As originally published in the SMTA International Conference Proceedings.

IS CLEANING CRITICAL TO POP ASSEMBLIES?

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ABSTRACT
Package on package (PoP) assemblies are widely growing in use for applications that require small footprint technology. Typically, this integrated circuit design stacks and integrates logic and memory packages, thereby increasing board density and substantially expanding functionality within the same footprint of a single BGA. As a result, PoP's have become an ideal component selection for products such as advanced mobile platforms and digital cameras.

Cleaning is a critical process within the electronics manufacturing industry. Effective cleaning improves product reliability by ensuring optimal surface resistance and preventing current leakage that can lead to PCB failure. This paper will address the cleanliness level of PoP assemblies including underneath PoP components and in between packages.

The test procedure will utilize 14mm test boards with 3 x 5 arrays for 15 Package on Package components each incorporating 0.65mm ball pitch top and 0.5mm ball pitch bottom with daisy chain patterns in both packages. The boards will be populated with a no-clean paste and flux and reflowed with and without nitrogen for comparison. Subsequently, they will be cleaned utilizing an inline cleaner and several types of engineered aqueous cleaning agents.

Cleanliness evaluations will be made utilizing visual inspection, ion chromatography and SIR. A comparative cleaning analysis will include populated reflowed boards without cleaning and multiple cleaning scenarios with variable combinations of wash, rinse, dry and bake.

Expected results will empirically confirm the effectiveness of cleaning technologies for this rapidly evolving technology.

INTRODUCTION
Package on package components were introduced as an avenue for smaller assemblies to be able to house a larger amount of components, which in turn can fulfill a multitude of functions. For example, in the consumer electronics market, cell phones have been significantly reduced in size while meeting additional consumer demands. Nowadays, they contain games, email access, cameras, video cameras, radios, compasses, TVs, etc., all in one relatively small device.

At the same time, cleaning has become a critical component of the electronics manufacturing process, particularly if long-term board reliability and functionality is a must.

The use of PoP's when designing boards requires additional considerations with regard to cleaning as we not only have to clean the flux residues between the bottom package and the board but also the flux residues in between the top and the bottom package. The bottom package standoff height is usually less than 1 mil whereas the space between packages can vary. These standoff heights do not lend themselves to cleaning with water as the surface tension of 72 dynes/cm for DI-water is typically too high to penetrate these small spaces. In addition, no-clean pastes and fluxes are typically used for PoP soldering processes, which prohibit cleaning with DI-water as well.

Field experience and customer feedback have shown that cleaning PoP's has become increasingly difficult and that typical process settings and equipment configurations may not result in properly cleaned assemblies. The authors therefore designed this study to validate the effectiveness of using engineered cleaning agents and improved mechanical design features in the wash section of the inline equipment to clean PoP's. Additionally, the authors chose to reflow the test vehicles with and without nitrogen to assess any possible advantages/disadvantages for the cleaning process results.

ARTICLE SUMMARY
This three-phase collaborative study [1] was conducted to validate new machine design options and cleaning agents for cleaning PoP (package on package) assemblies. The authors used two different alkaline cleaning agents and compared their performance at various wash concentrations and belt speeds. Furthermore, the study analyzed the effect of nitrogen versus traditional reflow methodologies with regard to cleanability.

The three phases of the study are outlined below:

1. **Phase 1 – Cleaning Performance - Visual Inspection:** The cleaning performance was assessed via visual inspection with an Olympus SZ 40 microscope with up to 60x magnification.
2. **Phase 2 – Cleaning Performance - Ion Chromatography:** The cleaning performance was further verified via Ion Chromatography.

3. **Phase 3 – Cleaning Performance - Surface Insulation Resistance:** The cleaning performance was also measured using third party Surface Insulation Resistance (SIR) measurements.

Prior to performing the cleaning trials, a total of 18 PoP 14mm test boards (Figure 1) were populated and reflowed according to the following procedure:

1. A popular HF no-clean solder paste was printed onto 18 bare PoP 14mm test boards.
2. The accuracy of the print was inspected via microscope.
3. The bottom package was placed onto the board using a pick & place machine.
4. Subsequently, the top package was dipped into a HF PoP paste before placing it on top of the bottom package using a pick & place machine.
5. Following component placement, the boards were reflowed in a 9 zone reflow oven with nitrogen capability and according to the reflow profile outlined in Table 1. Fourteen boards were reflowed using Nitrogen and 4 boards were reflowed without Nitrogen. The same profile was used in both cases.
6. After reflow, several boards underwent x-ray inspection for bridging. No bridging was found.
7. Furthermore, an electrical test using a voltage meter was conducted on one board to ensure proper solder ball connections. The voltage was checked between each point. All boards passed.

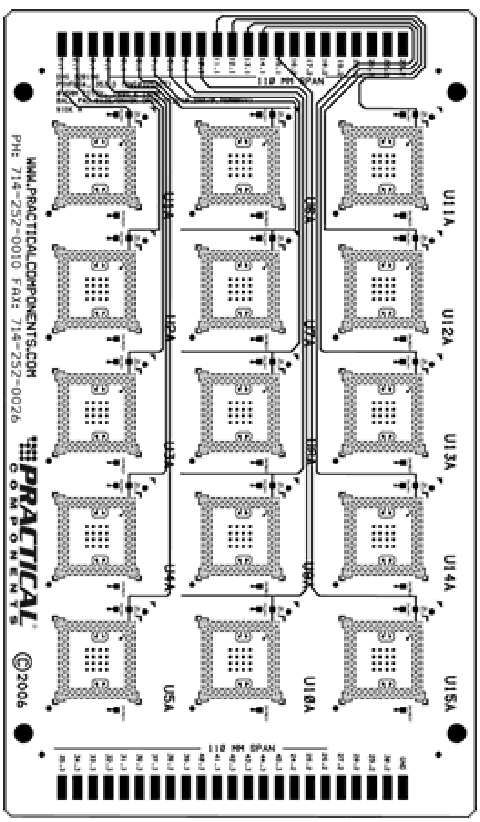

Figure 1. PoP 14mm test board

Table 1. Reflow profile for 18 PoP 14mm test boards

Zone	Temperature ºC
1	100
2	120
3	150
4	180
5	190
6	210
7	225
8	245
9	265
4 Cooling Zones	
60 cm/min conveyor speed	
O_2 level <50 ppm with Nitrogen	

Following reflow, all 18 test boards were subjected to cleaning trials and analytical tests as outlined below.

METHODOLOGY PHASE 1

Cleaning Performance – Visual Inspection

For the first part of the study, a total of 16 cleaning trials were conducted using a Speedline AS 200 inline cleaner. The independent process variables included the two different pastes used, the reflow with and without nitrogen, cleaning agents A and B, wash concentrations of 10% and 15%, a wash temperature of 150ºF (65.5ºC), belt speeds of 1 fpm an 0.5 fpm respectively, as well as a 12 bar spray configuration in the inline cleaner. In detail, the wash spray configuration consisted of 4 V-jet (V), 4 JIC (J) and 4 Deflector (D) spray bars. The spray bars were configured as follows: DVJVJDDVJVJD. This configuration was chosen based on empirical data and as recommended by the equipment manufacturer. It is important to note that typical inline machines are equipped with 4 spray bars. A summary of the independent process variables is provided in Table 2 below.

Table 2. Process variables

Variable	
Reflow Profile	With and without N_2
Cleaning Agent	A and B
Belt Speed	0.5 and 1 fpm
Fixed	
Cleaning Equipment	AS 200 inline cleaner
Spray Bar Configuration	DVJVJDDVJVJD
Wash Temperature	150ºF (65.5ºC)
Solder Paste (bottom level)	HF no-clean
PoP Paste (top level)	HF PoP paste

A visual inspection of the boards and component levels 1 (between board and bottom package) and 2 (between bottom and top package) was performed via 40x magnification and the results recorded. Prior to the inspection, the components were removed and separated.

RESULTS PHASE 1

Cleaning Performance – Visual Inspection

The findings of the visual inspection show that for cleaning agent A, only trials 1 and 2 presented problems. Both trials were conducted on boards reflowed without nitrogen at 10% concentration and belt speeds of 1 fpm (trial 1) and 0.5 fpm (trial 2) respectively. For trial 1, neither level 1 nor level 2 passed visual inspection, i.e. flux residues were found between the first component and the board as well as in between components. For trial 2, residues were found at level 1 only, i.e. level 2 was deemed clean. All remaining six trials passed visual inspection for both levels, i.e. no residues were found.

The results for cleaning agent A are summarized in Table 3 below:

Table 3. Results – visual inspection cleaning agent A (wash temperature 150ºF/65.5ºC)

Trial	Reflow	Concen-Tration (%)	Belt Speed (fpm)	Results Level 1	Results Level 2
1	no N_2	10	1	-	-
2	no N_2	10	0.5	-	+
3	no N_2	15	1	+	+
4	no N_2	15	0.5	+	+
5	N_2	10	1	+	+
6	N_2	10	0.5	+	+
7	N_2	15	1	+	+
8	N_2	15	0.5	+	+

- not clean
+ clean

The findings of the visual inspection show that for cleaning agent B, also only trials 9 and 10 presented problems. Both trials were conducted on boards reflowed without nitrogen at 10% concentration and belt speeds of 1 fpm (trial 1) and 0.5 fpm (trial 2) respectively. For trial 9, neither level 1 nor level 2 passed visual inspection, i.e. flux residues were found between the first component and the board as well as in between components. For trial 10, residues were found at level 1 only, i.e. level 2 was deemed clean. All remaining six trials passed visual inspection for both levels, i.e. no residues were found.

The results for cleaning agent B are summarized in Table 4:

Table 4. Results – visual inspection cleaning agent B (wash temperature 150ºF/65.5ºC)

Trial	Reflow	Concen-tration (%)	Belt Speed (fpm)	Results Level 1	Results Level 2
9	no N_2	10	1	-	-
10	no N_2	10	0.5	-	+
11	no N_2	15	1	+	+
12	no N_2	15	0.5	+	+
13	N_2	10	1	+	+
14	N_2	10	0.5	+	+
15	N_2	15	1	+	+
16	N_2	15	0.5	+	+

- not clean
+ clean

CONCLUSION PHASE 1

Cleaning Performance – Visual Inspection

The results based on the visual inspection show that both cleaning agents performed identically and equally well. After nitrogen reflow, consistently clean substrates were found at both wash concentration levels (10% and 15%) and belt speeds (0.5 fpm and 1 fpm). When reflowing without nitrogen, however, the faster belt speed as well as the lower wash concentration impacted the cleaning results. In particular, a 10% wash concentration for both cleaning agents as well as the higher belt speed of 1 fpm resulted in assemblies that were not clean. The same concentration and slower belt speed provided partially clean assemblies. It is important to note, though, that the results were identical for both cleaning agents.

In summary, reflowing PoP's with nitrogen opens the cleaning process window, i.e. wash concentration levels and belt speeds can be adjusted to meet the needs of the manufacturer. While the wash concentration can be reduced to 10%, the belt speed can be increased to 1 fpm, which in the long run will save cleaning process costs and time. However, one should not lose sight of the fact that using nitrogen for reflow is typically much more expensive.

If a reflow process with nitrogen is not available or cost prohibitive, the manufacturer has to be more selective as the cleaning process window will be narrower. Only 15% wash concentration at both belt speeds and for both chemistries provided completely clean assemblies.

The authors conclude that there are several potential reasons for these results. First, any lack of cleaning performance after oxygen reflow could be related to concentration, i.e. 10% may be too low of an effective concentration to clean these challenging components properly. Second, the results show that the higher the belt speed, the more difficult it is to clean due to a lack of exposure time to the cleaning agent, in particular after reflow without nitrogen. However, as mentioned above, reflowing with nitrogen can be cost prohibitive and may not provide the desired cost benefit. By increasing the concentration of both cleaning agents to 15%, the PoP's can be properly cleaned without using nitrogen and at lower as well as higher belt speeds.

In order to further quantify and qualify these findings, several additional test vehicles were chosen and cleaned with both solutions. Subsequently, this new set of boards was subjected to Ion Chromatography and SIR analysis in order to further evaluate any residues underneath the components and more precisely gauge the assemblies' cleanliness levels. Previous studies have shown that relying on visual inspections only may not always be best practice [2].

METHODOLOGY PHASE 2

Cleaning Performance – Ion Chromatography

The object of performing additional Ion Chromatography testing according to IPC-TM-650 method 2.3.28 was to move beyond visual inspection and conduct a more detailed cleanliness analysis of both cleaning agents [3]. Ion Chromatography is a test for ionic cleanliness that determines if contaminants are present on electronic assemblies and bare boards. Such contaminants, when mixed with moisture and an applied voltage, often contribute to electrochemical failures [4].

Based on the assessment during the preliminary cleaning trials, four additional trials were conducted using the higher concentration level (15%) and the slower belt speed (0.5 fpm). The process parameters are outlined in Table 5 below:

Table 5. Independent process variables – Ion Chromatography

Trial #	Re-flow	Cleaning Agent	Wash Concen-tration %	Wash Temp. ºF	Belt Speed fpm
1	no N_2	A	15	150*	0.5
2	N_2	A	15	150*	0.5
3	no N_2	B	15	150*	0.5
4	N_2	B	15	150*	0.5

*65.5ºC

RESULTS PHASE 2

Cleaning Performance – Ion Chromatography

The ion chromatography results indicate that all substrates passed inspection as the contamination levels found were well below the maximum allowable levels. Overall, in less than half (42%) of all possible cases a small amount of ionic contamination was detected. For anions, this constitutes 30% and for cations 62.5%. In detail, minute amounts of chloride, bromide, nitrate, ammonium, magnesium and calcium were found during all four trials. Sodium, on the other hand, was only detected in trials 1, 2 and 3. No sodium was found in trial 4. Furthermore, no other anions or cations were detected.

The ion chromatography test results are summarized in Tables 6 and 7 below.

Table 6. Ion chromatography test results for anions

ANION SPECIES ALWAYS TESTED FOR					
Ionic Species	**Max. Contami-nation Levels μ/in²**	**Board # 1 μ/in²**	**Board # 2 μ/in²**	**Board # 3 μ/in²**	**Board # 4 μ/in²**
Fluoride (F^-)	**3**	n.d.	n.d.	n.d.	n.d.
Acetate ($C_2H_3O_2^-$)	**3**	n.d.	n.d.	n.d.	n.d.
Formate (CHO_2^-)	**3**	n.d.	n.d.	n.d.	n.d.
Chloride (Cl^-)	**4**	0.15	0.19	0.15	0.18
Nitrite (NO_2^-)	**3**	n.d.	n.d.	n.d.	n.d.
Bromide (Br^-)	**10**	0.09	0.21	0.16	0.12
Nitrate (NO_3^-)	**3**	0.09	0.10	0.14	0.16
Phosphate (PO_4^{2-})	**3**	n.d.	n.d.	n.d.	n.d.
Sulfate (SO_4^{2-})	**3**	n.d.	n.d.	n.d.	n.d.
WOA (Weak Organic Acid)	**25**	n.d.	n.d.	n.d.	n.d.

n.d. = non detected

Table 7. Ion chromatography test results for cations

CATION SPECIES ALWAYS TESTED FOR					
Ionic Species	**Max. Contami-nation Levels μ/in²**	**Board # 1 μ/in²**	**Board # 2 μ/in²**	**Board # 3 μ/in²**	**Board # 4 μ/in²**
Lithium (Li^+)	**3**	n.d.	n.d.	n.d.	n.d.
Sodium (Na^+)	**3**	0.08	0.20	0.03	n.d.
Ammonium (NH_4^+)	**3**	0.08	0.09	0.12	0.18
Potassium (K^+)	**3**	n.d.	n.d.	n.d.	n.d.
Magnesium (Mg^{2+})	**1**	0.05	0.11	0.11	0.12
Calcium (Ca^{2+})	**1**	0.31	0.45	0.48	0.34

n.d. = non detected

CONCLUSION PHASE 2

Cleaning Performance – Ion Chromatography

On average, cleaning agent A removed slightly more contamination compared to cleaning agent B. Contrary to the visual inspection results, the above numbers indicate that cleaning agent A performed better on boards reflowed without nitrogen than with nitrogen which is somewhat surprising and contradictory to the visual inspection results. The IC testing for boards 3 and 4, which were cleaned with cleaning agent B, on the other hand confirmed the visual inspection results. However, one should not lose sight of the fact that all boards passed the IC testing and that the contamination levels detected were well below the maximum allowable limits for each ionic species.

METHODOLOGY PHASE 3

Cleaning Performance – Surface Insulation Resistance (SIR)

The goal of performing a third-party SIR analysis was to further validate the cleanliness levels. SIR (Surface Insulation Resistance) testing evaluates the propensity for assembly failure caused by shorts or current leakage between metal conductors. It is an electrical test that measures a change in current over time and is typically performed at elevated temperatures and humidity levels [5].

Based on the previous cleaning trial results, a total of 10 boards were populated and reflowed with nitrogen. Eight were cleaned according to the process parameters outlined in Table 8. Additionally, one bare board was used as control. The same cleaning equipment, i.e. a Speedline AS 200 inline cleaner with a 12 spray bar configuration (4 V-Jet, 4 JIC, 4 Deflector; DVJVJDDVJVJD) was used to clean the boards.

Table 8. SIR Process Parameters

Trial#	Reflow	Cleaning Agent	Wash Conc. %	Wash Temp. ºF	Belt Speed fpm
1	N_2	A	15	150*	0.5

*65.5ºC

In detail, the first two boards were populated and soldered only in order to test the reliability of the flux. They were not washed The second two boards were populated, soldered, cleaned, rinsed and dried, which constitutes standard process protocol. Another two boards were populated, soldered, cleaned, rinsed, dried and baked to check if the drying process is efficient. The following two boards were populated, soldered, only cleaned (not rinsed) and dried. The rinse step was omitted here to simulate possible cleaning agent residues due to improper rinsing. The last two boards were populated, soldered, only cleaned (not rinsed), dried and baked. The boards were not rinsed to simulate the potential of dried cleaning agent residues. It is important to note, that the boards were baked at 85ºC for 30 minutes. The control board was not treated. The test was conducted for a total of 192 hours at 85ºC and 85% relative humidity. Initial and final testing was done at ambient temperatures and humidity. Furthermore, the wires were carefully soldered with only the end of the board protruding from the bags to minimize contamination.

The SIR board preparation steps are outlined in Table 9 below.

Table 9. SIR board preparation

Board #	SIR Board Preparation
1	Control Board
2 A & B	Populate + Solder + No Wash
3 A & B	Populate + Solder + Clean + Rinse + Dry
4 A & B	Populate + Solder + Clean + Rinse + Dry + Bake
5 A & B	Populate + Solder + Only Clean + Dry
6 A & B	Populate + Solder + Only Clean + Dry + Bake

In order to obtain the results, three data points were manually assessed, i.e. one before the test, one at 96 hours and one at the conclusion of the test. The resistance at each daisy chain was recorded for each data point. The SIR test was conducted in accordance with IPC standard IPC-TM-650 Method 2.6.3.7.

RESULTS PHASE 3

Cleaning Performance – Surface Insulation Resistance (SIR)

All boards subjected to SIR analysis passed the test. In particular, the in-situ measurements were about 0.6 ohms higher than the initial/final measurement, which matched quite well with the resistance temperature dependence of copper. A 0.7 ohm rise was calculated between 25ºC and 85ºC from the equation.

The SIR test results are graphed in Figure 2 below.

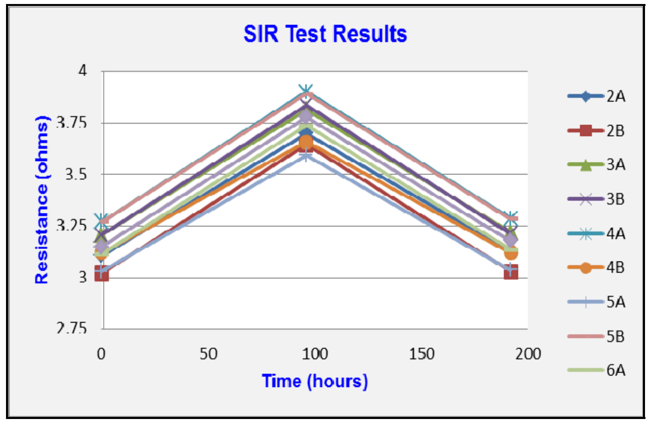

Figure 2. SIR test results

CONCLUSION PHASE 3

Cleaning Performance – Surface Insulation Resistance (SIR)

The SIR results indicate that all boards, i.e. even the boards that were not cleaned, passed SIR testing. For the boards that were cleaned but not rinsed, this means that any chemistry left behind on the board may not cause any problems. For the boards that were not cleaned at all, however, the results are not necessarily an indication that PoP assemblies do not need cleaning at all. For one, not all no-clean fluxes have the same signature, i.e. some can be more corrosive than others. Any potential corrosion will more than likely not occur until the boards are deployed in the field. Second, as the SIR testing was conducted in a very controlled environment, the test results are not necessarily an indication of any board failure potential once they are subjected to temperature and humidity fluctuations. Long-term exposure to varying environmental conditions may stress and crack the inert resin layer, which will expose flux activators to the atmosphere and can lead to electrochemical migration and dendrite growth. Ultimately, this can cause board failure.

FINAL CONCLUSION

The results of all three phases of the study show that with new generation cleaning agents and an improved mechanical design in the wash section of an inline cleaning machine, PoP assemblies can be effectively cleaned.

As for this paper only two package components were used on a test vehicle, ZESTRON is planning to collaborate with industry partners to develop and validate cleaning process parameters for multiple stack PoP assemblies in the future.

This research paper is part of a series written by ZESTRON on optimizing precision cleaning processes for electronics manufacturing industry. These studies have been presented at the industry's known conferences SMTAI and IPC/APEX. Based on our findings, key market developments have been initiated, thereby addressing the current shortcomings observed in the industry.

ACKNOWLEDGEMENTS

The authors would like to thank Universal Instruments, Speedline, DfR Solutions, and StenTech for their assistance and support with this project.

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