IMPROVING THE PCB ASSEMBLY MANUFACTURING PROCESS BY UTILIZING AN ALTERNATIVE SOLDER PASTE: A STATISTICAL EVALUATION

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ABSTRACT

To address the requirements of component miniaturization, high-density board designs and ever-increasing throughput and yield, solder paste technology is evolving. Not only must next-generation solder materials offer meaningful improvements in process performance, but also provide more manufacturing flexibility by expanding the process window. The ability to effectively accommodate manufacturing environments where assembly processes are interrupted, where the luxury of long start-up times are non-existent and where materials are often handled non-optimally, materials capabilities in the modern age of manufacturing are critical.

Results from an investigation that studied and characterized a novel lead-free solder paste as compared to traditional solder materials will be presented. As basis for the analysis, solder materials were exposed to harsh environments to understand if the new solder paste technology is capable of withstanding the realities of modern manufacturing processes for fine pitch components (0.3 mm CSPs and 01005/0201 passives). Evaluation of solder paste printing performance was a primary focus of the investigation, taking into consideration numerous common board finishes and stencil aperture designs. Paste volume measurements acquired by SPI were used to verify solder paste volume on pads to quantify performance. Challenging manufacturing processes were simulated by aging the pastes at room versus elevated temperatures and then printing at defined time intervals. Simulated extended continuous printing was also examined. A detailed statistical analysis identifies the relationship between the condition of the solder paste and the paste volume on the pad of a given component type.

INTRODUCTION

With increasing pad counts on circuit assemblies, the need for a robust and consistent print process that can produce defect-free product is essential to a successful business. It has often been suggested that up to 70% [1] of all defects can be attributed to the print process, and many of these can be a direct result of the print characteristics of the solder paste. Unfortunately, the ubiquity of solder paste has resulted in it being viewed as a commodity rather than the technologically advanced engineering material it is. Defects as diverse as bridging/solder shorts, tombstoning, mid-chip solder balling and head-in-pillow (HIP) all have contributions from the printing process and variations in the volume and shape of the deposit created. Low deposit volumes can lead to solder joints that do not meet workmanship standards such as the IPC 610 E[2]. Variable deposit volumes have been linked to both tombstoning/drawbridging (due to differential wetting) and an increase in the occurrence of the HIP defect, which is a particularly difficult defect to detect as it is hidden under an array component.

The relentless miniaturization push has only exacerbated the prevalence of defects. Attempting to ensure sufficient paste transfer through ever-smaller apertures onto correspondingly smaller pads can result in excess paste volumes for larger apertures (0402 components and above). If the excess paste volume is underneath a chip component, it has been shown to be a significant contributor to mid-chip solder balling[3]. The advent of solder paste inspection (SPI) equipment has made the problem more manageable, as potential defects can be identified and the board reworked (cleaned and reprinted) prior to reflow, which minimizes cost.

Another approach for managing printing defect reduction is through adherence to the IPC 7525B[4] design rule. This rule dictates that the area of the aperture wall is no smaller than 0.66 of the area of the pad, a measurement which is often referred to as the Area Ratio or Aspect Ratio. However, the standard only defines what is required for a reliable solder joint based on the ability of a typical solder paste to release from a stencil. The need to maintain the aperture Aspect Ratio at or above 0.66 (though some processes have been successful at slightly below this ratio) has driven the industry to thinner and thinner stencils and, in turn, finer powders. For example, with the Aspect Ratio standard, an 80 µm thick stencil will require Type 5 powder simply to allow efficient filling of the aperture by the solder particles. But this approach comes with a cost; Type 5 solder pastes typically require a nitrogen (N_2) atmosphere for effective reflow. In order to accommodate both the small aperture deposits alongside the larger required deposits and optimize the paste volume, a variety of solutions have emerged. These include step stencils, over printing, and alterations to aperture geometry, but all have limitations. With solder pastes that can reliably exceed this criteria, the industry has taken the first step toward the paradigm shift of having the board design and components drive the stencil requirements rather than the solder paste.

Despite this shift, there are still limitations in the particle size of the solder paste, though this is now driven by the ability of the particles to effectively pack into the aperture. Equipment advances such as vibrating squeegees have allowed extensions in the use of any given particle size distribution.[5] The general rule of thumb that the smallest aperture width being used should accommodate at least five particles still informs the particle size choice (see **Table 1**). Once the particle size of the powder is determined, the solder paste flux selection follows. This is determined by a variety of criteria, with the primary factor being the substrates onto which the components will be soldered. Sometimes, however, the need for an L0 classification [6] determines the flux choice. Unfortunately, this is often as far as flux consideration goes, with little thought given to the flux stability and performance in the print process. To better understand the flux significance, this paper will analyze the printing performance of four different solder pastes and evaluate their printing performance as it relates to the impact on process capability.

Experimental

Material Selection:

Four of the more commonly used, commercially available solder pastes were selected for this study and are summarized in **Table 2**. All of the lead-free pastes are also halogen-free as defined by the IPC [7] and meet the IPC J-STD 006 classification of Type 4 powder.

Printed Circuit Board Design:

A solder paste evaluation is only as good as the printed circuit board (PCB), stencil and printer set up. Rather than evaluating all four pastes under the same print conditions, it was decided that each paste would be processed under its optimum print conditions (as determined by each material's TDS). With this approach, true paste performance could be evaluated and a poor performance would not be the result of printing conditions.

The test board was designed to evaluate material performance for current miniaturized components and interconnects. Intentionally, the PCB design ensured that for pads which were not square or round, both parallel and perpendicular pad orientations were present for evaluation. Finally, it was necessary to consider the number of pads present on the board. A claimed 20 part per million (ppm) defect rate is not unusual in many print processes, and corresponds to one failure every 50,000 pads. In order to identify changes to this defect rate, a significant number of pads are required. The lack of pads on any given board can be replaced by increasing the number of boards printed. With this in mind and considering the necessary real estate required, 200 of each of the passive components were used (100 parallel and 100 perpendicular), yielding a total of 400 passive pads per board. The array components were a bit less complex to design for evaluation, as each component has several hundred I/O and each component is square, which means there were no parallel and perpendicular pad orientations to accommodate. Therefore, 10 of each type of array component per board were used (see **Table 3** for the full list of components and **Figure 1** for the board layout). This design yielded a total of 21,461 pads per board (excluding the ground planes for the QFN). To improve statistics and to confirm print performance consistency, 10 boards were printed for each solder paste's optimal print condition. The array components were all daisy chained and the board was designed so that each side could be probed for continuity to help locate solder defects for failure analysis.

The stencil aperture design used rectangular apertures for the passive components with an area of 90% of the associated board pad, while the array components used a rectangular aperture with rounded corners. The rounding of the aperture corners results in an increase in the Aspect Ratio over the standard rectangle (see **Table 4**). Even with this adjustment, the IPC 7525B has a 01005, a 0.3 mm CSP, a 0.4 mm CSP and a PoP component with Aspect Ratios below the recommended 0.66. To meet this criterion would require an 80 μm thick stencil for the array components and a 73 μm thick stencil for the 01005.

The move to thinner stencils will necessitate the use of a finer powder and, with this, a likely move to nitrogen inerted reflow with the associated costs to the process. Therefore, it is desirable to remain with a Type 4 powder as long as possible. Consequently, this evaluation was conducted using Type 4 powder.

Equipment and Procedure:

An ASM Assembly Systems' DEK Horizon 01iX stencil printer, fitted with vacuum tooling was used to print the selected pastes onto the PCB. The boards were supported by vacuum tooling, as edge clamps were found to impact print performance up to 1.25" in from the edge of the boards. All pastes were printed under their optimum print pressure for the chosen print speed of 75 mm/s^{-1}. For each experiment, a fresh jar of solder paste was used. The paste was opened and stirred for one minute, following which 250 g of solder paste was weighed with a plastic weighing dish. The measured paste was then placed on the stencil in a single bead, extending approximately 25 mm beyond the end of the apertures on the stencil. The paste was then subjected to a four stroke knead cycle to fully wet out the apertures, after which a dry underside stencil wipe with vacuum was performed. Ten virgin boards were printed, and the volume of the solder deposits measured. After the tenth print, the stencil was once again subjected to a dry underside stencil wipe and the solder paste was left stationary 60 minutes. The second ten virgin boards were then printed and the solder paste deposit volumes measured; again, a dry underside wipe of the stencil was performed. This time, the paste was allowed to sit for 480 minutes (8 hrs.) before a final set of ten virgin boards was printed and the deposit volumes measured. (See **Figure 2** for process flow.)

Inspection of each printed board was performed using a Koh Young 8030-2 solder paste inspection (SPI) system, which utilizes white light interferometry (Moiré interferometry) to measure the area and height of the solder deposit. This measurement is then used to calculate a volume for the deposit and the measured volume is compared to the theoretical volume of the stencil aperture to yield a nominal volume in % (see **Equation 1** below).

Equation 1

Theoretical aperture volume = aperture area from design file x specified aperture volume

Percent nominal volume = (measured volume of solder deposit/theoretical aperture volume) x 100

Data Analysis:
The C_p and C_{pk} values were calculated for the various materials and apertures using 100% nominal volume as the target volume and ±50% as the upper and lower specification limits. These percentages were selected based on the results of a straw poll of SPI users and reflect industry common practice rather than limits based on post reflow defect levels. Both C_p and C_{pk} are process capability measures which are used to extrapolate the collected data to determine the expected amount of data that will fall outside the desired specification limits. The higher the C_p or C_{pk} value, the narrower the distribution and the fewer expected defects (see **Table 5** and **Figure 3**).

The C_p value is a measure of the current process variation capability if the distribution is centered in the specification range. The C_{pk} value takes into account the actual location of the measured distribution within the specification limits. Thus, if the C_p and C_{pk} value are the same, then the actual distribution is perfectly centered within the specification limits. Conversely, if C_p is high and C_{pk} is low, this would suggest that the measured distribution is shifted to one end of the specification limits and that action needs to be taken to alter the distribution. For this study's comparisons between prints, simple box and whisker plots were used, which allow for a graphical comparison of the data spread from print to print.

Results and Discussion

The fluid nature of the solder paste results in a situation where the downward force applied by the squeegee on the paste in front of it is, in part, balanced by the weight of the column of paste behind it (see **Figure 4**). This will result in paste being pushed up above the height of the stencil. The high viscosity of solder paste means that it takes a little time to reach the equilibrium, consequently this phenomenon is not observed for small apertures where the time the paste bead is over the aperture is short. This results in a gradual increase in the volume of paste as aperture dimensions increase (see **Figure 5A**). This qualitative approach ignores the impact of release on deposit volume. Consequently, with small apertures, the volume drops below 100% for all materials except material A, which remains around 100% of nominal volume (see **Figure 5B**).

Looking at the same data for deposit height (**Figures 6A** and **6B**), the effect is less pronounced except for material A. This suggests there is some peaking of the material, as it is pulled out of the aperture for materials B, C, and D. So, for materials B, C and D, the IPC 72525 B recommendation of an Aspect Ratio of 0.66 would be appropriate, while material A appears to be limited more by particle packing.

This phenomenon of liquid flow under pressure can also be used to explain the deposit shape for lager apertures. The exact equilibrium volume for a given paste is a combination of the aperture size, print speed, and pressure. Since the paste requires a finite time to reach equilibrium as the paste nears the end of the aperture, there is insufficient time for the paste immediately behind the squeegee to reach equilibrium. The result is a small, finite slope on the deposit in the direction of squeegee travel. For small apertures this will be across the full width of the aperture; for larger apertures, it will only be at the end of the deposit. The distance this slope extends and the print speed will determine the time required for the paste to reach equilibrium.

In addition to other contributors, this excess paste volume may lead to the generation of mid-chip solder balls. This increase in volume can be seen by looking at the shift in the volume distribution of the various component apertures. The distribution moves steadily to the right (see **Figures 6C-6F**) as the component size increases. Although it is not obvious, the distribution also narrows, as can be seen by an increase in the C_p for each of the various component apertures (see **Figure 7** and **Table 6**).

Unfortunately, gains in C_p are more than offset by the movement of the distribution away from the center of the specification range, as shown by the drop in C_{pk} (see **Table 6** and **Figure 7**). In most cases, the practical impact of this additional volume can be seen by the presence of mid-chip solder balls, which have been shown to be related to the volume of paste deposited. It is the excess paste in large apertures that results in the defects and the drop in C_{pk}. For small apertures (0201 and below), it is the poor release that yields insufficient solder paste and lowers C_{pk} values for pastes B, C, and D, thus 0201 and 0402 components are optimum for most pastes.

The insufficient solder paste resulting form poor release of small apertures with low aspect ratios has received more attention because the solution is more complex (reducing the stencil thicknes and utilizing a finer solder powder). However, the data for paste A clearly shows an increase in C_{pk} even though there is a widening of the volume distribution. This is achieved by centering the distribution at

96.8% close to the target volume of 100%, while the other materials are centred at lower volumes (Paste B 86%, Paste C 84.2%, Paste D 78.3%). This, combined with wide distributions, translates to C_{pk} of below 1.0 for the latter materials, while paste A has a much narrower distribution and achieves a C_{pk} of over 2.0 (less than one ppm defect rate). An Aspect Ratio of 0.53 would be expected to yield improved consistency. However, the change in apertutre shape from a rectangle to a square with rounded corners appears to counter the expected advantages of the new Aspect Ratio. This suggests that not all apertures perform equally with respect to relase and that the aperture Aspect Ratio may be an over simplification when values are below 0.66. Particle packing may be more of an influence.

The test board has two sets of 200 µm by 200 µm apertures in two different locations. One is for the 0.3 mm CSP and one is for the 0.4 mm CSP. Comparison of the average deposit volumes for the different locations shows a significant difference in volume and consistency, which isn't easily understood. The most likely explanation of this effect is the pin tooling used. The 0.3 mm CSP was at one end of the board, while the 0.4 mm CSP was along the side close to the transfer rails, which provided additional support and improved gasketing. This difference requires further study. However, the performance of the 0.4 mm CSP pads rather than that of the 0.3 mm CSPs should be considered to be the optimum performance of each paste.

Again, paste A yielded higher average paste volumes and higher C_{pk} values than the other three materials (see **Figures 8A-8D** and **Table 7**). These apertures on a 100µm stencil would require the user to source a thinner stencil and a finer powder to achieve the desired result. Even paste A was below 1.33 Cpk for the 0.3 mm CSP component apertures, although it achieved better than 5σ for the same apertures elsewhere on the board. This result only serves to reinforce the importance of correct tooling support for boards.

Finally, the ability of the paste to remain on the stencil and still be capable of printing must be considered. Since neither pastes B, C, or D yielded a capable process, only the data for paste A will be considered in depth. After one hour without printing, the initial print for all pastes produced unacceptable leves of deposits with insuffcent solder paste (see **Figure 9**). The second print yielded paste volumes equivalent to those observed for the initial prints. This situation was exacerbated by leaving the paste on the stencil for an additional 8 hours. Pastes A, B and C required four prints to return to initial volumes, while paste D required 5 (see **Figure 10**).

However, as discussed previoiusly, the average voume is not necessarily a good indication of a process being in control. Rather, the C_{pk} value, which includes both the average and the distribution of deposit volumes, is a much better indication of a material's process capability. The C_{pk} values for Paste A were calculated using the last nine prints after one hour of abandon time and the last six prints after eight hours abandon time. The data shows that Paste A's performance remains conisistent (see **Table 8** and **Figures 11** and **12**), which suggests that any residual material in the apertures does not exhibit excessive drying which can inhibit release. The paste is capable of achieving a four sigma process and, in a number of cases, five and six sigma processes were achieved. It is likely that five sigma is possible with optimized tooling.

CONCLUSION

Although significant differences in performance were observed across the different pastes, a number of common trends were documented. As aperture size increases, the deposit volume distributions typically narrow (C_p increases), eventually stabilizing for component apertures of 0402 and above. All pastes exhibited a reduction in process capability (C_{pk} decreases) with increasing aperture size due to a shift in the center of the deposit volume distribution to above the 100% target. This is a result of the hydrostatic characteristics of solder pastes and yields deposits that are higher than the thickness of the stencil. The extra paste may also contribute to mid-chip solder balling. Paste A consistently yields the greatest C_p and C_{pk} values when compared to the other pastes.

For apertures with Aspect Ratios less than the IPC 7525B guideline of 0.66, only Paste A was able to yield sufficient deposit volumes to produce a viable process, even down to 01005 apertures which have an Aspect Ratio of 0.46. Aperture shape was found to be significant, as square apertures with rounded corners and higher aspect ratios performed more poorly than the 01005 rectangular apertures.

All pastes required an initial print after one hour of inactivity, and multiple prints after eight hours to return the average print volumes experienced on the initial prints. C_p and C_{pk} values for paste A also returned to similar levels as those achieved for the initial prints.

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APPENDIX

Table 1: Minimum Aperture Size for Different Particle Sizes

Pitch / mm	Aperture size / mm	Stencil Aspect ratio (should be above 1 : 1.5)				PSD				
		0.15	0.125	0.1	0.075	T3	T3.5	T4	T5	T6
0.6	0.4	2.67	3.20	4.00	5.33	0.40	0.40	0.40	0.40	0.40
0.5	0.35	2.33	2.80	3.50	4.67	0.35	0.35	0.35	0.35	0.35
0.4	0.25	1.67	2.00	2.50	3.33	0.25	0.25	0.25	0.25	0.25
	0.24	1.60	1.92	2.40	3.20	0.24	0.24	0.24	0.24	0.24
	0.23	1.53	1.84	2.30	3.07	0.23	0.23	0.23	0.23	0.23
	0.22	1.47	1.76	2.20	2.93	0.22	0.22	0.22	0.22	0.22
	0.21	1.40	1.68	2.10	2.80	0.21	0.21	0.21	0.21	0.21
	0.2	1.33	1.60	2.00	2.67	0.20	0.20	0.20	0.20	0.20
	0.19	1.27	1.52	1.90	2.53	0.19	0.19	0.19	0.19	0.19
	0.18	1.20	1.44	1.80	2.40	0.18	0.18	0.18	0.18	0.18
	0.17	1.13	1.36	1.70	2.27	0.17	0.17	0.17	0.17	0.17
	0.16	1.07	1.28	1.60	2.13	0.16	0.16	0.16	0.16	0.16
0.3	0.15	1.00	1.20	1.50	2.00	0.15	0.15	0.15	0.15	0.15
	0.14	0.93	1.12	1.40	1.87	0.14	0.14	0.14	0.14	0.14
	0.13	0.87	1.04	1.30	1.73	0.13	0.13	0.13	0.13	0.13
	0.12	0.80	0.96	1.20	1.60	0.12	0.12	0.12	0.12	0.12
	0.11	0.73	0.88	1.10	1.47	0.11	0.11	0.11	0.11	0.11
0.2	0.1	0.67	0.80	1.00	1.33	0.10	0.10	0.10	0.10	0.10
	0.09	0.60	0.72	0.90	1.20	0.09	0.09	0.09	0.09	0.09
	0.08	0.53	0.64	0.80	1.07	0.08	0.08	0.08	0.08	0.08
0.1	0.07	0.47	0.56	0.70	0.93	0.07	0.07	0.07	0.07	0.07
	0.06	0.40	0.48	0.60	0.80	0.06	0.06	0.06	0.06	0.06
	0.05	0.33	0.40	0.50	0.67	0.05	0.05	0.05	0.05	0.05

Table 2: Summary of Solder Pastes Evaluated

Solder Paste	Halogen free	IPC Classification	Viscosity (cP)	Particle Size	Alloy
A	Yes	ROL0	2000	Type 4	SAC305
B	Yes	ROL0	1300	Type 4	SAC305
C	Yes	ROL0	1900	Type 4	SAC305
D	Yes	ROL0	1300	Type 4	SAC305

Table 3: Test Board Pad Count

Component	Horizontal	Vertical	Total Pads	Total Paste Measurements (10 boards)
01005	100	100	400	4,000
0201	100	100	400	4,000
0402	100	100	400	4,000
0603	100	100	400	4,000
1206	100	100	400	4,000
0.3mm CSP	10		6,760	67,600
0.4mm CSP	10		4,320	43,200
0.4mm POP	10		6,200	62,000
0.4mm QFN	10		1000	10,000

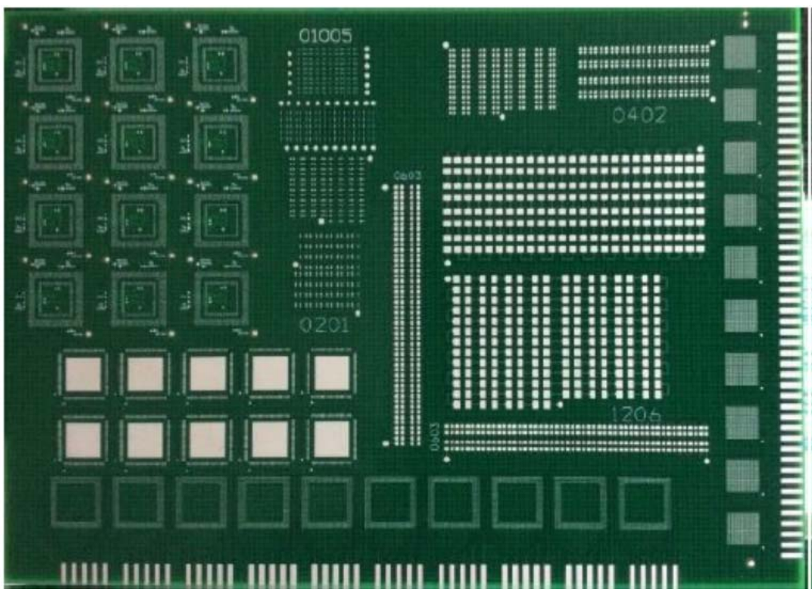


Figure 1: Test Board Layout

Table 4: Effect of Stencil Thickness and Shape on Aspect Ratio

Component	Aperture Shape	Width (µm)	Height (µm)	Area (μm^2)	Stencil Thickness (µm)	Wall area (µm2)	Aspect Ratio
01005	Rectangle	206	183	37698	100	77800	0.48
01005	Rectangle	206	183	37698	80	62240	0.61
01005	Rectangle	206	183	37698	73	56794	0.66
0.3mm CSP	Rectangle	200	200	40000	100	80000	0.50
0.3mm CSP	Square with rounded corners	200	200	37855	100	71420	0.53
0.3mm CSP	Rectangle	200	200	40000	80	64000	0.63
0.3mm CSP	Square with rounded corners	200	200	37855	80	57136	0.66
0.4mm CSP	Rectangle	200	200	40000	100	80000	0.50
0.4mm CSP	Square with rounded corners	200	200	37855	100	71420	0.53
0.4mm CSP	Rectangle	200	200	40000	80	64000	0.63
0.4mm CSP	Square with rounded corners	200	200	37855	80	57136	0.66
0.4mm PoP	Rectangle	203	203	41209	100	81200	0.51
0.4mm PoP	Square with rounded corners	203	203	39064	100	72620	0.54
0.4mm PoP	Rectangle	203	203	41209	80	64960	0.63
0.4mm PoP	Square with rounded corners	203	203	39064	80	58096	0.67
00201	Rectangle	274	343	93982	100	123400	0.76
0.4mm QFN	Square with rounded corners	200	600	120000	100	160000	0.75
0.4mm QFN	Rectangle	200	600	117855	100	151420	0.78
00402	Rectangle	526	594	312444	100	224000	1.39
00603	Rectangle	686	800	548800	100	297200	1.85
01206	Rectangle	1257	1600	2011200	100	571400	3.52

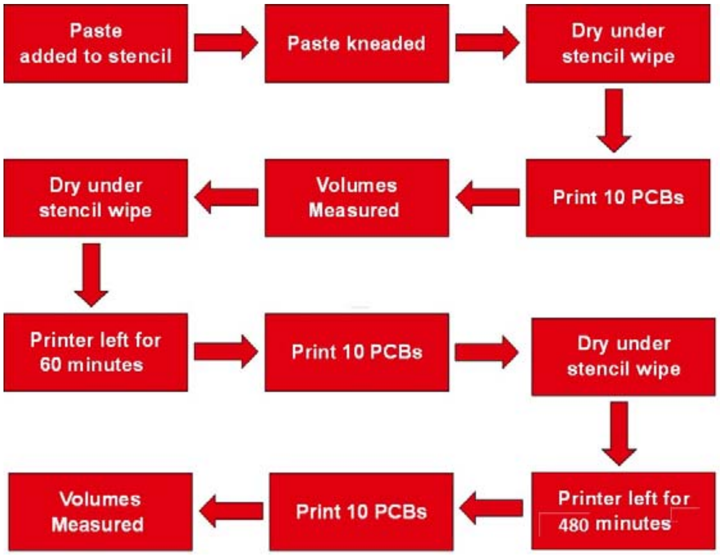


Figure 2: Experimental Flow Chart

Table 5: The Relationship of C_{pk} to Defect Rates

Cpk	Sigma Level	Defects Per Million
0.33	1	317,311
0.67	2	45,500
1.00	3	2,700
1.33	4	63
1.67	5	1
2.00	6	0.002

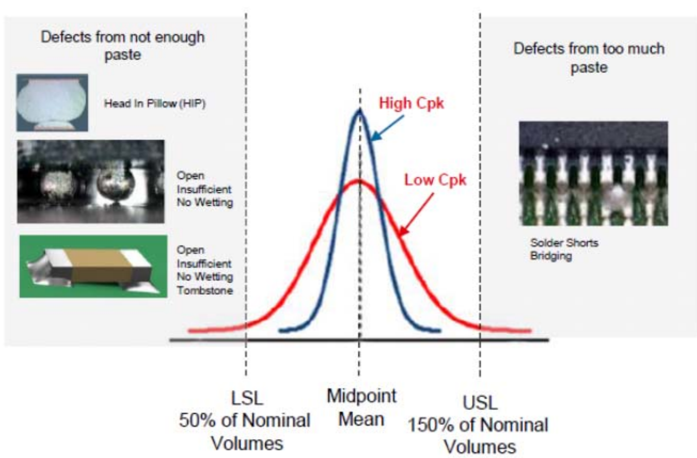


Figure 3: Graphical Representation of the Relationship of C_{pk} to Defect Rates

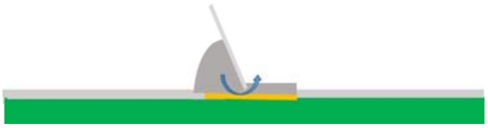


Figure 4: Effect of Pressure on Solder paste in Large Apertures

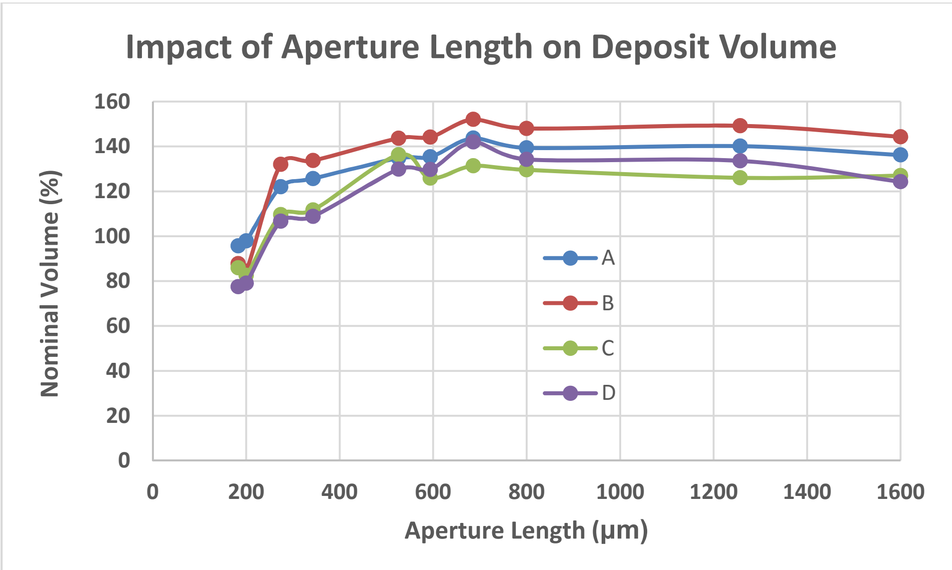


Figure 5A: Impact of Aperture Length on Deposit Volume

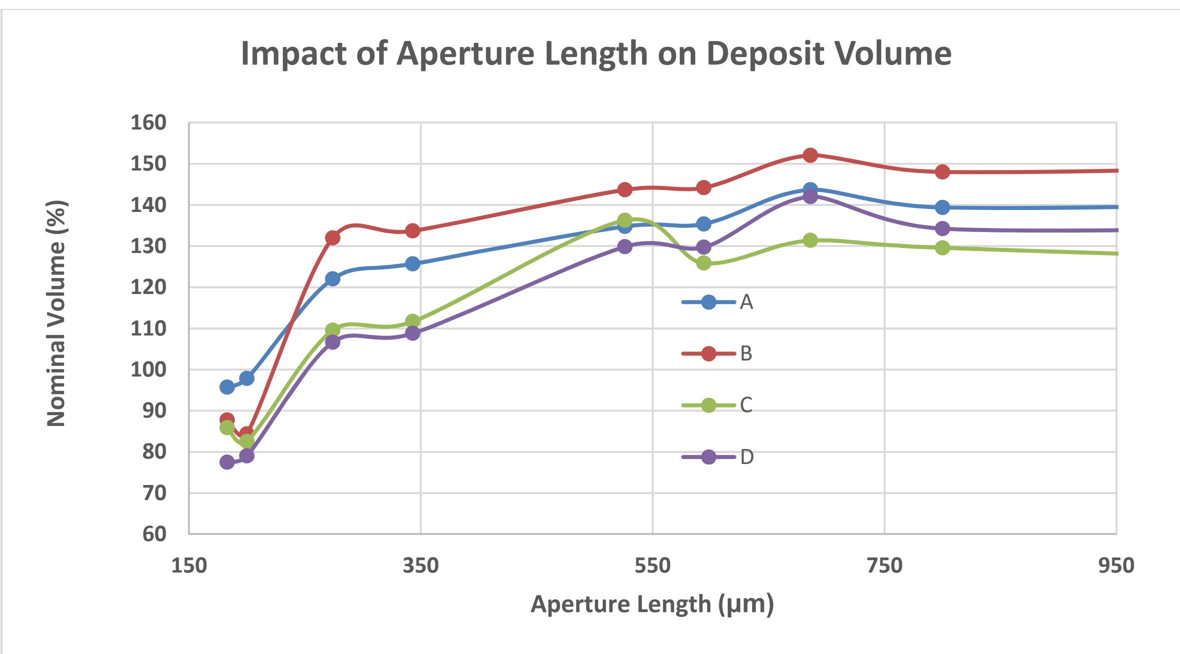


Figure 5B: Impact of Aperture Length on Deposit Volume

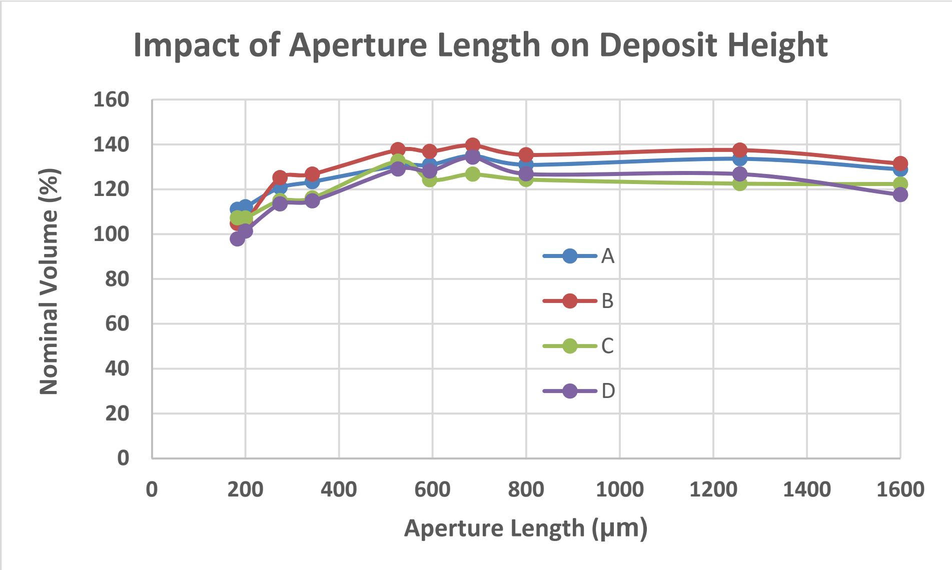


Figure 6A: Impact of Aperture Length on Deposit Height

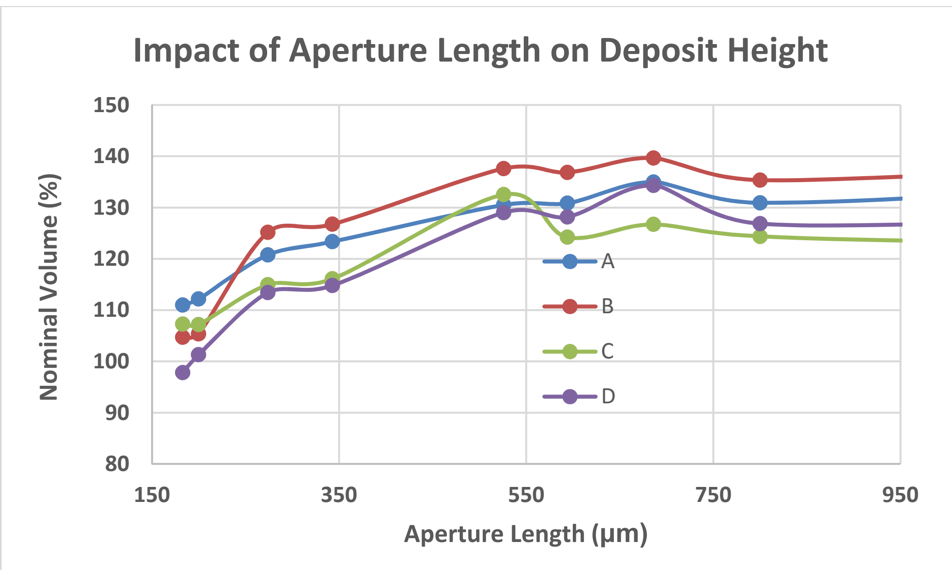


Figure 6B: Impact of Aperture Length on Deposit Height

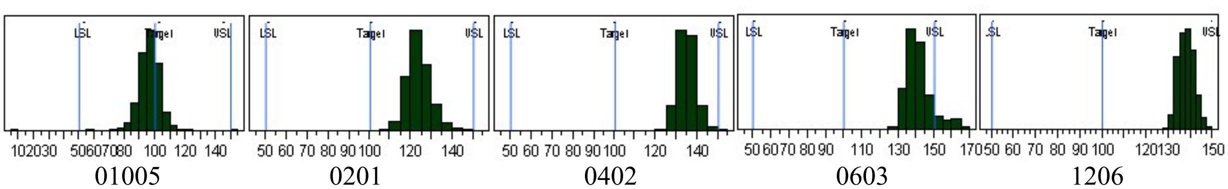


Figure 6C: Effect of Component Size on Print Volumes for Paste A

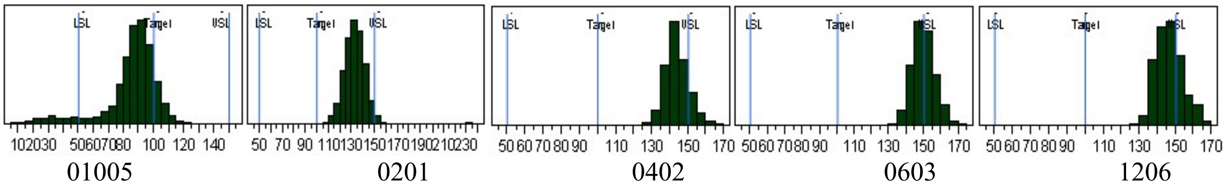


Figure 6D: Effect of Component Size on Print Volumes for Paste B

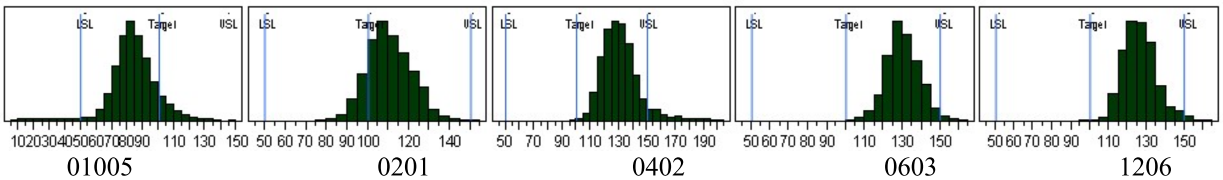


Figure 6E: Effect of Component Size on Print Volumes for Paste C

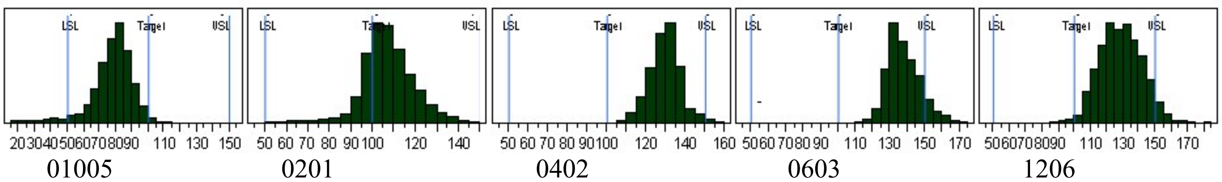


Figure 6F: Effect of Component Size on Print Volumes for Paste D

(Data is the accumulation of ten boards printed without an underside stencil wipe; 200 components per board, 100 parallel and 100 perpendicular).

Table 6: Effect of Aperture Size on C_p and C_{pk} for Different Solder Pastes

Component	Paste	C_p	C_{pk}
01005	A	2.672	2.500
01005	B	0.996	0.719
01005	C	1.170	0.800
01005	D	1.329	0.751
0201	A	3.115	1.630
0201	B	2.001	0.687
0201	C	1.596	1.275
0201	D	1.507	1.275
0402	A	4.179	1.249
0402	B	2.794	0.340
0402	C	1.318	0.499
0402	D	2.254	0.912
0603	A	2.360	0.400
0603	B	2.724	0.000
0603	C	2.022	0.790
0603	D	1.852	0.440
0603	A	4.825	1.143
1206	B	2.360	0.153
1206	C	1.987	0.934
1206	D	1.337	0.564

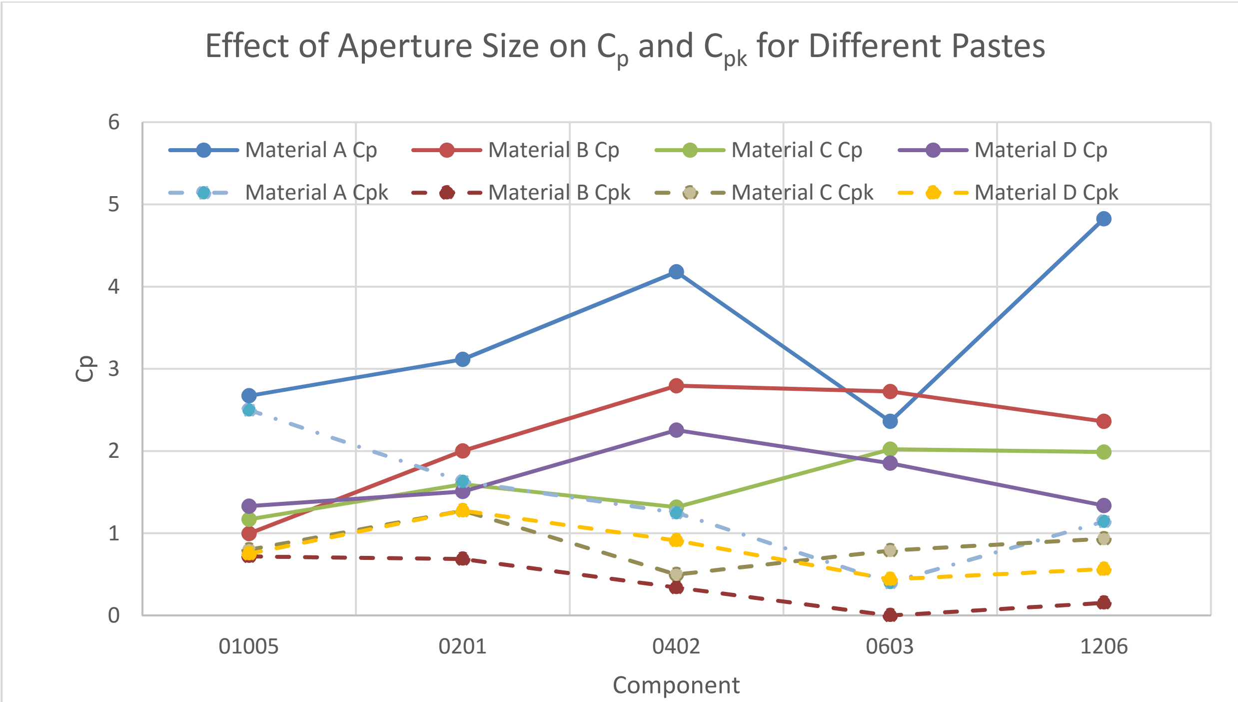
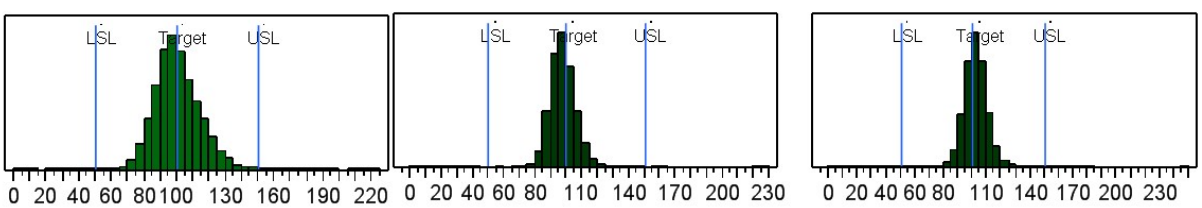


Figure 7: Effect of Aperture Size on C_p and C_{pk}

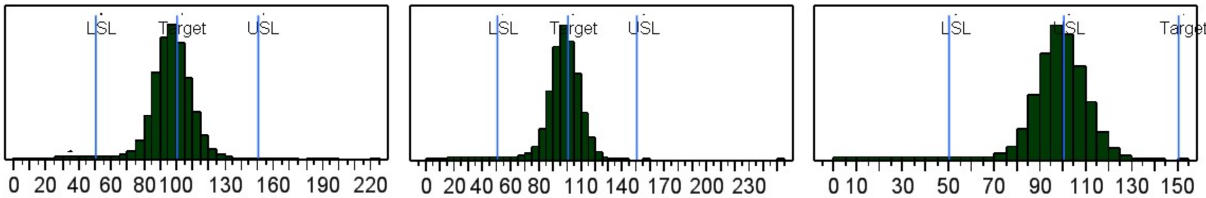
Table 7: Effect of Aperture Aspect Ratio on Average Deposit Volumes and C_{pk}

Aperture	Aspect Ratio	Material	Average (%)	Cpk
0.3 mm CSP	0.53	Paste A	100.76	1.258
0.3 mm CSP	0.53	Paste B	96.45	1.123
0.3 mm CSP	0.53	Paste C	80.04	0.828
0.3 mm CSP	0.53	Paste D	88.80	0.945
0.4 mm CSP	0.53	Paste A	97.70	1.687
0.4 mm CSP	0.53	Paste B	96.62	1.053
0.4 mm CSP	0.53	Paste C	83.07	0.679
0.4 mm CSP	0.53	Paste D	85.91	0.874
0.4 mm PoP	0.54	Paste A	102.41	1.590
0.4 mm PoP	0.54	Paste B	96.68	0.942
0.4 mm PoP	0.54	Paste C	82.78	0.673
0.4 mm PoP	0.54	Paste D	85.72	0.832



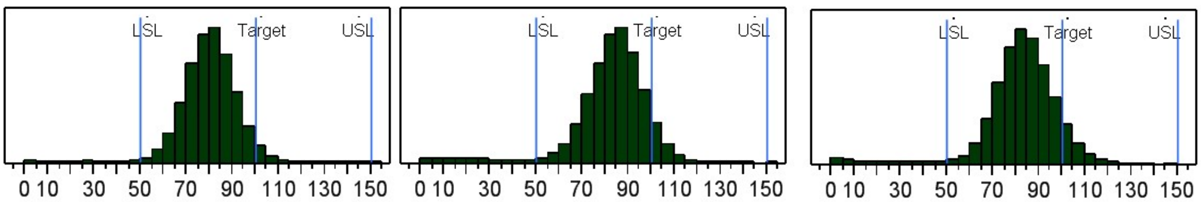
0.53 Aspect Ratio (0.3mm CSP) 0.53 Aspect Ratio (0.4mm CSP) 0.54 Aspect Ratio (0.4mm CSP)

Figure 8A: Print Volumes Distributions for Low Aspect Ratio Square Apertures with Rounded Corners (Paste A)



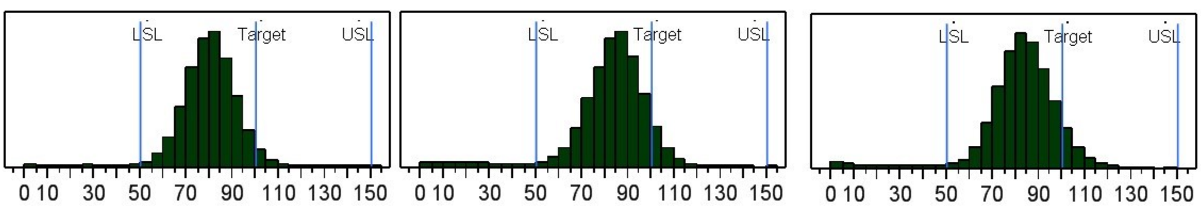
0.53 Aspect Ratio (0.3mm CSP) 0.53 Aspect Ratio (0.4mm CSP) 0.54 Aspect Ratio (0.4mm CSP)

Figure 8B: Print Volumes Distributions for Low Aspect Ratio Square Apertures with Rounded Corners (Paste B)



0.53 Aspect Ratio (0.3mm CSP) 0.53 Aspect Ratio (0.4mm CSP) 0.54 Aspect Ratio (0.4mm CSP)

Figure 8C: Print Volumes Distributions for Low Aspect Ratio Square Apertures with Rounded Corners (Paste C)



0.53 Aspect Ratio (0.3mm CSP) 0.53 Aspect Ratio (0.4mm CSP) 0.54 Aspect Ratio (0.4mm CSP)

Figure 8D: Print Volumes Distributions for Low Aspect Ratio Square Apertures with Rounded Corners (Paste D)

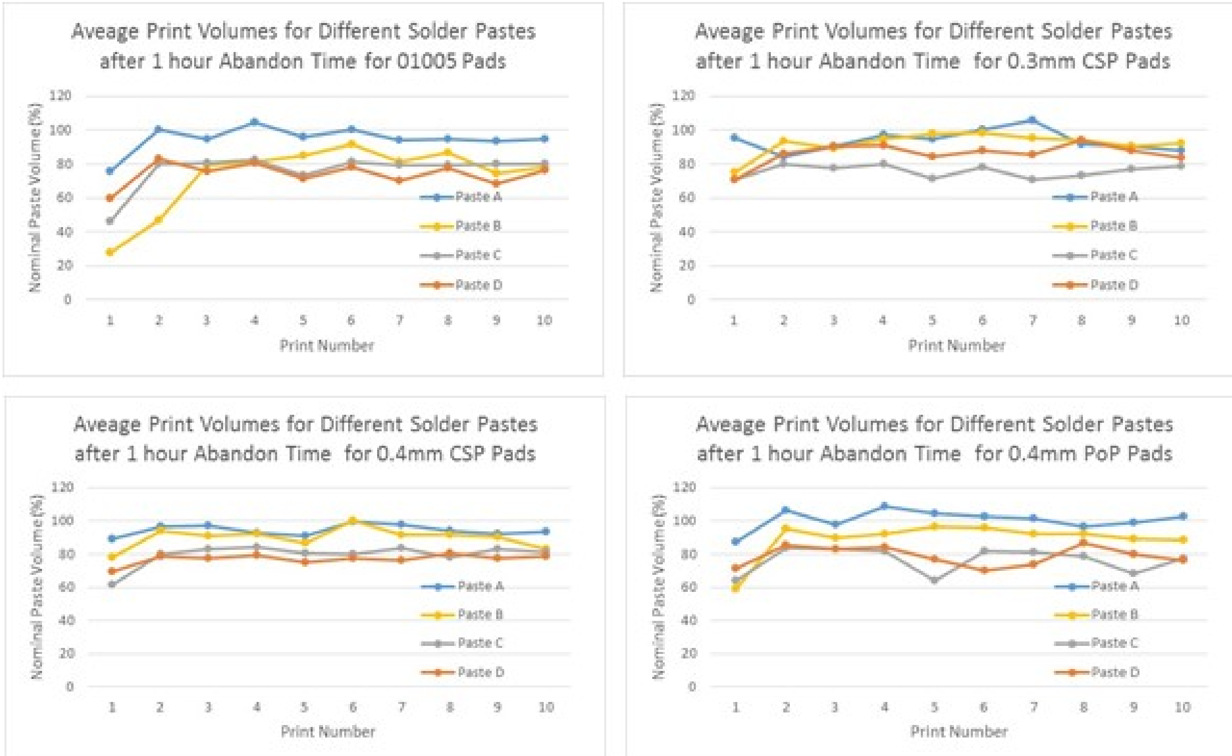


Figure 9: Effect of 1 Hour Abandon Time on Deposit Volumes

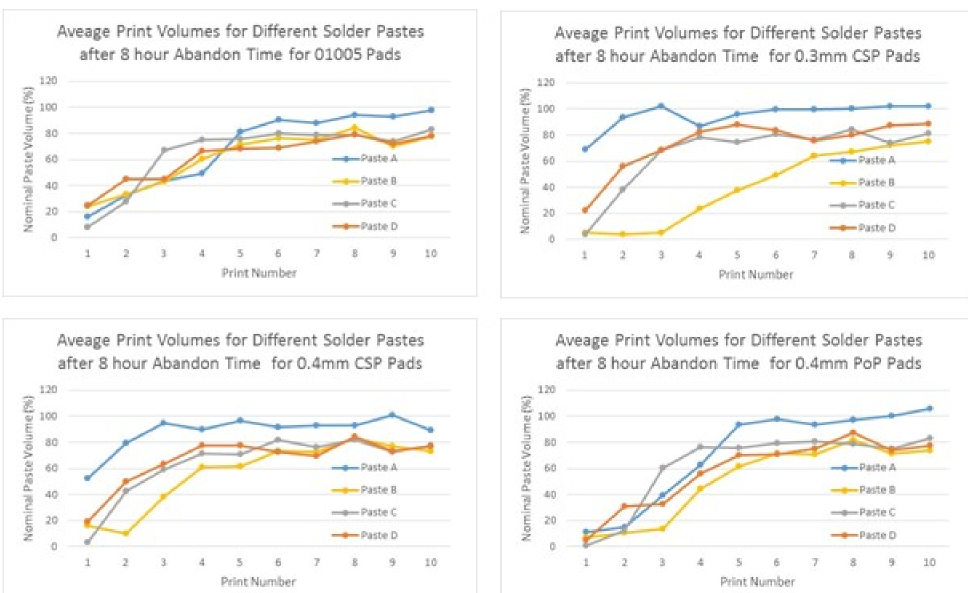
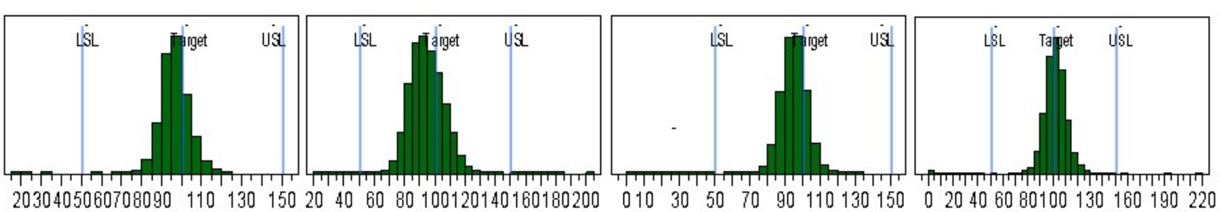
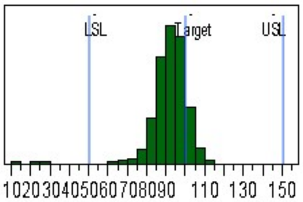


Figure 10: Effect of 8 Hours Abandon Time on Deposit Volumes

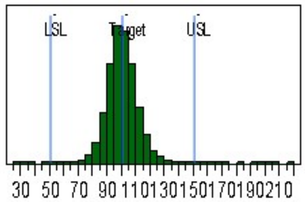


01005 Component 0.3 mm CSP Component 0.4 mm CSP Component 0.4 mm PoP Component

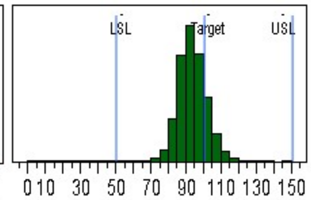
Figure 11: Effect of One Hour Abandon Time on Deposit Distributions for Apertures with Aspect Ratios below 0.66



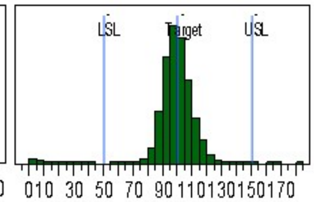
01005 Component



0.3 mm CSP Component



0.4 mm CSP Component



0.4 mm PoP Component

Figure 12: Effect of Eight Hour Abandon Time on Deposit Distributions for Apertures with Aspect Ratios below 0.66

Table 8: Effect of Abandon Time on Print Perfromance for Apertures with Aspect Ratios below 0.66

Abandon Time	Component	Aspect Ration	Average (%)	Cpk
0	01005	0.48	96.78	2.500\
0	0.3 mm CSP	0.53	100.76	1.258
0	0.4 mm CSP	0.53	97.70	1.687
0	0.4 mm PoP	0.54	102.41	1.590
1 hr	01005	0.53	96.61	2.187
1 hr	0.3 mm CSP	0.53	94.83	1.398
1 hr	0.4 mm CSP	0.53	94.88	2.018
1 hr	0.4 mm PoP	0.53	101.75	1.530
8 hr	01005	0.54	97.25	1.872
8 hr	0.3 mm CSP	0.54	100.74	1.659
8 hr	0.4 mm CSP	0.54	96.31	1.620
8 hr	0.4 mm PoP	0.54	99.06	1.282