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COMPARISON OF APERTURE DESIGNS, SOLDER PASTES, NANOCOATINGS AND PRINT/INSPECTION SYSTEMS

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ABSTRACT

To optimize aperture designs for miniaturized components with a legacy solder paste, an experiment was devised to test the transfer efficiency and repeatability of several aperture designs for 0402, 0201 and 01005 discretes, as well as 0.4 and 0.5mm BGAs. The twelve laser-cut stainless steel stencils that were tested included two different basic aperture designs on 4 and 5 mil thicknesses, with no coating, wipe-on nanocoating, and cured polymer nanocoating (2x2x3 full factorial). The solder paste driving the experiment was a tin-lead RMA product, developed at least 20 years prior, and presents as a high viscosity paste that is more challenging to print when compared with modern formulations.

The experiment was performed on the user's assembly line using one set of printer and SPI equipment, and then replicated in the equipment supplier's laboratory using a different printer and SPI gear. The results of each individual print test are discussed and then compared.

The experiment was then extended at the laboratory to include different solder pastes and show their response to different stencil designs, and potential for improving print capability of the assembly line.

Key words: stencil printing, nanocoating, miniaturization, SPI, solder paste

INTRODUCTION

High reliability PCB assemblers face multiple challenges from the mainstream industry's migration to lead-free solders. One of the major challenges is in the solder paste itself. Solder paste manufacturers have been continuously developing new lead-free solder pastes for approximately 15 years. Few, if any solder suppliers, have introduced new tin-lead solder pastes however, due largely to the low market demand for them. And even if better tin-lead paste formulations were available, changing them in a mission-critical application would require a great deal of due diligence and qualification testing.

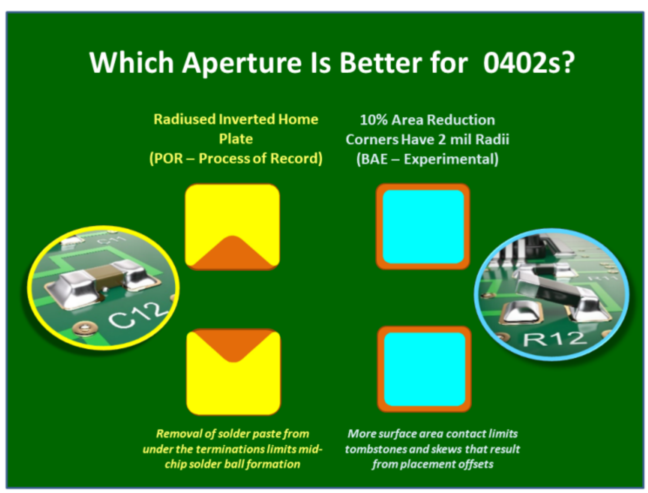


Figure 1. Aperture designs tested for 0402 (1005M)

The overall approach to SMT process optimization starts at the front of the assembly line and reviews each individual process moving down the line. Therefore, the method of optimizing production of discrete sizes 01005 to 0402 (Imperial) starts with optimizing the print.

The aperture design in the Process of Record (POR) for these component packages is shown in Figure 1. It is known as the "Inverted Home Plate," "Crown," "Bowtie," or "Pac Man" aperture design. This is a common aperture design to minimize solder paste under the terminations, and therefore the propensity for mid-chip solder balls. It was identified in 2004[1] as the optimum aperture design to limit mid-chip solder balls with tin-lead solder paste and 5 or 6 mil foils. At the time of the study, 0402 packages were the smallest available to test; fifteen years later they are mainstream and many lessons have been learned. The acute angles in the corners, although radial, are still very tight on 0402s and can create release issues for solder paste. The release issues can then lead to defect modes such as tombstoning, skews or non-wets, especially if placement is slightly off-target.

This experiment examines the printability of the POR aperture design with a simple rectangular one with a 10% area reduction for 0402s. Printability of the two aperture types are compared using Transfer Efficiency and Coefficient of Variation as output variables, on the assembler's production line, using their qualified solder paste.

The next experiment does the exact same thing with the exact same solder paste, but in a laboratory environment as opposed to a production line, and uses an earlier model SPI machine from the same manufacturer.

The final test also takes place in the laboratory, comparing a slightly newer version of tin-lead solder paste with a SnPb paste made with a "backwards compatible" flux. The term backwards compatible indicates that the flux was designed for higher temperature, lead-free products, but works well with SnPb solder powder and does not present electrochemical reliability concerns after a cooler, SnPb reflow cycle.

The assembler cannot bring the solder paste in-house to test, so the study looks for correlations in SPI readings on the control paste in order to determine if the experimental product will make enough impact on print quality to invest in the qualification process.

EXPERIMENTAL DESIGN

Test Vehicle

The test used the SMTA miniaturization test vehicle shown in Figure 2. It contains numerous miniaturized components; the ones primarily studied in this test are:

- Ten 0.5 mm BGAs
- Nine 0.4 mm BGAs
- Eight blocks of 01005 (0402M) components, 100 each
- Eight blocks of 0201 (0603M) components, 100 each
- Eight blocks of 0402 (1005M) components, 100 each

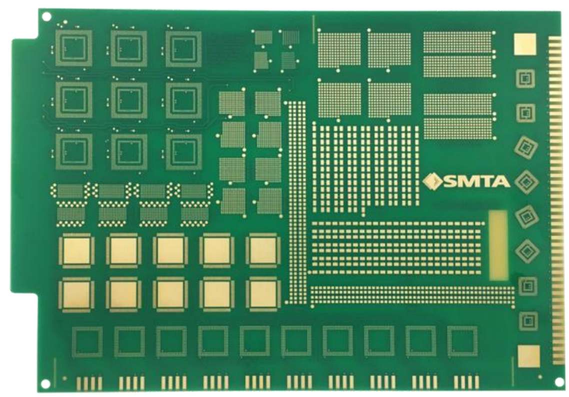


Figure 2. Test PCB[2, 3]

Sample sizes for each ten-print test were:

- 2880 0.5 mm BGA deposits
- 5,580 0.4mm BGA deposits
- 16,000 0402 (1005M) deposits
- 16,000 0201 (0603M) deposits
- 16,000 01005 (0402M) deposits

Stencils

Six of each stencil thickness were tested, configured as described in Table 1.

Table 1. Stencils used in test

Stencil Thickness (mil)	Aperture Shape	Coating
4	POR - Inverted Home Plate 1:1 with pads	Wipe On
		Naked
		Cure On
	BAE - squircle with 10% area reduction (01005 and 008004 are 1:1)	Wipe On
		Naked
		Cure On
5	POR - Inverted Home Plate 1:1 with pads	Wipe On
		Naked
		Cure On
	BAE - squircle with 10% area reduction (01005 and 008004 are 1:1)	Wipe On
		Naked
		Cure On

All stencils were laser cut from fine grain stainless steel and mounted at standard tension (~34 N/cm). Six each were produced in 4 and 5 mil thicknesses. 3 of each thickness had the POR aperture design (per IPC 7525[4]) and 3 had the experimental (abbreviated BAE in the data reduction) aperture design. Each set of three stencils was then subdivided by coating. One had no coating (naked) one had ceramic coating (cured on) and one had a phosphonate coating (wipe on).

Based on experience with variability on the 0402 POR apertures and the sizes of 0201 and 01005 apertures, inverted home plate designs were not attempted for the smaller devices. Both the POR and BAE stencils used the same aperture sizes for 0201 and 01005 components. They are shown in Table 2.

Table 2. Aperture and pad sizes for miniaturized discretes

Package	0201 (0603M)	01005 (0402 M)
Pad Size	12 x 15 mil	8 x 8 mil
Aperture Size	10.8 x 13.5 mil	8 X 8 mil
Area Ratio 4 mil	0.75	0.50
Area Ratio 5 mil	0.60	0.40

TEST EXECUTION

Each print test consisted of 10 prints, with a wipe between each print. The assembly line used

- Vac , Wet, Oscillate
- Vac, Dry, Oscillate
- Dry, Vac, Oscillate

And the laboratory used a dry/vac, dry/vac between prints.

The assembler's production floor used a new EKRA Serio 4000 stencil printer that was certified by Cetaq[5] and a Koh Young Aspire 3 SPI machine with 4 projectors and a 12 MP camera at 15 µm resolution.

The laboratory used a new MPM Edison 2 stencil printer that had been recently certified via Cetaq, and a Koh Young 8030, a 2 projector system with a 4 MP camera at 15 µm resolution. It was later upgraded to an Aspire 3 with 4 projectors and a 12 MP camera at 10 µm resolution between the incumbent paste print tests and the follow up ones.

Both facilities used hand-held ultrasonic stencil cleaners[6] to insure the best possible removal of residual solder paste from the apertures before transferring the stencils to the other facility. Also, stencils were cleaned with ultrasonic cleaning systems upon arrival from the stencil manufacturer.

Note that it is important to clean new stencils before they are put into service to remove any residual burrs or contaminants from the cutting process. Stencils with cured on coatings do not need to be cleaned upon arrival because they receive a thorough cleaning before the coating is applied. In fact, they should not be exposed to any harsh, flux-dissolving solvents for 72 hours after their cure, to allow for complete cure of the coating.

Both the control and experimental solder pastes were Type 3, tin-lead, no-clean products. Because the boards in this test were not populated, flat plates were used for tooling support on the production floor. Custom tooling plates were used in the laboratory. Again, because nothing was populated, the PCB support – a key element of the printing process – was excellent regardless of facility.

The production facility used metal squeegees mounted at 65° angles, and the laboratory used surgical steel squeegees mounted at 60° angles.

DATA ANALYSIS

Data was output from the SPI machines into comma separated files, and opened and saved in Microsoft Excel format. In Excel, columns were added for:

- Stencil thickness (4 or 5)
- Aperture design (POR or BAE)
- Stencil coating (naked, cured on or wipe on)
- Solder paste (control or experimental)
- Location – Nashua, NH or Hopkinton, MA

Each facility produced 12 SPI files with 187,000 lines of data for each solder paste.

RESULTS

This section contains detailed statistical results from the tests. For an overview of the findings, see the Discussion and Conclusion sections.

Key Findings

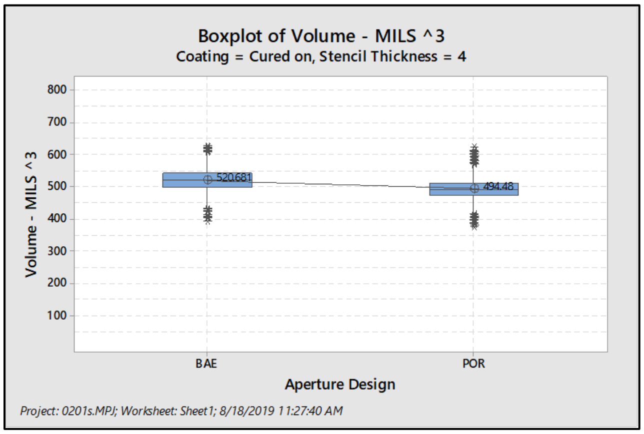
The purpose of the study was to answer specific questions about process changes before implementing any on high-reliability products, especially those currently in production. Questions include:

- What is the impact of migrating from 5 mil foils to 4 mil foils?
- Would different aperture designs improve the repeatability of the print process?
- What is the smallest device we can repeatably print with the current solder paste formulation?
- Would qualifying a new solder paste provide enough quality and cost improvement to justify the effort?

5 mil vs 4 mil Foil Thickness

Neither foil thickness could adequately print 01005s with the production solder paste, on the production line. For both foil thicknesses and all surface treatments, Coefficients of Variation (CVs) ranged from 25 to 45%. The CV is simply the standard deviation divided by the mean, expressed as a percent. Typically, less than 10% is preferred, 10-15% is considered acceptable or marginal, and greater than 15% is considered unacceptable. These features were not expected to print well, given their area ratios and the older, Type 3 solder paste.

0201s showed good capability for all stencil types. CVs ranged from 5.8 to 7.0, all in the preferred range. The best performer was the cured on coating. In the boxplots shown in Figures 3 and 4, the apertures labeled BAE are the experimental (short for BAE Modifications) and the POR are the current Process of Record that reflects the current aperture library.



Results for Coating = Cured on, Stencil Thickness = 4

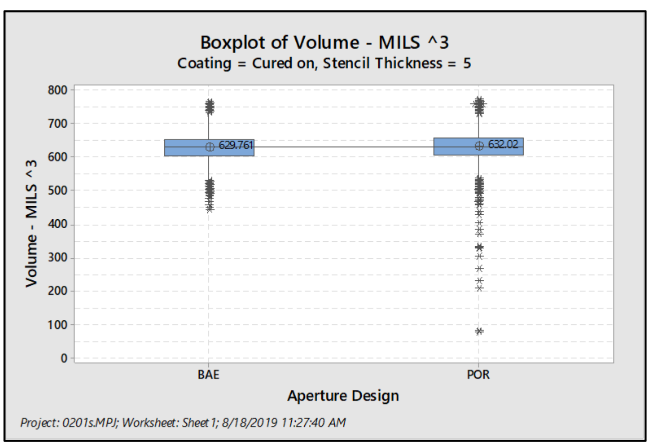
Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	520.68	0.244	30.83	5.92	393.03	499.22
	POR	16000	0	494.48	0.235	29.74	6.01	375.95	474.57

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	521.50	542.45	627.49
	POR	493.26	513.01	624.14

Boxplot of Volume - MILS ^3

Figure 3. Boxplot and statistics for 0201 prints with a 4 mil foil and cured on coating



Results for Coating = Cured on, Stencil Thickness = 5

Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	629.76	0.292	36.99	5.87	443.98	604.80
	POR	16000	0	632.02	0.303	38.36	6.07	79.29	608.37

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	629.47	654.92	765.71
	POR	631.34	656.14	773.24

Boxplot of Volume - MILS ^3

Figure 4. Boxplot and statistics for 0201 prints with a 5 mil foil and cured on coating

The volumes are relatively the same between the BAE and POR apertures. They should be, because in the case of 0201s, they are the same.

The 4 mil foil prints a much tighter distribution than the 5 mil foil. The 5 mil foil also tended to produce more insufficients (lower area ratio). The 5 mi foil deposits a mean volume of 630 mil^3, whereas the 4 mil foil deposits approximately 500 mil^3. The roughly 20% reduction in solder volume is not expected to impact solder joint integrity, as the 500 mil^3 average is still typical for the package type. The reduction in variation – especially the limiting of insufficient deposits that cause tombstone, skew and non-wet defects – should improve end-of line quality. A 4 mil foil is preferred for 0201s for higher quality output.

Aperture Designs

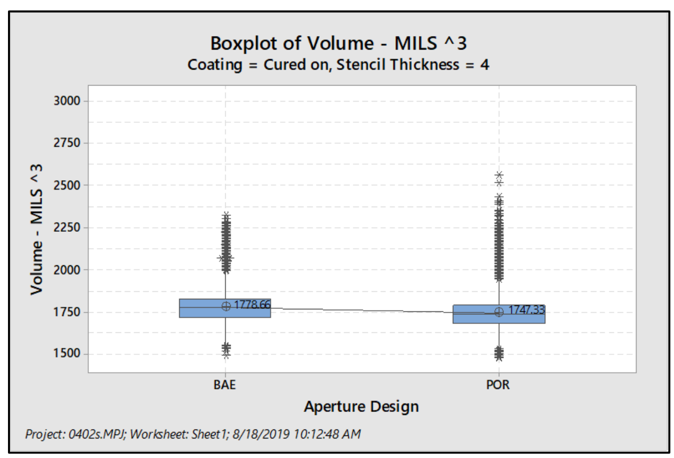
Two different aperture designs were tested on two different component types.

For 0402 components the POR aperture is the radiused inverted home plate, and the BAE aperture is a rectangle with radiused corners, also known as the "squircle." The corner radii are 2 mil; the radii help prevent solder paste buildup in the aperture corners.

For the 0.5 mm BGA components, the POR aperture is a circle at 1:1 with the pad (10 mil), and the BAE aperture is a squircle the same size with 2 mil radii.

Radiused Rectangle vs Inverted Homeplate on 0402s

Figures 5 and 6 show the boxplots for 4 and 5 mil stencils with the cured on coating.



Results for Coating = Cured on, Stencil Thickness = 4

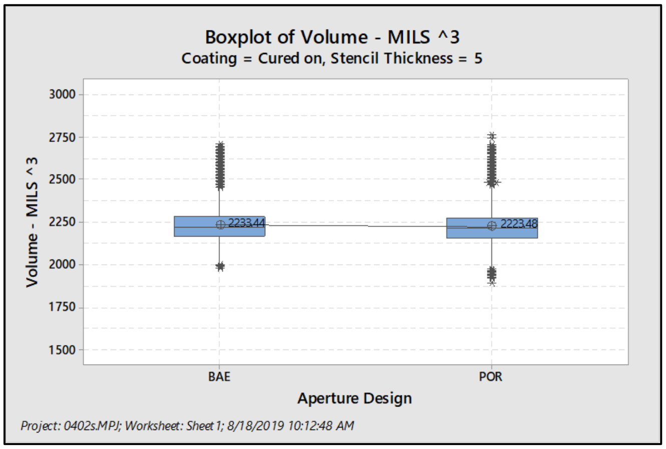
Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	1778.7	0.702	88.8	4.99	1488.0	1718.4
	POR	16000	0	1747.3	0.779	98.6	5.64	1479.1	1685.7

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	1774.8	1828.1	2325.4
	POR	1734.0	1788.7	2559.7

Boxplot of Volume - MILS ^3

Figure 5. Boxplot and statistics for 0402 prints with a 4 mil foil and cured on coating



Results for Coating = Cured on, Stencil Thickness = 5

Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	2233.4	0.707	89.5	4.01	1976.0	2171.7
	POR	16000	0	2223.5	0.788	99.6	4.48	1895.2	2155.3

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	2224.3	2283.3	2706.4
	POR	2214.1	2278.9	2763.7

Boxplot of Volume - MILS ^3

Figure 6. Boxplot and statistics for 0402 prints with a 5 mil foil and cured on coating

Both aperture designs on both stencil thicknesses showed good capability, with CVs well below 10%.

Both aperture designs showed similar mean volumes on their respective stencil thicknesses, despite having different geometries. The reduction of volume of approximately 20% when thinning the stencil 20%, with no impact on variation indicates that area ratio is not a factor on the 0402s.

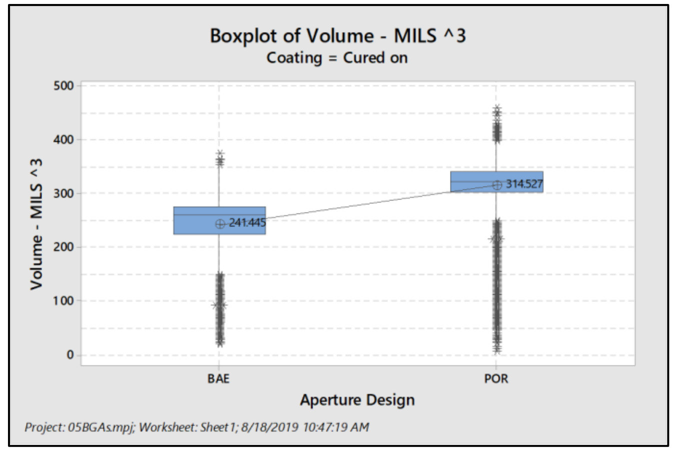
Either stencil thickness or aperture design appears equally viable from a print capability perspective. Therefore, moving to a POR aperture or 4 mil foil will not negatively impact print quality, and merits investigation into its effects on end-of-line yield, particularly with respect to the production of tombstone/skew vs. mid-chip solder ball defects.

Circle vs. Radiused Square for BGAs

In the case of the 0.5 mm BGAs the circular aperture has a 10 mil diameter, and the squircle aperture also has a 10 mil side length, with 2 mil radii.

Data was only analyzed for the 4 mil foil. If the 4 mil foil showed good capability, the 5 mil would have been analyzed also.

The data for the 4 mil foil with cured on coating is shown in Figure 7.



Results for Coating = Cured on

Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	22800	0	241.44	0.360	54.41	22.53	18.28	224.53
	POR	22800	0	314.53	0.315	47.53	15.11	6.11	303.19

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	259.09	275.37	373.16
	POR	322.36	340.21	458.41

Boxplot of Volume - MILS ^3

Figure 7. Boxplot and statistics for 0.5 mm BGA prints with a 4 mil foil and cured on coating

The circular (POR) aperture produced higher volumes, with less variation but more outliers than the squircle (BAE) aperture; however, both have unacceptable CVs.

Previous studies[7,8] have shown typical 0.5mm BGA volumes in the 300 – 350 mil^3 range for newer solder paste formulations. If the variations in these datasets were acceptable, the larger volume would likely be preferred. However, no realistic conclusions regarding volume and variation can be made with CVs over 15%.

The 0.5 mm BGA print process is currently in place in production using POR apertures. Based on this test data, it is recommended to maintain the POR apertures while investigating other ways to improve print performance. Given that the production process already uses the best performing stencil technology, the best in class tooling and squeegee blades, and the printers are certified by a third party, the remaining option is to investigate the performance of newer solder paste formulations.

The 0.4 mm BGAs showed complete incapability on the 4 mil foils, with CVs upward of 50% for cured on coating, 60% for wipe on coating and 80% for no coating. No inferences or conclusions can be drawn based on this dataset.

For reference, the POR aperture on the 0.4 mm BGAs is an 8 mil circle; the BAE experimental is a 7.5 mil squircle with 2 mil radii on the corners,

Coating Comparison

Figure 8 shows the main effects plot for volume for 0402 components. The trends shown for the 0402s are mimicked throughout the results for all datasets. The main driver for volume differences is foil thickness. Secondary to that, cured on coatings showed higher volumes than naked stencils or wipe on coatings, in that order. Not shown in the main effects plot are the variations of each coating. Review of all the data shows that the cured on coatings produced lower CVs than the wipe on coatings or naked stencils, in that order.

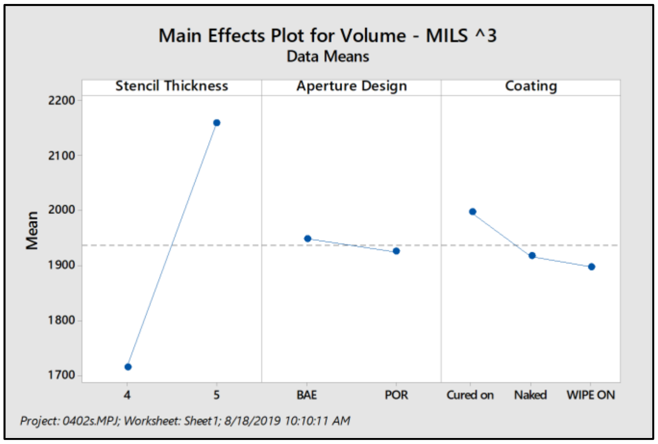


Figure 8. Main effects plot for volume on 0402s on production line

The Smallest Features to Print Repeatably

These test results showed that print process is robust down to 0201 components, using the current equipment and solder paste. It also shows that 4 mil foils are better than 5 mil foils for this package size, because the 5 mil foils tend to produce more insufficient deposits.

0.5mm BGAs were borderline marginal at best using the 4 mil foil with cured on coating. They showed lower than expected volumes and 15% CV.

Note that the population density of this PCB puts more demands on the solder paste than a typical production PCB would. A print process considered borderline on this PCB layout will likely perform better on less densely populated production boards with fewer apertures and less fine feature component types.

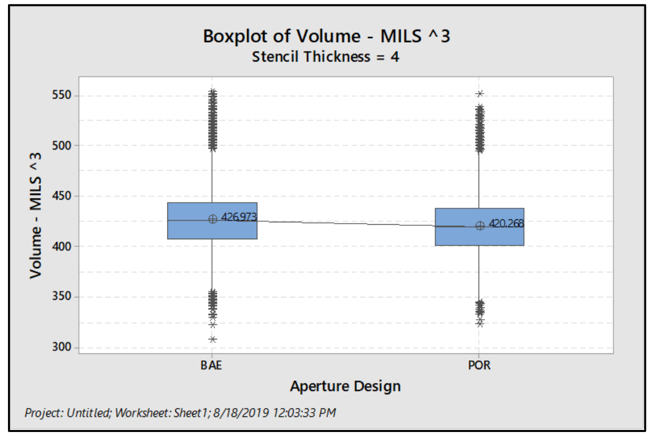
Will Moving to a Newer Formulation Improve the Process?

Qualifying a new solder paste requires a tremendous amount of effort for any PCB assembler, let alone a high reliability one. When considering undertaking such a substantial mission, it is important to understand if it is worth it.

To understand if a newer formulation SnPb solder paste will afford a wider process window, sample tests were run in a nearby laboratory. First, the current production solder paste; then, the newer product.

The strongest data sets, i.e., 0201, 0402 and 0.5mm BGA apertures with cured on coating are compared. These tests used the same SnPb solder paste as the assembler.

Figures 9 and 10 show the data for the 0201s from the laboratory for comparison with that Figures 3 and 4, which was generated on the assembler's production line.



Results for Stencil Thickness = 4

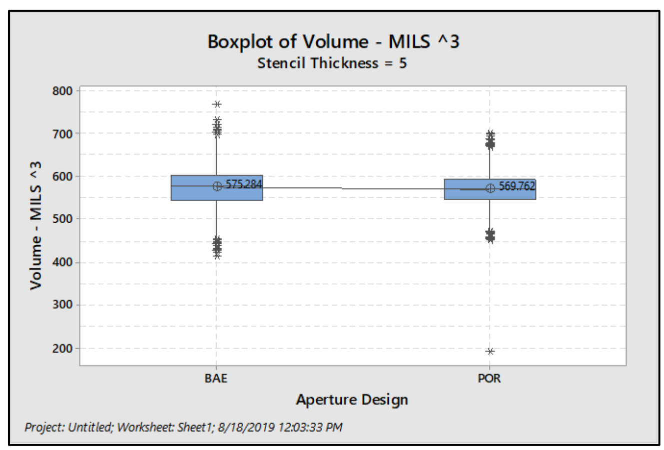
Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	426.97	0.226	28.64	6.71	308.51	408.30
	POR	16000	0	420.27	0.226	28.61	6.81	323.00	401.07

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	426.64	443.62	553.29
	POR	419.83	438.42	551.87

Boxplot of Volume - MILS ^3

Figure 9. Boxplot and statistics for 0201 components printed with a 4 mil foil in the equipment laboratory



Results for Stencil Thickness = 5

Statistics

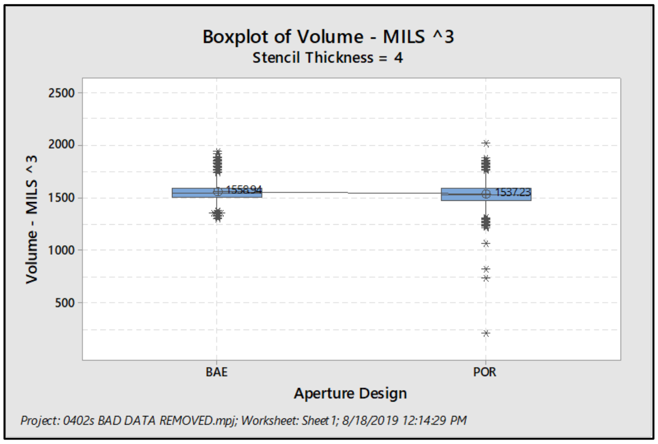
Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	575.28	0.318	40.19	6.99	413.49	544.12
	POR	16000	0	569.76	0.270	34.18	6.00	191.64	544.89

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	577.05	604.68	767.58
	POR	570.83	594.14	699.83

Boxplot of Volume - MILS ^3

Figure 10. Boxplot and statistics for 0201 components printed with a 5 mil foil in the equipment laboratory

Both the assembly line and the laboratory produced prints with CVs of approximately 6%. The volume readings on the line were higher than those in the lab. This could possibly be due to the difference in SPI machines, or the difference in printers. As with the previous 0201 data, the volumes are similar because the apertures are similar.



Results for Stencil Thickness = 4

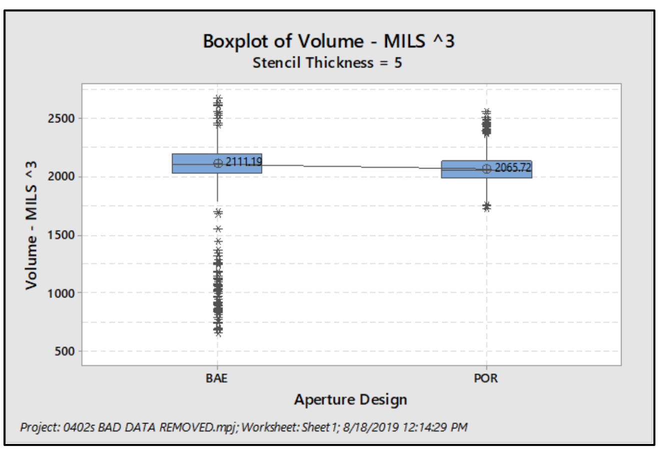
Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	1558.9	0.616	77.9	4.99	1302.8	1509.3
	POR	16000	0	1537.2	0.701	88.6	5.77	211.9	1478.8

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	1556.0	1600.3	1940.0
	POR	1534.5	1591.4	2019.1

Boxplot of Volume - MILS ^3

Figure 11. Boxplot and statistics for 0402 components printed with a 4 mil foil in the equipment laboratory



Results for Stencil Thickness = 5

Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	16000	0	2111.2	1.01	128.1	6.07	653.7	2029.0
	POR	16000	0	2065.7	0.824	104.3	5.05	1730.9	1988.6

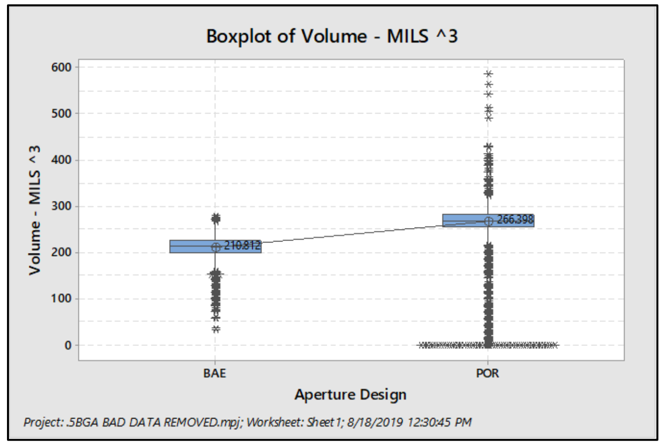
Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	2112.3	2193.6	2671.3
	POR	2064.2	2139.2	2555.6

Boxplot of Volume - MILS ^3

Figure 12. Boxplot and statistics for 0402 components printed with a 5 mil foil in the equipment laboratory

Figures 11 and 12 show the data for the 0402s from the laboratory, for comparison with that in Figures 5 and 6, which were generated on the assembler's production line.

As with the 0201s, the CVs of the two processes are very close. And again, the mean of the volumes are lower for the lab than the assembly line.



Descriptive Statistics: Volume - MILS ^3

Statistics

Variable	Aperture Design	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume - MILS ^3	BAE	22800	0	210.81	0.153	23.03	10.92	32.90	199.70
	POR	22800	0	266.40	0.196	29.66	11.13	0.000	254.70

Variable	Aperture Design	Median	Q3	Maximum
Volume - MILS ^3	BAE	213.70	225.97	278.83
	POR	267.90	281.30	583.48

Boxplot of Volume - MILS ^3

Figure 13. Boxplot and statistics for 0.5mm BGA components printed with a 4 mil foil in the equipment laboratory

The 0.5mm BGA, the finest feature to be compared, showed far less variation in the laboratory than on the assembly line. CVs for both aperture designs were acceptable, however the distribution is much tighter for the BAE (squircle) aperture than for the POR (round) one.

Considering this a viable dataset based on its CV of ~10%, the BAE (squircle) aperture is strongly preferred. Similar to the assembly line tests, it has fewer outliers than the POR, which produces many more insufficients. Also similar to the assembly line tests, the POR averages higher volumes. Similar to the comparisons of the 0201s and 0402s, the average volumes measured in the lab were lower than those measured on the line.

In an overall comparison of the datasets for 0402, 0201 and 0.5 mm BGA, the assembly line readings were consistently higher. The variations however were consistent, as were the main effects. A direct statistical correlation cannot be established, but the trends are consistent.

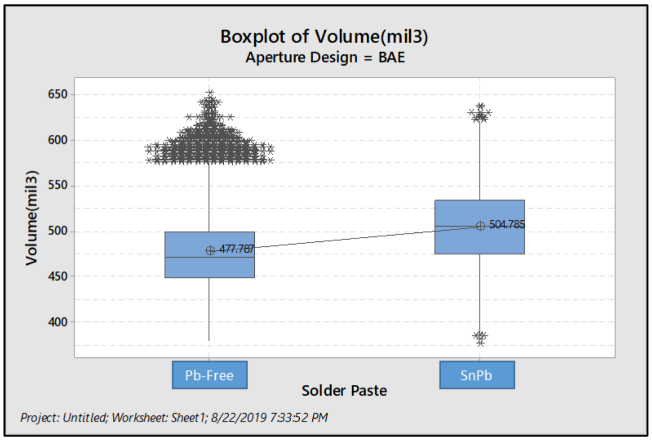
Next, a follow-up run with two potential replacement solder pastes were printed in the laboratory using the same stencils with cured on coatings. Because the 0.5 mm BGA and 0201s printed better with a 4 mil foil, and the foil thickness had no impact on print quality for 0402s, only the 4 mil foils were print tested.

Newer SnPb or Backwards Compatible Pb-free Flux with SnPb Powder?

Two solder paste "upgrade" options are available to the assembler:

1) Investigate a newer formulation SnPb solder paste that is well known as an excellent printing product
2) Investigate a formulation that was developed for Pb-free solders but provides the needed electrochemical reliability when used with SnPb alloy in SnPb reflow profiles.

Both were print tested in the laboratory. The results are shown in Figures 14 through 16.



Results for Aperture Design = BAE

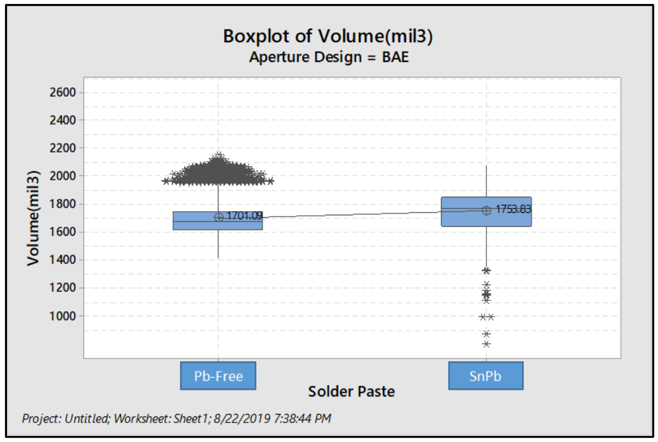
Statistics

Variable	Solder Paste	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume(mil3)	Pb-Free	16000	0	477.79	0.314	39.72	8.31	380.00	449.00
	SnPb	16000	0	504.78	0.333	42.14	8.35	377.00	475.00

Variable	Solder Paste	Median	Q3	Maximum
Volume(mil3)	Pb-Free	472.00	500.00	652.00
	SnPb	506.00	534.00	638.00

Boxplot of Volume(mil3)

Figure 14. Boxplot and statistics for 0201 volumes with newer solder pastes



Results for Aperture Design = BAE

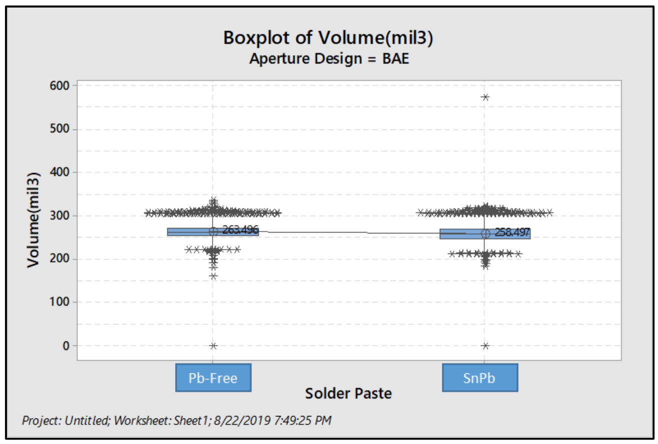
Statistics

Variable	Solder Paste	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume(mil3)	8.9HF 4.5	16000	0	1701.1	0.940	118.9	6.99	1420.0	1618.0
	SMQ92J	16000	0	1753.8	1.01	127.8	7.29	802.0	1645.0

Variable	Solder Paste	Median	Q3	Maximum
Volume(mil3)	8.9HF 4.5	1680.0	1753.0	2152.0
	SMQ92J	1776.0	1857.0	2083.0

Boxplot of Volume(mil3)

Figure 15. Boxplot and statistics for 0402 volumes with newer solder pastes



Results for Aperture Design = BAE

Statistics

Variable	Solder Paste	N	N*	Mean	SE Mean	StDev	CoefVar	Minimum	Q1
Volume(mil3)	8.9HF 4.5	22800	0	263.50	0.101	15.27	5.79	0.000	253.00
	SMQ92J	22800	0	258.50	0.107	16.20	6.27	0.000	247.00

Variable	Solder Paste	Median	Q3	Maximum
Volume(mil3)	8.9HF 4.5	262.00	273.00	336.00
	SMQ92J	258.00	269.00	573.00

Boxplot of Volume(mil3)

Figure 16. Boxplot and statistics for 0.5 mm BGA volumes with newer solder pastes

All of the aperture sizes tested (0.4mm BGA and 01005 not shown) demonstrated similar trends in the data: very tight distributions with an unusually high amount of outliers. Comparison of the 0.5 mm BGA print volumes for BAE apertures shown in Figure 16 against those in Figures 7 and 13 exemplifies the differences.

The follow-up dataset printed in the laboratory – the newer SnPb and Pb-Free/backward compatible solder pastes - was on a new lot of test boards. Subsequent investigation of the boards revealed the solder mask was higher than the pads, creating contact and gasketing problems between the stencil and the pad. This provides a highly plausible explanation for the atypical distribution of the volume data. An example of solder mask higher than the PCB pad is shown in Figure 17.

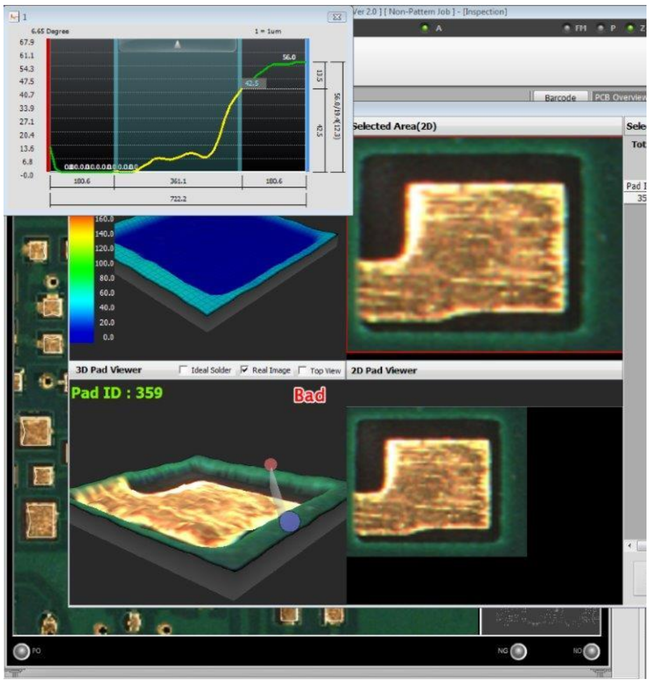


Figure 17. SPI screenshot showing solder mask taller than PCB pad, which prevents proper gasketing of the stencil to the board

Additionally, between the original print tests and the final set on the newer solder pastes, the SPI machine in the laboratory was upgraded to a Koh Young Aspire 3 with 10 micron resolution and four 12 MP cameras. It is faster and more accurate than the earlier model used in the main part of the laboratory study; however, there is little likelihood that the new machine contributed to the different distribution trends, other than measuring them more accurately that its predecessor.

The last two datasets, for the newer solder pastes, showed extremely good repeatability despite the print deficit of solder mask above the pads on the second set of test PCBs.

DISCUSSION

If each print process is evaluated using a criteria based on CVs, where less than 10% is considered capable, 10-15% is considered marginal and over 15% is considered not capable, performance can be easily categorized.

On the assembler's line using the current SnPb solder paste, this test showed the process was completely capable of printing 0201 and 0402 components, preferably with a 4 mil nanocoated foil to help get sufficient release on the 0201s. It also showed a borderline marginal/incapable CV of 15.4% on 0.5 mm BGAs with the POR aperture only, and complete incapability on smaller components. Again, it should be noted that the capabilities will improve on less densely populated production PCBs, as this test layout is designed to stress solder paste.

On the laboratory line using the current SnPb solder paste, the process was also capable of 0402, 0201 and marginally capable 0.5 mm BGAs (11% CV), regardless of aperture design. The volumes were slightly lower in all cases, and the CVs were much lower on the smaller apertures. The differences could be attributed to either the printer or the SPI machines.

The process improved with the newer SnPb solder paste formulation, which demonstrated good capability on 0.5mm BGAs and good/marginal on 01005s. Finally, the newest solder paste performed the best, showing good capability on all component sizes including 0.4 mm BGA and 01005, despite the handicap of excessive solder mask.

The best print performance was realized with the cured on nanocoating, followed by the wipe on nanocoating, with the naked stencil consistently showing the most variation. The assembler currently uses the cured on nanocoating as the preferred finish on all their stencils.

Table 3 summarizes the results for a 4 mil foil with cured on nanocoating.

Table 3. Summary of statistics for print process with 4 mil foil with cured on coating

Solder Paste Print Capability

Data for 4 mil foil with Cured On Coating

Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Current (Production Line)	1005	POR/BAE are the same	159	53	NO
	201	POR/BAE are the same	520	5.9	YES
	402	POR - IPC 7525	1747	5.6	YES
		BAE Experimental	1779	5	YES
	05BGA	POR - IPC 7525	315	15	MARGINAL
		BAE Experimental	241	23	NO
	04BGA	POR - IPC 7525	105	52	NO
		BAE Experimental	108	54	NO
Current (Lab)	1005	POR/BAE are the same	141	17	NO
	201	POR/BAE are the same	427	6.7	YES
	402	POR - IPC 7525	1537	5.8	YES
		BAE Experimental	1559	5	YES
	05BGA	POR - IPC 7525	266	11	MARGINAL
		BAE Experimental	211	11	MARGINAL
	04BGA	POR - IPC 7525	100	26	NO
		BAE Experimental	96	28	NO
Newer Gen SnPb (Lab)	1005	POR/BAE are the same	197	10.4	MARGINAL
	201	POR/BAE are the same	505	8.4	YES
	402	POR - IPC 7525	1686	5.7	YES
		BAE Experimental	1754	7.3	YES
	05BGA	POR - IPC 7525	310	4.8	YES
		BAE Experimental	259	6.3	YES
	04BGA	POR - IPC 7525	145	17	NO
		BAE Experimental	151	25	NO
Newest Pb-Free SnPb Compatible (Lab)	1005	POR/BAE are the same	195	8.7	YES
	201	POR/BAE are the same	478	8.3	YES
	402	POR - IPC 7525	1768	5.8	YES
		BAE Experimental	1701	7	YES
	05BGA	POR - IPC 7525	322	4.9	YES
		BAE Experimental	264	5.8	YES
	04BGA	POR - IPC 7525	162	8.8	YES
		BAE Experimental	166	8.5	YES

CONCLUSIONS

The information sought and gained by the test includes:

What is the impact of migrating from 5 mil foils to 4 mil foils?

Reducing the stencil thickness from 5 mil to 4 mil reduces the volume on the 0402s by approximately 20%, but maintains excellent repeatability and provides enough solder to form a proper joint. Reducing the thickness *helps improve the 0201 process* by eliminating insufficient deposits that lead to wetting problems. It also helps the 0.5 and 0.4 mm BGA deposition processes in a similar fashion.

0.5mm and 0.4 mm BGAs showed poor print performance with the incumbent solder paste on 4 mil foils and complete incapability on 5 mil foils, but fared better with the newer solder paste formulations, particularly on the 4 mil foils. The main differences between BAE and POR aperture outputs on the 0.5 mm deposits were the volumes, not the repeatability, as both showed similar CVs. The two designs' performance was almost identical on the 0.4 mm deposits with the only capable solder paste (the newest).

Would different aperture designs improve the repeatability of the print process?
For 0402s, the POR and BAE apertures deposit equivalent amounts of solder paste, but the BAE experimental aperture is believed to limit tombstone defects better than the POR. Because the volumes are similar, it should be easy to implement on an assembly line to see if it helps with tombstone and other wetting-related defects.

For BGAs, the POR is currently better for the 0.5 mm prints, but neither aperture is acceptable for 0.4 mm prints in the current process. With the newest solder paste, the 0.5 mm benefited from the BAE experimental aperture, whereas the 0.4 mm did not show a significant difference between the two designs.

What is the smallest device we can repeatably print with the current solder paste formulation?
0201s. A 4 mil foil provides better quality in terms of less insufficient deposit volumes.

Would qualifying a new solder paste provide enough quality and cost improvement to justify the effort?
Based on the findings in the laboratory, the assembler can gain a great deal of print capability by modernizing their solder paste formulation. Increases in print capability lead directly to decreases in defects, rework, scrap and lost time.

A tremendous amount of effort is required to change solder pastes, so the increase in productivity must be weighed against the investment and timed appropriately to continue the flow of new product introductions with miniaturized components. However, if the investment is made, the obvious choice would be to qualify the newest flux formulation in the backward compatible SnPb solder paste. The print performance difference is considerable and will eventually be needed as the miniaturization trend continues.

FUTURE WORK

The stencils have been preserved to continue studying print capability on the fine features. The assembler may use them in further investigating new solder paste products to improve their assembly process. Additionally, other solder pastes may be printed in similar tests to benchmark performance among popular products.

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[1] Shea, C., and Pandher, R., "Optimizing Stencil Design for Lead-Free Processing," Proceedings of SMTA International 2004

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Comparison of Aperture Designs, Solder Pastes, Nanocoatings and Print/Inspection Systems

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Agenda

- Introduction
- Experimental setup
- Key Questions
- Results
- Discussion and Conclusions
- Q & A

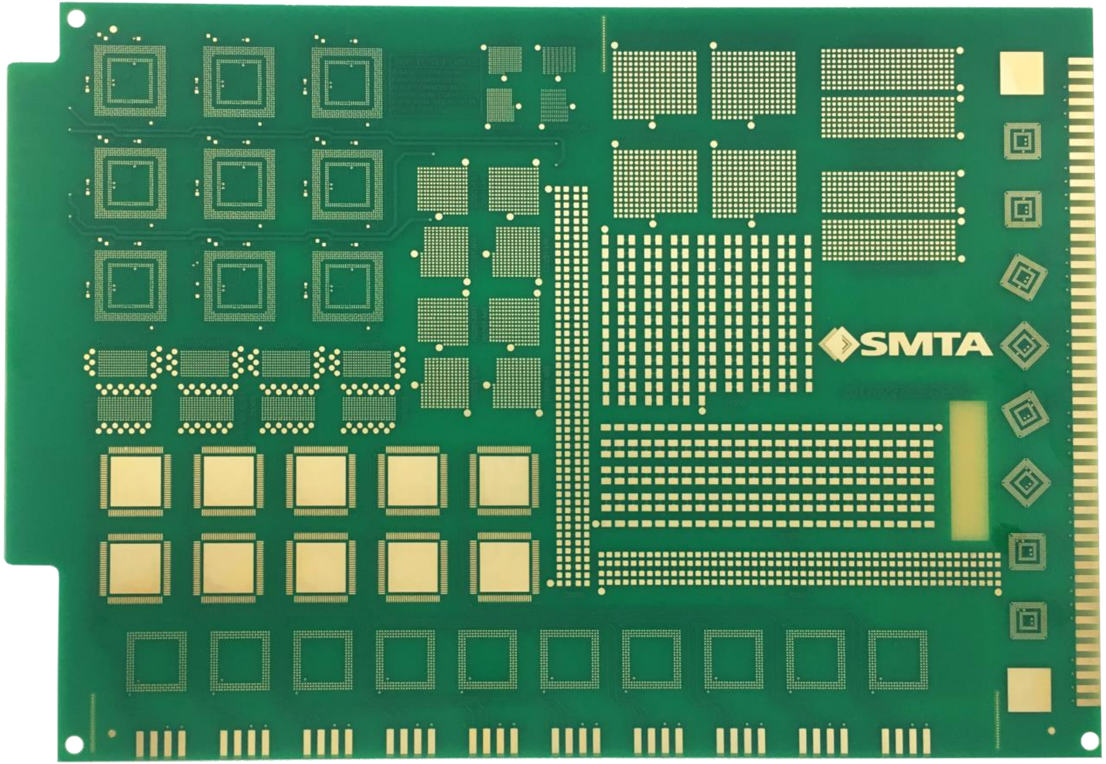
Current Situation on SMT Line

- High reliability, mission-critical products use SnPb solder paste and 5 mil stencil foils
  - A "very mature" solder paste formulation is spec'd in
  - Tombstoning on 0402s is an issue - by today's standards it shouldn't be
  - There are newer SnPb formulations that would print better than the current one (and they are 20+ yrs old!)
- Miniaturized devices are in the design pipeline
  - Is the process ready for them?

Study

- Compare 5 and 4 mil foil thicknesses to gauge effect of thinning to 4 mils
- Compare incumbent SnPb solder paste with newer, improved solder pastes
  - But don’t bring paste samples in house!
- Revisit nanocoatings for up-to-date data

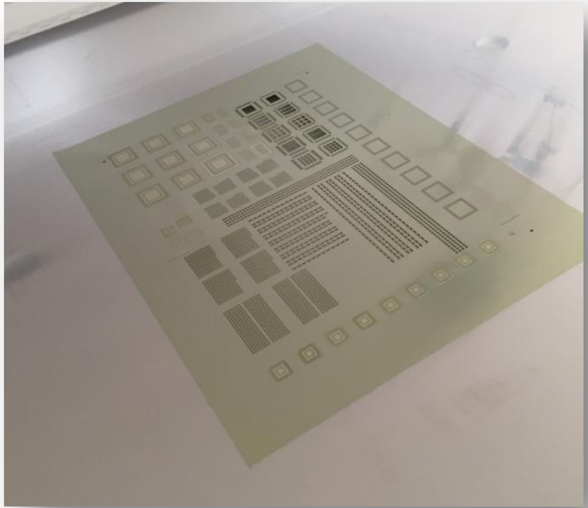
Test Vehicle



Experiment

- 12 stencils
  - **2 aperture design rules**
    - POR = Process of Record
    - BAE = BAE Experimental
  - **2 foil thicknesses**
    - 4 and 5 mil (100 and 125vµm)
  - **3 coatings**
    - Cured on nano, wiped on nano, naked

12 stencils in full factorial

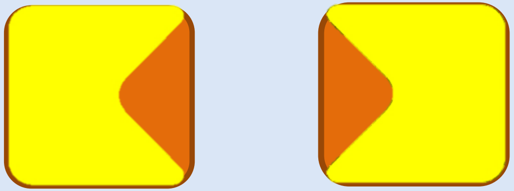


Stencil with cured on nanocoating

POR vs BAE – 0402s & up

POR – Process of Record

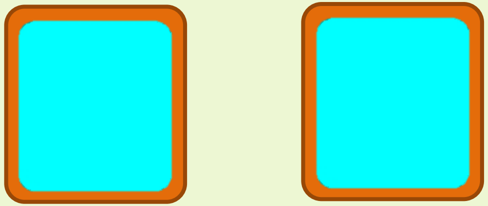
Radiused Inverted Home Plate



Removal of solder paste from under the terminations limits mid-chip solder ball formation

BAE – Experimental

10% Area Reduction

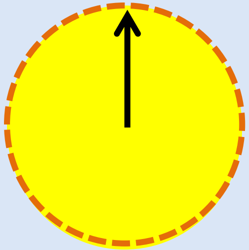


More surface area contact limits tombstones and skews that result from placement offsets

POR vs BAE – BGAs

POR – Process of Record

Circle at 1:1 with the pad

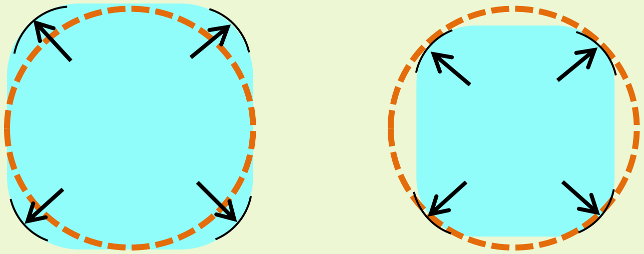


__Circle:__ **Entire boundary of shape is a common distance from its center point (radius)**

The equal forces around the perimeter at separation don't enable a "peel point"

BAE – Experimental

Squircle at 1:1 or 10% Area Reduction



__Squircle__**: 4 sided shape with radiused corners**

The unequal forces enable "peel points" at the corners during separation

POR vs BAE – 0201 & smaller

Package	0201 (0603M)	01005 (0402 M)
Pad Size	12 x 15 mil	8 x 8 mil
Aperture Size	10.8 x 13.5 mil	8 X 8 mil
Area Ratio 4 mil	0.75	0.50
Area Ratio 5 mil	0.60	0.40

Look at how thinning the stencil foil affects area ratio!

Solder Pastes & Test Sites

- Incumbent paste can be tested at assembler
  - *Potential replacement pastes cannot*
- Test incumbent paste on production line and in equipment supplier's lab and and look for correlation
- If reasonable, test newer pastes at equipment lab to demonstrate opportunity for improvement

Test Equipment

Assembler's Line

- Ekra Serio 4000
- Koh Young Aspire 3 with 4 projectors and a 12 MP camera at 15 µm resolution

Supplier's Lab

- MPM Edison 2
- Koh Young 8030 with 2 projectors and a 4 MP camera at 15 µm resolution
- Later upgraded to Aspire 3 with 4 projectors, and a 12 MP camera at 10 µm resolution

The same programs written by BAE were used in all tests

Managing the Data

- From SPI export to crunching stats
  - Convert .csv to _modified.xlsx
  - Sort to remove obstructing headers
  - Metric to Imperial - mils preferred
  - Clean up decimals
  - Add columns for variables
  - Ready for pivot tables or statistical sw

SPI EXPORT

	A	C	F	G	H	I	J	K	M	N
1	PCB ID	Component ID	Volume(%)	Area(%)	Volume(um3)	Height(um)	OffsetX(um)	OffsetY(um)	Size X	Size Y
1117	32	C13	111.511	96.335	32427740	117.605	8.34	20.093	513	558
1118	32	C13	113.41	96.06	32979950	119.95	-7.443	23.229	513	558
1119	32	C130	91.744	98.462	156136100	94.668	-9.821	15.198	1034	1620
1120	32	C130	91.431	98.398	155604300	94.407	-12.352	18.513	1034	1620
1121	32	C1300	0	0	0	0	0	0	128	152

READY TO CRUNCH

	A	B	C	D	E	I	L
1	Solder Paste	Stencil Thickness	Aperture Design	Coating	PCB ID	Component ID	Volume - MILS ^3
2		4	BAE	Cured on	135	C1000	482
3		4	BAE	Cured on	135	C1000	483
4		4	BAE	Cured on	135	C1001	493
5		4	BAE	Cured on	135	C1001	483

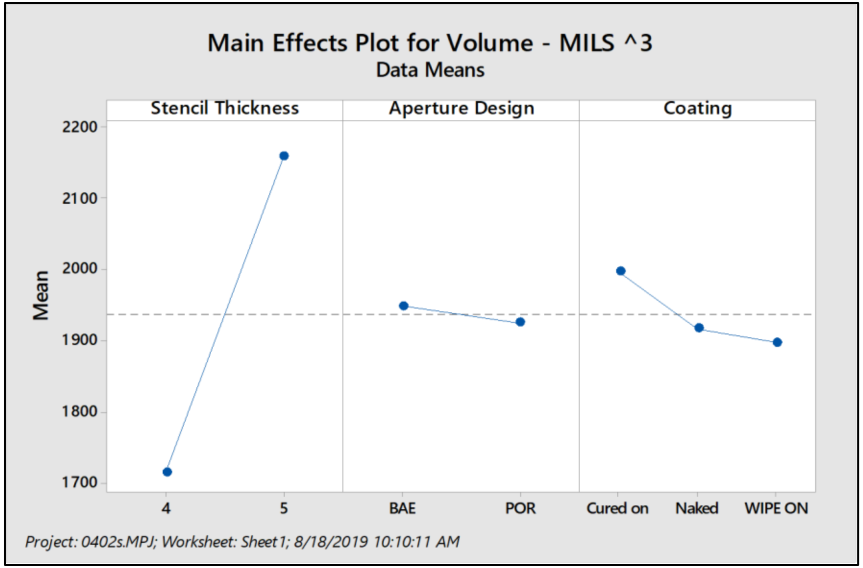
Data Management – Lessons Learned

- Export in familiar units – mils
  - Easy to compare target volumes
  - Offsets more obvious in mils
  - Aperture sizes export more accurately
- File sizes are HUGE
  - Separate into smaller files if over 1 million lines
  - Autosave bogs down Excel performance
- DO NOT try Minitab 19!!!!
  - It is not ready for prime time and cannot be saved as version 18

Results

Results - Coatings

- Volume (shown)
  - Cured on deposited higher volumes than naked stencils or wipe on nanocoating, in that order
- Variation (not shown)
  - Cured on showed the least variation, followed by wipe on and naked stencils



Cured on coating is the standard for this operation
All subsequent data reported is with cured on coating

4 Key Questions

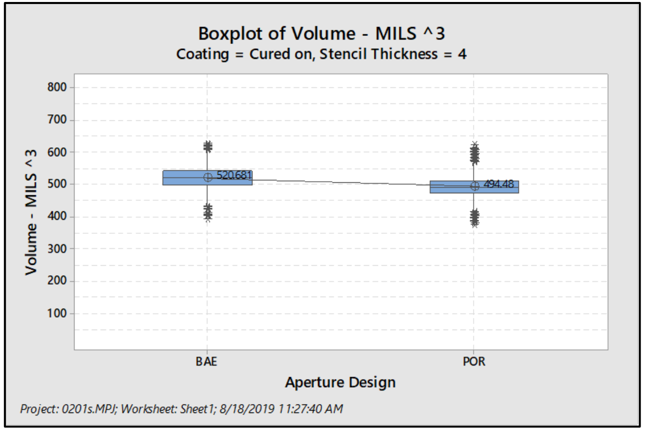
- What is the impact of migrating from 5 mil to 4 mil foil thickness?
- Would different aperture designs improve the repeatability of the process?
- What is the smallest device that can currently be printed repeatably?
- Would qualifying a new solder paste be worth the effort?

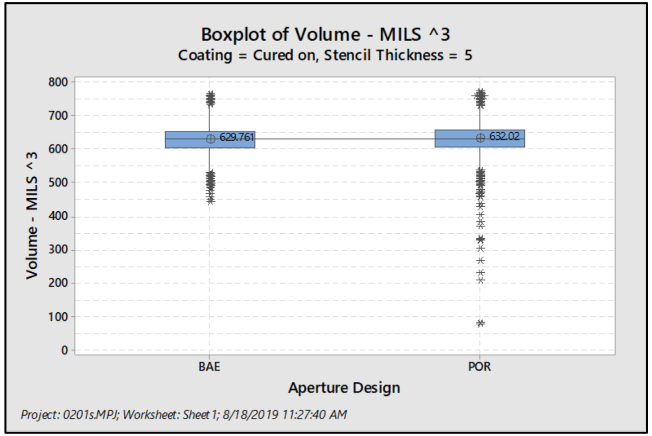
Criteria

- Paste volumes
  - Using absolute volumes instead of Transfer Efficiency %s because of different foil thicknesses
- Coefficient of Variation (CV)
  - Dividing the standard deviation by the average and expressing it as a percentage normalizes it
  - **Preferred: CV<10%**
  - **Acceptable: 10<CV<15%**
  - **Unacceptable: CV>15%**

Thinning the Foil

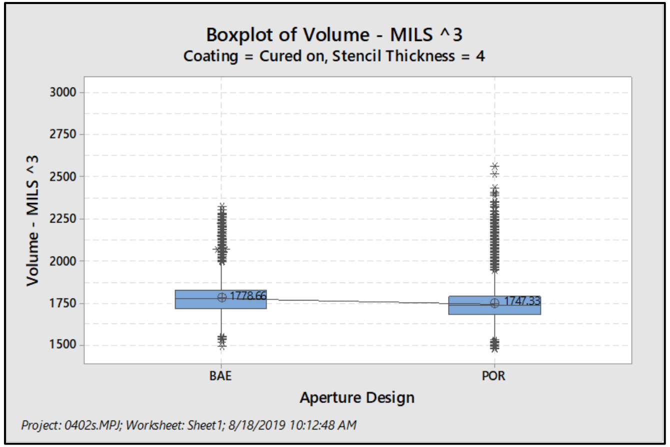
- 01005s – Neither thickness can print with incumbent paste (not shown)
- 0201s – Either thickness can print (shown at right)
  - BAE and POR are the same
  - All CVs ~6%
  - 5 mil foil has more outliers
  - 4 mil is preferred

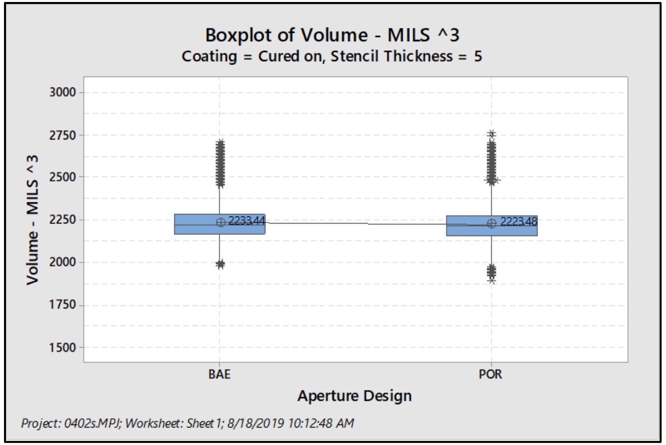




0402s

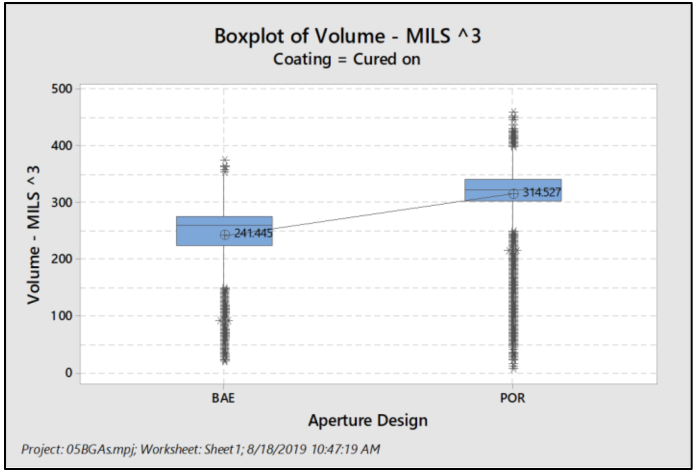
- Both thicknesses and designs are capable (all CVs ~4-5)
- Both aperture designs have similar areas (and therefore volumes)
- 5 mil deposits 20% more than 4 mil; AR is not a factor
- Can assembler live with 20% less paste?





Circle vs Squircle

- 04BGAs – Neither thickness can print with incumbent paste (not shown)
- 05BGAs – only 4 mil foil can print with incumbent paste (shown at right)
  - CV is 23% for BAE (squircle) and 15.1% for POR (circle)
  - POR has higher volume and tighter distribution but more outliers than BAE
  - POR marginally acceptable



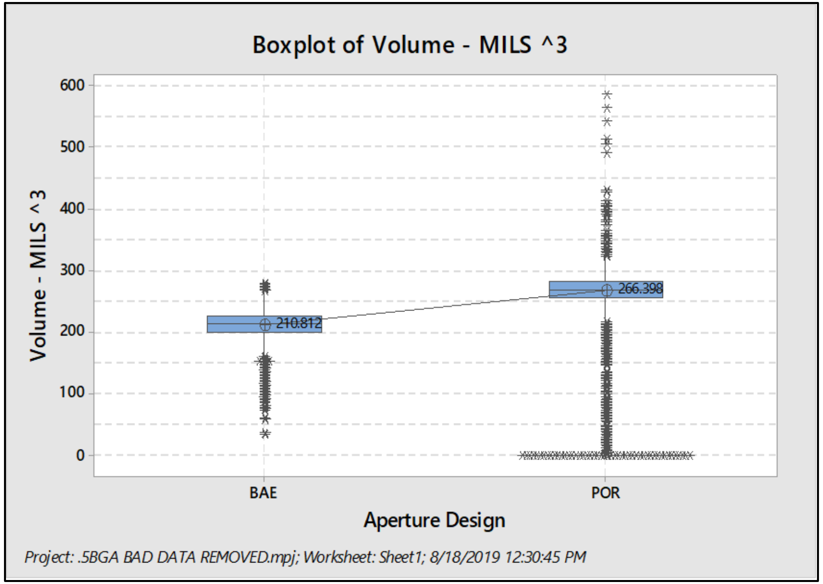
Did the circle beat the squircle on the production line? *Technically yes*, but neither distribution looks desirable.

Commentary on BGA Performance

- 15.1% CV for POR aperture on assembly line is marginal at best
- This PCB design puts more demands on solder paste more than a traditional PCB layout
  - Aperture density is much higher
  - “Drains” fill pressure from the moving paste bead
- Assembly line print performance on a live product containing a 0.5 mm BGA is likely much better than the print performance on this test board

Circle vs Squircle in the Lab

- Same solder paste as the line
- Newer printer with 8 µm alignment and isolated Z-axis motion
- BAE (squircle) aperture far superior to POR (circle)
  - Too many insufficients from circular aperture



Smallest Feature to Print Repeatably

- On the assembly line:
  - 0201s perfectly acceptable; better on 4 mil foil
  - 05BGA marginally acceptable on 4 mil foil only
- In the lab
  - Same trend…

Correlate Line to Lab…Summary

Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Current (Production Line)	1005	POR/BAE are the same	159	**53**	**NO**
	201	POR/BAE are the same	520	**5.9**	**YES**
	402	POR - IPC 7525	1747	**5.6**	**YES**
		BAE Experimental	1779	**5**	**YES**
	05BGA	POR - IPC 7525	315	**15**	**MARGINAL**
		BAE Experimental	241	**23**	**NO**
	04BGA	POR - IPC 7525	105	**52**	**NO**
		BAE Experimental	108	**54**	**NO**

Current (Lab)	1005	POR/BAE are the same	141	**17**	**NO**
	201	POR/BAE are the same	427	**6.7**	**YES**
	402	POR - IPC 7525	1537	**5.8**	**YES**
		BAE Experimental	1559	**5**	**YES**
	05BGA	POR - IPC 7525	266	**11**	**MARGINAL**
		BAE Experimental	211	**11**	**MARGINAL**
	04BGA	POR - IPC 7525	100	**26**	**NO**
		BAE Experimental	96	**28**	**NO**

New Formulation Capability

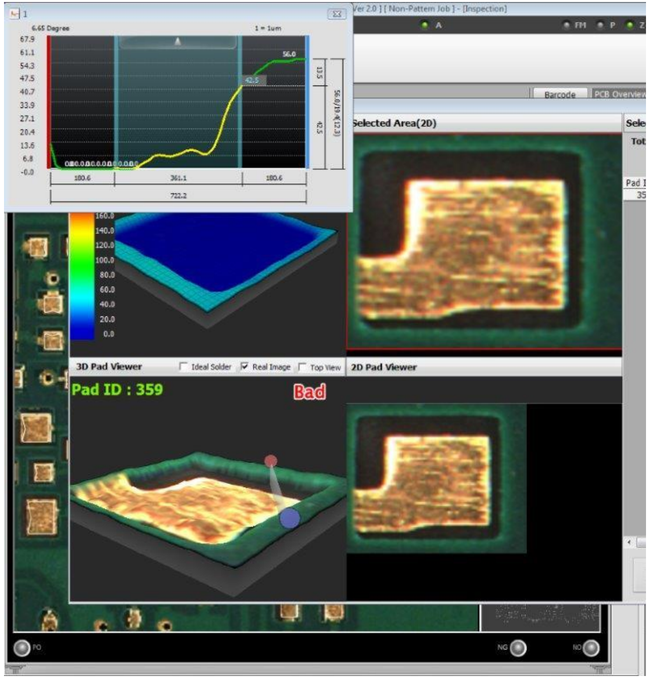
Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Newer Gen SnPb (Lab)	1005	POR/BAE are the same	197	**10.4**	**MARGINAL**
	201	POR/BAE are the same	505	**8.4**	**YES**
	402	POR - IPC 7525	1686	**5.7**	**YES**
		BAE Experimental	1754	**7.3**	**YES**
	05BGA	POR - IPC 7525	310	**4.8**	**YES**
		BAE Experimental	259	**6.3**	**YES**
	04BGA	POR - IPC 7525	145	**17**	**NO**
		BAE Experimental	151	**25**	**NO**

Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Newest Pb-Free SnPb Compatible (Lab)	1005	POR/BAE are the same	195	**8.7**	**YES**
	201	POR/BAE are the same	478	**8.3**	**YES**
	402	POR - IPC 7525	1768	**5.8**	**YES**
		BAE Experimental	1701	**7**	**YES**
	05BGA	POR - IPC 7525	322	**4.9**	**YES**
		BAE Experimental	264	**5.8**	**YES**
	04BGA	POR - IPC 7525	162	**8.8**	**YES**
		BAE Experimental	166	**8.5**	**YES**

One More Interesting Finding

- Pad below solder mask
- Came in on second lot of PCBs
- Skewed data with outliers on the follow up runs with newer pastes, which still outperformed the incumbent, despite the handicap

Has this happened on your production line?



Conclusions

Key Question #1

What is the impact of migrating from 5 mil to 4 mil foil thickness?

- Reduces 0402 volume by 20%
- Improves 0201 process
- Presents the only viable way to print µBGAs ≤0.5 mm pitch

Key Question #2

Would different aperture designs improve the repeatability of the process?

- For 0402s, the aperture designs have similar areas and therefore similar volumes
  - Both designs have similar repeatabilities
  - The BAE Experimental is likely to decrease tombstoning rates

Key Question #2

Would different aperture designs improve the repeatability of the process?

- For BGAs, the data was somewhat conflicting
  - On the line, neither aperture was acceptable; POR was borderline marginal/unacceptable, but slightly better
  - In the lab, the BAE aperture far outperformed the POR in many test scenarios (other coatings and stencil thicknesses) not reported here

Guidance is for assembler to continue to use POR, but overall, the squircle should still be considered more robust than the circle

Key Question #3

What is the smallest device we can repeatably print with the current solder paste formulation?

- 0201s
- 0.5 mm BGAs

Key Question #4

Would qualifying a new solder paste provide enough quality and cost improvement to justify the effort?

- YES

Key Question #4

Current:

Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Current (Production Line)	1005	POR/BAE are the same	159	53	NO
	201	POR/BAE are the same	520	5.9	YES
	402	POR - IPC 7525	1747	5.6	YES
		BAE Experimental	1779	5	YES
	05BGA	POR - IPC 7525	315	15	MARGINAL
		BAE Experimental	241	23	NO
	04BGA	POR - IPC 7525	105	52	NO
		BAE Experimental	108	54	NO

Potential:

Solder Paste	Component Size	Aperture Design	Mean Volume (cu mil)	CV - %	Capable?
Newest Pb-Free SnPb Compatible (Lab)	1005	POR/BAE are the same	195	8.7	YES
	201	POR/BAE are the same	478	8.3	YES
	402	POR - IPC 7525	1768	5.8	YES
		BAE Experimental	1701	7	YES
	05BGA	POR - IPC 7525	322	4.9	YES
		BAE Experimental	264	5.8	YES
	04BGA	POR - IPC 7525	162	8.8	YES
		BAE Experimental	166	8.5	YES

Thank You!

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