

Pockets of Contamination That Are Causing Field Failures and How to Avoid Them

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Abstract

The areas of entrapment on cleaned and no-clean assemblies are showing higher levels of contamination around BGA's, in microvias and particularly under components like the QFN. Flux residues trapped under and around low standoff components that are causing leakage paths are negatively impacting field performance, and are showing up as no trouble found return more often than ever. Microvias are corroding open during soldering due to the contamination from fabrication found in vias from the etch steps and poor cup rinsing of the plugged vias. This paper will cover techniques for investigating pockets of contamination using a localized extraction method and ion chromatography analysis to establish root cause, and the development of corrective action plans for field failure projects. Defining, implementing and monitoring corrective action plans for the failed assemblies has allowed us to understand the processing variables, and optimize the critical parameters that meet the performance needs of today's technology.

Introduction

Today's technology calls for smaller circuit boards with more functionality than ever, and with that comes a myriad of issues that have to be addressed if these smaller boards are to function properly with the latest and greatest advancements in components. If a PCB build process is planned properly and the hard work is done up front, there will be very low risk in producing a product with these new components that have very tight lead spacing, or very tight body to board spacing. Building with components like the QFN, high density BGA's or one of the newer hybrids of QFNs incorporated into the bottom side of a TQFP challenge even the best build houses and designers. With body to board spacing of less than .5mm, and lead spacing even tighter in some cases, the ability to either remove all flux residues, or to ensure that any no-clean flux is completely benign and poses low-to-no risk of corrosion is more important than ever. The most commonly used industry recognized methods for examining ionic cleanliness have the potential to overlook contaminants that are present in small volume when considering the entire board surface, but are localized to a sensitive area of circuitry where they can react with moisture and applied voltage to create a system failure. Research has been forged to examine the localized residue effects around such sensitive areas of circuitry, and results have uncovered the negative effects of these localized residues through a number of analyses. To expound upon ionic cleanliness, it can be defined as a result, or signature, of the assembly process, materials and secondary processes required to create a finished assembly. Ionic residue types and levels are the product of assembly cleanliness; how these residues react pad-to-pad and hole-to-hole determines the quality of electrical performance. Through correlation analysis, it has been found that circuit board field performance, good or bad, is directly proportional to the specific amount of visible and invisible residues between pads and holes in all areas of active circuitry. This paper will compare and contrast today's methods for determining ionic cleanliness, and identifies what the most common residue types are as well as where they commonly come from. This paper will also exemplify how utilizing techniques to examine localized contamination have proven highly effective in troubleshooting field failures, and can also be used as a preventative process control tool to monitor localized cleanliness right in the production line. Finally, this paper will discuss cleaning challenges brought forth by localized contamination issues, and how processing residues affect cleaning process effectiveness. There are two ways to determine if a build process is effective or not: proactive or reactive. Usually, the former will save money in the long run; the latter will sometimes teach you more, but with the side effect of painful money loss and customer dissatisfaction. This paper examines the latter, the lessons learned and what tools can be used to identify root cause.

Extraction & Testing Methods to Assess Localized Contamination

Ion chromatography has been proven time and again as a very meaningful and valuable tool in determining ionic contamination levels that are indicative of potential field performance problems. One aspect that this test method has not been able to approach until recently is the potential for localized pockets of contamination to become overlooked with standard extraction techniques. With closer circuit spacing and advanced surface mount devices, there is great potential for ionic residues to become concentrated and entrapped in such sensitive areas that directly impact product performance. Because of the need to look at circuitry from a localized perspective, it was important to research methods in which to accomplish this goal.

Through combined research and development efforts between Foresite and Rose Hulman University, as well as a 21st Century Technology Research Grant, a tool was designed to analyze a 0.1 in² area of circuitry by providing a localized cleanliness reading, and extracting a sample for ion chromatography testing.

The designed system uses a deionized steam extraction system to collect a 2.2 ml sample from a 0.1 in² area of circuitry. The system produces a microburst of steam that is allowed to soak for 20 seconds, and is then aspirated into a collection cell. This steam is applied 5 times to achieve effective residue removal from the area of analysis. After 9 collection cycles, an electrical test is performed across a sacrificial y-pattern electrode to check for electrical leakage. 10v of electricity is applied, and the system makes a determination after 60 seconds as to whether or not the sample is 'clean' or 'dirty'. The current threshold for considering a sample clean is 500 μ A, and is based on 13 years of data collection through ionic analysis in failure analysis applications. The electrical test continues to run for two minutes after the cleanliness determination is made, and current readings are recorded in the testing program. The extracted sample can then be used for ion chromatography analysis to determine the exact type and quantity of the localized contamination.

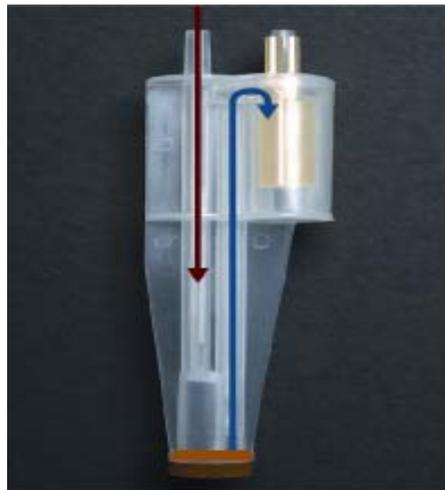


Figure 1 Diagram of localized steam extraction test and collection cell

This evaluation used Ion Chromatography per IPC-TM-650, method 2.3.28 to characterize process residues. All testing was performed on a Dionex ICS 2000 ion chromatography system using Chromeleon software. Controls and blanks were performed on the Dionex ICS 2000 ion chromatography system before the test began. *NOTE: Foresite uses NIST-traceable standards for all system calibrations.* A 1.5mL sample of each test samples' extracted solution was analyzed using a 1.7mM sodium bicarbonate/1.8mM sodium carbonate eluent using the AS4A-SC column and all results were reported in μ g/in².

Test Subjects

Flux volatilization is a critical factor in maintaining ionic cleanliness levels that lend to reliable performance. In a no-clean process, when the flux is activated and fully volatilizes, it leaves a benign residue carrier or solvent that will not have a negative impact on field performance. As previously mentioned, new and compact forms of integrated circuit packaging, particularly PQFN packages, solve spacing issues for power electronics assemblers but have been shown to entrap flux residues by not allowing a volatilization path. This occurrence can cause the entrapment of a high concentration of gooeey flux residue that contributes to a high propensity for product failures. Though space is saved by a smaller footprint and replacement of axial leads, potential for flux entrapment becomes a huge concern to those using this type of package. In other words, sometimes space conservation comes at a cost. A customer of Foresite was using a PQFN package in an automotive application and was experiencing stray voltage failures. This caused LEDs to stay on, and eventually caused failures. Upon mechanically removing this package from the assembly heavy visible flux residues were discovered. This customer sent several assemblies for us to analyze and determine what the source and type of ionic contamination was. This was a no-clean process with some selective soldering sites as well. There were visible flux residues on the assembly, and the areas we looked at included the PQFN package component as well as several selective soldering and reference sites. We also looked at the cleanliness of incoming bare boards, and virgin PQFN packages. The selective sites showed low residue levels indicating that the no-clean flux had done its job, and volatilized. The failure area around the PQFN package showed only

one flux activator group, and gave readings of high weak organic acids (WOA). These residues were coming from marginal cleanliness levels of the bare board and components combined with the flux used in wave solder.

All of these elements combined and trapped under the PQFN package create a very high risk for conductive pathways to form. It was found that they used a nominal range profile for the reflow oven used with the no-clean paste. We tried modifying to a higher reflow profile, but there was still gooeey, non-complexed flux under the package. The reason for this phenomenon is that as the weight of the PQFN package collapses over the molten solder paste during reflow, flux from the outside is sinking over and becoming trapped underneath the package where it cannot be complexed and released. The PQFN, which sits atop solder paste at a 6 mil stencil thickness, is able to drop down to 3-4 mils, thus trapping the flux and blocking the solvent path of volatilization. The parts were sheared off of the assembly to perform the site specific extraction and further testing with ion chromatography, results are in Table 1, photo of underside of component with flux in figures 1&2.

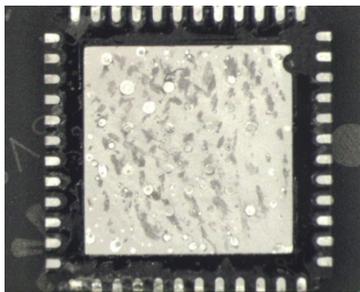


Figure 2 Bottom of PQFN with Flux

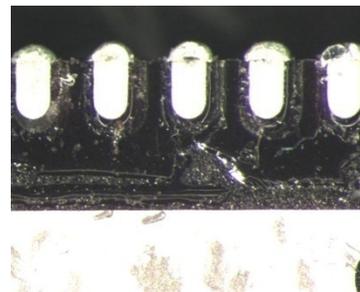


Figure 3 Close-up of same PQFN

Table 1-Ion Chromatography Results

Sample Description	Ion Chromatography						C3 Tester	
	Cl ⁻	Br ⁻	WOA	SO ₄ ⁻	Na+	NH ₄ +	Results	Time(sec)
Board #1 PQFN area	3.42	2.53	114.17	3.25	5.11	3.69	Dirty	33
Board #1 Reference Area	3.09	2.77	16.33	3.69	5.33	3.51	Clean	86
Board #2 PQFN area	3.19	2.62	182.08	3.18	4.12	4.02	Dirty	39
Board #2 Reference Area	3.49	2.44	14.63	3.27	4.32	3.87	Clean	74
Board #3 PQFN area	3.26	3.12	102.82	3.09	4.29	2.94	Dirty	41
Board #3 Reference Area	3.41	3.08	18.37	3.39	4.01	2.88	Clean	82
Board #4 PQFN area	1.08	3.17	92.65	0.27	1.21	0.27	Dirty	56
Board #4 Reference Area	0.89	2.98	11.52	0.23	1.47	0.33	Clean	180
Board #5 PQFN Area	3.78	3.50	59.36	3.21	4.32	3.05	Dirty	59
Board #5 Reference Area	3.62	3.14	18.78	3.09	4.74	3.66	Clean	91
Board #6 PQFN Area	1.67	3.33	71.32	1.21	1.69	1.21	Dirty	51
Board #6 Reference area	1.23	3.05	14.62	1.11	1.84	1.06	Clean	165
Board #7 PQFN area	3.60	3.27	68.36	3.34	4.69	3.55	Dirty	34
Board #7 Reference Area	3.53	3.44	13.21	3.64	4.41	3.16	Clean	82
PQFN package in tape and reel #1	1.02	0.22	0.00	0.24	0.39	0.15	Clean	180
PQFN package in tape and reel #2	0.89	0.29	0.00	0.15	0.31	0.11	Clean	180
Bare Panel#1	1.35	3.19	0.00	2.19	0.22	1.77	Clean	180
Bare Panel#2	1.26	3.44	0.00	2.36	0.26	1.98	Clean	163

All values in $\mu\text{g} / \text{in}^2$

We were asked to develop a corrective action plan to prevent future field failures, and recover the contaminated assemblies through rescue cleaning. This customer implemented several corrective actions suggested by Foresite in order to prevent the flux entrapment. The first recommended action was a design change suggested which was to remove some of the pads from underneath the PQFN components. Fewer pads mean lowered opportunities for contamination. The final design change

suggested was the widening of the gap between the power and the ground. This wider spacing decreases the risk of bridging. In addition to these design changes, also suggested was closer monitoring of solder paste deposition, and the use of less solder paste and to monitor the cleanliness levels of incoming bare boards as well as the components. To analyze whether or not these suggested changes were effective in eliminating the problem of goeey contamination under the PQFN parts, we analyzed additional samples manufactured with the original process, and compared them to assemblies manufactured with the suggested design changes. As seen in the analysis from table 2, the original process produced assemblies with high amounts of weak organic acid flux residues, and still exhibited a thick, goeey flux residue underneath the PQFN components. The assemblies built with the suggested design changes, including modified spacing and pad placement, showed acceptable low levels of weak organic acid residues. The flux residue was able to volatilize under these conditions, and all ionic residue levels for these assemblies fell within limits for reliable field performance. Table 2 shows ion chromatography results on follow up samples with suggested changes; figure 3 is a depiction of changes made to component design and details.

Table-2 Ion Chromatography Follow Up Results

Sample Description	Ion Chromatography						C3 Tester	
	Cl ⁻	Br ⁻	WOA	SO ₄ ⁻	Na+	NH ₄ ⁺	Results	Time(sec)
Unit Built with Foresite's Recommended Design Changes								
Area 1: PQFN Removed from Board	0.83	10.38	4.46	2.54	3.98	2.39	Clean	180
Area 2: PQFN Removed from Board	0.64	10.62	2.99	2.33	3.47	3.01	Clean	180
C3 extraction of Area 1 on Board	1.78	1.04	19.35	1.97	2.99	2.24	Clean	153
C3 extraction of Area 2 on Board	1.06	1.69	18.81	2.14	1.87	2.54	Clean	161
Unit Built with Original Process - Goeey Contamination under PQFN								
Area 1: PQFN Removed from Board	0.51	9.99	38.57	2.76	2.48	2.29	Dirty	27
Area 2: PQFN Removed from Board	0.81	10.01	30.16	1.88	3.43	3.23	Dirty	23
C3 extraction of Area 1 on Board	1.12	0.67	49.39	1.76	3.97	2.78	Dirty	18
C3 extraction of Area 2 on Board	1.46	0.87	43.41	2.39	1.33	2.26	Dirty	13

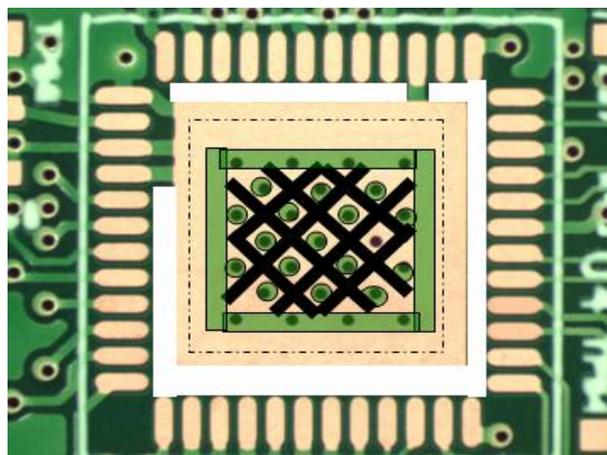


Figure 4- Depiction of PQFN recommended changes and details

1. Remove inside area soldermask (except on ground contact pads or attach the ground to the thermal vias on the other side and eliminate traces to ground pad)
2. Reduce Center pad by 15% on all sides
3. Plug all via's with mask and place
4. Solder mask in the mask defined area with diamonds (black)

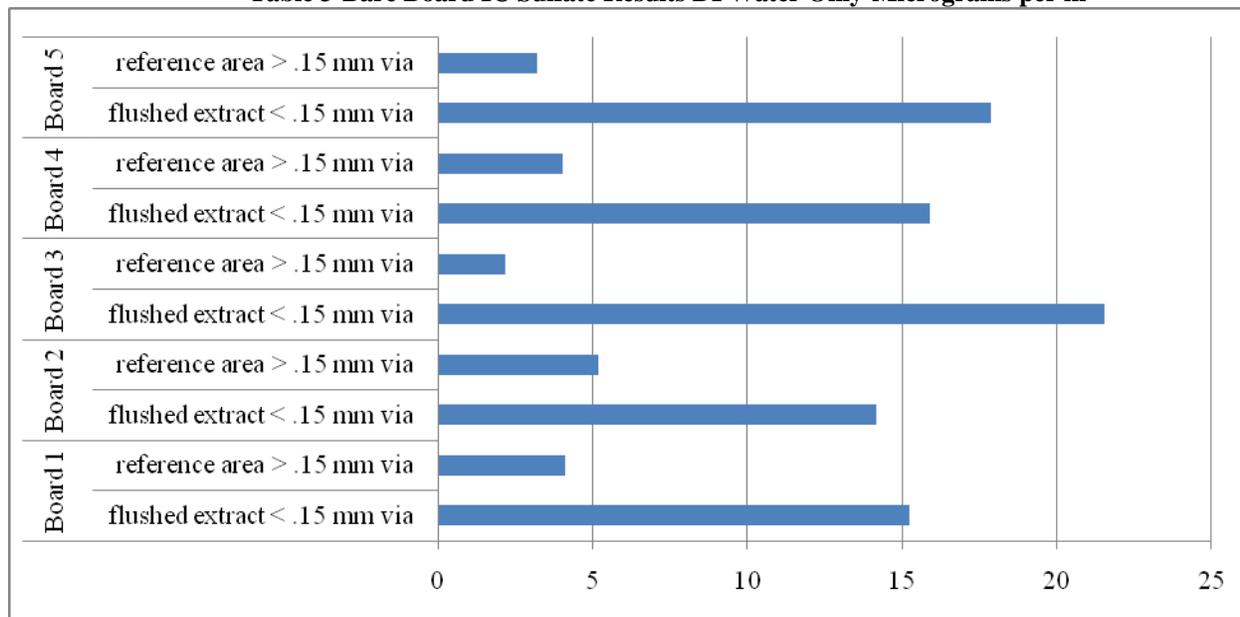
Foresite was also asked to design a cleaning protocol to recover parts built with the original process. We proved out a process that included saponified cleaning, and the use of a hand held steamer that produces 195 psi continuously directed heavily around the PQFN.

After the cleaning process, a few boards were sacrificed, and the PQFN was sheared off of the board, and the area locally extracted for ion chromatography. The results were very similar to the boards processed with the recommended changes, and to date are performing well in the field.

Issues with Vias and Micro-Vias

A companion issue to flux residue beneath the PQFN package is a concern with contaminated vias, especially when directly under components. We have found a few bare board fabricators that historically have had no issues with bare board cleanliness that were being asked to put tighter cleanliness acceptance levels in place because of the sensitive nature of the surface mount PQFN problems previously discussed. When the process window tightens, all of the materials involved must be held to cleaner standards than ever before. For years, vendor X produced boards with typical levels of <3 +/- 2 from time-to-time on sulfate without issue, but when one of the assembly houses began building with several of the PQFN packages, a series of field failures were found directly related to cleanliness underneath these low standoff components. A study of via cleanliness was performed, and areas with vias >.15 mm were found to be much cleaner than the vias that were smaller than that. Simple surface tension was the main culprit. The normal DI water alone was not able to penetrate the smaller vias, and remove the etchants used in processing. The level of sulfate residues in addition to other process residues, and a normal amount of humidity found in service, was enough to cause the failures (see table 3). A 5% solution of saponifier/DI water was put in place, and this was enough of a decrease in surface tension to access the etchant residues entrapped in the smaller vias, and adequately rinse them out (see table 4). Levels dropped to very comparable sulfate residue amounts across the surface of the bare board. We have not found any further field failures to date with this product related to the cleanliness in vias issue.

Table 3-Bare Board IC Sulfate Results DI Water Only-Micrograms per in²





Pockets of Contamination that are causing field failures and how to avoid them

Presented by

Eric Camden
Lead Investigator



Components with pockets of contamination that are primary contributors to field failures

- Grid Arrays

PGA, BGA, LFBGA, CGA CCGA

- Quad-In-Line

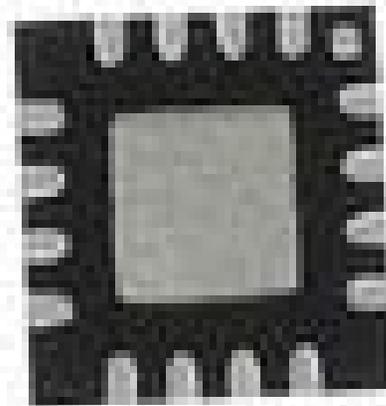
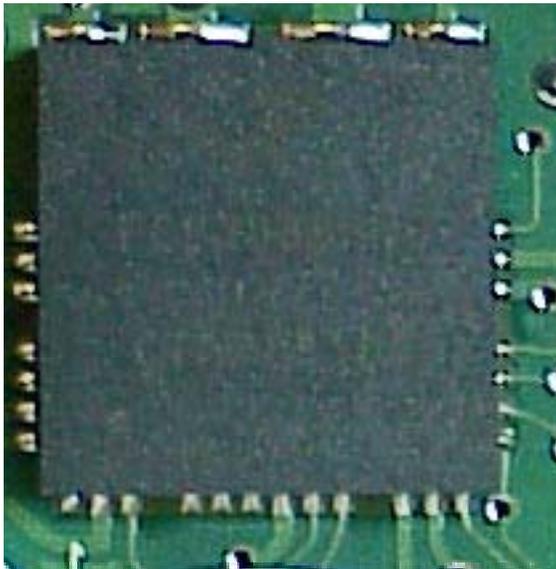
PLCC, QFP, LQFP, PQFP, CQFP, TQFP,
QFN, LCC, PQFN

- Dual-In-Line

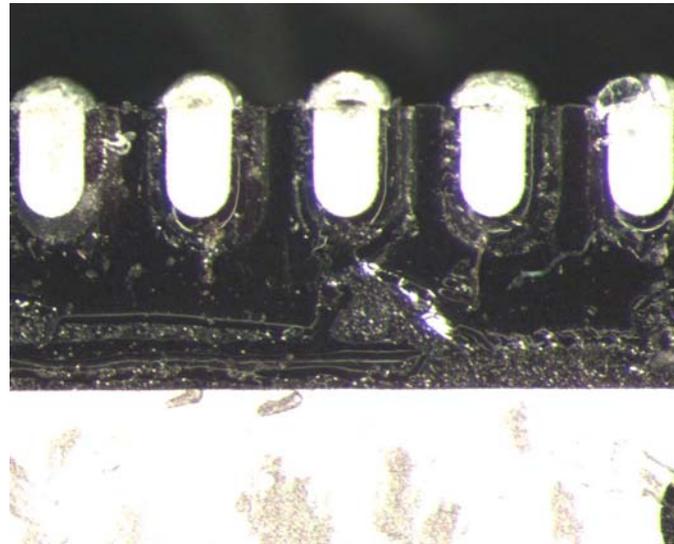
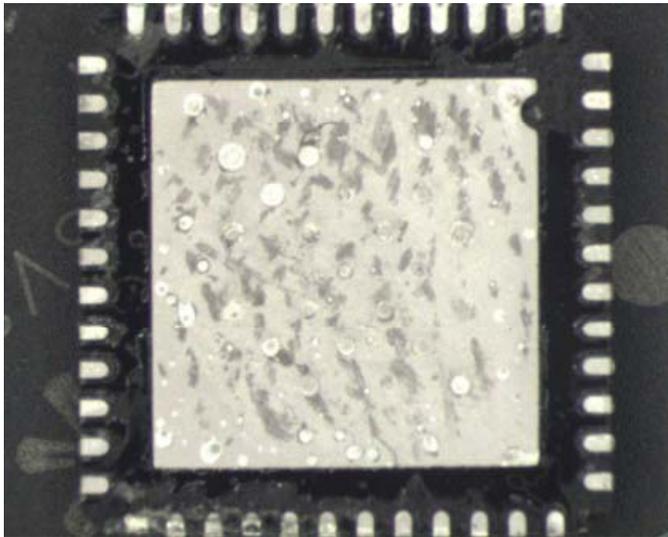
SOIC, TSOP, VSOP

Let's Focus on the PQFN

Do you build with components that look like these when you start?

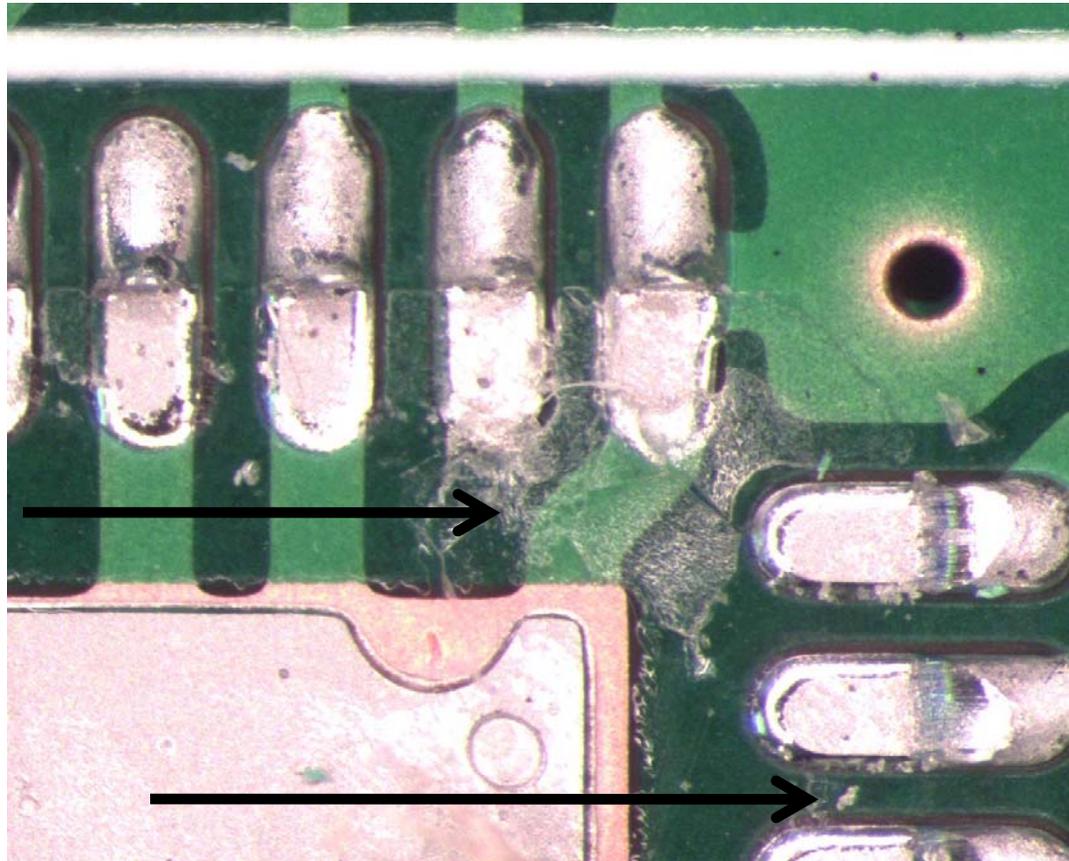


Do they look like this when you're done?



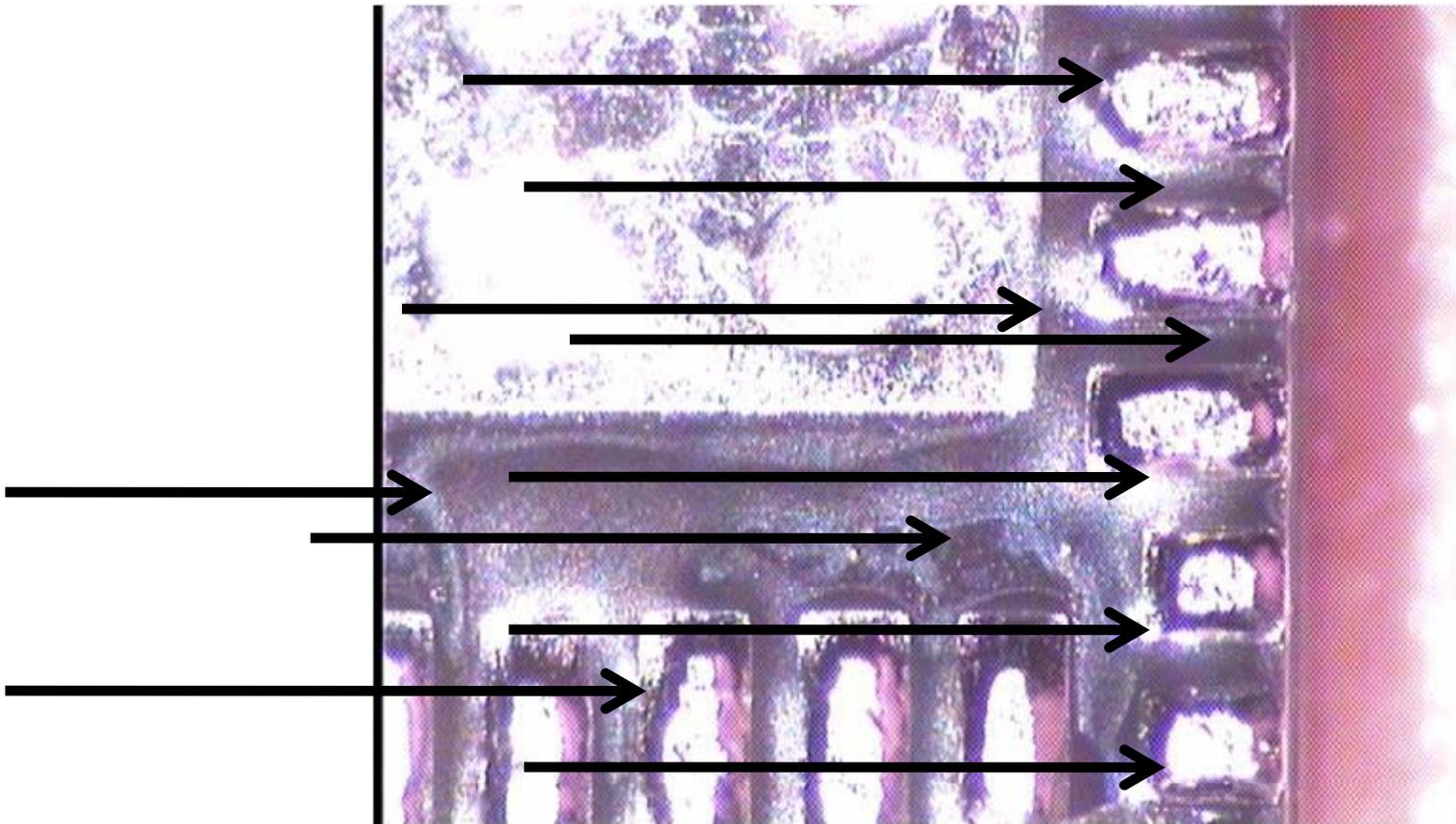
Are you sure?

Board Level #1



Heavy Flux Residue Under PQFN

Board Level #2



Sorry, there is lots of active flux here

Q&A (kind of)

If you are leaving this kind of residue there are two questions that have to be answered:

1. Is it benign?
2. Is it benign?

OK, that's one question but it is one important question to know!

Ways to determine the Answer

Ion Chromatography

One of the most common tools used to identify residues and determine the level of activity is IC. If you perform a localized extraction beneath the component, either by cutting the area from the board and use standard IPA/DI extraction or using a tool for site specific extraction, it is very important to mechanically remove the component and not subject the residues to thermal excursion, as this can alter the results.

IC Procedure

The component was mechanically removed with a clean blade to expose the flux residues. Remember that any secondary thermal exposure it can alter results.



Localized Extraction

A commercially available localized extraction method was used to harvest sample for IC analysis. An overall standard extraction would not tell if there is an issue beneath components



Ion Chromatography

- All testing was performed on a Dionex ICS 2000 ion chromatography system using Chromeleon software
- Controls and blanks were performed on the Dionex ICS 2000 ion chromatography system before the test began. *NOTE: NIST-traceable standards were used for all system calibrations*
- A 1.5mL sample of each test samples' extracted solution was analyzed using a 1.7mM sodium bicarbonate/1.8mM sodium carbonate eluent.

IC Findings

- These are IC results from the area below the removed component as well as a reference area 1/2 inch away from extraction area.

all values are reported in microgram per in²

Sample Description	Cl ⁻	Br ⁻	WOA
Under Component	1.42	2.53	114.17
Reference Area	1.09	2.77	16.33

Results

- Not good.
- Weak organic acids from the flux are at levels that put this particular PCB at great risk of electromigration with a small amount of moisture under normal operation conditions.

Now what?

- Recovery cleaning of all suspect assemblies can mitigate this issue. As I have reported in previous presentations this can be done with a mix of low pressure saponified in-line wash techniques that also incorporate a secondary steaming step that uses enough heat and pressure to “push” the saponifier under low standoff components and remove the detrimental amounts of active flux residues.

Steam Cleaning Recap



Did it work?

- IC results after steam cleaning show that the flux residues have indeed been removed, and low levels of ionics pose little to no threat of electromigration under normal service conditions.

POST SAPONIFIED AND STEAM CLEANING

all values are reported in microgram per in²

Sample Description	Cl⁻	Br⁻	WOA
Under Component	1.01	2.23	10.24
Reference Area	1.26	2.50	8.50

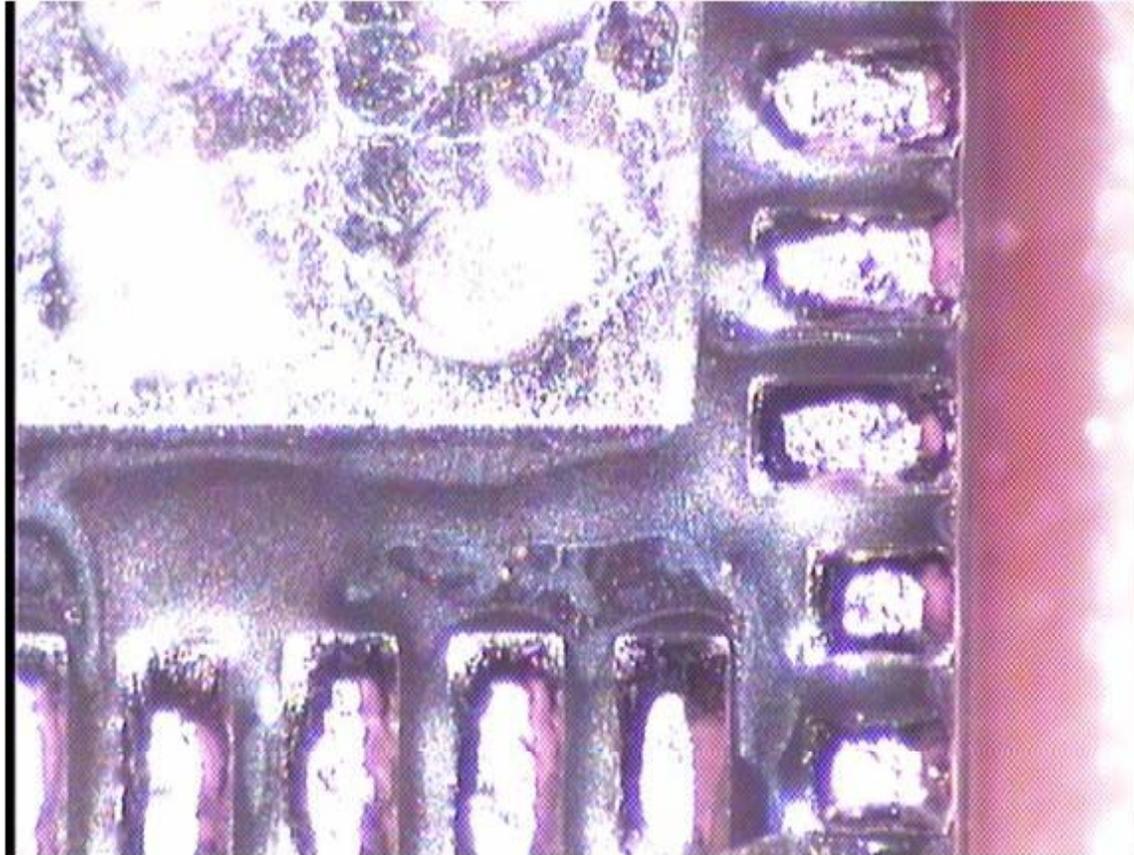
Methods to Avoid the Crisis

- OK, we have taken care of all the suspect inventory in the warehouse but how could this have been avoided in the first place?
- First things first, what are the main factors that cause the contamination under the component in the first place? We have found 2 main contributors along with 2 minor players.

Main Contributor #1

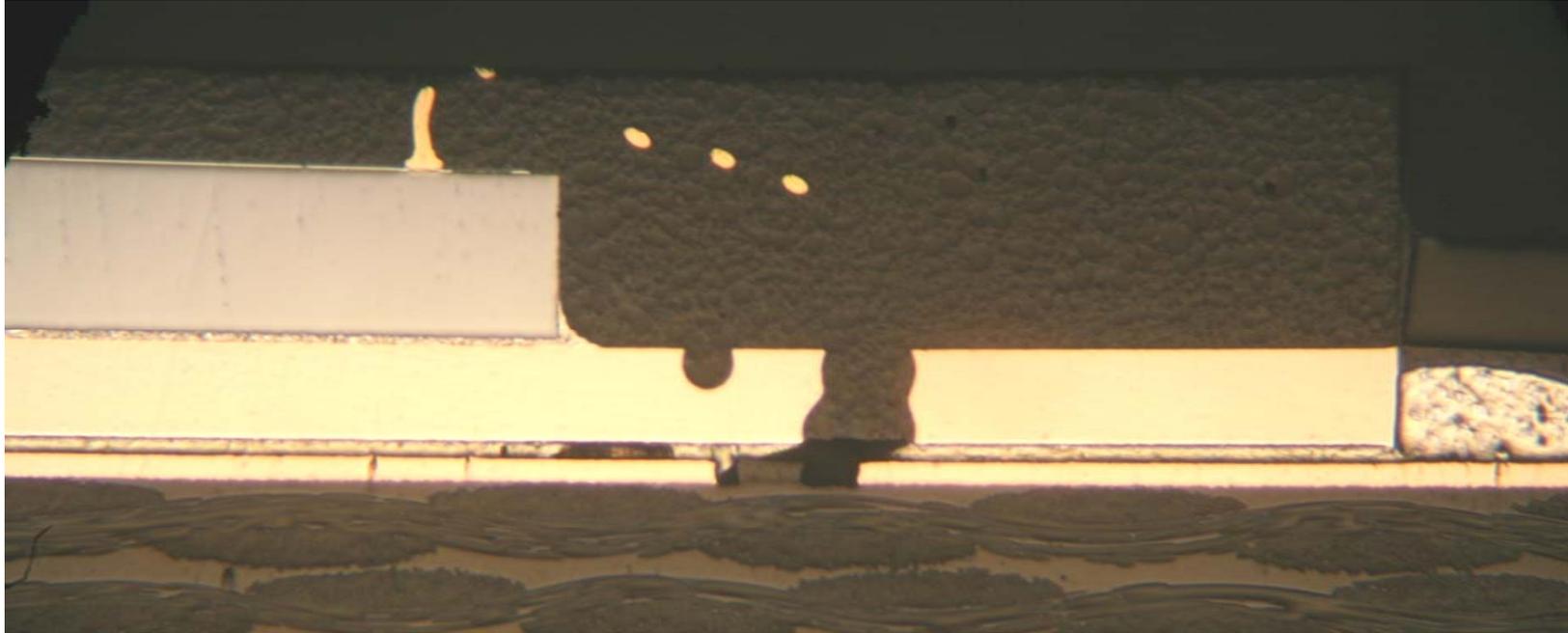
We have found the main issue with flux being trapped under low stand-off components is the inability to find an exit path from underneath the part. Paste is applied in the 6mil range and as the solder melts the part drops down to the 3mil range, thus creating dams in areas meant to vent flux gasses. This is very clear after cross section analysis.

Remember this Part?



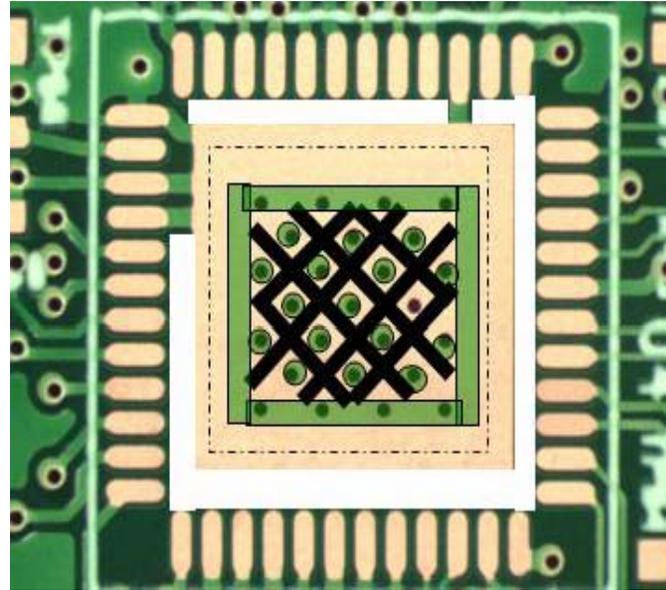
The large thermal ground pad in the center of the pad causes a lot of problems with residues

Cross Section Analysis at 50X



QFN pulls down to 2.0 mils off the board surface trapping flux and the flux carrier between the center pad (ground) and power pad, also the QFN is not self centering and shows a shift occurs reducing the space from 10 mils to 5 mils or less. You can also see a large amount of solder pushed from beneath the component on right hand side.

Possible Solutions



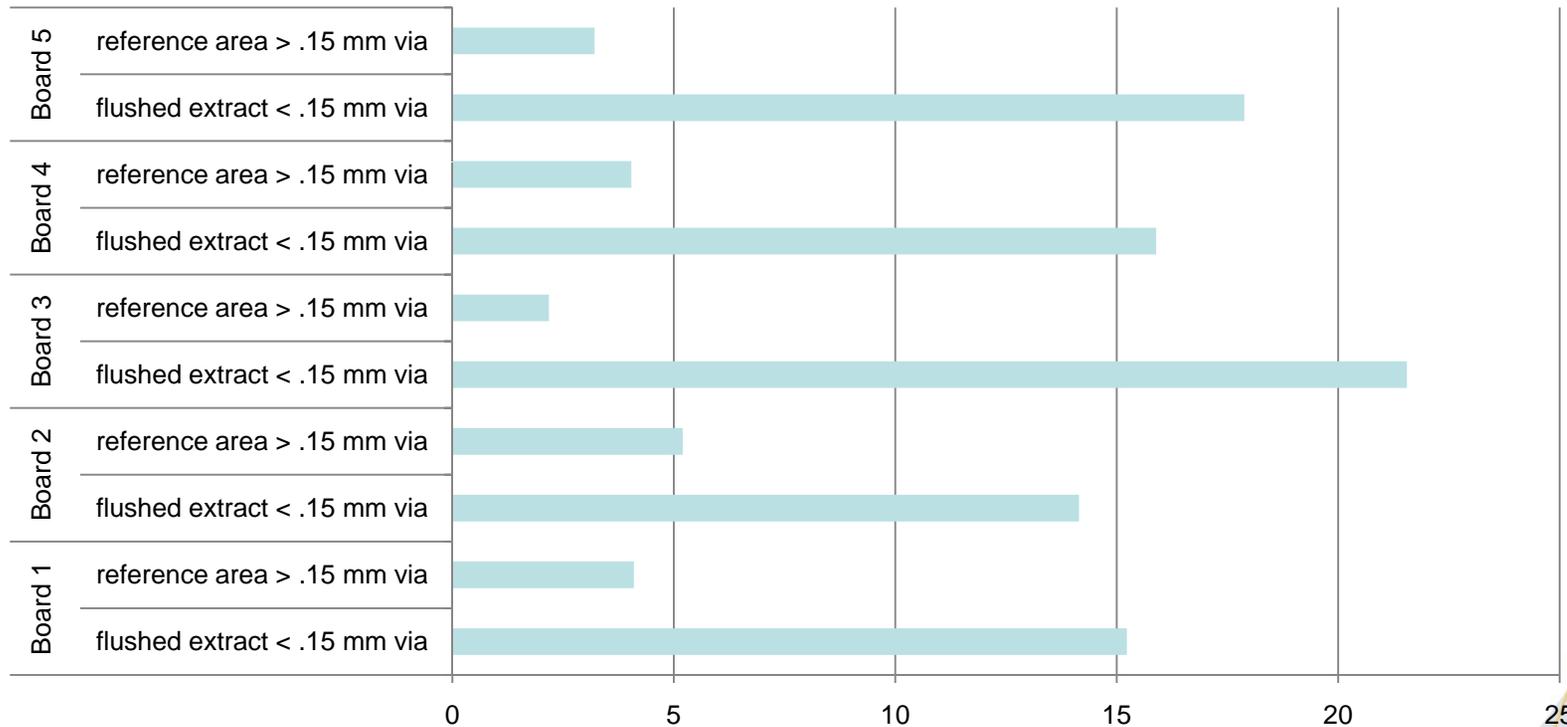
1. Remove inside area soldermask (except on ground contact pads or attach the ground to the thermal vias on the other side and eliminate traces to ground pad)
2. Reduce Center pad by 15% on all sides
3. Plug all via's with mask
4. Solder mask in the defined area with diamonds (black)

Main Contributor #2

- Dirty vias and the inability to clean them with normal water wash process.
- Boards with vias smaller than .15mm were found to have high levels of sulfate due to DI waters inability to penetrate and clean board fab residues that compound the problem.
- Comparatively larger vias were found to be much cleaner and did not add to the problem

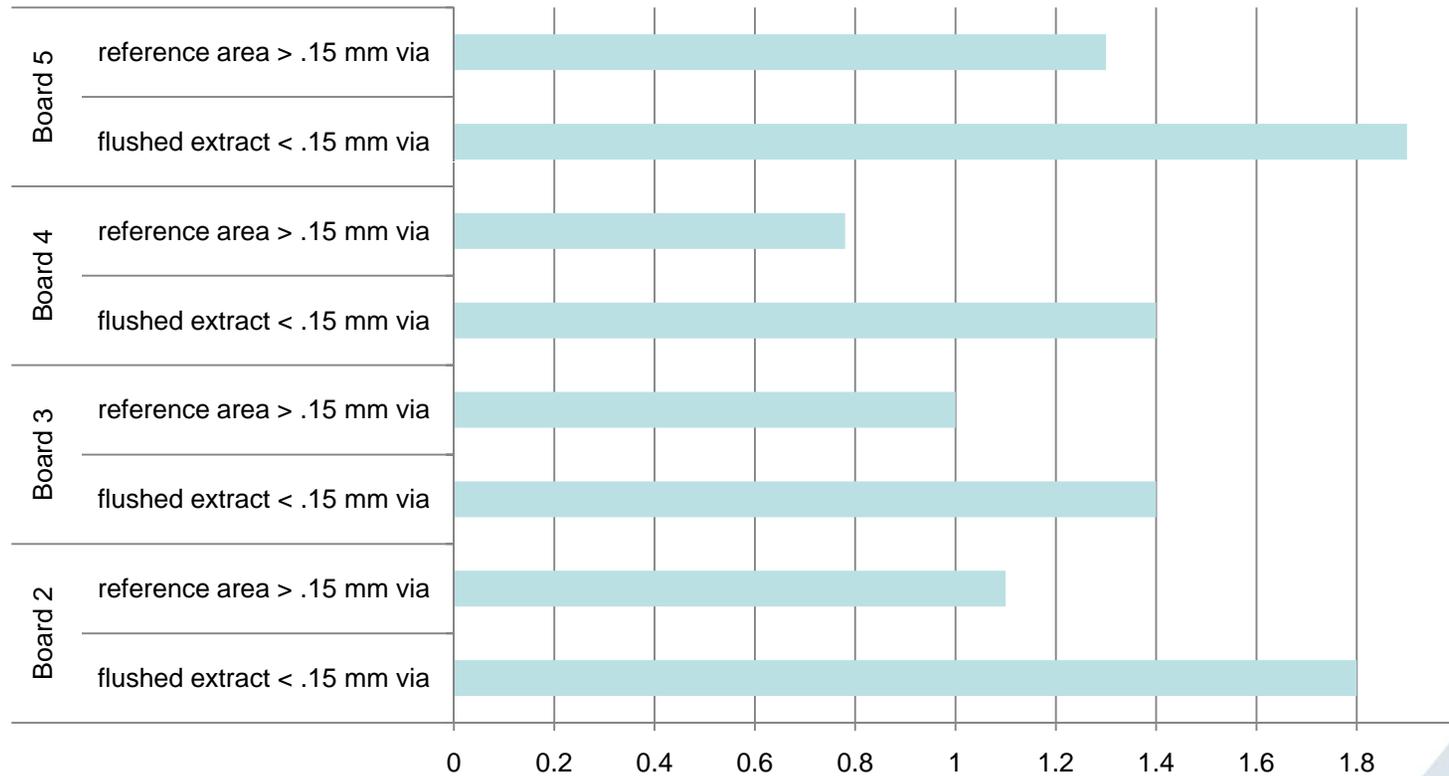


Board IC Sulfate Results DI Water Only- Micrograms per in²





IC Sulfate Results Saponifier Added Wash - Micrograms per in²



Results

Using the same extraction method as before on units that had the design changes implemented

Unit Built with Recommended Design Changes	Cl-	Br-	WOA
Area 2: PQFN Removed from Board	0.64	2.41	2.99
Area 1: PQFN Removed from Board	0.83	1.85	4.46

Conclusions

- A design change to the soldermask and requiring the bare board fab shop to use saponifier to ensure that micro-vias are properly cleaned went a long way to produce assemblies with low to no risk of electromigration under normal operating conditions.



Acknowledgments

- Special thanks goes to
- Terry Munson
- Paco Solis
- Meaghan Munson
- Every Assembly/Board Fab House in the World

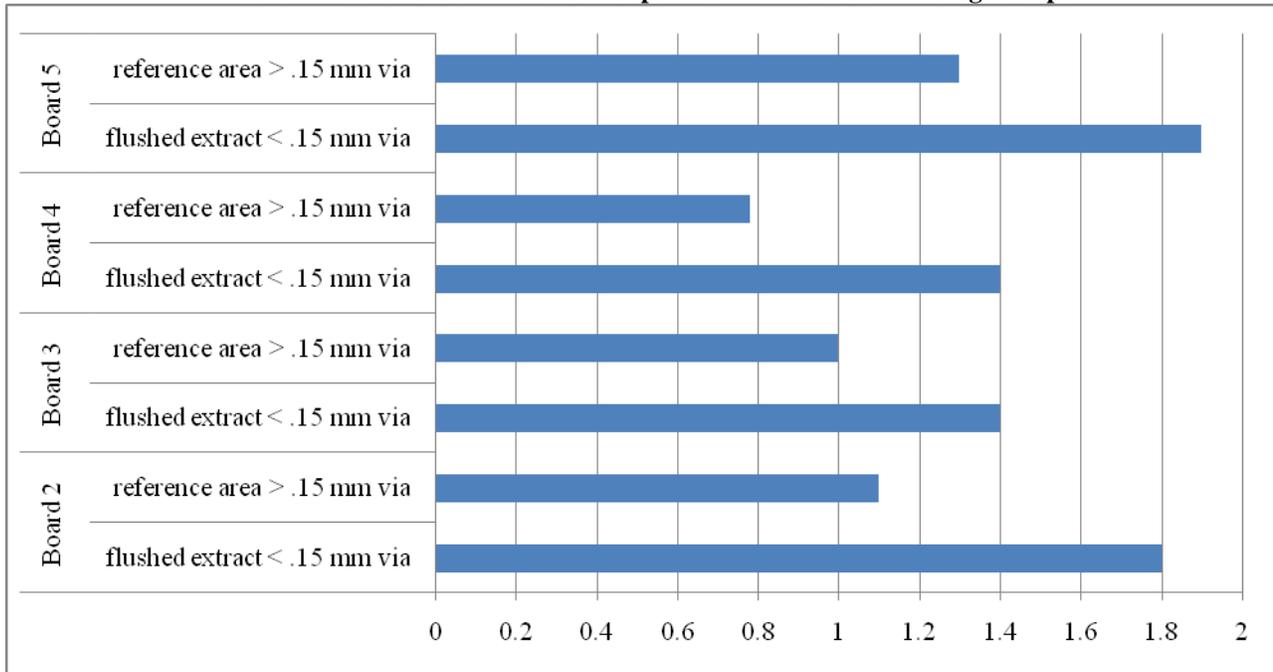


Questions?

Thanks for your time and interest
Eric Camden



Table 4- Board IC Sulfate Results Saponifier Added Wash -Micrograms per in²



Conclusions

Cleanliness has been a critical issue since the advent of surface mount components and the drive for both consumer and military goods to be smaller and more functional than ever has no doubt brought great technological advances, but also many challenges, for the manufacturer of these products. This paper covered two different but related cleanliness issues with the first being a major change in the build process, and the second a minor one in the fabrication process. These two issues were, however, equal in the eyes of potential failure. When using micro-BGA's or PQFN packages, it is worth the trouble to look at cleanliness of bare boards with a tighter eye, as well as the virgin component cleanliness, as both add potential for cleanliness related issues.