ELECTROCHEMICAL RELIABILITY AS A FUNCTION OF COMPONENT STANDOFF

Mike Bixenman & Mark McMeen
Magnalytix, LLC
TN, USA
mbixenman@magnalytix.com

ABSTRACT

A significant contributor to electrochemical related “no-fault found” customer returns are leakage current failures. Leakage current failures depend on the humidity levels, presence of ionic contaminants, and potential bias between metal interconnects on an electronic circuit. This type of failure is difficult to isolate as the fault may occur due to an initial interruption to functionality without further recurrence. Isolating the root cause of leakage current failures is gained by understanding proper design rules for low clearance components.

One of the significant factors for controlling the water film formation and subsequent corrosion failure is the process-related contamination resulting from the reflow soldering process. The effect of flux residue on humidity related failures depends on the amount and chemistry of the residue, especially the ionic activator component in the flux component. The standoff height, from the assembly surface to the bottom of the component, factors into the level and activity of the flux trapped under the components termination.

The purpose of this paper is to research the activity of flux residues as a function of the standoff height using insulation resistance. A second factor that will be part of this research is design options for outgassing flux residues.

INTRODUCTION

Highly dense electronic assemblies drive size reduction to components. Miniaturized components create numerous challenges resulting in a shorter distance between conductors of opposite polarity, solder sphere size reduction, low standoff gaps, flux entrapment under the bottom termination, blocked outgassing channels, and more significant potential for leakage currents[1]. These leadless packages are typically electrically connected using solder paste (Figures 1& 2).

In the presence of humidity, moisture hydrogen bonds with ionic contaminants to create an electrolytic solution. Ions such as flux activators can dissolve metal oxides present in the flux residue or at the soldered connection[2]. When the system is in operation, the electrical field attraction of the positively charged metal ions will migrate to the negative conductor and plate out as leakage currents.

Figure 1: Passive Size Reduction

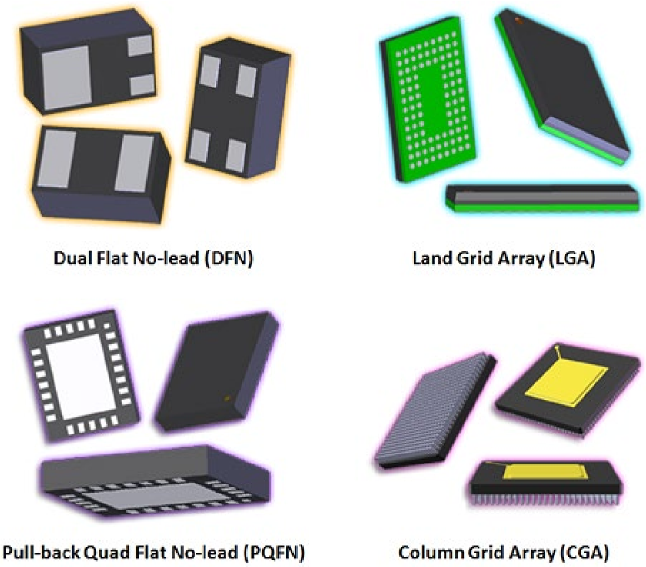


Figure 2: Bottom Terminated Component Examples

Standoff gaps lower than 50µms can cause the flux residue to build upon itself to the point that it underfills the bottom termination[3]. Flux outgassing channels can become blocked. Flux activators, solvents, surfactants, and functional additives can be left behind[4]. This is counter to the design of no-clean soldering materials. Instead of marginal flux residue at the solder connection, a heavy residue is left. Blocked outgassing channels leave flux that is still mobile and pliable. For no-clean designs, this residue is easily mobilized from humid moisture. The net result is no-clean soldered boards failing in the field.

Figure 3 illustrates this problem on passive components. Pay close attention to the level of flux residue and bubbles near the center of the component. These bubbles represent flux activators designed to outgas at a reflow temperature near 170°C. With the flux residue totally underfilling the component, outgassing channels were blocked. Even though this is a No-Clean solder paste, the residue is highly problematic to electrochemical interactions when moisture is present.

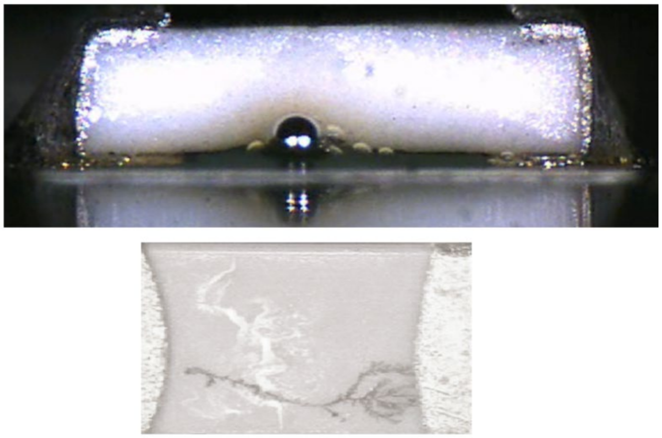


Figure 3: Passive Component Example

Bottom Terminated Components are equally as challenging. The high mass of solder under the component termination renders a significant amount of flux residue. Similar to the passive components, the standoff gap is typically less than 50µm. Tight spacing between the power and ground creates a condition that is ripe for electrochemical migration when the device is operated in humid environments. Figure 4 illustrates flux residues on the outer peripheral of a QFN component.

Metal oxide silicon transistor (MOSFET) components represent another example. The base of these components is soldered directly to the PCB. These power devices can leave flux residues at the signal pin region. The strong electrical field combined with an active residue can lead to electrochemical failures. Figure 5 illustrates this effect.

Electrochemical failures have greater potential to occur on these miniaturized leadless components. To design for electrochemical reliability, test vehicles representative of these complex components is required. Electrical testing is effective at quantifying any harmful effects that might arise from solder flux or other process residues left on surfaces after soldering.

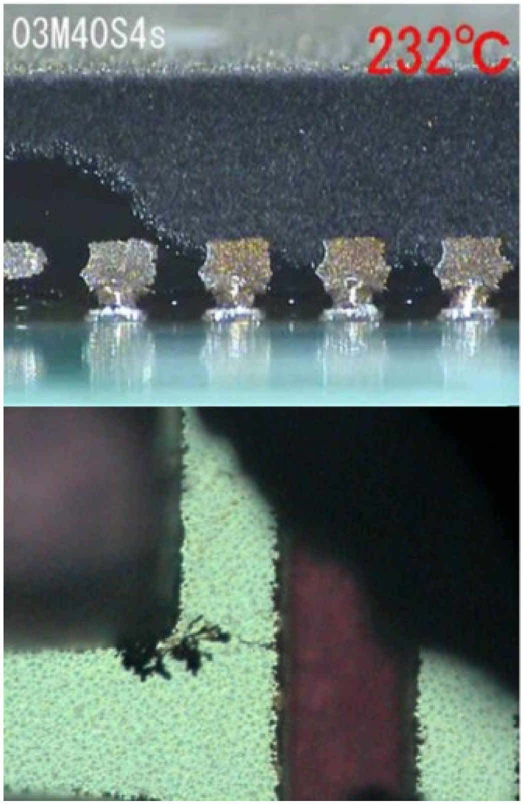


Figure 4: Bottom Terminated Component Example

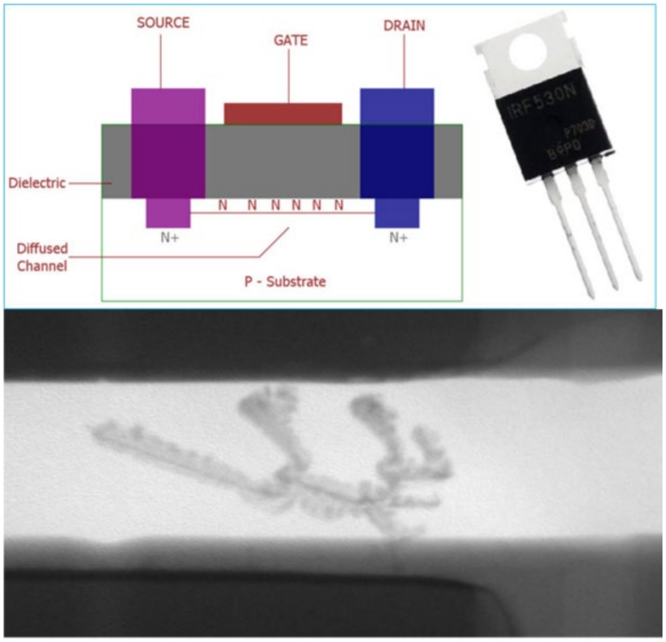


Figure 5: MOSFET Component Example

Electrical Testing using Hot-Humid Conditions

The electrical test method measures surface insulation resistance (SIR) across conductors of opposite polarity[5]. Test boards populated with the components in question have sensors routed to the signal pins and bottom termination. The test fixture is placed into an environmental chamber set at a specific test temperature and humidity level.

SIR testing is the "gold standard" for quantifying any harmful effects that might arise from solder flux or other process residues left on external surfaces after soldering. These residues can cause unwanted electrochemical reactions that grossly affect reliability (Figure 6). The SIR test instrument is equipped with a high-impedance meter and power supply. Matrix-switching cards are used to turn on and off the applied voltage during the test period. When taking a measurement, the voltage is switched off.

Ionic residues dissolve into monolayers of moisture. This water layer forms an electrolytic solution. If the contaminants in this electrolytic solution are sufficient to dissolve metal ions present in process residues or at the soldered regions, the positively charged metal ions will migrate to the cathode. Small dendrites will start to plate at the conductor. These small dendrites are known as leakage currents. These leakage currents cause performance lag and intermittent failures. If the metal dendrite grows from the cathode to the anode a dead short occurs. At this point, the electronics will fail. If the dendrite tree structure fractures, the device will recover and start working again.

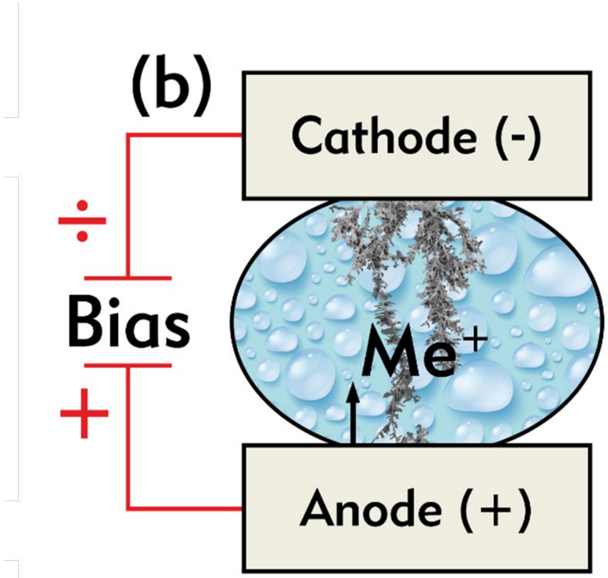


Figure 6: Electrochemical Reactions that affect Reliability

Experimental

Three separate studies were conducted and reported in this paper.

- Study 1: Evaluated the insulation resistance on specific leadless and bottom terminated components. Cleanliness conditions tested for were [1] No-Cleaning, [2] Inline Cleaning, and [3] Batch cleaning.
- Study 2: The second study was a comparison Study of Mechanical versus Laminate Dummies designed for SIR testing. The standoff gap and location of the signal were significant differences.
- Study 3: The third study builds off the second study. The component design was a key factor of this study to understand the cubic volume of flux residue as a function of the size of the signal pins.

Study #1

A series of test boards populated with leadless and bottom terminated components were used to study the activity of the flux residue following the soldering process. Test boards were evaluated at various cleanliness conditions.

For the first study, a high-reliability No-Clean Sn-Pb solder paste was selected. The four-channel test board is designed to evaluate four different components (Figure 7).

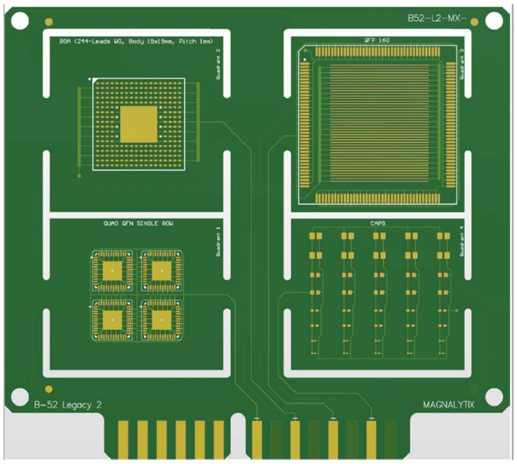
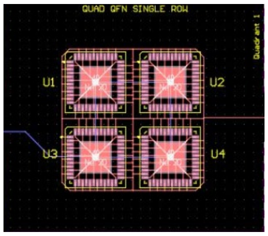
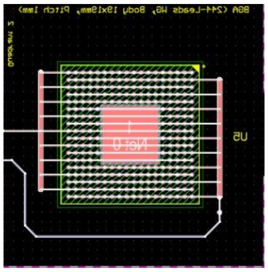
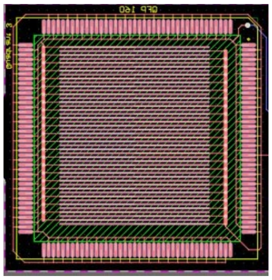


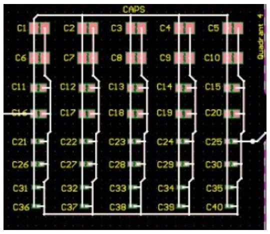
Figure 7: Four-Channel Test Board

- Channel 1: QFN-48T.5-F-ISO
  - 28-Leads, Body 7x7 mm
  - Pitch 0.5 mm
  - 

- Channel 2: FBGA 244 with Center Lug
  - 244-Leads, WG, Body 19x19mm
  - Pitch 1 mm

- 

– Channel 3: QFP 160
    - Body 28x18 mm
    - Pitch 0.65 mm
    - 

– Channel 4: 10pF Caps
    - 0805 / 0603 / 0402 / 0201
    - 

SIR Test Method: IPC TM-650 2.6.3.7

- 40°C
- 90% RH
- 5V Bias
- 168 Hours

Board 1: Not-Cleaned following Reflow

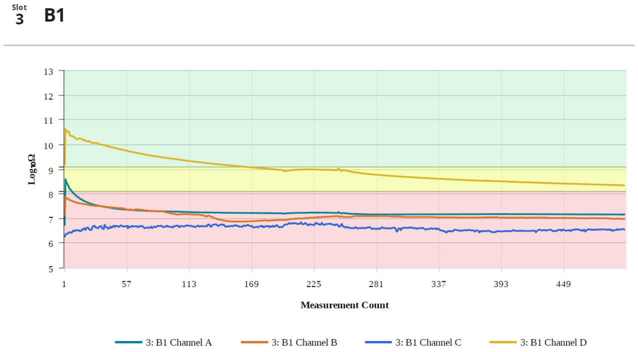
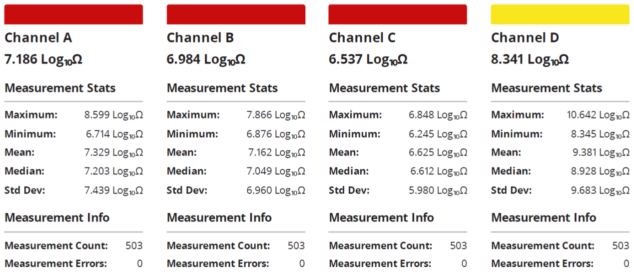


Figure 8: SIR Values in Log$_{10}$Ωs – No Cleaning

Table 1: Board 1 SIR Stats



🟥	🟥	🟥	🟨
Channel A	**Channel B**	**Channel C**	**Channel D**
7.186 Log$_{10}$Ω	**6.984 Log$_{10}$Ω**	**6.537 Log$_{10}$Ω**	**8.341 Log$_{10}$Ω**
Measurement Stats	**Measurement Stats**	**Measurement Stats**	**Measurement Stats**
Maximum: 8.599 Log$_{10}$Ω	**Maximum:** 7.866 Log$_{10}$Ω	**Maximum:** 6.848 Log$_{10}$Ω	**Maximum:** 10.642 Log$_{10}$Ω
Minimum: 6.714 Log$_{10}$Ω	**Minimum:** 6.876 Log$_{10}$Ω	**Minimum:** 6.245 Log$_{10}$Ω	**Minimum:** 8.345 Log$_{10}$Ω
Mean: 7.329 Log$_{10}$Ω	**Mean:** 7.162 Log$_{10}$Ω	**Mean:** 6.625 Log$_{10}$Ω	**Mean:** 9.381 Log$_{10}$Ω
Median: 7.203 Log$_{10}$Ω	**Median:** 7.049 Log$_{10}$Ω	**Median:** 6.612 Log$_{10}$Ω	**Median:** 8.928 Log$_{10}$Ω
Std Dev: 7.439 Log$_{10}$Ω	**Std Dev:** 6.960 Log$_{10}$Ω	**Std Dev:** 5.980 Log$_{10}$Ω	**Std Dev:** 9.683 Log$_{10}$Ω
Measurement Info	**Measurement Info**	**Measurement Info**	**Measurement Info**
Measurement Count: 503	**Measurement Count:** 503	**Measurement Count:** 503	**Measurement Count:** 503
Measurement Errors: 0	**Measurement Errors:** 0	**Measurement Errors:** 0	**Measurement Errors:** 0

The QFN, BGA, and QFP160 had SIR values in the Danger Zone. Each of these components failed SIR testing. The Cap channel slowly declined during the test period with a SIR value in the cautionary zone. These low SIR values are due to low standoff gaps, high levels of flux residue next to the signal pins and under the component termination, and poor outgassing.

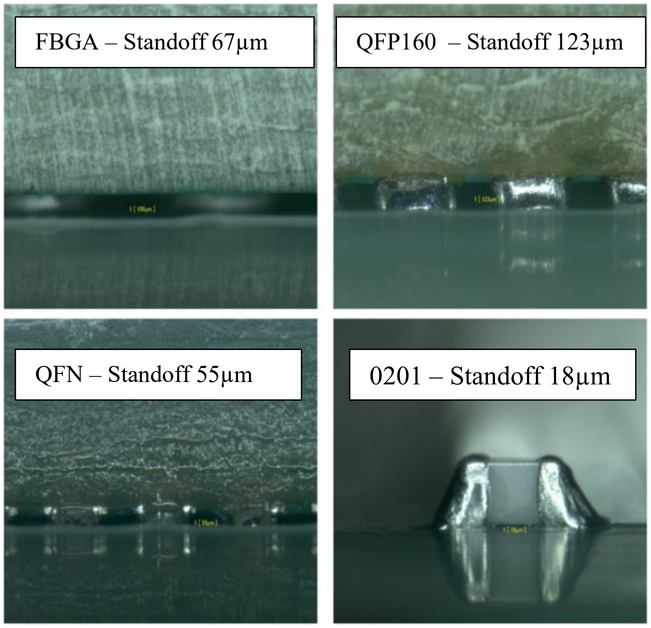


Figure 9: Side Images Post Reflow – No Cleaning

Board 5: Cleaned in an Aqueous Inline Process

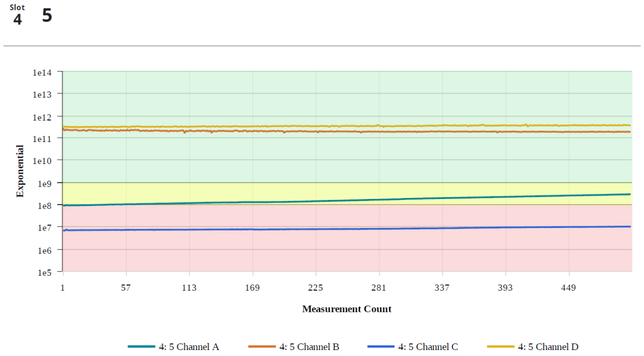
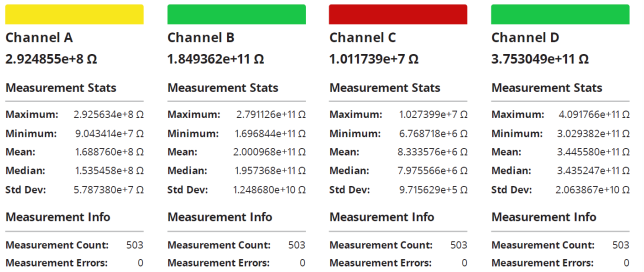


Figure 10: SIR Values in Log$_{10}$Ωs – Inline Cleaned

Table 2: Board 5 SIR Stats



🟨 Channel A	🟩 Channel B	🟥 Channel C	🟩 Channel D
2.924855e+8 Ω	**1.849362e+11 Ω**	**1.011739e+7 Ω**	**3.753049e+11 Ω**
Measurement Stats	**Measurement Stats**	**Measurement Stats**	**Measurement Stats**
Maximum: 2.925634e+8 Ω	**Maximum:** 2.791126e+11 Ω	**Maximum:** 1.027399e+7 Ω	**Maximum:** 4.091766e+11 Ω
Minimum: 9.043414e+7 Ω	**Minimum:** 1.696844e+11 Ω	**Minimum:** 6.768718e+6 Ω	**Minimum:** 3.029382e+11 Ω
Mean: 1.688760e+8 Ω	**Mean:** 2.000968e+11 Ω	**Mean:** 8.333576e+6 Ω	**Mean:** 3.445580e+11 Ω
Median: 1.535458e+8 Ω	**Median:** 1.957368e+11 Ω	**Median:** 7.975566e+6 Ω	**Median:** 3.435247e+11 Ω
Std Dev: 5.787380e+7 Ω	**Std Dev:** 1.248680e+10 Ω	**Std Dev:** 9.715629e+5 Ω	**Std Dev:** 2.063867e+10 Ω
Measurement Info	**Measurement Info**	**Measurement Info**	**Measurement Info**
Measurement Count: 503	**Measurement Count:** 503	**Measurement Count:** 503	**Measurement Count:** 503
Measurement Errors: 0	**Measurement Errors:** 0	**Measurement Errors:** 0	**Measurement Errors:** 0

The inline cleaned board dramatically improved insulation resistance on the BGA and Caps SIR channels. The QFN improved to the cautionary zone. The QFP160 also improved but failed SIR testing with an average of 6.83 $Log_{10}\Omega$s. The side image of each component is shown in Figure 11. Visible flux residue was detected on the QFN, QFP 160 and Caps.

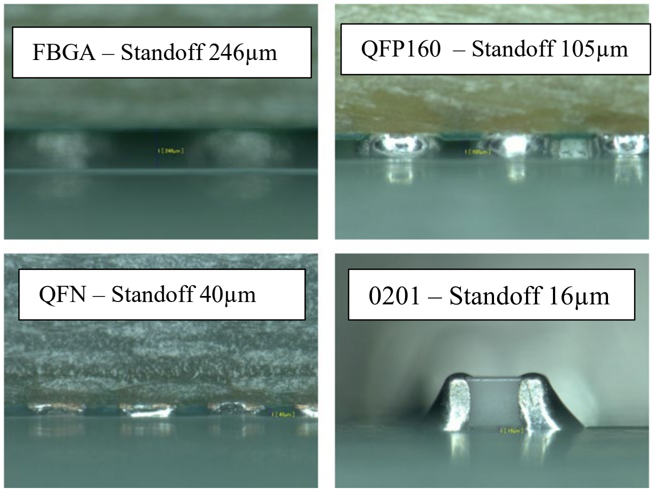


Figure 11: Board 5 Side Images

Board 8: Cleaned in an Aqueous Cabinet Style Batch Process

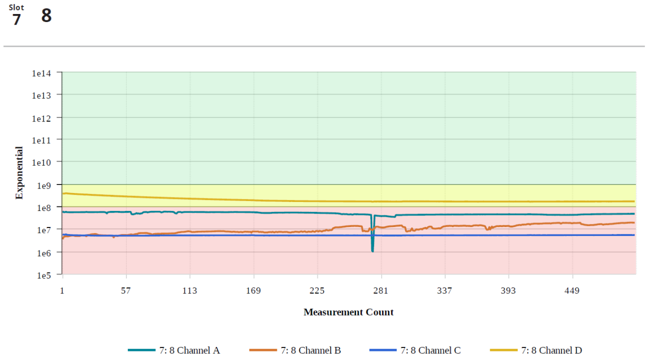
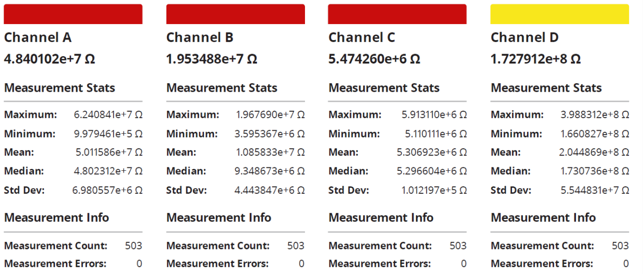


Figure 12: SIR Values in $Log_{10}\Omega$s – Batched Cleaned

Table 3: Board 8 SIR Stats



🟥 Channel A	🟥 Channel B	🟥 Channel C	🟨 Channel D
4.840102e+7 Ω	**1.953488e+7 Ω**	**5.474260e+6 Ω**	**1.727912e+8 Ω**
Measurement Stats	**Measurement Stats**	**Measurement Stats**	**Measurement Stats**
Maximum: 6.240841e+7 Ω	**Maximum:** 1.967690e+7 Ω	**Maximum:** 5.913110e+6 Ω	**Maximum:** 3.988312e+8 Ω
Minimum: 9.979461e+5 Ω	**Minimum:** 3.595367e+6 Ω	**Minimum:** 5.110111e+6 Ω	**Minimum:** 1.660827e+8 Ω
Mean: 5.011586e+7 Ω	**Mean:** 1.085833e+7 Ω	**Mean:** 5.306923e+6 Ω	**Mean:** 2.044869e+8 Ω
Median: 4.802312e+7 Ω	**Median:** 9.348673e+6 Ω	**Median:** 5.296604e+6 Ω	**Median:** 1.730736e+8 Ω
Std Dev: 6.980557e+6 Ω	**Std Dev:** 4.443847e+6 Ω	**Std Dev:** 1.012197e+5 Ω	**Std Dev:** 5.544831e+7 Ω
Measurement Info	**Measurement Info**	**Measurement Info**	**Measurement Info**
Measurement Count: 503	**Measurement Count:** 503	**Measurement Count:** 503	**Measurement Count:** 503
Measurement Errors: 0	**Measurement Errors:** 0	**Measurement Errors:** 0	**Measurement Errors:** 0

The batch cleaning process was less effective at cleaning under the bottom terminations. The QFN, BGA, and QFP80 failed SIR testing. The Caps channel tracked in the Cautionary Zone with a mean SIR of 8.17 $Log_{10}\Omega$. The side images of the components are shown in Figure 13. Visible flux residue was present on the QFN, QFP80, and Caps.

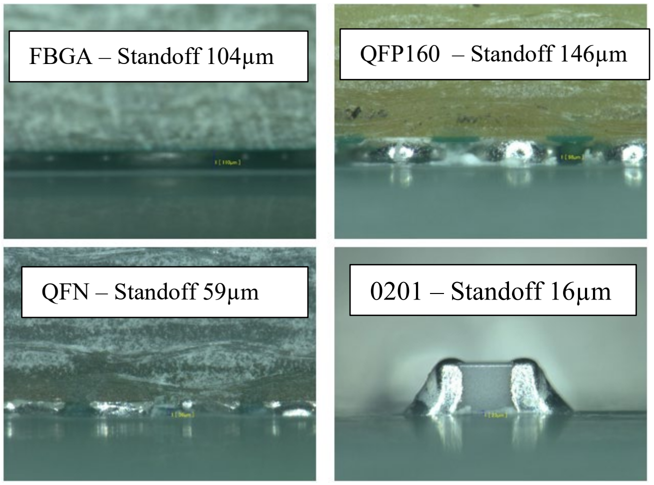


Figure 13: Board 8 Side Images

Inferences from the First Study

Miniaturized Leadless and Bottom Terminated components are challenging components from a residue perspective. Lower standoff gaps increase the amount of flux residue left under the bottom termination. The SIR data finds that these residues are active. Cleaning does help. To clean these components, longer wash time and deflection energy are critical factors.

Study #2

The second study compared Mechanical Dummy components to Laminate Dummy components. Mechanical dummy components are supplied by the component manufacturers. Laminate dummies are lower-cost components designed from FR-4 board materials. The test board was a single-sided, 0.062 inches thick multifunctional FR-4 Laminate, with an IPC-SM-840 Class H qualified solder mask (Figure 14).

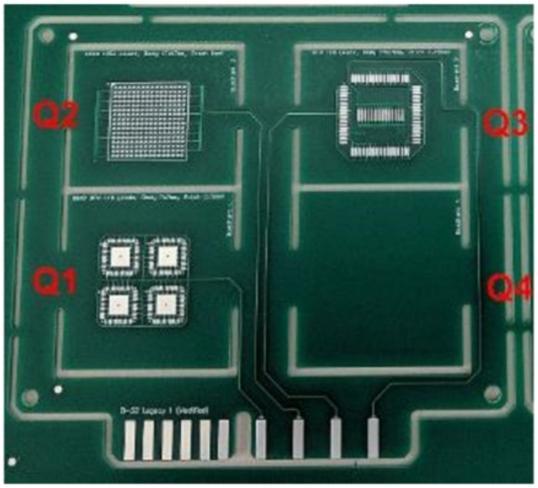
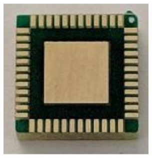


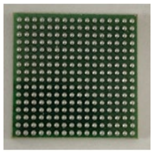
Figure 14: Second Study Test Board

- Channel 1: QFN-48T.5-F-ISO
    - 28-Leads, Body 7x7 mm
    - Pitch 0.5 mm

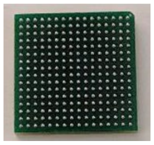
    - Mechanical Dummy



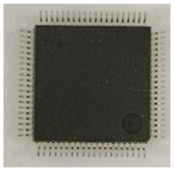
    - Laminate Dummy
- Channel 2: BGA
    - 256 I/O, Body 16x16 mm
    - Pitch 1.0 mm



    - Mechanical Dummy

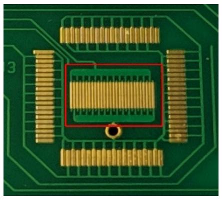


    - Laminate Dummy
- Channel 3: QFP 80 Signal Pins
    - 80 I/O, Body 12x12mm
    - Pitch 0.5 mm
    - Mechanical Dummy – J-Leads



    - Laminate Dummy - Signal pins under the body of the component

    - The mechanical dummy versus the laminate dummy is significantly different.
    - The mechanical is a J-Leaded component and has a higher standoff
    - The laminate is a leadless component and has a much lower standoff
- Channel 4: QFP 80 SIR Comb
    - 250µm (10 mil) spacing between SIR combs
    -



The test boards were assembled with a SAC 305 High-Reliability No-Clean Solder Paste. The boards were inline cleaned before placing them into the SIR test.

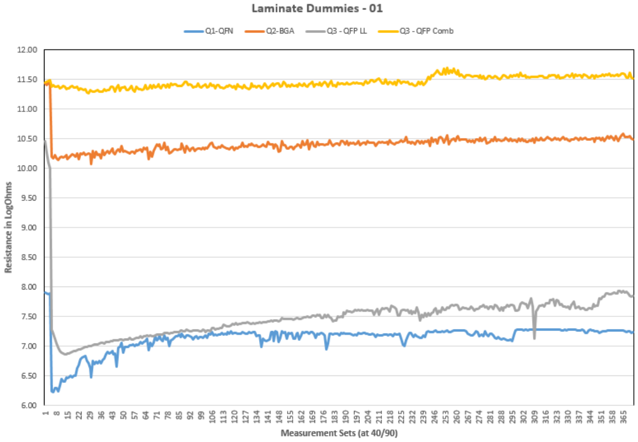


Figure 15: SIR Values in $\text{Log}_{10}\Omega$ for Laminate Dummies

Laminate Dummy Results

The QFN and QFP80 channels failed SIR. Both the BGA and QFP 80 SIR comb pattern achieved high SIR values and ran stable over the test period. The QFP80 signal pins placed under the body of the component exhibits similar challenges to the QFN component.

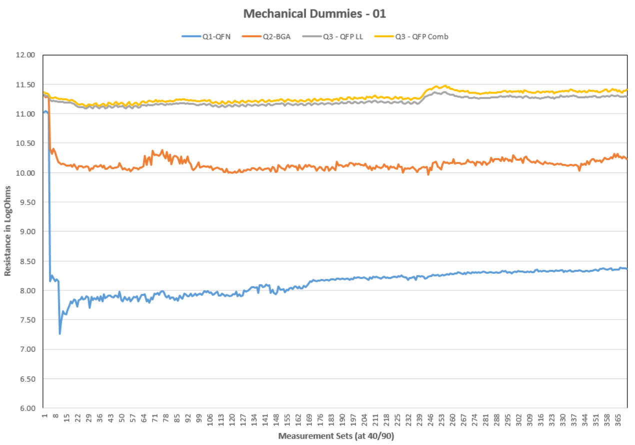


Figure 16: SIR Values in $\text{Log}_{10}\Omega$ for Mechanical Dummies

Mechanical Dummy Results

The QFN mechanical dummy initially failed the SIR test but recovered above log 8 Log10Ωs half way through the test. The other test quadrants passed SIR testing with the BGA, QFP80 pin to pin and QFP80 SIR comb pattern being above 10 $\text{Log}_{10}\Omega$s.

Laminate dummy vs. Mechanical dummy Results

The QFN channel was marginally better in the mechanical dummy versus the laminate dummy. Even though there were differences, the QFN laminate is comparable to the laminate dummy. The data finds that the QFN laminate dummy is slightly more difficult to clean and outgas compared to the mechanical part. The BGA and SIR Comb were comparable to the laminate dummies. The J-Lead QFP 80 mechanical dummy was significantly more straightforward to clean than was the Leadless laminate dummy because the laminate QFP 80 dummy had bottom leadless terminations. The J-Leads are on the components outside peripheral. The flux residue properly outgasses and is easier to clean.

The QFP80 laminate dummy has a higher cubic volume of solder paste in a leadless format. When reflowed, the QFP80 dummy releases a larger volume of flux residue into the gap. Closing up this gap reduces flux outgassing. Technically, this component represents a tougher cleaning challenge.

Study #3

The first two studies find that the cubic volume of flux residue under the bottom termination and the standoff height are critical factors. The combination of the low standoff height and high amounts of flux residue (volume) result in low SIR values. The common logic is to raise the standoff height. As the number of interconnects increases along with the addition of thermal lugs, increasing standoff gaps are difficult to design.

The QFP 80 laminate design is the focus of the third study. The narrow pitch, width, length of the signal pins bridges flux residue across the signal pins. To address this challenge, the pad dimensions were resized. The revised pad dimension size was 0.35 x 0.9 mm as compared to 0.45 x 1.8mm. The new dimension increases the distance (gap) between signal pins by 0.1 mm and reduces pad length by 0.90 mm. The reduced pad size does not increase standoff height. The reduced pad size does reduce the cubic volume of flux residue that is now released into the pad to pad gap and thus improves outgassing channels. The reduction in pad size aids in cleaning energy impingement access.

The original pad dimensions for the laminate QFP pin to pin area is .45 mm by 1.8mm with a .65mm center to center gap. By reducing the length and the width of the pads we were able to reduce the cubic flux residue volume between the solder pads and improve outgassing and cleaning performance.

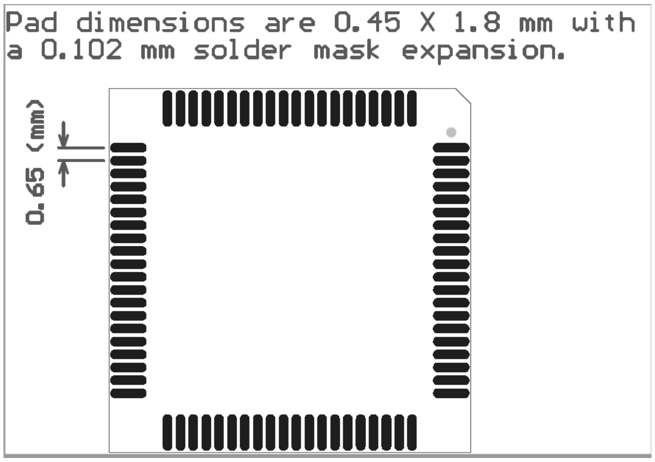


Figure 17: QFP 80 Laminate Dummy Pad Dimensions

After respinning the test board, a new set of test boards were populated and soldered with the same SAC 305 Pb-Free solder paste. The boards were inline cleaned using the following belt speeds:

- 2.0 FPM
- 1.5 FPM
- 1.0 FPM
- 0.5 FPM

The test boards were SIR tested using the same test conditions (40°C / 90% RH / 5V / 168-hours).

- 2.0 FPM Cleaned – Mechanical slightly better than the Resized Laminate design by 0.5 $\text{Log}_{10}\Omega$s.

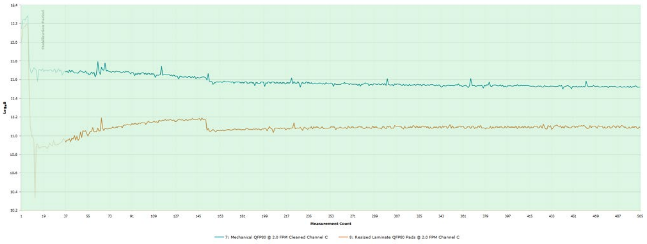
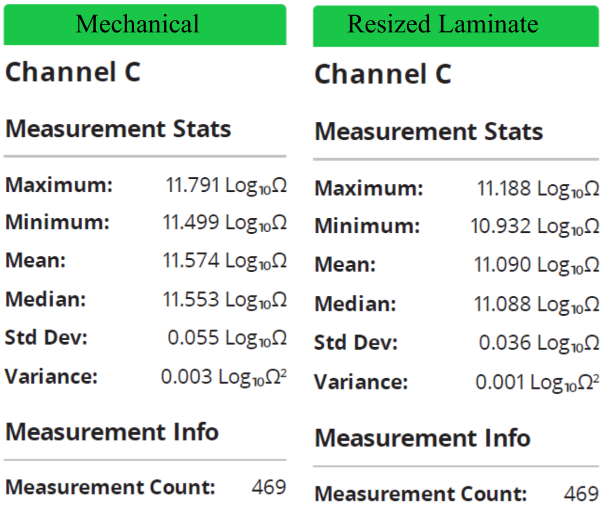


Figure 18: Mechanical / Laminate Comparison @ 2.0 FPM Inline Cleaned

Table 4: Mechanical / Laminate Stats @ 2 FPM Cleaned



Mechanical		Resized Laminate	
Channel C		**Channel C**	
Measurement Stats		**Measurement Stats**	
Maximum:	11.791 Log$_{10}\Omega$	**Maximum:**	11.188 Log$_{10}\Omega$
Minimum:	11.499 Log$_{10}\Omega$	**Minimum:**	10.932 Log$_{10}\Omega$
Mean:	11.574 Log$_{10}\Omega$	**Mean:**	11.090 Log$_{10}\Omega$
Median:	11.553 Log$_{10}\Omega$	**Median:**	11.088 Log$_{10}\Omega$
Std Dev:	0.055 Log$_{10}\Omega$	**Std Dev:**	0.036 Log$_{10}\Omega$
Variance:	0.003 Log$_{10}\Omega^2$	**Variance:**	0.001 Log$_{10}\Omega^2$
Measurement Info		**Measurement Info**	
Measurement Count:	469	**Measurement Count:**	469

- 1.5 FPM Cleaned – Mechanical and Resized Laminate were identical SIR Results

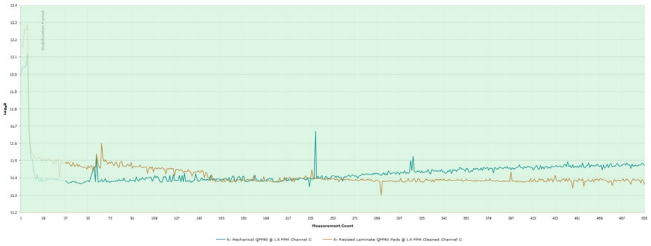
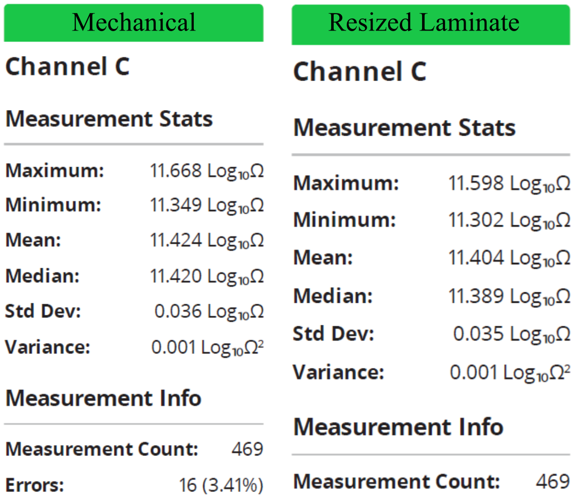


Figure 19: Mechanical / Laminate @ 1.5 FPM Cleaned

Table 5: Mechanical / Laminate @ 1.5 FPM Cleaned



Mechanical		Resized Laminate	
Channel C		**Channel C**	
Measurement Stats		**Measurement Stats**	
Maximum:	11.668 Log$_{10}\Omega$	**Maximum:**	11.598 Log$_{10}\Omega$
Minimum:	11.349 Log$_{10}\Omega$	**Minimum:**	11.302 Log$_{10}\Omega$
Mean:	11.424 Log$_{10}\Omega$	**Mean:**	11.404 Log$_{10}\Omega$
Median:	11.420 Log$_{10}\Omega$	**Median:**	11.389 Log$_{10}\Omega$
Std Dev:	0.036 Log$_{10}\Omega$	**Std Dev:**	0.035 Log$_{10}\Omega$
Variance:	0.001 Log$_{10}\Omega^2$	**Variance:**	0.001 Log$_{10}\Omega^2$
Measurement Info		**Measurement Info**	
Measurement Count:	469	**Measurement Count:**	469
Errors:	16 (3.41%)		

- 1.0 FPM Cleaned – Mechanical was more stable and better than the Resized Laminate design in this case sample.

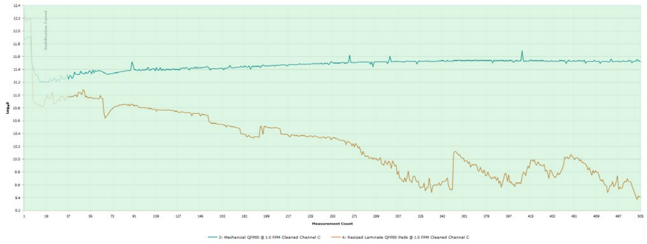
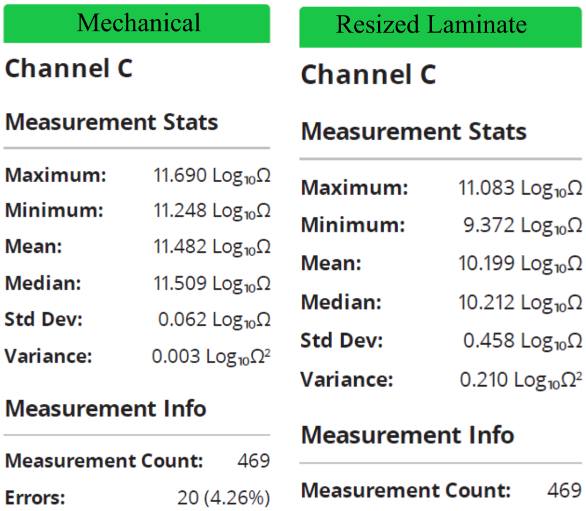


Figure 20: Mechanical / Laminate @ 1.0 FPM Cleaned

Table 6: Mechanical / Laminate @ 1.0 FPM Cleaned



Mechanical		Resized Laminate	
Channel C		**Channel C**	
Measurement Stats		**Measurement Stats**	
Maximum:	11.690 Log$_{10}\Omega$	**Maximum:**	11.083 Log$_{10}\Omega$
Minimum:	11.248 Log$_{10}\Omega$	**Minimum:**	9.372 Log$_{10}\Omega$
Mean:	11.482 Log$_{10}\Omega$	**Mean:**	10.199 Log$_{10}\Omega$
Median:	11.509 Log$_{10}\Omega$	**Median:**	10.212 Log$_{10}\Omega$
Std Dev:	0.062 Log$_{10}\Omega$	**Std Dev:**	0.458 Log$_{10}\Omega$
Variance:	0.003 Log$_{10}\Omega^2$	**Variance:**	0.210 Log$_{10}\Omega^2$
Measurement Info		**Measurement Info**	
Measurement Count:	469	**Measurement Count:**	469
Errors:	20 (4.26%)		

- 0.5 FPM Cleaned – Laminate Dummy is more stable and better than the true mechanical dummy in this case sample

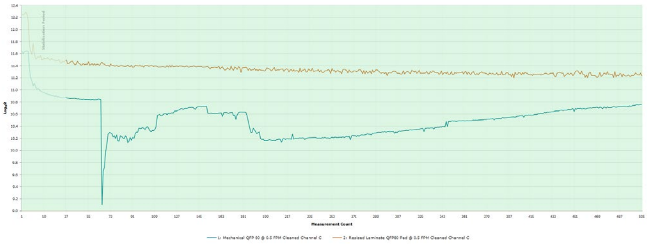
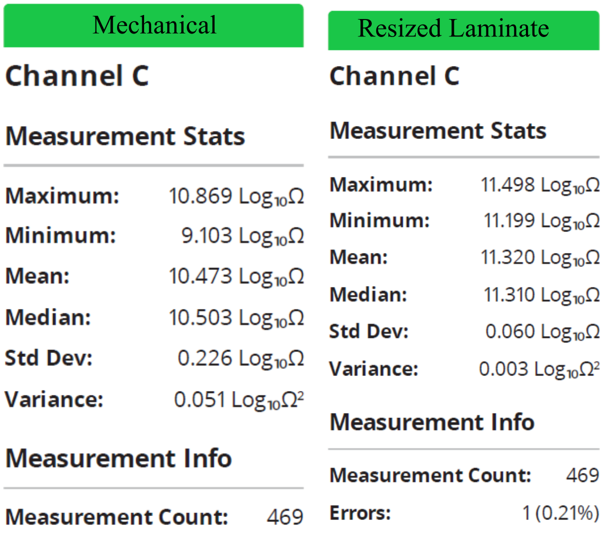


Figure 21: Mechanical / Laminate @ 0.5 FPM Cleaned

Table 7: Mechanical / Laminate @ 0.5 FPM Cleaned



Mechanical

Channel C

Measurement Stats

Maximum:	10.869 $\text{Log}_{10}\Omega$
Minimum:	9.103 $\text{Log}_{10}\Omega$
Mean:	10.473 $\text{Log}_{10}\Omega$
Median:	10.503 $\text{Log}_{10}\Omega$
Std Dev:	0.226 $\text{Log}_{10}\Omega$
Variance:	0.051 $\text{Log}_{10}\Omega^2$

Measurement Info

Measurement Count:	469

Resized Laminate

Channel C

Measurement Stats

Maximum:	11.498 $\text{Log}_{10}\Omega$
Minimum:	11.199 $\text{Log}_{10}\Omega$
Mean:	11.320 $\text{Log}_{10}\Omega$
Median:	11.310 $\text{Log}_{10}\Omega$
Std Dev:	0.060 $\text{Log}_{10}\Omega$
Variance:	0.003 $\text{Log}_{10}\Omega^2$

Measurement Info

Measurement Count:	469
Errors:	1 (0.21%)

Inferences from the Data Findings

These studies show that flux residue is a complex multi-variable problem that takes requires a number of different variables or parameters to be controlled to achieve repeatable and consistent SIR values. The following insights can be drawn from this work.

1. Component standoff height is not the single most important variable influencing SIR values
2. Cleaning time/dwell has a large variable impact on SIR values
3. No-Clean is only successful when there are adequate outgassing channels to ensure all activators are catalyzed.
4. Pad design and pad gap spacing plays a significant role in outgassing and cleaning access
5. Flux cubic volume residue and z-axis height plays a significant roll in SIR values
6. Laminate dummy parts can be made to replicate their actual real mechanical part very closely for SIR testing
7. Objective Evidence and real test data can be used to design more reliable hardware by understanding component and circuit board design options.
8. SIR testing can aid system design engineers in designing more robust and better performing electronics for their infield use environments by assisting them in a higher degree of understanding of failure modes by component type and style in different operating environments from benign to harsh environments.
9. SIR is a tool used to evaluate circuit designs and components, process control engineers, quality reliability engineers, and the ability to assess which flux systems to use. Manufacturing processes and process parameters must be dialed in to obtain repeatable product hardware.

CONCLUSIONS

The ability to quantify and qualify the multiple variables that impact cleanliness and reliability with a SIR tool allows both designers and process engineers to quantify any harmful effects that might arise from solder flux, component designs, or other process residues left on external surfaces after soldering.

Different industries and products require different levels of reliability and warranty expectations. The ability to determine the level of insulation resistance using high-resolution testing allows one to determine which material sets, processes and process parameters are needed to meet the system design engineers' reliability and warranty objectives.

Cleanliness is becoming a significant concern for reliability due to the miniaturization and reduction in form factors of today's electronics. The ability to measure and understand surface contamination and corrosivity underneath our electronic components are essential to our future. SIR testing is the tool that paves the way for future miniaturization by allowing engineers to know and measure surface insulation resistance underneath high I/O devices, bottom terminated components and leadless devices.

The above three studies showed us the importance of finding all the variables that influence SIR values underneath components and that the flux cubic volume of residue plays just as big a role as standoff height, flux type and they're ionic makeup. Our challenge of tomorrow is to continue to design test tools and test vehicles that continue to allow us to gather real actionable data for these small and miniature locations where ionic contamination can exist and activate into leakage currents and electrochemical migration paths.

REFERENCES

[1]. IPC-J-STD-001G, Amendment 1. (September 2018). *Requirements for Soldering Electrical and Electronic Assemblies.* IPC, Bannockburn, IL.

[2]. Bixenman, M., Sitko, V., & McMeen, M. (Feb 2020). *Qualified Manufacturing Process Development by Applying IPC J-STD-001G Cleanliness Standard.* IPC APEX 2020.

[3]. Capen, B., Edgar, J., McMeen, M., & Bixenman, M. (Sep. 2019). *Risk Management of Class 3 Electronics as a Function of Cleanliness.* SMTAI 2019.

[4]. McMeen, M., & Bixenman, M. (Sep. 2019). *Printed Circuit Board Design can Impact Electrochemical Reliability.* SMTAI 2019.

[5]. IPC 9202. (October 2011). *Material and Process Characterization/Qualification Test Protocol for Assessing Electrochemical Performance.* IPC, Bannockburn, IL.