78	9.76	9.76	9.75	9.74	9.73	9.71	12.03

Figure 48: The Reflow Pathway Elimination Effect – After Reflow–1000 hrs -- (HF Material-L)

More Discussion on Pathway Elimination

It is apparent that at least 6X Reflow at 260°C can be good for the CAF end result. However, reflow can also be bad associated with material damage and its effects on long term reliability and thermal cycling in the application. It is also clear that a number of materials that can pass CAF Testing at 500 hours and some at 1000 hours with 6X Reflow at 260°C, but they cannot pass without reflow. Thus the question arises about the effect reflow (one or more) at some lower temperatures. Although this would not be an elegant solution to be reflowing boards as preconditioning before assembly, nonetheless it would be strategic to know if we could indeed obtain passing CAF results at lower reflow temperatures and cycles. This is a key question for assemblies soldered with SnPb at lower temperatures typically than used for Pb-free assembly or for board subjected to few numbers of thermal cycles.. Are these applications in trouble on CAF if all we do is build and submit to assembly?

It is necessary to know where all of this stands for different assembly conditions besides the classic 6X Reflow at 260°C peak temperatures. Additionally there is the challenge associated with compliant pin only, non-soldered, backplan assemblies previously addressed.

From a practical sense, most PCB fabricators do not have a reflow oven. They really have no option if it proves out that some degree of reflow is totally beneficial and enables a material to pass CAF or Ionic Migration requirements, as has demonstrated in the data presented. Will baking improve CAF resistance the way reflow does? For lead-free surface finishes such as Immersion Sn, Immersion Ag, Electroless Nickel/Immersion Gold (ENIG), and Organic Solder Preservatives (OSP), baking the finished PCB can ruin solderability. Thus if baking is to be considered, it has to be done at the right time in the PCB Fabrication process. First we must understand if baking can have a similar effect to reflow on CAF performance.

Thus with all the preceding discussion in mind, a reduced reflow and separate baking test was conducted with the few extra boards that were left over from this study. Some boards were first reflowed at the different conditions listed in Table 8 below. Then some boards were separately baked only at the single condition also listed in Table 8. All samples were then submitted to Microtek for CAF testing at 65°C/87%RH for 1000 hours at 100 volts. These final results of pass/fail are based on the previous criteria in this paper and are depicted below in Table 8. Those boxes in Table 8 that are highlighted in green showed significant improvement for CAF Testing and those highlighted in light brown essentially were determined as no significant effect. The sample (Sa) selection was limited, but an attempt was made to use all three types of materials (FR4, HF and Hi-Speed).

Table 8: Preliminary Results for Pathway Elimination by using Reduced Reflow Conditions and Baking separately

Pathway Elimination with Reflow--*Limited Sa Size*												
	1 X 220R		1 X 240R		1 X 260R		3 X 220R		3 X 240R		3 X 260R	
	Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons	
Material	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs
HiSpd-U	5/6	6/6	5/6	6/6	0/6	3/6	N/A	N/A	N/A	N/A	N/A	N/A
FR4-C	8/10	8/10	2/10	2/10	0/10	2/10	1/10	1/10	2/10	3/10	3/10	5/10
HF-M	2/6	3/6	0/6	2/6	1/6	3/6	2/6	3/6	0/4	0/4	1/4	2/4
HF-N	1/8	4/8	0/8	2/8	4/8	5/8	0/6	0/6	2/6	2/6	1/6	1/6
FR4-H	1/8	1/8	1/6	2/6	1/6	2/6	1/6	1/6	1/6	1/6	0/6	2/6
FR4-B	0/6	1/6	0/6	2/6	1/6	2/6	1/6	2/6	0/6	1/6	0/6	0/6

Pathway Elimination with Bake--*Limited Sa Size*				
	No Bake		Bake 4hrs @ 150C	
	Fails/coupons		Fails/coupons	
Material	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs
HF-N	4/4	4/4	0/3	0/3
HF-K	1/4	2/4	0/4	3/4
FR4-H	2/4	3/4	2/4	3/4
FR4-B	2/4	4/4	0/4	1/4

For results at 1X reflow, based on this data, and considering the one Hi-Speed material and one of the FR4 samples, it would appear that the 260°C temperature is critical and not the number of cycles.. For the two HF materials it would appear that a lower reflow temperature of 240°C is sufficient to improve CAF performance. For the remaining FR4 materials there appeared to be no significant effect. In looking at the 3X multiple reflows, it appears that again temperature is more significant than the number of reflow cycles. It is also worth noting that the higher temperature effect for reflow is indicative that moisture removal alone or in part is not a significant part of the Pathway Elimination process since a single reflow can effect a desired result. This is only a preliminary study and first attempt at exploring this phenomenon. The sample size was

very limited and more detailed trials need to be pursued with appropriate larger set of samples. However, these initial results appear to promising for Pathway Elimination from an empirical standpoint.
However, this may not be from a practical standpoint since very few PCB Fabricators have access to reflow machines. Reflow of non-soldered boards prior to assembly and an assembly location is not practical due to the potential surface finish degradation that can occur by reflow.

Baking is a much more practical solution for the PCB fabricator if done at the right time in the process to affect Pathway Elimination. However what temperature and time is required to be effective? The results in Table 8 for baking would indicate that 150°C shows some promising results as well as reflow. The question what does this mean relative to understanding the mechanism behind the improvement in CAF performance associated with reflow and possibly baking?. Thus baking like reflow will require a much more intensive study with many more samples coupled with different preconditioning followed by CAF testing.

Summary and Conclusions
Material suitability for CAF resistance has been presented for twenty-seven 20 layer builds with and without Pb-free 6X Reflow at 260°C. These builds included a broad spectrum of 20 different materials to represent the different classes of materials for selected FR4, Halogen-Free and High-Speed. Seven of the 27 builds incorporated a higher resin content of the same material and contained 106 glass constructions for cores only for study as well. Included were CAF testing results and FMA analysis to elucidate the potential mechanisms for CAF failure and success. Not only are CAF mechanisms discussed, but also internal Ionic Migration as part of the CAF process in expanding on the failure modes that are seen and relating this to particular PCB applications that cannot tolerate this phenomena.

Significant differences are observed for the before and after reflow CAF or IM results. It is clearly apparent that there are few material choices when CAF resistance is required in applications without reflow as Backpanels. Reflow improved the CAF test results for at least 11 of the 27 material builds. This is clearly identified after 500 hours of testing and is still noticeable after 1000 hours of testing. Pb-free reflow at 6x 260°C can greatly improve CAF performance, turning a failing material into a passing one. Conversely, Pb-free reflow can negatively affect CAF performance, turning a passing material into a failing one due to potential internal material damage.

Evaluation of materials for CAF performance both as built (no reflow) and after simulated assembly reflow is critical in understanding the true performance of the materials.

Pathways for DHW to DHW modes of CAF/IM failure have been demonstrated and are clearly present before Pb-free reflow. These pathways manifest themselves predominantly as resin/glass separations and are not hollow fibers nor are they now considered by the authors as moisture problems. There are also clear signs of incomplete wetting of the resin to glass interfaces. These are probably due to inadequate initial coating of the resin to the glass. In some cases, the pathways are very large and can be observed as macroscopic voiding of the resin around the glass or in between multiple glass fibers in what is known as triple point de-wetting. There is also microscopic separation of the resin from the glass observed as part of and with the CAF growth mechanism

Unexpected results of the 106 Glass Effect, the Low Bulk Resistivity Effect and the Reflow Pathway Elimination Effect are reported, discussed and appropriate mechanisms proposed. However, solutions to these problems in some cases are going to take detailed further investigation.

High speed materials appear to have more problems than the classic FR4 or Halogen-Free materials and that may attributable to simply that they are not as mature a material class as the others at this point in time. Alternatively, it may be a direct result of the flow and wetting characteristics of these materials.

CAF/IM is a very complex issue as demonstrated. To understand material suitability for a specific application, the only real answer is extensive and in-depth testing.

Acknowledgements
Special thanks to Bob Neves and his staff at Microtek Laboratories for all sample preparation and CAF testing including all FMA analysis. Also special thanks to Zhou Jing of Viasystems for all the remaining CAF FMA analysis including many X-sections, subsequent metallography and SEM work.

References:
[1] Smetana, Joe, Sack, Thilo, Rotschild, Wayne, Birch, Bill, and Morton, Kim, “Bare Board Material Performance after Pb-free Reflow”, IPC/APEX, Las Vegas, NV, 2009.

[2] W Rothschild and J Kuczynski, "Lessons Learned About Laminates during Migration to Lead-free Soldering," S30-1, Proceedings of IPC Expo 2007. Reproduced (without references) in OnBoard Technology, November 2007
[3] G Tennant, M Kelly, W Rothschild and A Khan, "Lead-free Laminates: Surviving Assembly & Rework Processes to Deliver High Quality and High Reliability Products," CMAP Lead-free Conference 2005
[4] Joe Smetana, Ken Ogle, Bob Sullivan, "Via (Plated Through Hole) Integrity with Lead-Free Soldering", Proceedings of IPC/APEX, February 2006.
[5] Joe Smetana, "Plated Through Hole Reliability with High Temperature Lead Free Soldering", The Board Authority, Volume 4, Number 1, April 2002, pp. 50-64
[6] Birch, B., Furlong, J. "Electrically Quantifying Material Damage Through Assembly and Validating PWB Product Construction", IPC/APEX, Las Vegas NV, 2011
[7] K.T. Knadle and M.G. Ferrill, Failure of Thick Board Plated Through Vias with Multiple Assembly Cycles, The Hidden BGA Threat, Proceedings of Surface Mount International Conference, April 1997, pp. 109-115.
[8] Lando, D.J., Mitchell, J.P., Welsher, T.L., "Conductive Anodic Filaments in Reinforced Polymer Dielectrics: Formation and Prevention", 17th Annual Proceedings of Reliability Physics, vol. 17 (1979) no. -, pp. 61-63
[9] Smetana, J., Birch, B, Sack, T., Morton, K., Yu, M., Katzko, C., Helminen, E., "Reliability Testing of Pb-Free PWB Plated Through Holes in Air-to-Air Thermal Cycling and Interconnect Stress Testing", IPC/APEX, Las Vegas NV, 2011.

Appendix I

Detailed CAF Sample Preparation and Testing Procedure at Microtek

MICROTEK(CHANGZHOU) LABORATORIES

Conductive Anodic Filament

TEST SPECIMEN

CAF Test Coupon

REFERENCE

IPC-TM-650, Method 2.6.25 and Customer Master Drawing

REQUIREMENT

Data Handling & Analysis
Lognormal plots are recommended for plotting percent of samples above an insulation resistance value, versus insulation resistance. Use the log value of the insulation resistance.

Visual Examination
After completion of the test, the test boards shall be removed from the environmental chamber and examined at 10X magnification for evidence of surface insulation resistance failure (i.e., discoloration, corrosion), handling or processing defects other than CAF.

Assignable Cause
Where an assignable cause of low insulation resistance can be properly attributed to a handling or processing defect other than CAF (IE: contamination on the insulating surface of the board, scratches, cracks, or other obvious damage affecting the insulation resistance between the conductors), then such a value should be excluded.

Sample Identification
Use a method for identifying each test board that does not cause contamination, such as a scribe, making marks away from the biased area(s) of the specimen. Test boards shall be handled by the edges of the board only, and the use of non-contaminating gloves is recommended.

Pre-screen for Opens and Shorts
Perform as-received insulation resistance measurements using a multimeter to make connection to each net, and check for gross defects. Check for shorts at 1.0 megohms setting, and no opens in connected nets are allowed.

Cleaning
Entirely clean each sample (CAF test board) per IPC-TM-650; method 2.3.25 (Resistivity of Solvent Extract) by immersion washing until the level of ionic contamination is reduced to less than 1.0 ugNaCl/cm^2 and for a maximum of 20 minutes. Board not achieving this level of cleanliness within 20 minutes shall be scrapped for the purposes of this test.

Connecting Wire
Plated through holes near one edge of the board may be used for connecting wires to each test circuit. Cover the test board with non-contaminating film to prevent flux spattering during the wire attaches process. After stripping back the wire insulation, use water white rosin (per J-STD-004, Type B) and best soldering technique (per J-STD-001, Class 1 or 2) to solder (per J-STD-006, Type Sn63) PTFE or PFE insulated wires to the connection points on each test board. Ensure against damaging PWB laminate material adjacent to the plated holes during soldering, soldering by using appropriate time/temperature parameters for the soldering iron.

Conductive Anodic Filament

TEST SPECIMEN

CAF Test Coupon

REFERENCE

IPC-TM-650, Method 2.6.25 and Customer Master Drawing

REQUIREMENT

Data Handling & Analysis

Lognormal plots are recommended for plotting percent of samples above an insulation resistance value, versus insulation resistance. Use the log value of the insulation resistance.

Visual Examination

After completion of the test, the test boards shall be removed from the environmental chamber and examined at 10X magnification for evidence of surface insulation resistance failure (i.e., discoloration, corrosion), handling or processing defects other than CAF.

Assignable Cause

Where an assignable cause of low insulation resistance can be properly attributed to a handling or processing defect other than CAF (IE: contamination on the insulating surface of the board, scratches, cracks, or other obvious damage affecting the insulation resistance between the conductors), then such a value should be excluded.

Sample Identification

Use a method for identifying each test board that does not cause contamination, such as a scribe, making marks away from the biased area(s) of the specimen. Test boards shall be handled by the edges of the board only, and the use of non-contaminating gloves is recommended.

Pre-screen for Opens and Shorts

Perform as-received insulation resistance measurements using a multimeter to make connection to each net, and check for gross defects. Check for shorts at 1.0 megohms setting, and no opens in connected nets are allowed.

Cleaning

Entirely clean each sample (CAF test board) per IPC-TM-650; method 2.3.25 (Resistivity of Solvent Extract) by immersion washing until the level of ionic contamination is reduced to less than 1.0 ugNaCl/cm^2 and for a maximum of 20 minutes. Board not achieving this level of cleanliness within 20 minutes shall be scrapped for the purposes of this test.

Connecting Wire

Plated through holes near one edge of the board may be used for connecting wires to each test circuit. Cover the test board with non-contaminating film to prevent flux spattering during the wire attaches process. After stripping back the wire insulation, use water white rosin (per J-STD-004, Type B) and best soldering technique (per J-STD-001, Class 1 or 2) to solder (per J-STD-006, Type Sn63) PTFE or PFE insulated wires to the connection points on each test board. Ensure against damaging PWB laminate material adjacent to the plated holes during soldering, soldering by using appropriate time/temperature parameters for the soldering iron.

Conductive Anodic Filament

METHOD

Cleaning after Attachment

Perform appropriate local cleaning and rinsing after the attachment of the connecting wires. (This is not a no-clean flux operation). Isolation resistance between connecting wire attachement sites should remain excellent through 96 hours conditioning. Note: Each CAF test failure that does occur during subsequent testing should be checked to determine whether the connecting wires attach area is the low resistance site. If the connecting wires attach area rather than the daisy chain area is the low insulation resistance site, then that test sample is no longer valid for data analysis.

Dry

Bake sample boards for six hours in clean oven at 105° ± 2°C (221.0 ± 3.6°F), than recovery at the specified 23 ± 2°C (73.4 ± 3.6°F) with 50 ± 5% relative humidity at least 24 hours.

Placing in Temperature/Humidity/Bias (T/H/B) Chamber

Place the specimens in the environmental test chamber in a vertical position such that the air flow is parallel to the direction of all test boards in the chamber. Allow at least 2.5 cm (1 inch) between each test board. Place the test boards as much as possible towards the center of the chamber to help ensure against non-optimum air flow and/or drops of condensation falling onto the test boards. Dress all wiring away from the test patterns, keeping the wires away from the test patterns as they are routed to the outside of the chamber. Also, wire should not impede airflow around the samples. Set the chamber temperature and humidity with a ramp rate of one hour.

Resistance Measurements

Measure the insulation resistance of each test board daisy-chain net using 100 VDC per second rate of rise and minimum hold time of 60 seconds at 100 VDC test voltage. The polarity of the bias (conditioning) voltage and the polarity of the test (measurement) voltage must always be the same. 100 VDC applied voltage is used as the test voltage for insulation resistance measurements.

After initial insulation resistance measurements are taken, close the environmental test chamber and allow the test boards to stabilize for 96 hours (± 30 minutes) at the specified 65 ℃ [149℉] with 87 % relative humidity and no bias applied. After the 96 hour (± 30 minutes) stabilization period, insulation resistance measurements shall be made between each daisy chain net and ground. Resistance monitoring measurements shall be taken every 48 hours for first 96 hours without bias, and every 48 hours to 1000 hours of bias (conditioning) voltage during the duration of the test, ensuring that the polarity of the insulation measurement voltage and the bias voltage are always the same.

After 1000 hours of applied bias, again perform the resistance measurements as before.

Suspect CAF test failures may be checked to determine whether the connecting wire attached area is the low resistance site rather than the daisy-chain area. This requires cutting the trace near the daisy chain (destructive). After all testing is completed, if the connecting wire attached area rather than the daisy chain area is then found to be the low insulation resistance site, then that test sample is no longer valid for data analysis.

The Effects of Lead-Free Reflow On Conductive Anodic Filament (CAF) Performance of Materials

(April 13, 2011)

Kim L Morton (Viasystems)
Joe Smetana (ALU)
Gordon Qin (Viasystems)

Agenda

Results of CAF Testing 20 Materials / 27 Builds with and without Lead-Free Reflow at 6X 260C

1) CAF Mechanisms
2) Testing Criteria for Pass vs Fail ➔ Potential Applications Affected
3) Material sets Tested ➔ TV + Conditions Used + Preconditioning
4) General Results
    a) Before / After Reflow 500 hrs
    b) Before / After Reflow 1000 hrs
    c) FMA of CAF / EM failures
5) Unexpected Results
    a) The 106 glass effect
    b) Bulk Resistivity effect
    c) After Reflow ➔ Beneficial?
6) Summary and Conclusions

What exactly is CAF?

Conductive Anodic Filament

CAF → **Formation of Solid Cu Filament** between different nets within PCB at different potentials → follows a glass weave pathway internally in the PCB → acts as dead short → *then possibly the fire*

CAF → **Multiple step Process** (PCB Internally)

1) Pathway Formation between different PCB Nets internally
   a) Separation of glass/resin interface
      - Incomplete wetting of initial coating of resin to glass
      - PCB / PCBA Fabrication (Therm / Mech / Chem)
   b) Degradation of glass/resin bond – Temp/Humidity
   c) Can be Hollow Fiber
2) Ionic Electromigration (IM) down a Pathway → *Anode to Cathode*
3) Growth of Solid Cu Filament → *Cathode to Anode*

CAF Failure → can occur before solid Cu filament formation

Electromigration (IM) → can lead to catastrophic drops in resistance

What exactly is Electromigration (IM) for CAF?

1) Electromigration of e^- and Ions under the influence of applied voltage ➔ *(PCB Internally)*

2) Electromigration of e^- and Ions Between Vias (*HW-HW*)
   a) In 2 different electrical nets
   b) At different potentials (one hole relative to the other)

3) Must be a electrical pathway between hole pairs
   a) not the pure resin
   b) but at the glass/resin interface or Hollow-Fiber (microscopic)
   c) resin holes between the glass filaments (macroscopic)

Incomplete Resin wetting ➔ Triple Point

Elements Needed for *CAF* / *IM* Failure

Pathway

I - *Separation of Glass Fiber / Epoxy Interface*

Material Fabrication ➔ Incomplete wetting glass/resin

PCB + PCBA Fabrication ➔ Therm / Mech / Chem Stresses

Degradation of Glass/Resin Bond (Temp / Humidity)

II - *Hollow Glass Fiber? ➔ Today much better*

Moisture

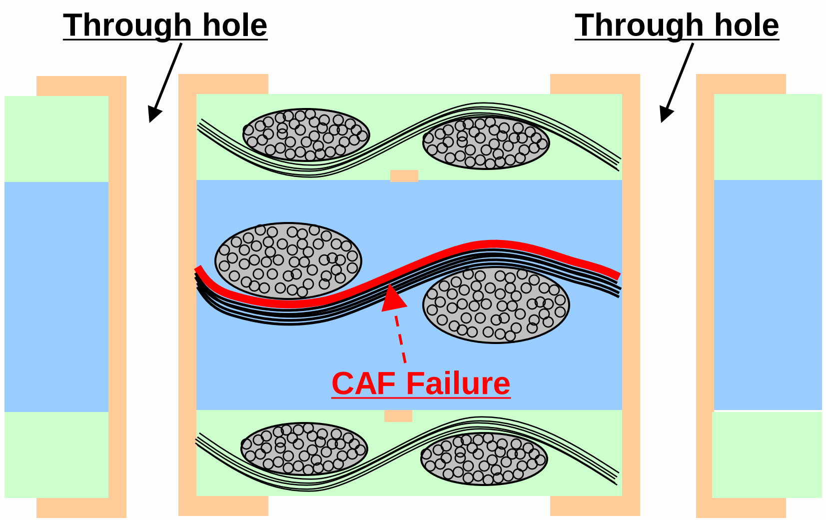
PCB + PCBA Fabrication

Final Part Field Operation

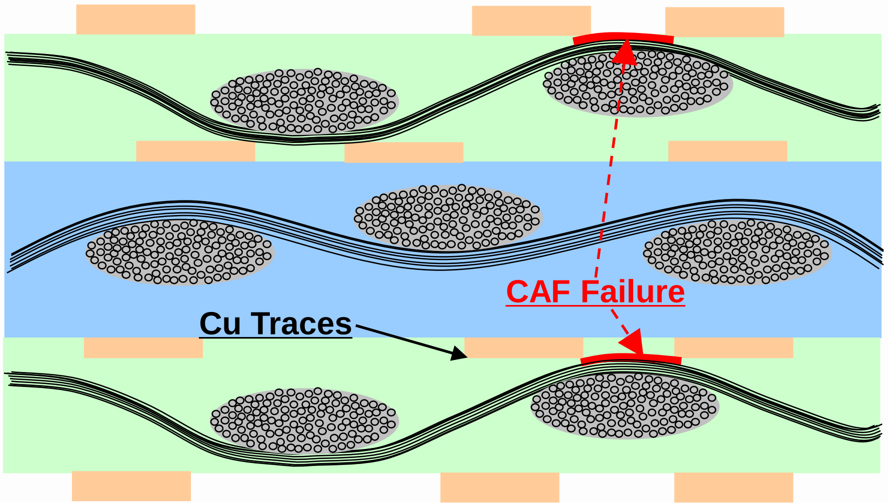
Applied Bias Voltage

Operation of Final Part (between Different Nets at Different Potentials)

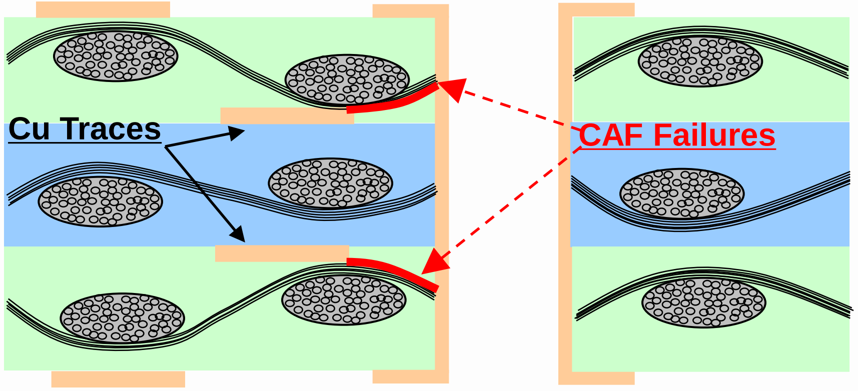
4 Potential modes of CAF / IM failure
(3 can be Prevented by use of correct Buttercoats)



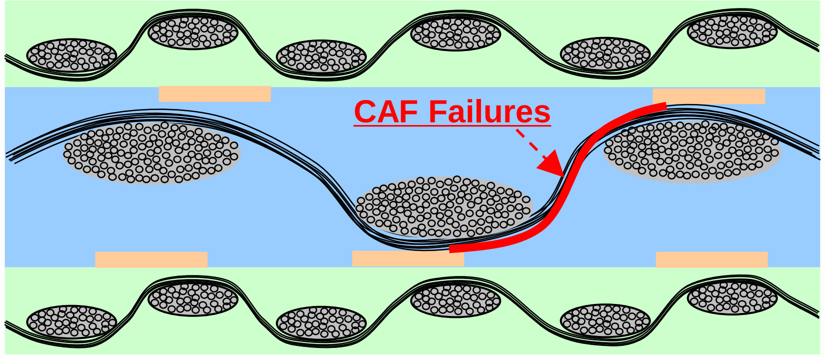
Through hole to through hole



Trace to Trace



Hole Wall to Trace

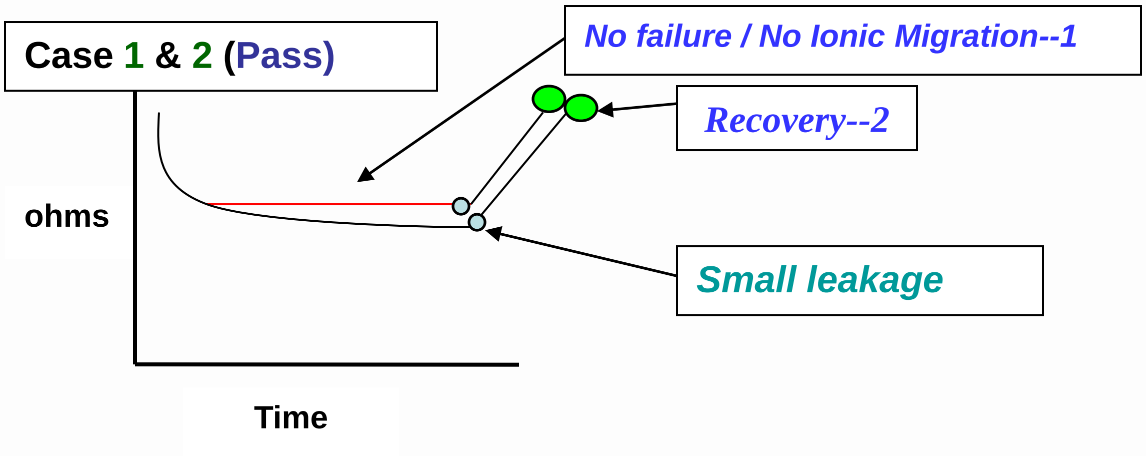


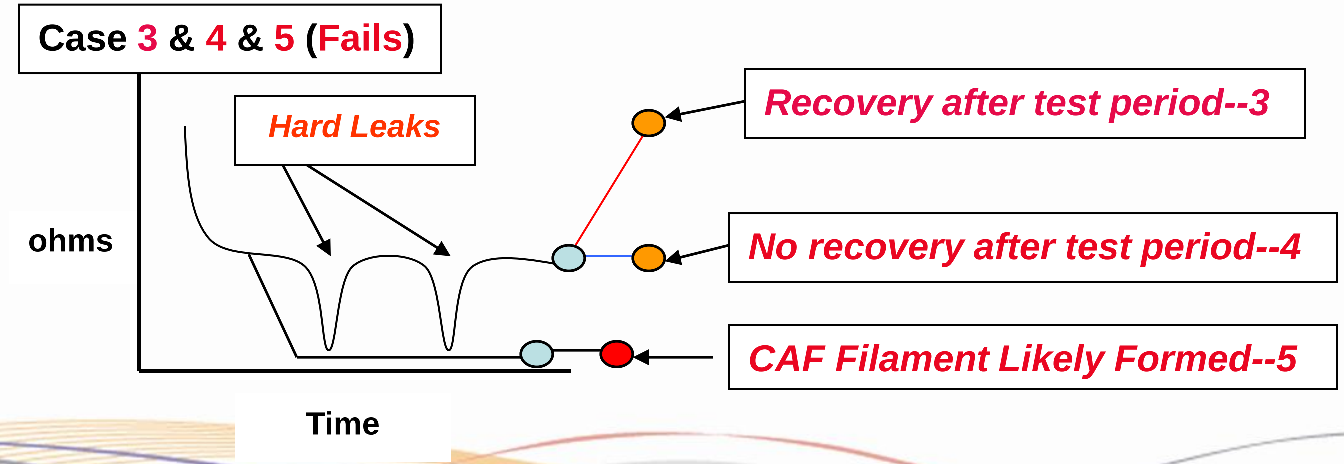
Layer to Layer

CAF / IM Testing

Pass vs Fail

Graphical View of CAF Testing Success vs Failure (Resistance vs Time and Leakages)





Failure Focus

Electromigration Focus (*Not just CAF*)

Hard Leak ➔ Resistance drop < 10 megohms or ~ 4 decades (>1 Time Interval)

Typical Measurement Time Interval ➔ every 48 hrs

Soft Leak ➔ Resistance drop > 1-2 decades below IR1 (> 1 Time Interval)

Passing Protocol

Generally for This Study

No Hard / Soft Leaks for 500 hrs at 100V Bias Condition

Sometimes judgment call for Soft Leaks

Mean Time Failure (MTF)

Estimated at 7-13 yrs for 10-5V Field Applications

Mild Temp and Humidity Exposures

Telecommunications or Light Automotive Industry

However for Some Customer Applications

Insist on absolutely No Failure Leaks for 500 hrs @ 100V

Insist on No Failure Leaks for 1000 hrs @ 100V

Potential Applications Susceptible To Electromigration Failure (Hard Leaks)

Automotive Industry

a) Brake Controllers
b) Other Controllers

Telecommunications Industry

a) Any circuit with a high impedance ➔ radically affected
b) Phase Locked Loops (control of the system clocks)
c) Analog and RF circuits

Other Industries

A-D and D-A converters

Don't need to have The Fire from a CAF Cu Short before you get into trouble

General CAF Testing Protocol

Materials

20 Different Materials

27 Different Builds ***(7 with Hi-Resin Content or 106 glass)***

Viasystems -- Meadville -- Multek

8 FR4 Hi-Tg, Filled Phenolics (2 with HR or 106 cores only)

6 Halogen-Free (2 with HR or 106 cores only)

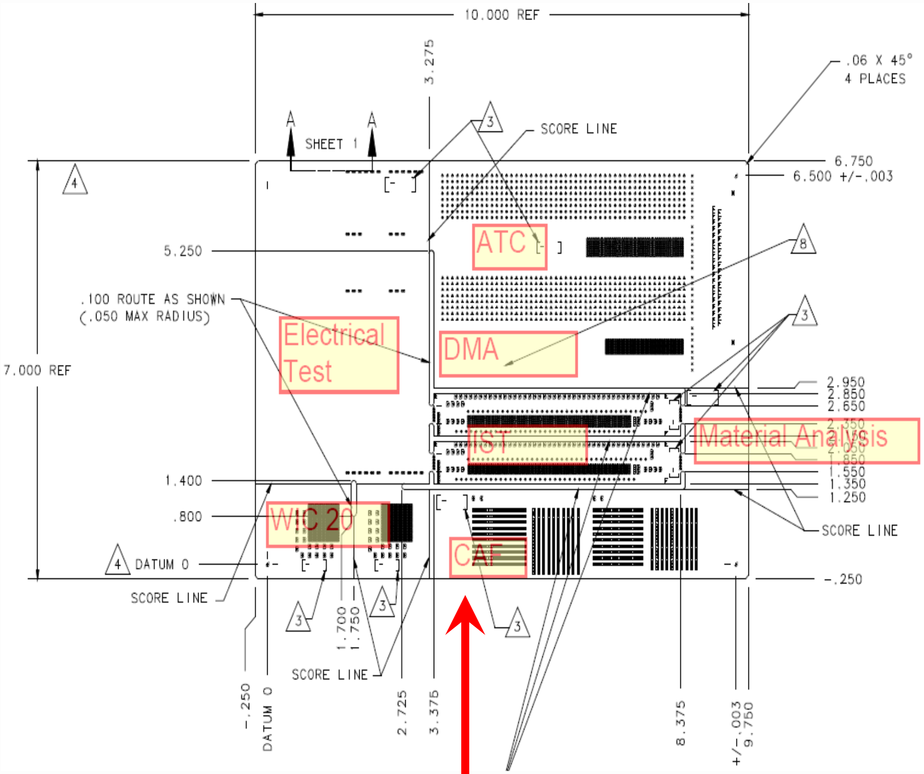
6 Hi-speed (3 with HR or 106 cores only)

CAF Coupons & Testing Conditions (20L HDPUG CAF TV)

16 and 20 mil DHW to DHW with 35 mil DHS (190 hole prs X and Y)
With and without 6X 260C Reflow preconditioning
65C / 87% RH Chamber condition
96 hrs non-bias + 1000 hrs with 100V bias
100V testing at 48hr increments for ~ 1 min
IPC Preparation Methods otherwise
ImAg surface finish

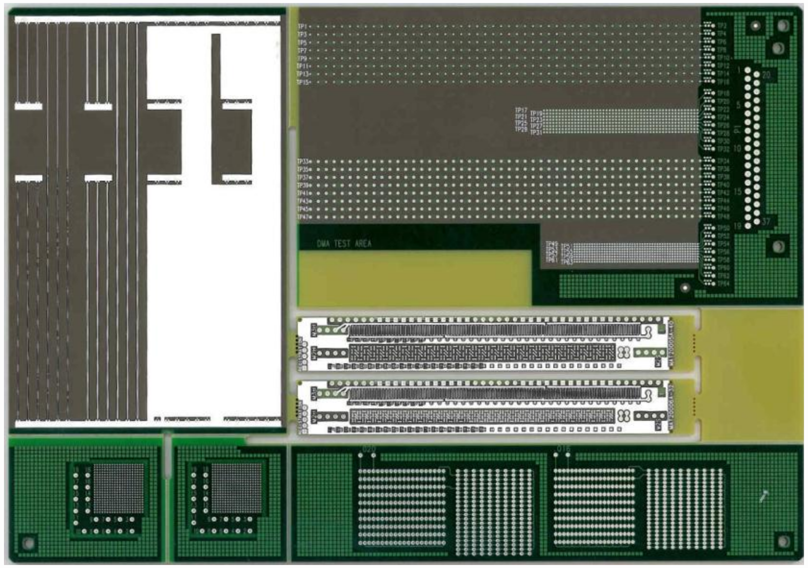
Big Acknowledgement to Microtek for all Sa Prep and CAF Testing

MRT3 Test Vehicle Sections



7 sections
On new Test Vehicle MRT3

Full Test Vehicle Below



CAF Coupons

Brief Summary of CAF Testing Results

Before Reflow (500 hrs)

- ***2/27*** **Builds passes 16 mils (1 HF, 1 HiSpd)**
- ***6/27*** **Builds passes 20 mils (2 FR4, 2 HF, 2 HiSpd)**
  - ***7/8 above fail 20 mils After Reflow at 500 hrs (Material Damage)***
  - ***8/8 above fail 20 mils After Reflow at 1000 hrs (Material Damage)***

Before Reflow (1000 hrs)

- ***0/27*** **Builds pass 16 mils**
- ***4 of same 6/27*** **Builds above pass 20 mils (1 FR4, 1 HF, 2 HiSpd)**
  - ***All 4 above fail 20 mils After Reflow at 1000 hrs (Material Damage)***

~~~~~~

After Reflow (500 hrs)

- ***5/27*** **Builds passes 16 mils (2 FR4, 2 HF, 1 HiSpd)**
- ***11/27*** **Builds passes 20 mils (6 FR4, 4 HF, 1 HiSpd)**

After Reflow (1000 hrs)

- ***2/27*** **Builds passes 16 mils (1 HF, 1 HiSpd)**
- ***4/27*** **Builds passes 20 mils (2 FR4, 2 HF)**
~~~~~~

CAF failures at 500 and 1000 hours

Tes Vehicle information			Visual Delam after 6X Reflow	Failures Before 500 Hours				Failures Before 1000 Hours			
APEX Coding	Stackup	Resin Content (%)		16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R	16 mil HW-HW BR	16 mil HW-HW 6X R	20 mil HW-HW BR	20 mil HW-HW 6X R
A	A	58	No	1_480	2	1_480	No	Many	Many	2	2
B	B	69	No	1_432	No	1_432	No	Many	Many	Many	No
C	A	58	No	Many	1_240	Many	No	Many	Many	Many	1_864
D	A	58	No	1_336	Many	Many	No	Many	Many	Many	Many
E	A	58	No	Many	Many	Many	Many	Many	Many	Many	Many
F	A	58	No	2	1_480	No	1_336	2	2	No	Few
G	B	69	No	1_192	No	2	No	3	1_624	3	No
H	A	58	No	Many	Many	Many	1_288	Many	Many	Many	Many
I	A	58	No	Many	Many	Many	2	Many	Many	Many	3
J	A	58	No	3	2	No	No	4	3	1_816	3
K	A	58	No	2	1_384	Many	No	Many	2	Many	1_1000
L	B	69	No	2	No	1_336	No	Many	No	1_336	No
M	A	58	No	Many	No	Many	No	Many	Many	Many	2
N	B	69	No	Many	2	Many	No	Many	Many	Many	No
O	A	58	No	1--> 10E8	1-->10E9	No	1_192	1--> 10E8	1-->10E9	No	1_192
P	A	58	No	Many	Many	Many	Many	Many	Many	Many	Many
Q	A	58	No	No	1_48	No	_144(10E8-	Many	2	2	2 (10E8+)
R	A	58	No	Many	Many	Many	Many(10E9	Many	Many	Many	3
S	A	58	No	1_432	No	1_480	No	1	No	1_480	1_672
T	B	69	No	Many	Many	Many	Many	Many	Many	Many	Many
U	A	58	No	Many	Low R	Many	Low R	Many	Low R	Many	Low R
V	A	58	Yes	No	Many	No	1_480	Many	Many	No	Many
W	B	69	Yes	Many	Many	No	Many	Many	Many	No	Many
X	A	58	No	Many	Many	2	Many	Many	Many	Many	Many
Y	A	58	No	Many	Many	Many	No	Many	Many	Many	2
Z	B	69	No	Many	Many	Many	Many	Many	Many	Many	Many
AA	A	58	No	Many	Many	2	2	Many	Many	3	2

Typical CAF Testing Data

Examples of

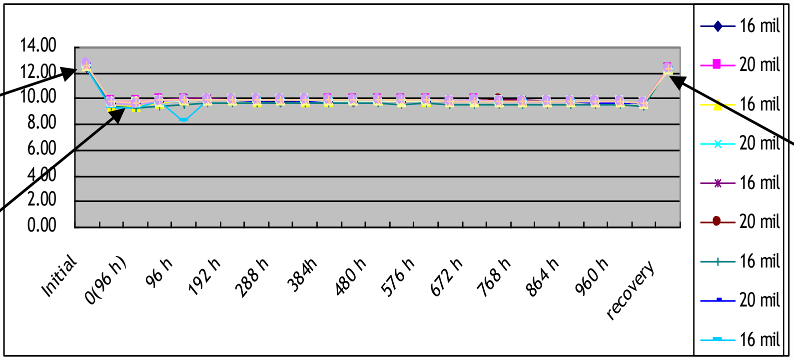
Hard and Soft Leaks

Before Reflow
And
After Reflow

Typical CAF / IM Data at 1000 hrs - Before Reflow
(*Same True* for *After Reflow*)

Initial

Bias



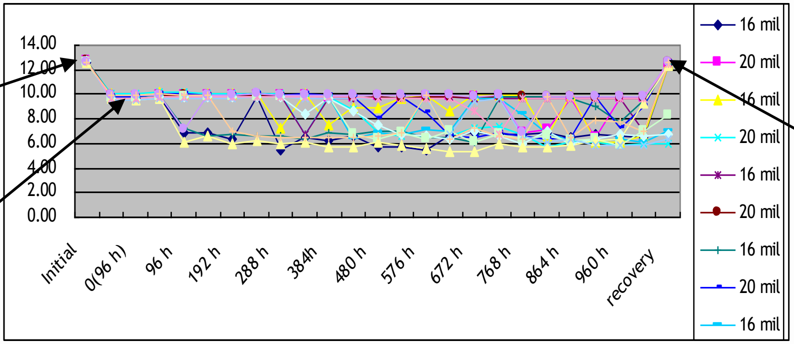
Recovery

Material HF-O

No Hard Leaks

Initial

Bias



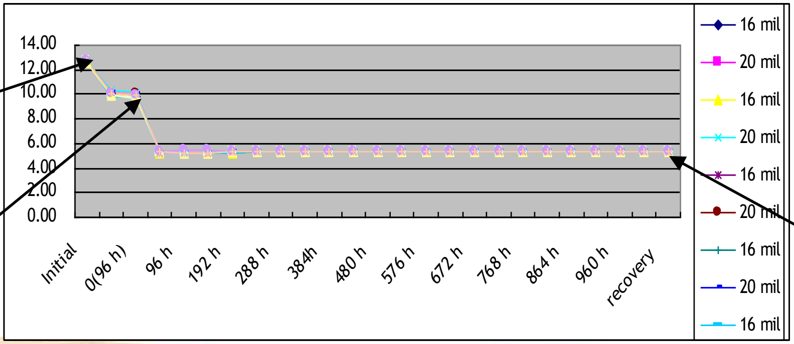
Recovery

Material FR4-C

Lots Hard Leaks

Initial

Bias



No Recovery

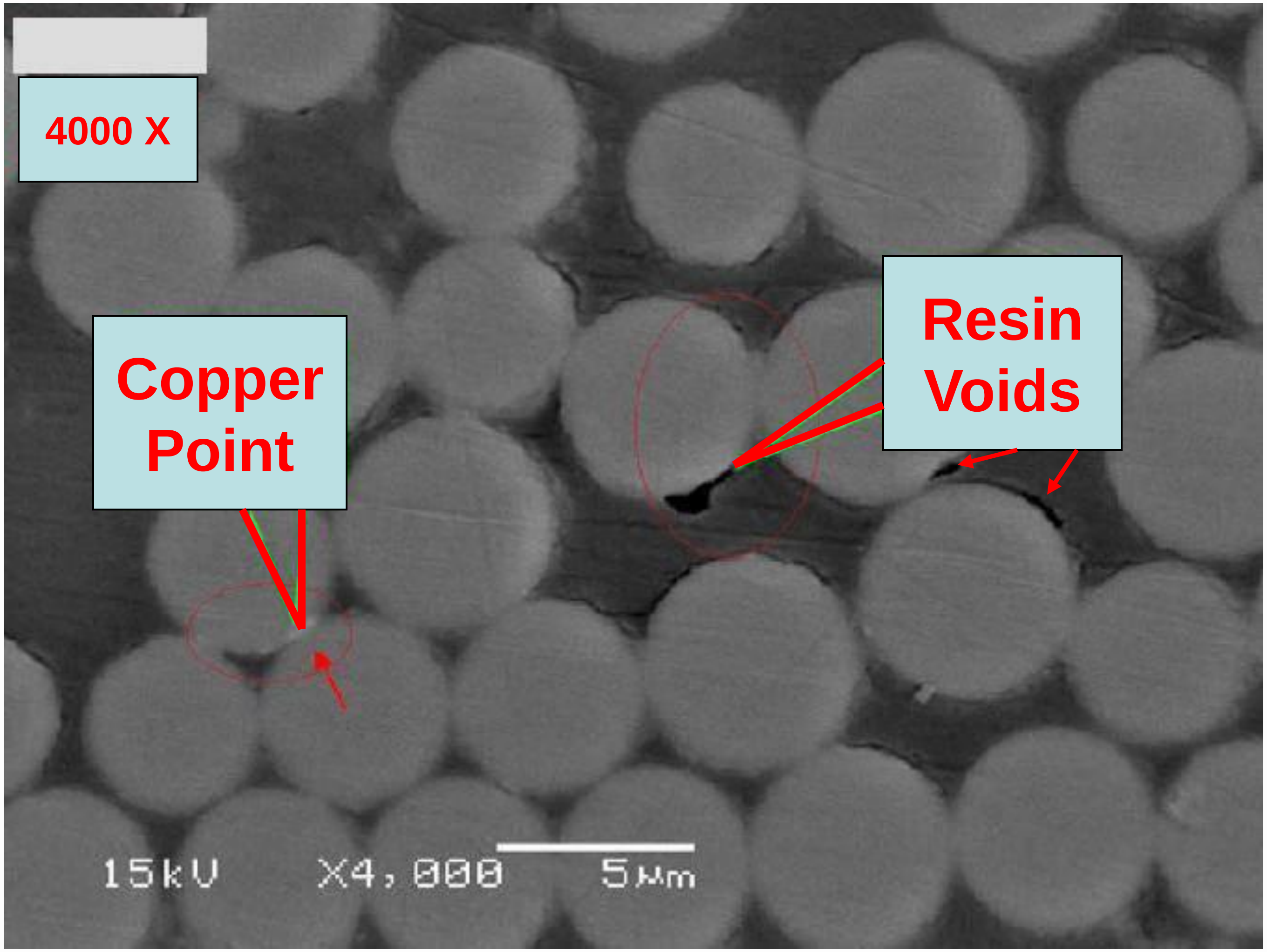
Material FR4-E

All Hard Leaks

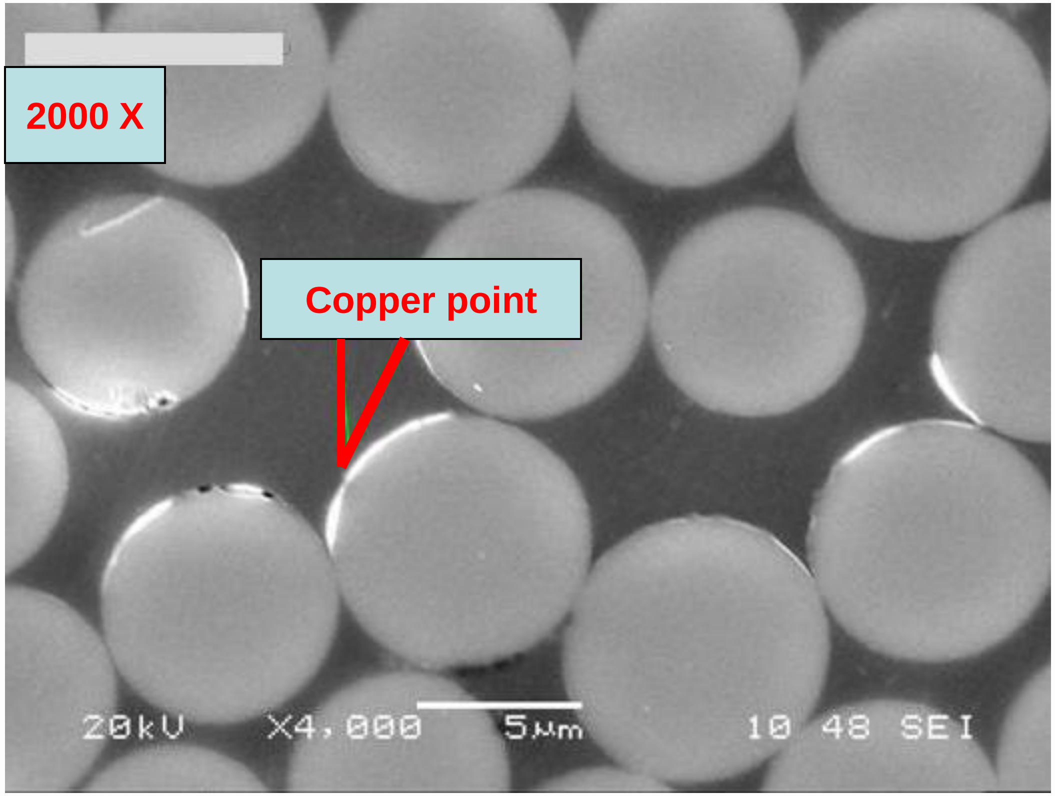
Typical FMA Examples of CAF Failures

Before Reflow

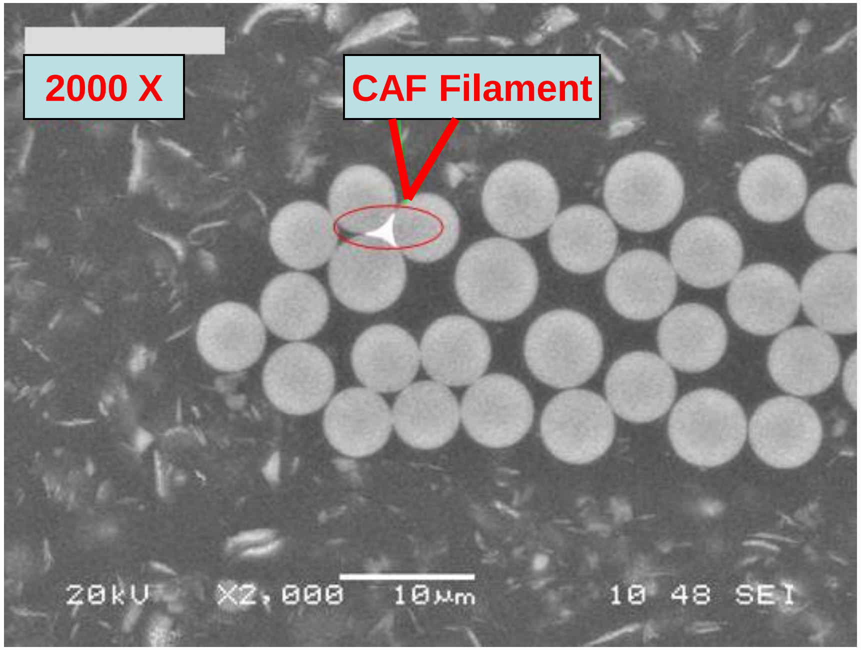
Typical Examples of CAF Failures
FMA X-sect Picture by SEM - (HiSpd-U)

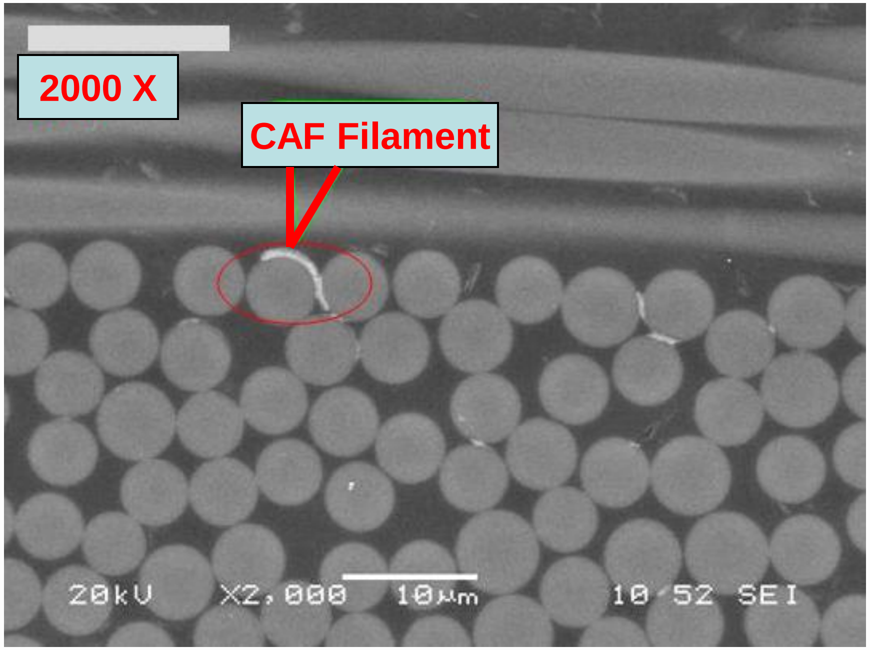


Typical Examples of CAF Failures
FMA X-sect Picture by SEM – (FR4-I)



Typical Examples of CAF Failures
FMA X-sect Picture by SEM – (HF-N)





Unexpected CAF / IM Testing Results

The 106 Glass effect

2 HiSpd Materials ➔ ***Wetability Issue in 106 cores only***

Before and After Reflow

The Low Bulk Resistivity effect

2 *Different* HiSpd Materials ➔ *Larger Pathway Issue*

Before and After Reflow

The Reflow Pathway Elimination effect

11 Different Materials (4 FR4, 4 HF, 3 HiSpd) ➔ Improve with Reflow

After Reflow only ➔ Reflow can be good????

Not a Moisture issue ➔ 9/11 Sa *Before Reflow* have *0.2-0.4% Volatiles only*

What about Back-panels with no Thermal Transients?

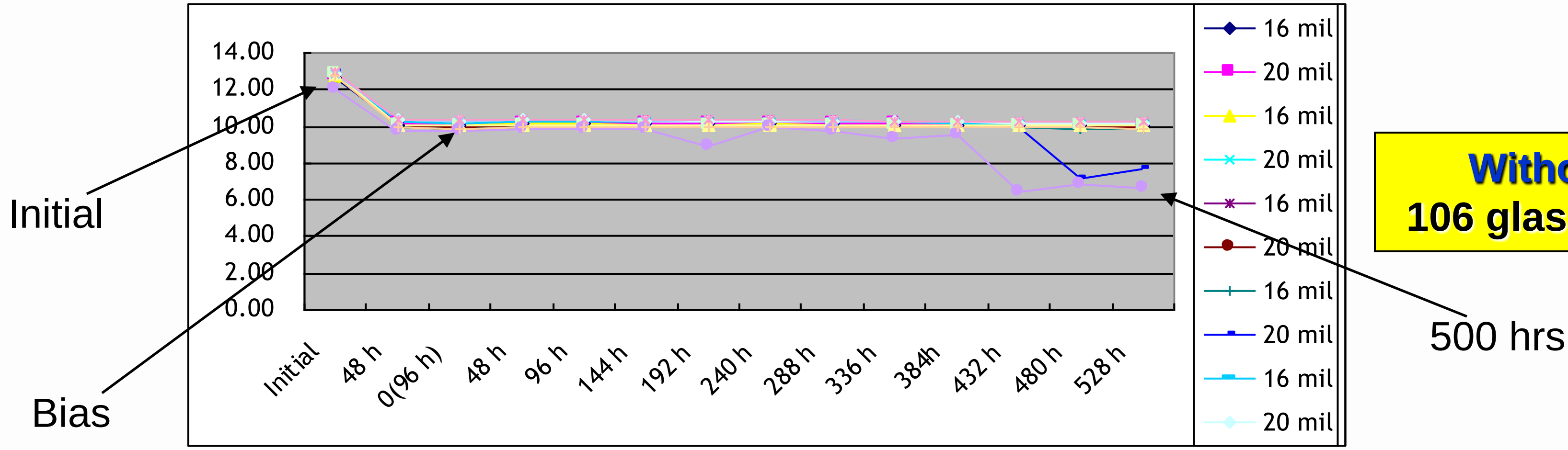
The 106 glass Effect

2 HiSpd Materials

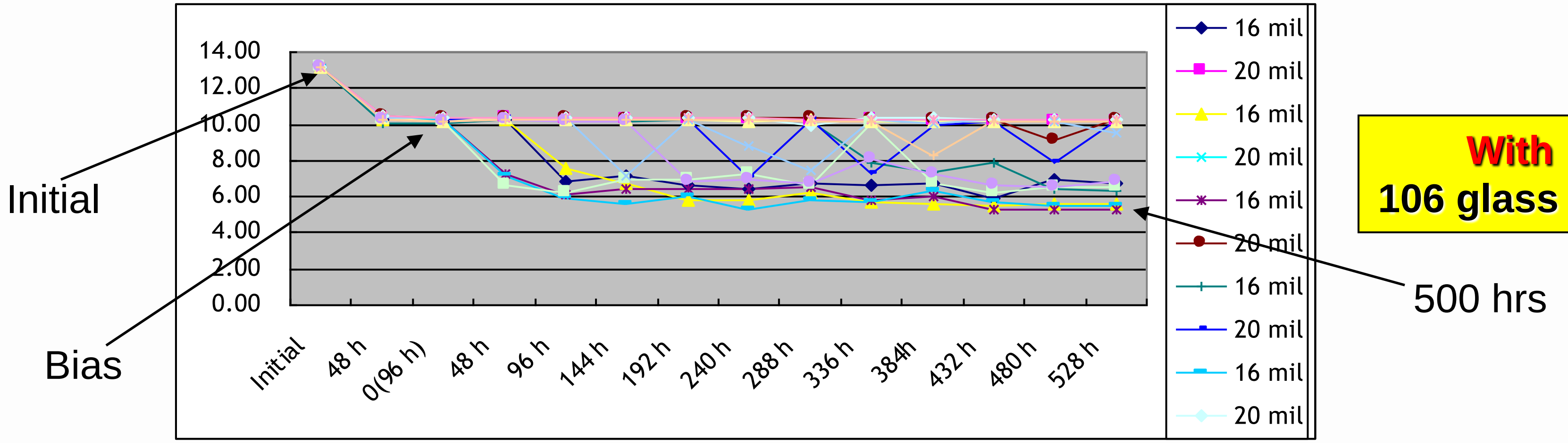
(106 glass in core for 7 HR builds only)

Before Reflow and After Reflow

HiSpd Material Builds (S + T) 106 Glass Effect
Before Reflow – 500 hrs
(*After Reflow same Result*)



Without 106 glass - LR

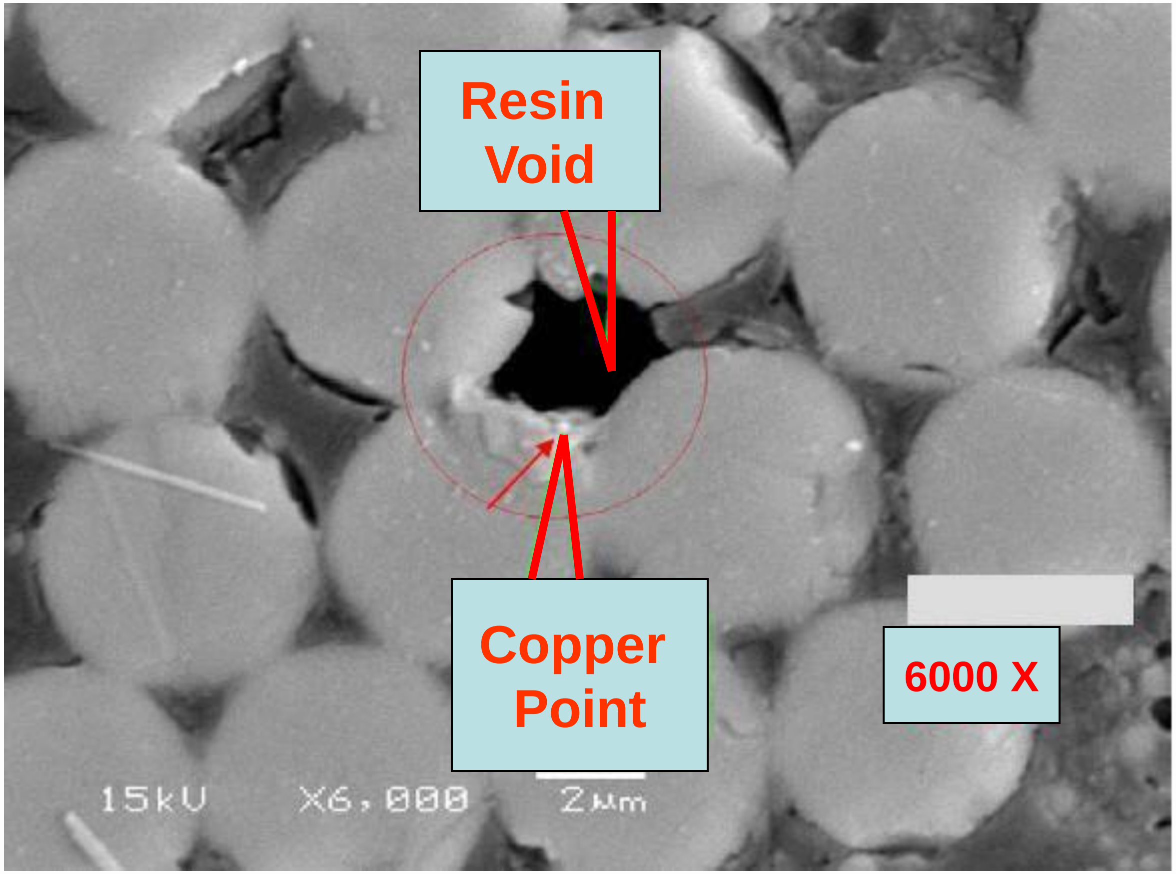


With 106 glass - HR

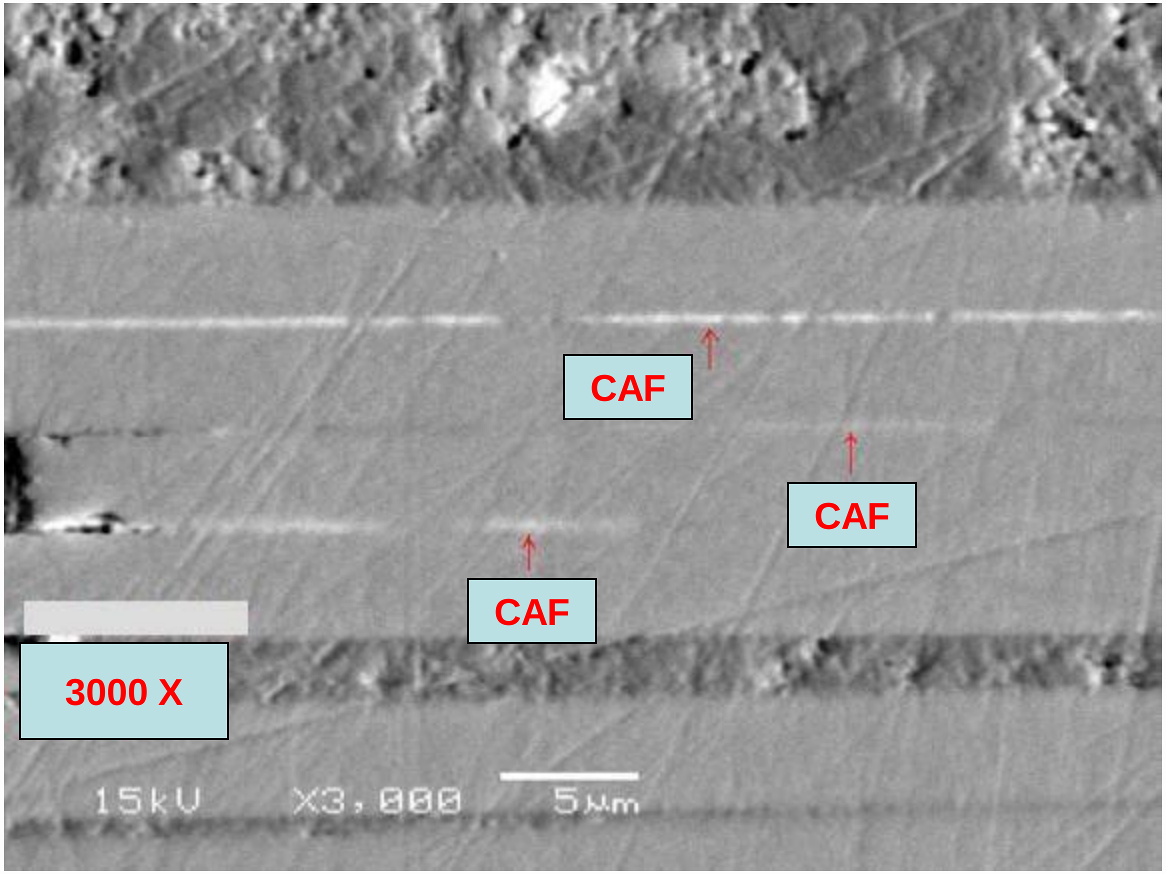
Typical FMA Examples of The 106 Glass Effect Failures

After Reflow

106 Glass Effect
FMA X-sect Picture by SEM - (HiSpd-T)



106 Glass Effect
FMA X-sect Picture by SEM - (HiSpd-Z)



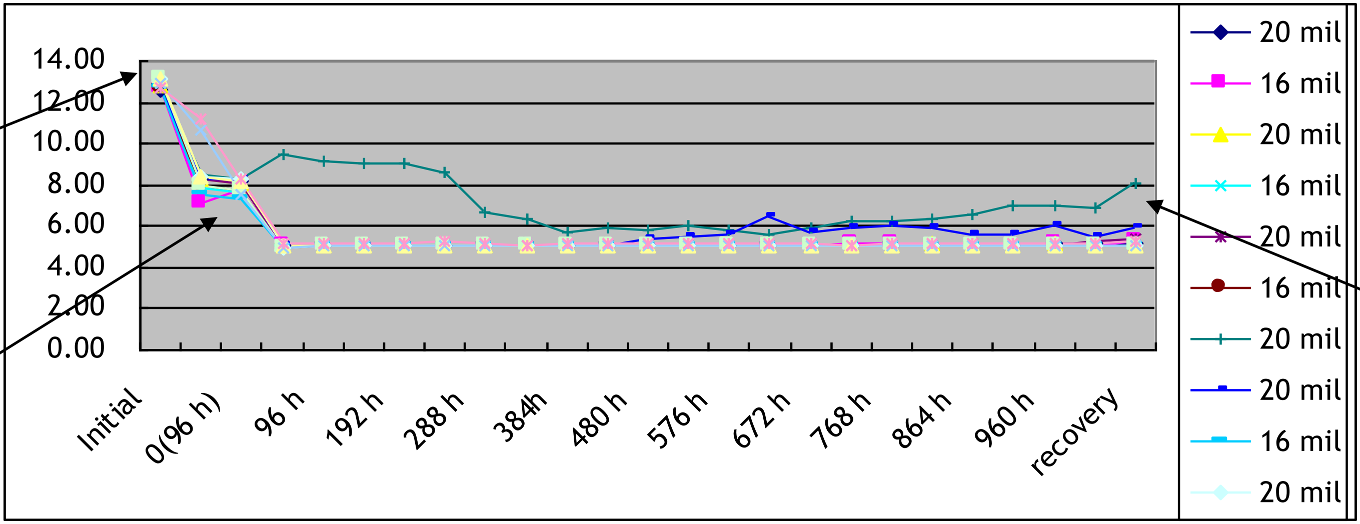
The Low Bulk Resistivity Effect

2 HiSpd Materials

Before Reflow and After Reflow

Low Bulk Resistivity Effect

HiSpd Material-U - 1000 hrs

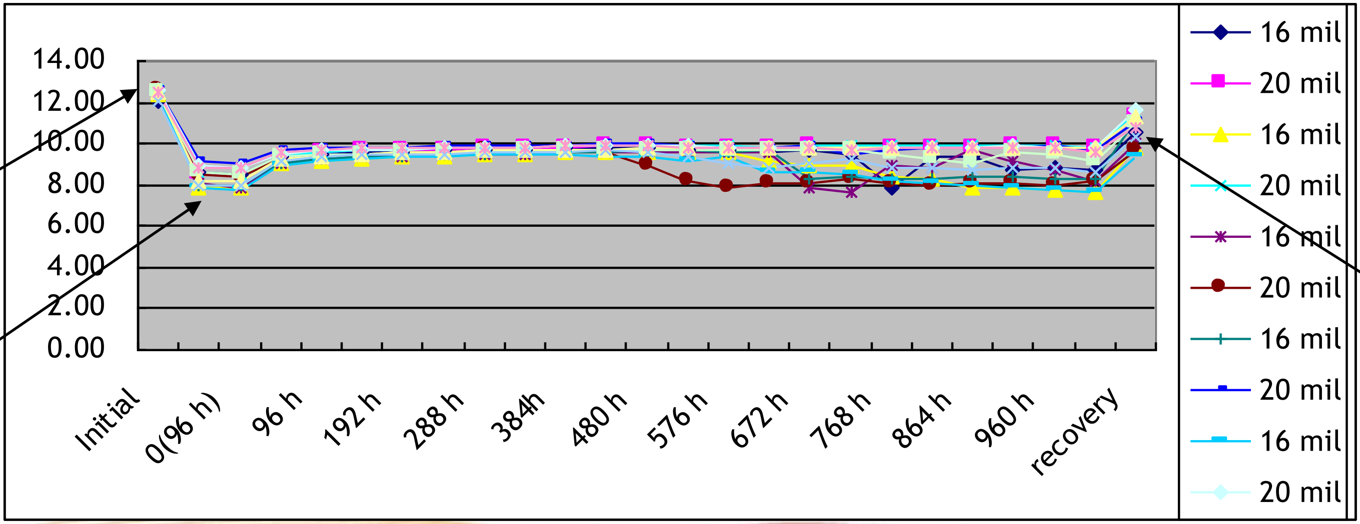


Initial

Bias

No recovery

Before Reflow



Initial

Bias

Partial recovery

After Reflow

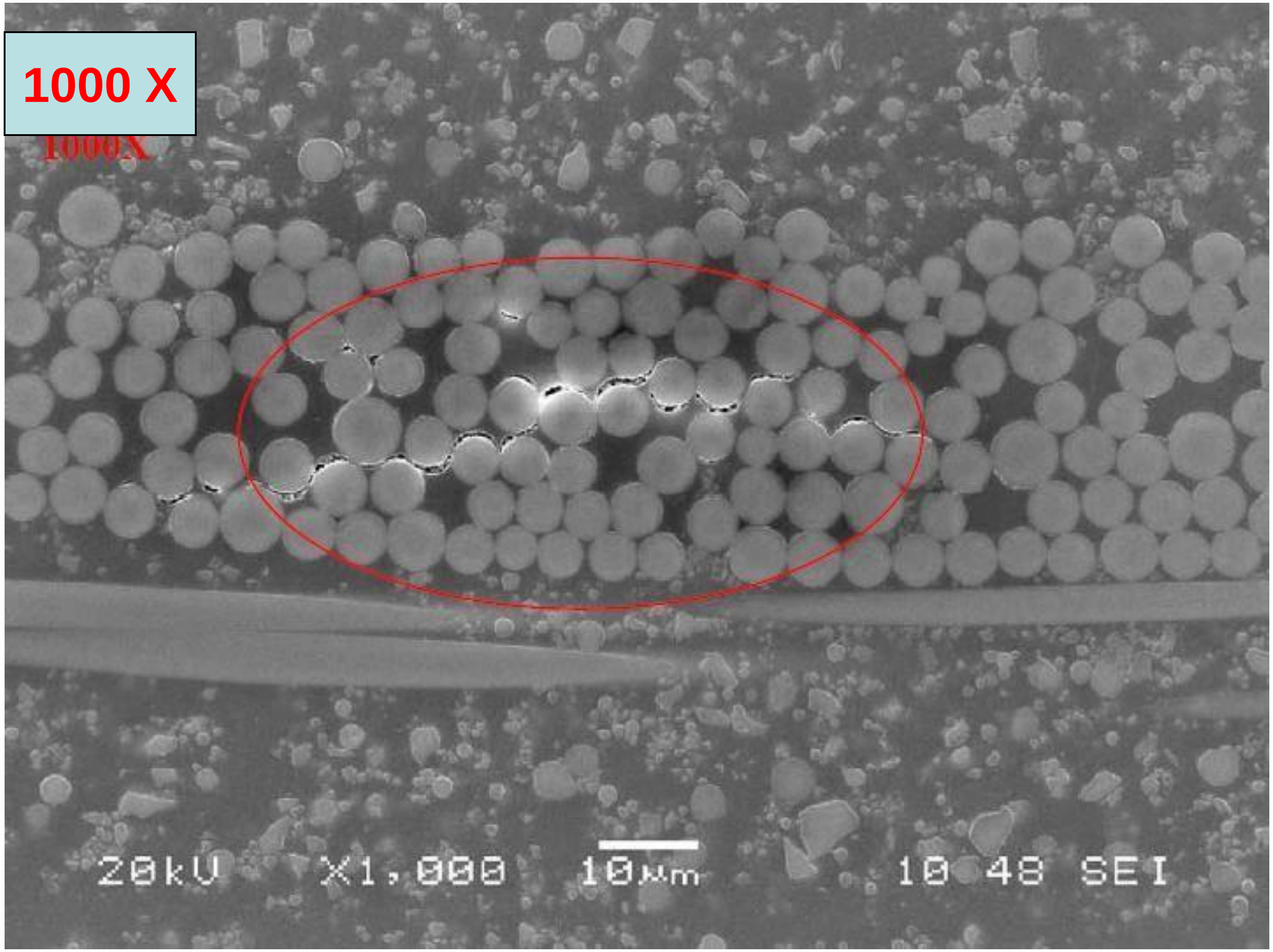
Typical FMA Example of The Low Bulk Resistivity Effect
Failure

Before Reflow

Low Bulk Resistivity Effect

FMA X-sect Picture by SEM - (HiSpd-U)

1000 X



The Reflow Pathway Elimination Effect

11 Materials Beneficial

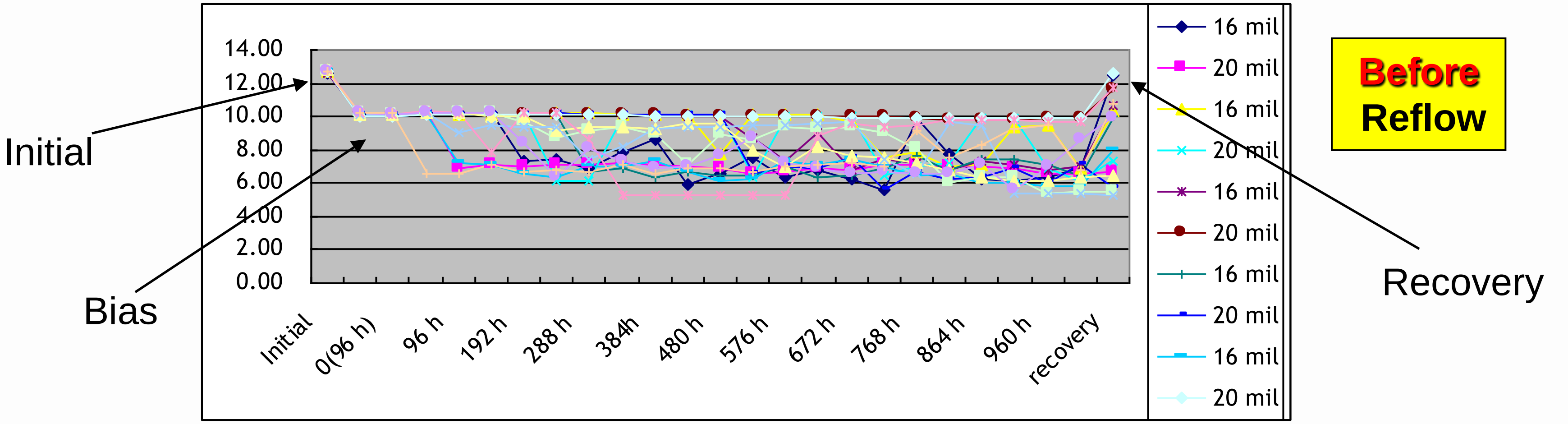
(5 FR4, 4HF, 2 HiSpd)

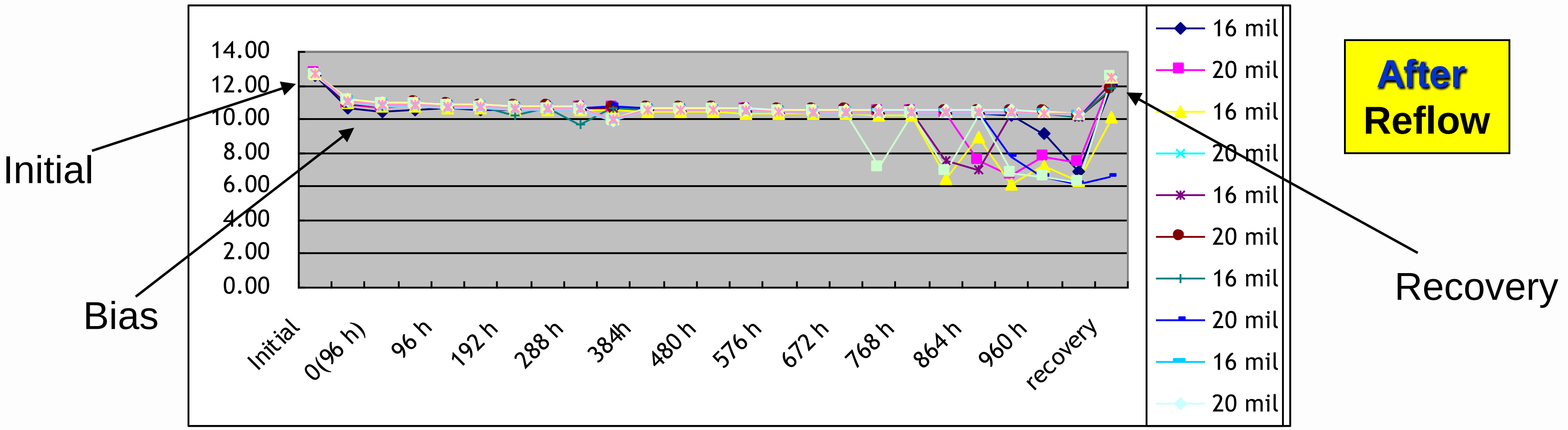
2 with high moisture

After Reflow

Reflow Pathway Elimination Example

HF Material-M + 10 other Materials





Potential Pathway Elimination Alternatives

OK What Can we Do?

For Backpanels → No Assembly Thermal Transients

For other Milder Lead-Free Assembly Conditions

- Reflow at lower Temp/Cycle(s) as PCB preconditioning?
- Bake as PCB preconditioning?

(Prior to Assembly)

Preliminary Results for Pathway Elimination

Pathway Elimination with Reflow--*Limited Sa Size*												
	1 X 220R		1 X 240R		1 X 260R		3 X 220R		3 X 240R		3 X 260R	
	Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons		Fails/coupons	
Material	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs
HiSpd-U	5/6	6/6	5/6	6/6	0/6	3/6	N/A	N/A	N/A	N/A	N/A	N/A
FR4-C	8/10	8/10	2/10	2/10	0/10	2/10	1/10	1/10	2/10	3/10	3/10	5/10
HF-M	2/6	3/6	0/6	2/6	1/6	3/6	2/6	3/6	0/4	0/4	1/4	2/4
HF-N	1/8	4/8	0/8	2/8	4/8	5/8	0/6	0/6	2/6	2/6	1/6	1/6
FR4-H	1/8	1/8	1/6	2/6	1/6	2/6	1/6	1/6	1/6	1/6	0/6	2/6
FR4-B	0/6	1/6	0/6	2/6	1/6	2/6	1/6	2/6	0/6	1/6	0/6	0/6

Pathway Elimination with Bake--*Limited Sa Size*				
	No Bake		Bake 4hrs @ 150C	
	Fails/coupons		Fails/coupons	
Material	500 Hrs	1000 Hrs	500 Hrs	1000 Hrs
HF-N	4/4	4/4	0/3	0/3
HF-K	1/4	2/4	0/4	3/4
FR4-H	2/4	3/4	2/4	3/4
FR4-B	2/4	4/4	0/4	1/4

Improvement

No effect

Much more Work needed

Summary and Conclusions

Not as many materials to choose from as we would like
Reflow is Good and Bad?
a) reduction of Pathway
b) but material damage
Clear wetting issues ➔ Glass/Resin ➔ Pathways already present
Step I of CAF (Resin/Glass interfacial separation) ➔ Evident
Testing data + FMA X-sect clearly show Pathway before Reflow
The 106 Glass effect
The Low Bulk Resistivity effect
Reflow Pathway Elimination? ➔ *Moisture appears not the issue (low for Sa)*
Is reflow or baking the answer or is there no answer?
But what about Backpanels with no Thermal Transients?
Hi-Speed Materials ➔ appear not as mature as FR4 + HF
CAF / IM ➔ *very complex issue*

In-depth Testing is the only answer!

Thank You