As originally published in the SMTA Proceedings

ECM AND IOT
HOW TO PREDICT, QUANTIFY, AND MITIGATE ECM FAILURE POTENTIAL

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INTRODUCTION

At its peak between 98-117 AD, the Roman Empire represented twenty percent of the world's population. While the Roman civilization can be credited with many technical and societal inventions, perhaps among the most important was the construction of aqueducts (Figure 1).

Figure 1. Roman aqueducts brought fresh water into the city

The Roman aqueducts allowed bountiful supplies of fresh water to be brought into the city center. Fresh water would be used for drinking, irrigation, and, most importantly, hygiene.

Rome is famous for its bath houses. With available clean water, residents of Rome were able to bathe regularly. In fact, bathing became a cultural ritual with public baths for the masses and even private baths for the wealthy.

In 476 AD, the last of the Roman emperors in the west was overthrown. As Rome fell, many of the inventions of the Romans were lost to history. This included the cultural embracement of personal hygiene. Personal cleanliness was no longer pursued and, in many cases, available. Many anthropologists believe the decline in post-Roman personal hygiene led to the spread of the great plagues of the middle ages.

BACKGROUND

Fast forward to current time. Today, our society embraces cleanliness. We expect, demand, and evaluate cleanliness in almost every aspect of our lives. We wash our cars and pets. We maintain high cleanliness standards in our hotels and public spaces. We require cleanliness in our restaurants and hospitals. We sanitize our hands throughout the day to prevent illness. We live in a clean-centric culture.

While we drive clean cars, stay in clean hotels and eat clean food, there is one part of our life where we actually abandoned cleanliness. Many of the circuit assemblies that affect almost every aspect of our daily lives are no longer required to be clean. Even though our life experience confirms the link between cleanliness and reliability, happiness, health, and safety, circuit assemblies no longer maintain that "cleanliness is next to Godliness" status.

This was not always the case. There was a time when virtually all circuit assemblies were cleaned. The removal of flux and other process-related contamination was commonplace. Cleaning was as normal as soldering. As we bring history into current time, one may relate the fall of Rome and its adoption of personal hygiene and the subsequent decline in human health to the large-scale abandonment of cleanliness expectations of circuit assemblies and the subsequent reliability issues it has created.

How did this happen? Has history repeated itself?

CIRCUIT ASSEMBLIES PRE-1989

Figure 2. Montreal Protocol signed in 1989

Once upon a time we cleaned virtually all circuit assemblies. That was until the discovery that certain Chlorofluorocarbons (CFC's) contributed to the loss of the ozone layer. The industry's most popular cleaning solvents, used to remove flux after soldering, contained CFC's. Eventually (in 1985), an international treaty known as the Montreal Protocol was signed (Figure 2), and our industry witnessed the elimination of many CFC-based cleaning solvents. Necessity being the mother of invention, alternate cleaning materials and methods were introduced. While these alternate materials and methods would prove effective, they paled in comparison to another technology introduced at the same time. This technology promised to eliminate the cleaning process altogether. This was the birth of "no-clean" flux. A flux that left behind very little residue, so little in fact, the assembly would not require cleaning.

It's interesting to note that the Montreal Protocol is one of only two treaties ratified by all United Nations Member Countries. Given the opportunity to eliminate an entire process step, much of the industry embraced "no-clean" technology. Those who were required to clean, adopted new cleaning materials and methods. In the early days after the transition, both elections (clean and no-clean) were successful.

Little did the industry know back in the 1980's and early 1990's that the theory behind "no-clean" fluxes and solder pastes had a flaw. This flaw began to be more obvious as circuit assemblies became smaller and component densities became higher. The theory behind "no-clean" flux was based on the principle that little residue would be left behind. The remaining residue would act as an encapsulater of flux activators and other "bad actors". What was not widely considered when cleaning was eliminated from the electronic assembly process was the fact that, while we referred to a de-fluxing process, it can more accurately be defined as a cleaning process. When the flux was removed from assemblies, so were other residue species, including residues from board fabrication, component fabrication, the assembly process, human-transferred residues, and, of course flux. When the industry stopped removing flux, it stopped removing everything.

A multitude of residue species were allowed to remain on the assembly. Fortunately, circuit assemblies were much less dense at that time (Figure 3). Through-hole components ruled the assembly landscape and surface mount components were relatively large, providing ample space between conductors.

Figure 3. Through-hole assembly

Over the past thirty-one years since the introduction of the ban on most CFC-based cleaning solvents and the ensuing elimination of a cleaning process, circuit assemblies have gone through a transformation. Modern assemblies are smaller, components are smaller and closer together (Figure 4). The physical distance between conductors has never been smaller. The reduction of conductor-to-conductor spacing reduces the circuit assembly's residue tolerance. This is the reason a no-clean strategy was successful in years past and is less successful today.

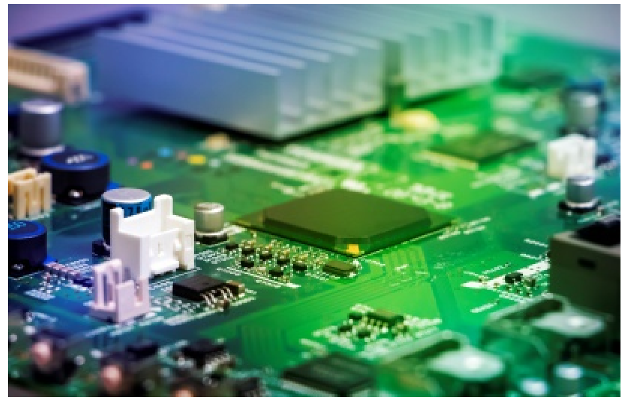

Figure 4. Modern low-profile surface mount assembly

Over the past three decades the percentage of assemblers cleaning boards reflowed with no-clean flux has increased. In fact, in a recent poll conducted by Aqueous Technologies, 53% of the respondents indicated that they clean assemblies reflowed with no-clean flux. While it's not likely that no-clean flux residue is the exclusive cause of residue-related failures, the totality of residues from board and component fabrication, assembly processes, and humans combine with flux residues to create the possibility of ECM related failure. Residue-related failures can fall into three primary categories:

- Cosmetic
- Electro-Chemical Migration (ECM)
- Adhesion

While this paper deals with ECM, the remedies for cosmetic and adhesion issues are identical to those of ECM.

Figure 5. Metal whiskers project perpendicularly from the surface

Figure 6 Tin whiskers

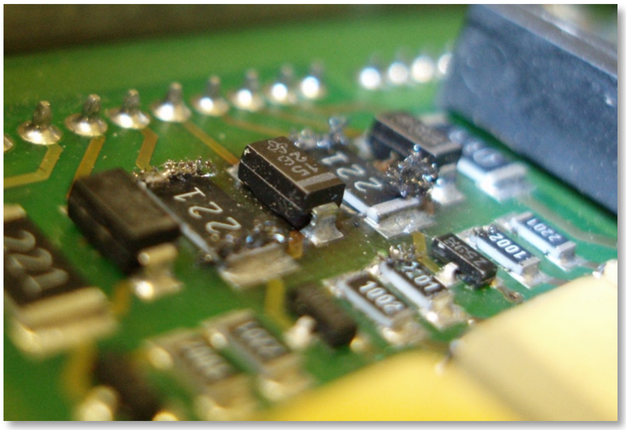

Figure 6. Tin whiskers

First, let's separate two similar but different issues, tin whiskers and electrical-chemical migration. Metal whiskers (Figures 5-6) differ from metallic dendrites in several respects; dendrites are fern-shaped, and grow across the surface of the metal, while metal whiskers are hair-like and project perpendicularly from the surface. Dendrite growth requires moisture capable of dissolving the metal into a solution of metal ions which are then redistributed by electro-migration in the presence of an electric potential. Tin whisker formation does not require either dissolution of the metal or the presence of an electromagnetic field.

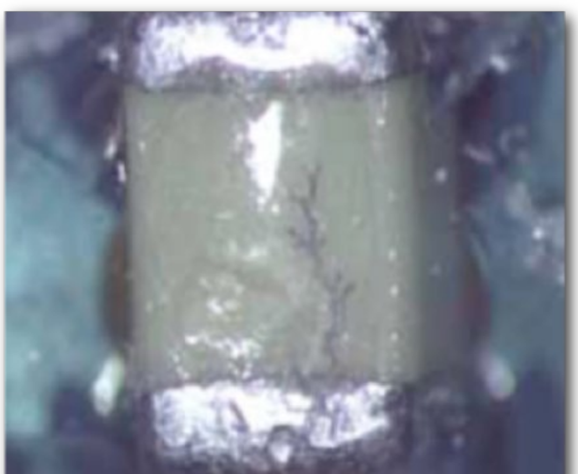

Figure 7. Metal whiskers grow under conformal coating on a circuit assembly. Courtesy Foresite

Electro-chemical migration (ECM) is a problem faced by an increasing number of assemblers. ECM manifests itself in three forms:

- Dendritic Growth (Figures 7,8)
- Parasitic Leakage
- Conductive Anodic Filament (CAF)

ECM is the dissolution and movement of metal ions in the presence of an electric potential, which results in the growth of dendrites (metal structures) between anodes and cathodes. In simple terms, metallic crystals connect anodes and cathodes, causing a decrease in electrical resistivity or a direct short.

While dendritic growth and parasitic leakage are board surface issues, CAF occurs between the layers of a board. Surface level electro-chemical migration requires three elements:

- Voltage
- Conductive residues
- Moisture

Figure 8. Dendritic growth. Courtesy Process Sciences

The elimination of any one of the above elements will result in the prevention of ECM. In the case of surface ECM, the elimination of residues is the most practical and effective method of preventing the occurrence of ECM. While the elimination of moisture will also prevent ECM, keeping an assembly away from moisture often proves difficult. Even the best conformal coatings are permeable, allowing small amounts of moisture to penetrate to the board's surface. ECM can occur under conformal coatings (Figure 7).

The decision to clean or not to clean is determined by at least two factors including:

- The assembly's residue tolerance
- The cost of failure

The assembly's residue tolerance is determined by several factors including:

- Conductor-to-conductor spacing
- Component density
- Component standoff height
- Voltage
- In-use climatic environment

A specific volume of ionic residue between two conductors may or may not be harmful. The ratio of ionic residue to distance between conductors determines the level of ECM potential. The decrease of component spacing corresponds to a decrease in time-to-failure[1]. Too much residue in too small a space increases ECM potential. Not only is an assembly's residue tolerance lowered when a single component's conductors are close together, a high density of components places the component's conductors close together, further increasing the likelihood of ECM. Likewise, components with ultra-low stand heights may trap flux activators beneath the component, raising the potential for ECM.

Voltage plays a role in ECM. The higher the voltage, when combined with ionic residue and moisture, the greater the ECM potential.

Conductive Anodic Filament (CAF) is a similar failure mechanism as dendritic growth. Whereas dendrites grow on the surface of an assembly, CAF grows between the layers. Like surface level dendritic growth, CAF requires a conducive material, electrical current, and moisture. Additionally, a fourth element is required for CAF. A pathway is required between the board layers in order for CAF to form.

CAF can be a result of board fabrication failures, assembly failures, and the in-use environment of the circuit assembly. First, there must be a pathway between cathodes and anodes. The pathway may be formed during the board fabrication process. As through-holes are drilled, small micro-cracks may form within the laminate. This can occur if too much pressure is placed on the board by the drill. Dull drills can increase the pressure required for drilling. Micro-cracks may also form as a result of "dry weave", an interfilament separation within the laminate. Additionally, micro-cracks can form during thermal excursions associated with multiple reflow processes. Each time a board is exposed to extreme temperatures common in the reflow or soldering process, the expansion and contraction effect of thermal excursions can create or exacerbate micro-cracks.

The conductive material required for CAF formation is commonly the result of plating solutions used in the through-hole plating process. Both component barrels and vias are normally plated (Figure 9). As micro-cracks normally begin at a hole location, plating solution may leach into the micro-cracks.

Next, moisture is required to react with the conductive materials. Inter-layer moisture entrapment is common in multi-layer circuit boards.

If left within the board, it can react with the conductive materials associated with plating solutions and electrical current to exploit the pathways and create unwanted electrical conductivity within the board (Figure 10).

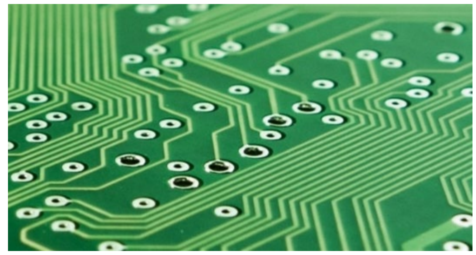

Figure 9. Plated through-holes and vias

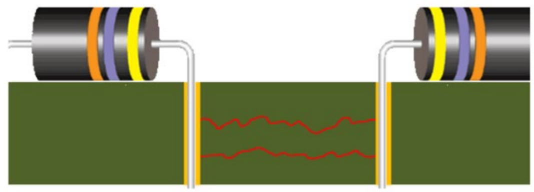

Figure 10. Electrical migration within inner-layer micro-cracks

Normally, CAF formations are very thin and delicate and do not result in a major fire-producing short circuit. CAF formations can however have damaging consequences by draining a circuit assembly's battery. Any unintended reduction of a laminate's dielectric properties can reduce the assembly's reliability.

Unlike surface-level ECM, cleaning is not a solution to CAF. The best solution to CAF is to prevent it. CAF resistant laminates are widely available. Additionally, assembly design, through-hole spacing, and voltage all play a role in CAF potential. If micro-cracks, conductive materials, and short spacing are inevitable, the elimination and prevention of inner layer moisture can prevent CAF formations.

One may refer to IPC TM650 2.6.25 (Figure 11) Conductive Anodic Filament Resistance Test which proports to "provide means to assess the propensity for conductive anodic filament (CAF) growth, a form of electrochemical migration within a printed wiring board (PWB). Conductive anodic filaments may be composed of conductive salts, rather than cationic metal ions, however inadequate dielectric for the applied voltage, component failures, and part use exceeding the maximum operating temperature (MOT) of the laminate can contribute to product failures as well. This test method can be used to assess PWB laminate materials, PWB design and application parameters, PWB manufacturing process changes and press-fit connector applications".

Figure 11. IPC 2.6.25

Even if a densely populated assembly is subjected to ionic residues, ECM is not a factor unless the assembly is subjected to moisture. This is true with both surface and inner-layer ECM concerns. This is where the assembly's in-use climatic environment plays a role. As stated earlier, voltage, ionic residues, and moisture are required for ECM. The higher the ionic residue content, the less moisture is required for ECM. Conversely, the lower the ionic residue content, the more moisture is required for ECM. This is where the term "Harsh Environment" becomes relative.

With some assemblies, it would take a very harsh environment, like a down-hole (Figure 12) application or an avionics device that lives in an unpressurized area of an aircraft to gain enough moisture to trigger an ECM event.

Figure 12. Stereotypical harsh environment

In assemblies with high ionic residue content and a high component density, normal everyday moisture such as environmental humidity may trigger an ECM event.

So, what is considered a harsh environment to a circuit assembly? It depends on the circuit assembly.

Finally, and perhaps most importantly, in the "to clean or not to clean" consideration, one should consider the cost of failure. When a product fails, is that good or bad? If a product fails, is it costly or not? Consider two products, both containing a circuit assembly. One product is an electronic flea collar (Figure 13), the other an implantable pacemaker (Figure 14).

Figure 13. Electronic Flea collar

Figure 14. Pacemaker

While the cost of failure for the electronic flea collar is an itchy dog, the cost of failure in the implantable pacemaker may be far worse. One would hope that the manufacturers of the implantable defibrillator took every precaution to reduce the chance of failure, which in most medical devices, includes the removal of residues after reflow.

ANECDOTE

One of my favorite anecdotes comes from a customer. This customer manufactures on-stage amplifiers for the music industry. Over the years, this manufacturer transitioned from tube to solid state technology, from through-hole to surface mount, from lead to lead-free, and from a clean to a no-clean process. As the circuit assemblies used in their products miniaturized, they noticed a degradation of sound quality emanating from their amplifiers. They requested that we clean their assemblies and return them for evaluation. We offered to subject the assemblies to Resistivity of Solvent Extract (ROSE) testing (an industry standard test to quantify the volume of ionic residue on a circuit assembly). They declined our offer, suggesting they had a better method of determining cleanliness. This unique cleanliness assessment required a musical "jam session" using the amplifier with newly cleaned circuit assemblies installed inside of it. The trained ears of professional musicians were able to hear a difference between music amplified with uncleaned circuit assemblies and music amplified with clean boards. This was their "sound of clean".

CONCLUSION

As miniaturization (both board and components) continues to progress, the amount of residue tolerable on and within an assembly continues to decline. Modern assemblies can tolerate less residue than their older counterparts. Today's assemblies must be cleaner in in order to prevent ECM in all of its manifestations.

The term "Harsh Environment" is relative. Through-hole circuit assemblies from many years ago could tolerate considerably more residue than a typical modern circuit assembly. Additionally, our industry transitioned from a clean strategy to a no-clean strategy. Formerly, circuit assemblies were cleaned. Not only was the flux removed, all other residue species were removed in the process. While flux is the intended target in a cleaning application, many other residues species are also removed. Residues from board fabrication, component fabrication, the assembly process, and human contamination combine with flux to create the total residue content on a circuit assembly (Figure 15).

When the electronic assembly industry stopped removing flux, it stopped removing everything. Because of the wide adoption of no-clean processes and the reduction of residue tolerance, we now witness a perfect storm of ECM possibilities.

BOARD FABRICATION	COMPONENT FABRICATION	ASSEMBLY PROCESS
Etch residues	Plating bath residues	Solder paste
Developer chemicals	Water quality rinses	Flux – wave
Water quality rinses for inner layers	Deflashing chemicals	Cored solder
Water quality rinses for outer layers	Mold release agents	Reworked/Repaired Fluxes
HASL Fluids (HO) and final rinses	Preplating oxide cleaning	Cleaning chemicals
Alkaline cleaners	Pretinning flux residues	Water rinse Quality
		Rework Cleaner

Figure 15. Circuit assembly residue sources

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IPC recently amended J-STD 001G[2] to mandate a combination of Surface Insolation Resistance (SIR) testing under bias with heat and humidity to qualify an assembly process and Resistivity of Solvent Extract (ROSE) testing to verify contamination levels. The combination of SIR under bias with heat and humidity and ROSE testing will ensure the assembly is clean enough for the intended use.

The removal of just one required factor for the creation of ECM (conductive residues), will prevent ECM related failures. Our industry has two choices, provide more space between conductors or a cleaner space between conductors. As our industry steams toward an historic expansion of electronic products as a result of IOT, wearables, and the increasing electrification of automobiles, the removal of residues and the resulting increase of reliability seems likely to bring cleaning back into a conventional wisdom status.

While there are several cleanliness quantification techniques, sometimes, one simply has to rely on the "sound of clean". Consider what your "sound of clean" is.

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