

THE IMPACT OF HARSH ENVIRONMENTS AND IONIC CONTAMINATION ON POST-REFLOW CIRCUIT ASSEMBLIES

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While there is well documented historical proof that post-reflow circuit assemblies, when subjected to harsh environments, are particularly vulnerable to failure mechanisms that can drastically reduce their performance and longevity. Modern electronic assemblies are far more susceptible to this phenomenon. Among the critical issues affecting these assemblies is ionic contamination, which can lead to a series of deleterious processes, including electrochemical migration (ECM). This paper explores the relationship between harsh environmental conditions, ionic contamination, and the resulting electrochemical effects on circuit assemblies.

Harsh Environments and Their Effect on Circuit Assemblies

Harsh environments for electronic assemblies typically include high humidity, extreme temperatures, salt spray, and exposure to corrosive chemicals. Such conditions are encountered in a wide variety of applications, from automotive electronics to aerospace systems and industrial machinery. These environments impose stress on circuit assemblies, accelerating degradation mechanisms that may remain dormant under milder conditions.

While most assemblers may view the above statement with a degree of relief, knowing their assemblies are not exposed to salt spray and/or exposure to corrosive chemicals, in reality, the degree for which a climactic environment may be considered harsh as far less than that.

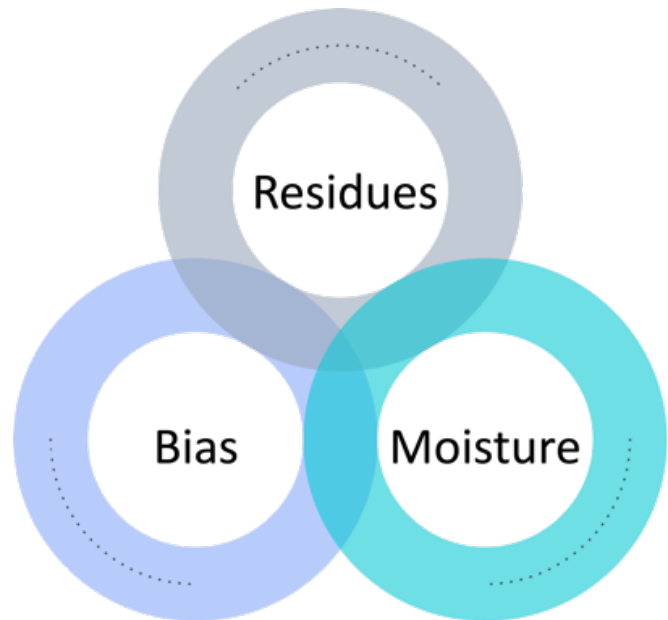


Figure 1: Three causes of ECM

In reality, there are three factors [Figure 1] which, when combined, have the potential to result in electrochemical migration. These three factors are an electrical bias, ionic residues, and moisture.

What is Electrochemical Migration (ECM) and What are its Associated Failure Mechanisms?

Electrochemical migration (ECM) is a degradation mechanism that occurs in the presence of moisture, a biasing voltage, and ionic contamination [Figure 2]. It involves the movement of metal ions across a substrate, leading to the formation of conductive metal filaments. This phenomenon is particularly problematic in high-density circuits, where tight

spacing between conductors increases the likelihood of short circuits.



Figure 2
Dendritic growth - Courtesy Process Sciences

Electrochemical migration typically involves the following steps:

1. Dissolution of Metal:

Under the influence of an applied electric field and in the presence of an electrolyte (water containing dissolved ions), metal atoms at the anode dissolve and become positively charged ions (e.g., Ag^+ , Cu^{2+}).

2. Migration of Metal Ions:

The dissolved metal ions migrate through the electrolyte, driven by the electric field, towards the cathode.

3. Deposition and Growth:

At the cathode, the metal ions are reduced back into solid metal, forming dendritic structures, also known as metal filaments. Over time, these dendrites grow and can bridge adjacent conductors, causing short circuits.

The most common metals involved in ECM are silver, copper, and tin, which are widely used in circuit assembly components. Silver, in particular, is highly susceptible to ECM due to its relatively high solubility in water and tendency to form dendrites under humid conditions.

Ionic Contamination and Its Sources

Ionic contamination refers to the presence of ionizable substances on the surface of circuit assemblies. These contaminants may originate from various sources during the manufacturing process, including solder flux residues, improperly cleaned solder joints, fingerprints, or airborne pollutants. The most common ionic species found on post-reflow assemblies are halides (chlorides, bromides), sulfates, and nitrates. These ions, when exposed to moisture, can dissolve and become conductive, leading to an increase in surface conductivity.

Post-reflow assemblies are particularly vulnerable to contamination from flux residues. During the soldering process, flux is used to remove oxides from metal surfaces, ensuring a clean, reliable connection. However, if flux residues are not adequately cleaned, they can leave behind ionic species that attract moisture from the environment, particularly in humid settings.

In the early 1990s, many assemblers, in an effort to eliminate a cleaning process, switched to the use of “no clean” fluxes. While this strategy was largely successful for the greater part of two decades, miniaturization along with accompanying high density component placement, reduced the circuit assembly’s tolerance for residue. Adding insult to injury, the elimination of a cleaning process not only allowed no-clean flux residues (albeit minimal), to remain on the assembly, it also allowed all other forms of contamination to remain on the assembly. This includes residues from board and component fabrication, various process residues, and human residues (the “usual



Figure 3: ECM Manifestations

suspects”) [Figure 3]. These residues, in totality, have proven to be problematic on modern circuit assemblies.

Electrochemical Migration: A Consequence of Ionic Contamination and the Manifestations of Electrochemical Migration

The primary manifestation of electrochemical migration is the growth of metal dendrites, which can bridge conductors, leading to catastrophic failure. These dendrites typically form between pads, traces, or solder joints on printed circuit boards (PCBs). The consequences of dendritic growth can vary depending on the location and nature of the circuit:

1. Short Circuits:

In the most severe cases, the dendritic growth will connect two adjacent conductors, creating a direct short circuit. This can result in immediate malfunction, damage to components, or even complete failure of the electronic system.

2. Intermittent Faults:

In some cases, the dendritic filaments may not fully bridge conductors but may create intermittent connections that lead to sporadic failures. These types of faults can be difficult to diagnose and often require time-consuming troubleshooting.

3. Leakage Currents:

Even without full bridging, ECM can cause increased leakage currents between conductors. This is the result of parasitic electrical leakage and can degrade the performance of sensitive analog circuits, cause signal integrity issues, or increase power consumption.

The Role of Harsh Environments in Accelerating ECM

Harsh environmental conditions, particularly high humidity, are key accelerants of electrochemical migration. Humid environments provide the moisture needed to dissolve ionic contaminants into a conductive electrolyte. The higher the humidity, the greater the amount of water available

to form this electrolyte, increasing the likelihood of ECM.

To make matters worse, some of the post reflow residue species may be hygroscopic (readily taking up and retaining moisture).

In environments where temperature fluctuations are common, condensation can also occur on the surface of circuit assemblies. This condensation can dissolve ionic residues left on the board and create localized wet areas where ECM is likely to take place. Additionally, in environments with high salt content, such as marine or coastal areas, the introduction of chlorides into the system further increases the potential for ECM and corrosion.

Mitigating the Effects of Ionic Contamination and ECM

To mitigate the effects of ionic contamination and electrochemical migration, manufacturers can employ several strategies:

1. Thorough Cleaning Processes:

Post-reflow cleaning processes are essential to remove flux residues and other potential contaminants. This can be done through various cleaning techniques, including aqueous and solvent-based cleaning.

2. Use of Low-Residue (No-Clean) Fluxes:

The use of no-clean or low-residue fluxes can reduce the amount of ionic contamination left on the board. However, it is important to ensure that even these low-residue fluxes do not leave behind enough contamination to trigger ECM under harsh environmental conditions.

Another factor to consider when using low-residue fluxes in order to avoid a cleaning process is that a decision to not remove the flux is also a decision to not remove any contamination. More on that later.

3. Protective Coatings:

Applying conformal coatings or encapsulants to circuit assemblies can shield them from environmental contaminants, reducing (not eliminating) the risk of moisture absorption and

ionic contamination. These coatings provide a physical barrier that reduces the possibility of moisture from reaching critical components and traces.

While conformal coatings may reduce or delay the likelihood of ECM, most conformal coatings are permeable and may allow small amounts of moisture to penetrate through the protective barrier.

4. Design Considerations:

Increasing the spacing between conductive elements can reduce the likelihood of dendritic growth. In some cases, designers may also consider using non-silver-based finishes or incorporating surface treatments that resist ECM.

High-Profile Documented Failures in Circuit Assemblies Related to Electrochemical Migration

Today, ECM, and its related failure mechanisms (dendritic growth and parasitic electrical leakage)² are not just theoretical issues. There have been many high-profile examples of ECM caused failures.

Electrochemical migration (ECM) is a well-documented phenomenon that has caused significant failures in electronic devices and systems across industries. The potential for ECM to create short circuits and intermittent failures makes it a critical concern for designers, manufacturers, and end-users alike. Over the past few decades, several high-profile failures have highlighted the devastating consequences of electrochemical migration, emphasizing the importance of rigorous design, materials selection, cleaning, and environmental control in the production of reliable electronics.³

Here are some of the most notable documented cases of ECM-related failures, the underlying causes, and the lessons learned from these incidents.

1. The Space Shuttle Solid Rocket Booster Electronics Failure [Figure 4]



Figure 4: Space shuttle's solid rocket boosters

One of the most infamous cases of electrochemical migration occurred during the early 1990s, when ECM led to the failure of a critical electronic assembly in NASA's Space Shuttle program. The incident involved the electronics controlling the solid rocket boosters, a vital system responsible for launching the shuttle into orbit.

Failure Analysis

In this case, electrochemical migration occurred in a circuit assembly where silver-based solder paste had been used. The assembly was exposed to high humidity levels during ground testing, which initiated the dissolution and migration of silver ions. Over time, silver dendrites formed between closely spaced conductors, eventually causing a short circuit.

The failure was discovered during routine testing, preventing what could have been a catastrophic malfunction during a shuttle mission. The incident led NASA to reevaluate its manufacturing and environmental testing protocols, ensuring that future assemblies were better protected against humidity-induced ECM.

Lessons Learned

The use of silver in soldering materials requires careful consideration, particularly in high-reliability applications exposed to humid environments.

Environmental testing must simulate real-world conditions to expose potential failure mechanisms like ECM before they become mission-critical issues.

4. Nokia Cell Phone Failures

In the early 2000s, Nokia, then the world's leading mobile phone manufacturer, faced widespread reports of device failures due to electrochemical migration. The affected models were subject to intermittent shutdowns, battery drainage issues, and, in some cases, total failure.

Failure Analysis

In this case, ECM occurred due to the ionic contamination of circuit assemblies during the manufacturing process. The contamination primarily originated from improperly cleaned solder flux residues that contained chlorides and other ionic species. When these devices were exposed to humid environments, such as users' pockets or tropical climates, moisture interacted with the residual ions, creating conditions favorable for ECM.

Silver migration was identified as the culprit, with dendritic growth between circuit traces leading to electrical shorts as well as parasitic electrical leakage and subsequent device malfunctions. Nokia eventually had to issue a recall of the affected devices, costing the company millions in warranty claims and damaging its reputation for reliability.

Lessons Learned

Thorough cleaning of assemblies after the reflow process is essential, particularly for devices that are likely to encounter humid environments.

Manufacturing processes must be tightly controlled to prevent the introduction of ionic contaminants, which can have long-term reliability impacts.

5. Xbox 360 "Red Ring of Death"



Figure 5: Xbox 360's "Red Ring of Death"

One of the most well-known failures in consumer electronics history is the infamous "Red Ring of Death" (RRoD) that plagued Microsoft's Xbox 360 gaming consoles [Figure 5]. While various factors contributed to the widespread failure, including poor thermal management, electrochemical migration also played a role in some of the failures.

Failure Analysis

The Xbox 360's motherboard design featured densely packed components, with small traces and vias vulnerable to the effects of ionic contamination. The lead-free solder used in the assemblies was highly susceptible to forming conductive paths when exposed to moisture. Reports indicated that ECM caused dendrite formation between the power and ground planes, leading to short circuits and intermittent failures in some units.

The problem was exacerbated by the console's thermal design, which allowed significant heat buildup during use. As the console cooled down, condensation could form, further promoting the conditions necessary for ECM to occur.

Lessons Learned

The failure highlighted the importance of considering both electrical and thermal stress when designing consumer electronics.

Proper encapsulation and environmental sealing of circuit assemblies are essential in products that may face fluctuating temperatures and potential moisture exposure.

6. Avionics Systems Failures in Commercial Aircraft

The aviation industry is highly sensitive to failures in electronic systems, given the potential risks to passenger safety [Figure 6]. Electrochemical migration has been implicated in several high-profile avionics failures, where short circuits caused by dendritic growth led to system malfunctions.



Figure 6: Modern electronic cockpit

Failure Analysis

In one well-known case, an avionics system controlling critical flight functions experienced intermittent malfunctions during high-humidity flights. The system used silver-based coatings on circuit traces, which, under conditions of high humidity and voltage bias, led to the migration of silver ions and the formation of dendrites. The resulting short circuits caused the system to intermittently fail, posing significant risks to flight operations.

Subsequent investigations revealed that the manufacturer had not adequately accounted for the operating environment of the avionics system, particularly the potential for condensation during

rapid altitude changes. The failure led to a widespread recall and redesign of the affected systems.

Lessons Learned

In high-reliability industries like aviation, even the slightest potential for ECM must be addressed through rigorous design, testing, and environmental protection measures.

The use of materials like silver, which are particularly prone to migration, must be carefully managed to prevent failures in safety-critical systems.

7. Electric Vehicle Sudden Shutdowns:



Figure 7: BMW i3

In 2018, BMW recalled all 2018 i3 EV models for an issue that could cause sudden power loss and shutdown [Figure 7].

Failure Analysis

According to paperwork filed by BMW, “A circuit board may not have undergone a sufficient cleaning process during Tier-2 supplier production.”

Lessons Learned

BMW attempted to mitigate a malfunctioning circuit board by shutting down all power to the car without notice. While this may have prevented further damage to the electronic assemblies, it presented a significant safety hazard to the driver, occupants, and surrounding vehicles.

BMW inadvertently created one problem by attempting to mitigate another.

Conclusion

The documented failures discussed above serve as critical reminders of the risks posed by electrochemical migration in electronic assemblies. From high-profile space missions to consumer electronics and public infrastructure, the consequences of ECM can be severe, leading to costly recalls, damage to brand reputation, and, in extreme cases, threats to human safety.



Figure 7: IPC J-STD-001

Manufacturers must prioritize the mitigation of ECM through a combination of materials selection, cleaning, and design best practices. Thorough cleaning processes and rigorous environmental testing, such as stated in IPC-J-STD001J (section 8) [Figure 7] can significantly reduce the risk of ECM and ensure that electronic assemblies perform reliably even in challenging conditions. Each of these high-profile failures offers valuable lessons that continue to shape the future of electronic design and manufacturing practices.

About the Author:

Mike Konrad is the Founder and CEO of Aqueous Technologies. Mike is a member of the SMTA Global Board of Directors where he is Vice President of Communications. Mike is a member of the Los Angeles/Orange County chapter of SMTA where is Vice President of Technical Programs.

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