Conductive Anodic Filament Failure:
A Materials Perspective

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Abstract

Conductive anodic filament (CAF) formation was first reported in 1976.[1] This electrochemical failure mode of electronic substrates involves the growth of a copper-containing filament subsurface along the epoxy-glass interface, from anode to cathode. Despite the projected lifetime reduction due to CAF, field failures were not identified in the 1980s. Recently, however, field failures of critical equipment have been reported.[2]

A thorough understanding of the nature of CAF is needed in order to prevent this catastrophic failure from affecting electronic assemblies in the future. Such an understanding requires a comprehensive evaluation of the factors that enhance CAF formation. These factors can be grouped into two types: (1) internal variables and (2) external influences. Internal variables include the composition of the circuit board material, and the conductor metallization and configuration (i.e. via to via, via to surface conductor or surface conductors to surface conductors). External influences can be due to (1) production and (2) storage and use. During production, the flux or hot air solder leveling (HASL) fluid choice, number and severity of temperature cycles, and the method of cleaning may influence CAF resistance. During storage and use, the principal concern is moisture uptake resulting from the ambient humidity.

This paper will report on the relationship between these various factors and the formation of CAF. Specifically, we will explore the influences of printed wiring board (PWB) substrate choice as well as the influence of the soldering flux and HASL fluid choices. Due to the ever-increasing circuit density of electronic assemblies, CAF field failures are expected to increase unless careful attention is focused on material and processing choices.

Background

Conductive anodic filament (CAF) formation was initially thought to have little impact upon service lifetimes. Boddy, Delaney, *et al.*[1] proposed "that for operating voltages below 100V, median lifetime of circuits in typical air-conditioned equipment space (25° - 35° C, 40%-60% RH) will be conservatively measured in tens of years." This prediction was based on extensive accelerated life testing with failure rates extrapolated to operating and use conditions. Bell Laboratories performed a number of experiments in order to investigate the mechanism of CAF formation and the factors that could affect its growth.

The most common PWB substrate material used in modern electronics is FR-4 epoxy-glass. FR-4 consists of an epoxy matrix ($T_g \approx 130°C$)[3], reinforced with several plies of e-glass fibers woven in a 0°/90° manner. Copper surface tracks and plated through holes (PTH) are then generated through standard patterning, etching, and plating techniques. For increased density, multilayer boards (MLB) are manufactured by laminating together several layers of B-stage epoxy and patterned C-stage layers in a sandwich-like fashion. MLBs may consist of a dozen or more layers of circuitry within a single substrate.

A model developed by Bell Labs researchers[4] in the late 1970s[5] details the mechanism by which CAF formation and growth occurs. The first step is a physical degradation of the glass/epoxy bond. Moisture absorption then occurs under high humidity conditions. This creates an aqueous medium along the separated glass/epoxy interface that provides an electrochemical pathway and facilitates the transport of corrosion products. Electrochemical corrosion results because the water acts as the electrolyte, the copper circuitry becomes the anode and cathode, and the operating voltage serves as the driving potential. Hence, the following reactions are proposed:

Anode:

$$Cu \rightarrow Cu^{n+} + ne^-, \qquad (1)$$

$$H_2O \rightarrow \tfrac{1}{2} O_2 \uparrow + 2H^+ + 2e^-, \qquad (2)$$

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 \uparrow + 2OH^-, \qquad (3)$$

$$Cu^{n+} + ne^- \rightarrow Cu, \qquad (4)$$

The generation of hydronium ions (H^+) at the anode, and hydroxide (OH^-) ions at the cathode creates a pH gradient between these electrodes. A simplified Pourbaix diagram[6] (Figure 1) is a tool for viewing the inter-relation between pH and corrosion. The diagram reveals that in the region of pH 7 to 11, copper is passivated and corrosion will not occur but for pH below 7 corrosion will occur at potentials greater than 0.2V. In the case of CAF formation electrochemical reactions generate hydronium ions at the anode causing the local pH to drop and the corrosion products to become soluble. The copper ions created at the anode travel along the epoxy/fiber interface attracted to the cathode. However, at pH above 5, the solubility of copper ions declines rapidly becoming nearly insoluble about pH 8.6.[7] Thus, when the copper ions reach this region they become insoluble and deposit on the interface. The copper-bearing filament known as CAF, then, is a copper salt, which appears to grow along the interface. The filament may initially grow in a random manner, but as time progresses, the growth direction of the filament is definitely toward the cathode. When contact is made, electrical failure occurs. However, if the bias voltage is removed prior to contact, CAF growth will terminate due to the cessation of the electrolytic corrosion reaction.

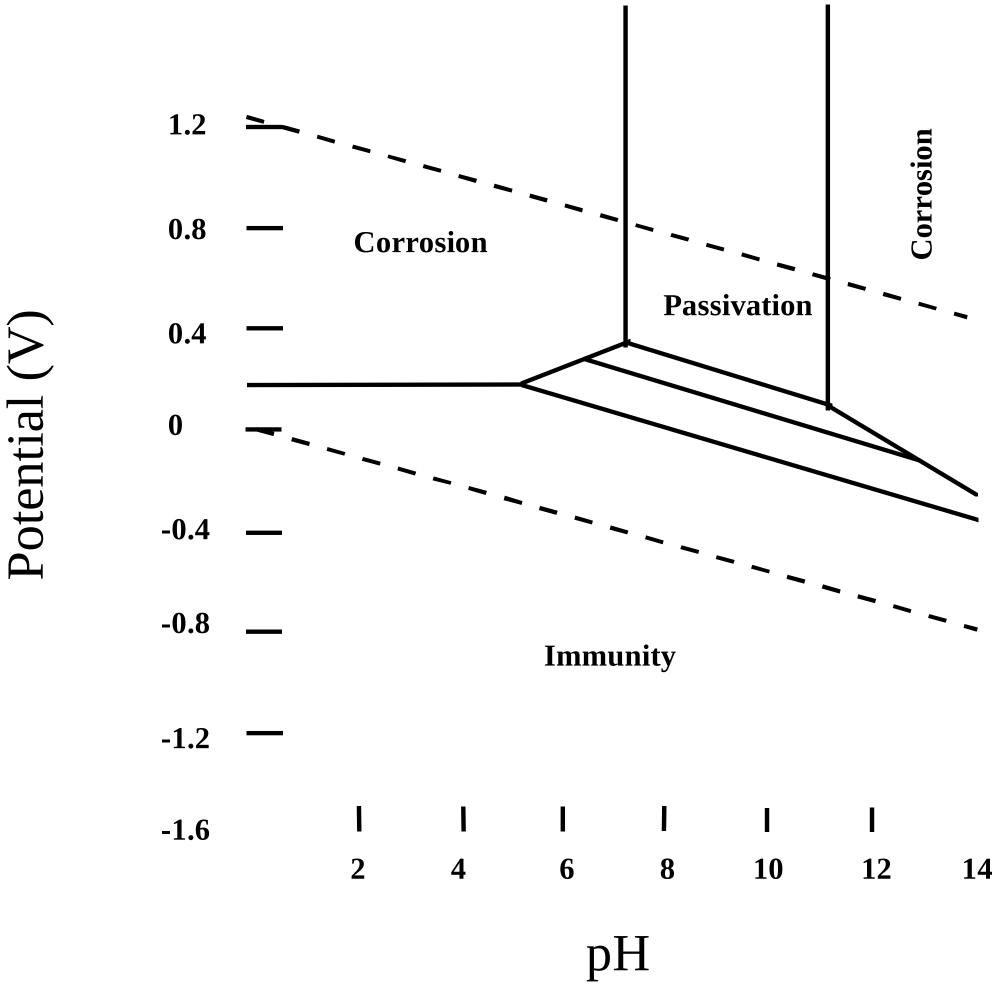


Figure 1: Simplified Pourbaix Diagram for Copper.

Electrical failures caused by CAFs may occur in either of two ways. The dissolution of the copper anode may deplete the conductor track of copper causing an “open” circuit. Alternatively the filament may grow until it reaches the cathode, resulting in a “short” circuit. This second mode is the one most frequently observed.

Factors Which Affect CAF Formation

There are a number of factors that can affect the susceptibility of a specific PWB to CAF formation and growth. These factors can be grouped into two types: (1) internal variables and (2) external influences.

Internal Variables

Internal variables are intrinsic to the design of the board. These include choices such as substrate material, as well as component and circuit layout. For a given assembly, the designer determines these variables and bases the decision on materials properties and product requirements.

Substrate Material Choice

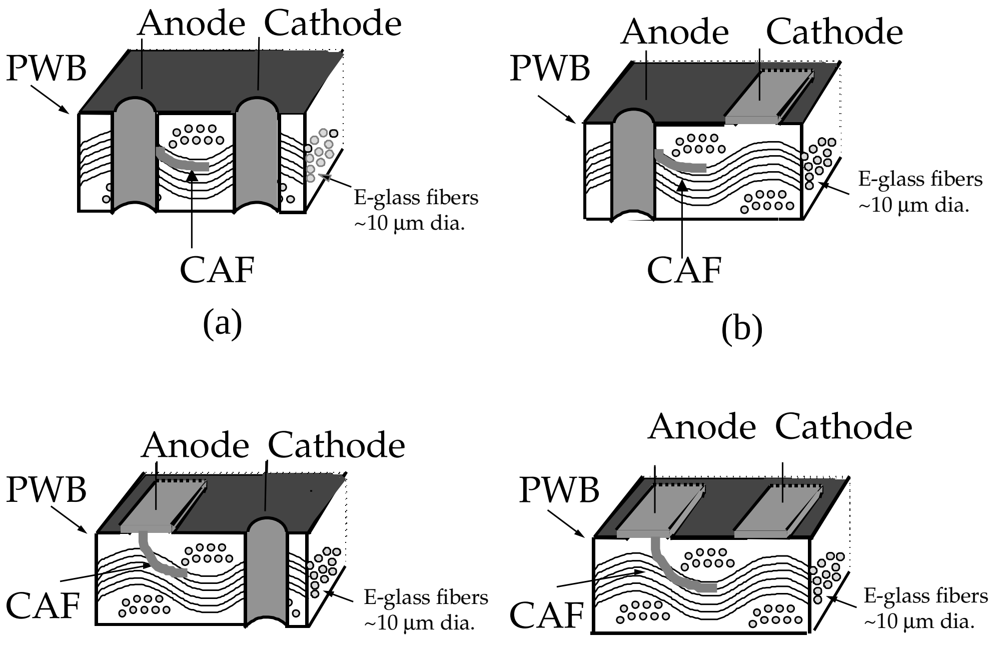
Lando, Mitchell and Welsher[4] compared FR-4 with several substrates: G-10 (a non-fire retardant epoxy/woven glass material), polyimide/woven glass (PI), triazine/woven glass, epoxy/woven kevlar, and finally polyester/woven and chopped glass. Similarly, Rudra, Pecht, and Jennings[8] performed an extensive experimental comparison among the substrates: bismaleimide triazine (BT), cyanate esters (CE) and FR-4. In addition, Ready[9] compared the CAF susceptibilities of FR-4 with CEM-3 (a substrate similar to G-10 except with chopped glass) and MC-2 (a blended polyester and epoxy matrix with woven glass face sheets, and a chopped glass core). Of all materials tested by these investigators, the BT material proved to be most resistant to CAF formation[4] (due to its low moisture absorption characteristics). Conversely, the MC-2 substrate proved to have the least resistance to CAF formation. The susceptibility of the materials follows the trend below and also depends on factors such as conductor configuration, conductor spacing, the presence of a conformal coating, etc.:

MC-2 >> Epoxy/Kevlar > FR-4 ≈ PI > G-10 > CEM-3 > CE > BT.

To insure immunity to CAF, the laminate of preference is BT. However, there is a cost penalty to consider.

Conductor Configuration

CAF filaments are typically no larger than 50 μm in diameter and 0.2 mm in length. Figure 2 contains a schematic depiction of the various “orientations” that a CAF can take. In the figure the dimensions are exaggerated for clarity.



(a) (b)

(c) (d)

Figure 2: Schematic Representation of CAF Pathways (dimensions exaggerated for clarity). (a) Hole to Hole, (b) Hole to Track, (c) Track to Hole, (d) Track to Track.

Conductor configuration is a critical variable in susceptibility to CAF formation. The work by Lando, Mitchell, and Welsher[4] showed that the hole-to-hole configuration (Figure 2a.) was the most susceptible to CAF. This is due to the direct contact of the PTH barrel with the e-glass fibers.[4] Lando, *et al*. also reported that the track-to-track configuration was the least susceptible. The susceptibility of other configurations is between these two extremes. The data of Rudra, Pecht and Jennings[8] confirmed these findings.

Voltage Gradient Effects

Another critical factor used in determining CAF susceptibility is the voltage gradient. By normalizing the applied voltage over a standard distance (1 mil, or 0.001 in.) a comparison between different assemblies with different pitch and operating voltages can be established. This is most graphically demonstrated by example. An assembly containing a +20V power plane with an adjacent via biased at +60V has a potential difference between the power plane and via of 40 volts. This is not considered a high potential difference for an electronic assembly. However, the separation between the power plane and the via – 5 mils (nominal) – creates a voltage gradient of 8 V/mil. Figure 3 reveals the circuit failure that occurred when a CAF bridged the spacing. The cause of this failure was ascribed to a processing chemical, which enhanced the voltage gradient effect.[2] This cause became evident when other boards that had a similar 8V/mil voltage gradient were processed with different fluxes and did not suffer CAF failure. Minimizing voltage gradients and the factors that enhance it is essential to reducing CAF formation.

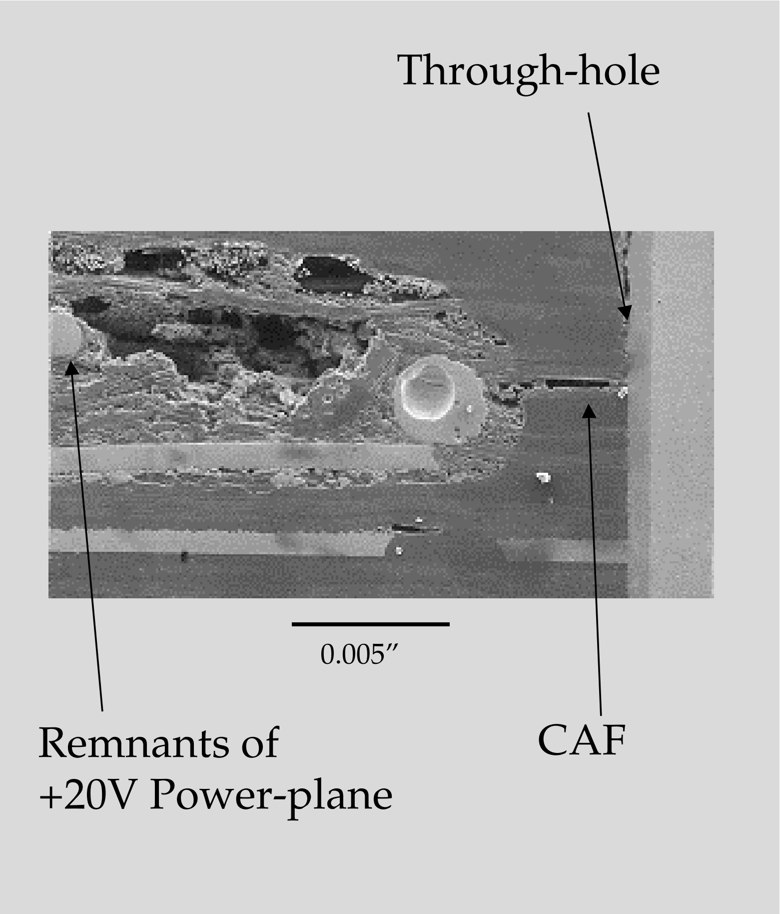


Figure 3: Catastrophic failure due to a CAF blowout of layers 6 and 7 of a 14-layer multi-layer board.

Directional Effects: Hole-Plane vs. Plane-Hole

An interesting aspect to consider with respect to PWB design involves comparison between the configurations depicted in Figures 2b and 2c. At first they appear identical, but closer inspections reveals that in 2b, the CAF emanates from a PTH (or via) while in 2c, the CAF emanates from a track. Which configuration is worse? The latter situation (2c) will be worse because the electrical potential between the two electrodes will be focused from the plane. The potential will be more diffuse when the hole is the anode. The maximum voltage stress between two electrodes spaced one unit apart (E_m) depends on the electrode configuration and is generally less than the average voltage stress between these electrodes. Formulas for determining this are available.[10]

External Influences

External influences are factors that can be easily changed or controlled while the assembly is in production or use. They are items such as the ambient conditions in the manufacturing plant, the chemical composition of the solder flux or HASL fluid, the presence or absence of conformal coating, the post-production cleaning process, and the number and severity of the temperature cycles that the assembly experiences during the manufacturing process.

Solder Flux / HASL Fluid Composition

It has been shown that polyglycols[11] diffuse into the epoxy during soldering.[12] This absorption occurs when the PWB is above its glass transition temperature where elevated temperatures and a more "open" structure of the polymeric matrix facilitate diffusion. This absorption has been shown to reduce performance by increasing moisture uptake by the substrate.[13] Jachim, *et al.*[14] were the first to link the use of polyglycols in soldering fluxes and fusing fluids to increased susceptibility to CAF formation. Furthermore, Ready, *et al.*[2] detail a field failure which occurred on only certain production lots. They show that this failure resulted from the use of a polyglycol containing HASL fluid during production. This fluid also contained hydrobromic acid that diffused into the brominated epoxy substrate resulting in an increased bromide concentration in the board. Both of these constituents increased the assembly's propensity for CAF formation by enhancing moisture absorption and providing an appropriate anion for the electrochemical reaction. Therefore, the use of polyglycols or hydrobromic acid-containing fluxes and fusing fluids should be avoided to reduce the likelihood of CAF formation.

Thermal Excursions

Diffusion of polyglycols into the PWB substrate occurs during soldering. Since the diffusion process follows Arrhenius behavior, the length of time the board is above the glass transition temperature will have an effect on the amount of polyglycol absorbed into the epoxy and that will, in turn, affect its electrical properties. Brous[13] linked the level of polyglycol in a board to surface insulation resistance (SIR) measurements. Jachim[14] reported on water-soluble flux-treated test coupons that were prepared using two different thermal profiles. Those which experienced the higher thermal profile exhibited a SIR level that was an order of magnitude lower than those processed under less aggressive thermal conditions. It is clear that the higher the soldering temperature, the greater the polyglycol absorption. Similarly, for each thermal excursion that occurs, the bonding between the epoxy and glass fibers is weakened due to different coefficient of thermal expansion characteristics of these two materials. Hence, to reduce CAF susceptibility the number and severity of thermal excursions should be minimized.

Cleaning

Zado[11] studied the effect of non-ionic water soluble flux residues such as polyethylene glycol (PEG) and found that they significantly reduced the insulation resistance of test samples. Test samples treated with PEG and cleaned in an aqueous medium showed reduced SIR values, while test samples treated with the other flux constituents gave SIR levels equivalent to unprocessed boards. He concluded that the cleaning step was ineffective in removing the polyglycol. Since the polyglycol rapidly diffuses into the epoxy at temperatures above T_g, diffusion out of the epoxy at temperatures below the T_g is expected to take much longer. Brous[13] studied several solvent combinations for removing PEG and other polyglycols from epoxy-glass and determined that soaking the board in acetonitrile for 24 hours provides the best removal process. Ionox FCR (Kyzen) has been used in our laboratory to remove polyglycol residues from boards processed with HASL fluids.

PWB Storage & Use: Ambient Humidity Effects

Augis, *et al.*[15] determined that there is a humidity threshold below which CAF formation will not occur. They found that this relative humidity threshold depends upon operating voltage and temperature. For example, they found that for a 50-volt circuit operating at 25°C the critical relative humidity for CAF formation is near 80%. It is important to remember that this relative humidity need not be present in the operating environment. Moisture absorption can occur during any part of the assembly's lifetime. This is particularly critical during transportation or storage, when the assembly may experience harsh environmental conditions.

De'Nève and Shanahan[16] studied moisture absorption by epoxy resin. They found that a 1 wt% water absorption led to an 8°C decrease in T_g. This is indicative of plasticization of the polymer.

Liu, Wang and Livingston[17] analyzed several laminate materials (FR-4, BT, and Driclad) and showed that FR-4 has the greatest affinity for moisture absorption. In addition, FR-4 moisture absorption is temperature dependent. They reported that high levels of moisture within the laminate could lead to serious reliability concerns, such as internal shorts, metal migration, delamination, poor electronic and mechanical performance and a change in dimensional stability. They hypothesized that moisture is drawn into the laminate at a variety of times during the board's lifetime, including, (but not limited to) storage, manufacture, transportation, and operation of the laminate assembly. Finally, they reported a similar 8°C decline in T_g with each 1 wt% increase in moisture content. Liu and Wang[18] furthered their earlier work on moisture absorption by PWB laminates when they found that FR-4 absorbed twice as much moisture as Driclad (an IBM proprietary high T_g substrate material). They attribute this difference in moisture uptake to less hydrophilic functional groups, and higher glass transition temperature, for Driclad.

Failure sites occurred in the FR-4 samples during the SIR testing of the laminates. Fourier transform mass spectroscopy (FTMS) coupled with a plasma etch was used to analyze these failure sites which consisted of internal shorts between power planes and PTHs. The presence of copper, oxidized from the plasma, was visible on the exterior of the reinforcement fibers. Also, in the negative ion mass spectrum, chloride ions were observed. This study confirmed that copper deposits had formed along the glass fiber surface at the epoxy interface showing that the interface provides the path most responsible for the electrical failure. This was observed particularly in regions with many PTHs. It was theorized that the punching or drilling of a PTH led to delamination of the epoxy/fiber interface at the PTH, creating a non-tortuous path for ion and mass transport. Although they did not recognize these copper regions as CAF, they exhibit similar characteristics to those described above. They conclude that a lowering of the moisture uptake affinity of the laminate accompanied by the use of a hydrophobic coupling agent offer the most favorable resistance to moisture related failures.

They further suggest that improvement of interface integrity or the total elimination of the glass cloth reinforcement may effectively depress or eliminate this copper migration.

Takahashi[19] confirmed that water diffusion is the rate-limiting process for surface insulation resistance (SIR) loss. He found that saturation time varied inversely with the square of board thickness. Additionally, the primary conduction path appeared to be along interfaces between the glass fiber mats and the epoxy matrix. He concluded that the minimum amount of time for catastrophic SIR loss is approximately 50 hours. He attributed this to the time required for water to penetrate the glass fiber mats. He suggested that dissolved water released or mobilized conductive species that may be present in the epoxy. Lefebvre[20] working with Takahashi expanded upon this concept of moisture causing a breakdown of the interface. They noted that an abrupt loss of adhesion at the epoxy/glass interface occurred when the epoxy is equilibrated in air whose relative humidity is in excess of a critical value. This critical relative humidity is defined as the point at which there is a surge in moisture pickup.[6] They determined that an irreversible loss of adhesion occurs and that the polymer chain was permanently altered when this critical relative humidity was exceeded.

Conclusions & Recommendations

This paper reported on the relationship between various factors and the nature of the CAF that was formed. Specifically, the influences of PWB material choice are evaluated, as are, the influences of soldering fluxes and HASL fluids. Due to the ever-increasing circuit density of electronic assemblies, CAF field failures are expected to increase unless careful attention is focused on material and processing choices.

Based on the findings of the authors and the cited references, the following can be concluded about CAF formation:

- Thermal excursions increase stresses at the epoxy/glass interface weakening this area.
- CAF requires moisture penetration of the epoxy.
- Certain polyglycols increase moisture absorption by the epoxy, and therefore increase the likelihood of CAF formation.
- Severe thermal excursions associated with soldering raise the substrate material above its T_g and increases polyglycol uptake.
- High voltage gradients exacerbate CAF formation.
- Polyglycols coupled with elevated hydrobromic acid concentrations increase CAF formation.
- A critical relative humidity threshold exists for all PWB materials.
- Different substrate materials have varying degrees of susceptibility to CAF formation.
- Hole-hole (or via-via) CAF formation is most rapid.
- Polyglycol removal from PWB substrates can be achieved with using an acetonitrile soak.

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References

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[1] Boddy, P.J., Delaney, R.H., Lahti, J.N. and Landry, E.F., “Accelerated Life Testing in Flexible Printed Circuits” *14th Annual Proceedings of Reliability Physics*, pp. 108-117 (1976).

[2] Ready, W.J., Turbini, L.J., Stock, S.R., and Smith, B.A., “Conductive Anodic Filament Enhancement in the Presence of a Polyglycol - Containing Flux.” *34th Annual Proceedings of Reliability Physics*, pp. 267-273. (1996).

[3] Olson, L.D. “Resins and Reinforcements” in *Electronic Materials Handbook Volume 1, Packaging*. ASM International. pp. 534-537, (1989).

[4] Lando, D.J., Mitchell, J.P., and Welsher, T.L. “Conductive Anodic Filaments in Reinforced Polymeric Dielectrics: Formation and Prevention.” *17th Annual Proceedings of Reliability Physics*, pp. 51-63 (1979).

[5] Lahti, J.N., Delaney, R.H., and Hines, J.N. “The Characteristic Wearout Process in Epoxy-Glass Printed Circuits for High Density Electronic Packaging.” *17th Annual Proceedings of Reliability Physics*, pp. 39-43. (1979).

[6] Uhlig, H.H., Corrosion and Corrosion Control, Second Edition, John Wiley and Sons Inc., New York, NY, p.322, (1971).

[7] Kawanobe, T, Otsuka, K., “Metal Migration in Electronic Components,” *Proceeding of the 32nd Electronic Component Conference*, May, 1982, pp. 220-228.

[8] Rudra, B., Pecht, M., and Jennings, D., “Assessing Time-to-Failure Due to Conductive Filament Formation in Multi-Layer Organic Laminates,” *IEEE Transactions on Components, Packaging, and Manufacturing Techniques - Part B.* Vol. 17., No. 3, pp. 269-276. (1994).

[9] Ready, W.J., “Factors Which Enhance Conductive Anodic Filament (CAF) Formation.” *Master of Science in Metallurgical Engineering Thesis, Georgia Institute of Technology*. January 1997.

[10] Dunbar, W. G., “Packaging of High Voltage Systems,” *Electronic Packaging and Interconnection Handbook*, ed. Charles A. Harper, McGraw-Hill, Inc., New York, 1991, p. 14.24.

[11] Zado, F.M., “Effects of Non-ionic Water Soluble Flux Residues.” *Western Electric Engineer*, Issue 1, pp. 41-48, (1983).

[12] Brous, J., “Electrochemical Migration and Flux Residues – Causes and Detection.” *Proceedings of NEPCON West 1992*, pp. 386-393, (1992).

[13] Brous, J., “Water Soluble Flux and its Effect on PC Board Insulation Resistance.” *Electronic Packaging and Production*, Vol. 21, No. 7, p. 80, (1981).

[14] Jachim, J.A., Freeman, G.B., Turbini, L.J., “Use of Surface Insulation Resistance and Contact Angle Measurements to Characterize the Interactions of Three Water Soluble Fluxes with FR-4 Substrates.” *IEEE Transactions on Components, Packaging, and Manufacturing Technology – Part B*, Vol. 20, No. 4, pp. 443-451, (1997).

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[15] Augis, J.A., DeNure, D.G., LuValle, M.J., Mitchell, J.P., Pinnel, M.R., and Welsher, T.L., "A Humidity Threshold for Conductive Anodic Filaments in Epoxy Glass Printed Wiring Board." *Proceedings of 3rd International SAMPE Electronics Conference*, pp. 1023-1030, (1989).

[16] De'Nève, B. and Shanahan, M.E.R. "Water Absorption by an Epoxy Resin and its Effect on the Mechanical properties and Infra-red Spectra." *Polymer,* Vol. 34, No. 24, pp. 5099-5105, (1993).

[17] Liu, P.C., Wang, D.W., and Livingston, E.D., "Moisture Absorption Behavior of Printed Circuit Laminate Materials." *Advances in Electronic Packaging*, Vol. 4-1, pp. 435-442, (1993).

[18] Liu, P.C., Wang, D.W., Fuerniss, S.J., Poliks, M.D., Orbzut, J., Siperko, L.M., Chen, W.T., Havens, R.D., and Murcko, R.M., "Moisture Absorption and its Effect on the Performance of Printed Circuit Materials," *Materials Research Society Symposium Proceedings*, Vol. 323, pp. 309-319, (1994).

[19] Takahashi, K.M. "Conduction Paths and Mechanisms in FR-4 Epoxy / Glass Composite Printed Wiring Boards." *Journal of the Electrochemical Society,* Vol. 138, No. 6, June, pp. 1587-1593, (1991).

[20] Lefebvre, D.R., Takahashi, K.M., Muller, A.J., and Raju, V.R., "Degradation of Epoxy Coatings in Humid Environments: the Critical Relative Humidity for Adhesion Loss." *Journal of Adhesion Science and Technology*. Vol. 5 No. 3, pp. 201-227, (1991).