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Stencil Printing Transfer Efficiency of Circular vs. Square Apertures with the Same Solder Paste Volume

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Abstract
It is frequently noted in surface mount printed circuit board assembly that most solder defects can be traced back to the stencil printing process. In addition, continuous miniaturization trends for electronic components and challenge posed by smaller solder paste deposit requirement, increase focus on stencil printing. Hence, a pristine printer setup, precision tooling, proper squeegee length, stencil type, and stencil aperture design, have become vitally important because of miniaturization trends.

To achieve successful stencil print performance, stencil aperture area ratio and print transfer efficiency are observed to be critical metrics to specify and control. Recent studies suggest that square apertures provide better transfer efficiency than circular apertures, and the argument is raised that given the same area ratio, the volume provided by the square aperture is greater.

This paper is a summary of best practices in optimizing the printing process focusing on comparison of large and small apertures, square vs. round, not with the same area ratio but with similar or the same volume. This paper will definitively clear the air on the round versus square aperture debate.

Detection of an Unstable Board Support System

Perhaps a most understated of best practices in optimizing a solder paste printing process is the importance of printer tooling to stabilize and support the board, and not simply modest board supports but it is most important that all printer tooling is completely stabilized during squeegee stroke action. To achieve aim there are two essential conditions. First, proper squeegee length must be selected, a length that matches the board support. Moreover, it is critical to observe that board and stencil do not move during the time the squeegee rolls the paste over the apertures. Secondly, set squeegee print pressure so that the paste gently rolls over the apertures, and be exceedingly careful to minimize squeegee force. Excessive squeegee pressure can cause the stencil to be moved by during squeegee action. This movement will result in variation of transfer efficiency. For paste deposits left by larger apertures, there may be greater tolerance for minimal variation, but there is less tolerance for variation for paste deposits left from smaller apertures.

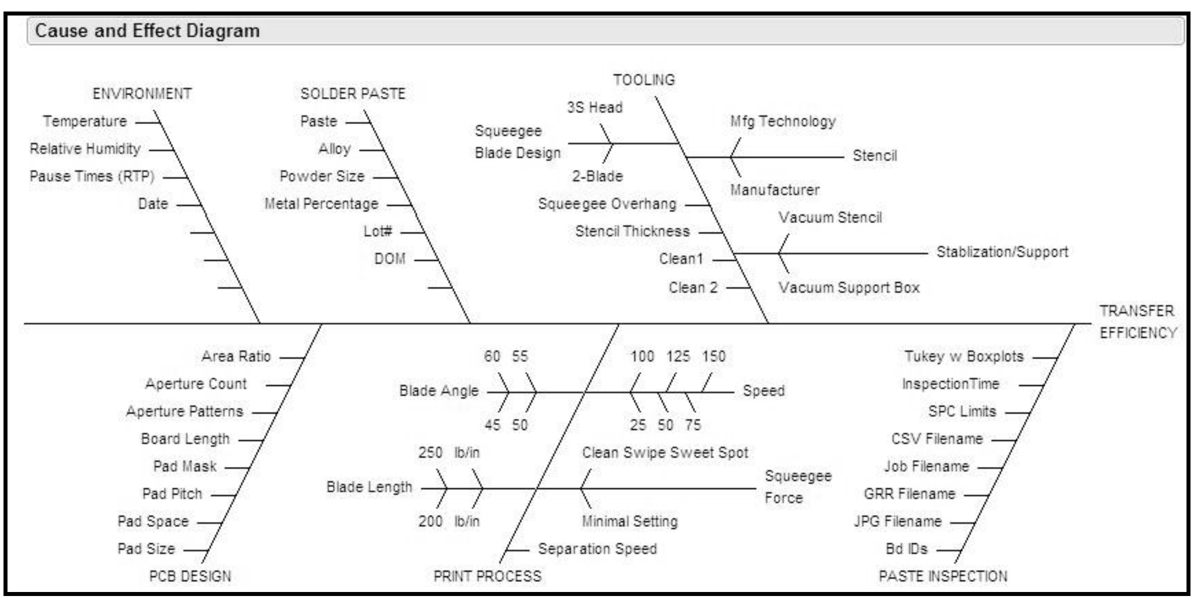


Figure 1. Cause & Effect Diagram of the Solder Paste Printing Process

Carefully consider application of squeegee pressure during both stencil printer setup and evaluation of paste print performance. When squeegee pressure is observed to become a major print performance factor, this is likely evidence excessive squeegee pressure is being applied. The easiest approach to minimize squeegee pressure setting is to use sufficient force so that the squeegee blade only gives a clean swipe over the surface of the stencil. Once a clean swipe is observed during setup, gradually lower squeegee pressure as much as possible, stopping at the setting that is a step above where a clean swipe is not achieved.

The initial step of any printer setup begins with checking stencil-and-board fiducial alignment in the stencil printer. It is important that a portion of the step includes checking to see the board support system adequately stabilizes movement of the stencil. Figure 2 shows two easy approaches to detect board support system stability. The photo on the left depicts an operator tenderly tapping a finger on the top of the stencil to detect any stencil movement between the board and stencil. The photo on the right depicts use of a gage to detect movement on the stencil surface. The consequence of not eliminating support system variation is evident in the box plots shown above the photos. The observation of variation shown in box plots on the left is evidence of a difference between forward and reverse squeegee strokes. The observation of variation shown in the box plots on the right is movement of stencil during the squeegee stroke.

Not only will transfer efficiency variation be minimized by lowering squeegee pressure, but opportunity for cumulative stencil wear will decrease. Long-term excessive squeegee pressure causes surface damage to appear on a thicker stencil, but on a thinner stencil damage to small apertures can occur, as well as, coining of board features can be seen. This kind of stencil wear inevitably will create additional variation in transfer efficiency.

Squeegee/Stencil/Board Must be Fully Supported
to Control Variation of Transfer Efficiency

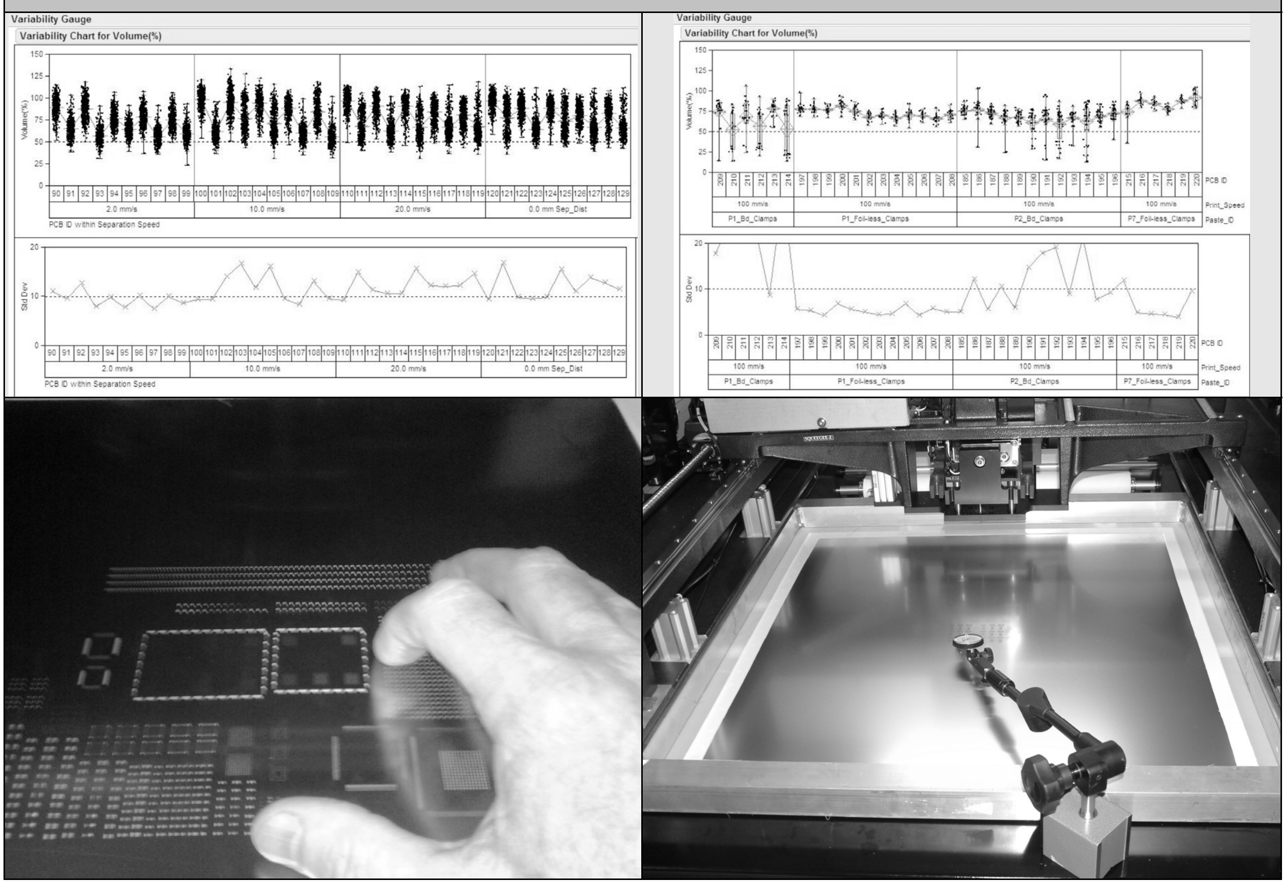


Figure 2. Detection of unstable board support system – test effect of stencil movement during squeegee stroke

<u>Aperture Volume and Area Ratio Calculations</u>

To achieve successful stencil print performance, stencil aperture area ratio and print transfer efficiency are often observed to be critical metrics to specify and control. In a common evaluation of print performance aimed for miniaturization trends, there could be a variety of aperture size dimensions specified for both circles and squares. Stencil thickness, therefore, provides a target value for both print area ratio and transfer efficiency calculations. These calculations are previously well-documented in industry publications, including in each of the references listed at the end of this paper.

Calculated Aperture Volume

A table of calculated values for a (6.0-14.0 mil) range of sizes of both circle and square apertures for five different stencil thicknesses is presented. A graph of calculated aperture volumes is created from this table. Among observations to be noted in the graph, it can be easy to depict that several apertures share similar volumes. An occurrence of similar volume may occur on the same stencil for different shapes, or a similar volume sometimes occurs using a different stencil thickness. Also, it is easily observed (on the same stencil) that similar dimension value means greater aperture volume for square shaped apertures.

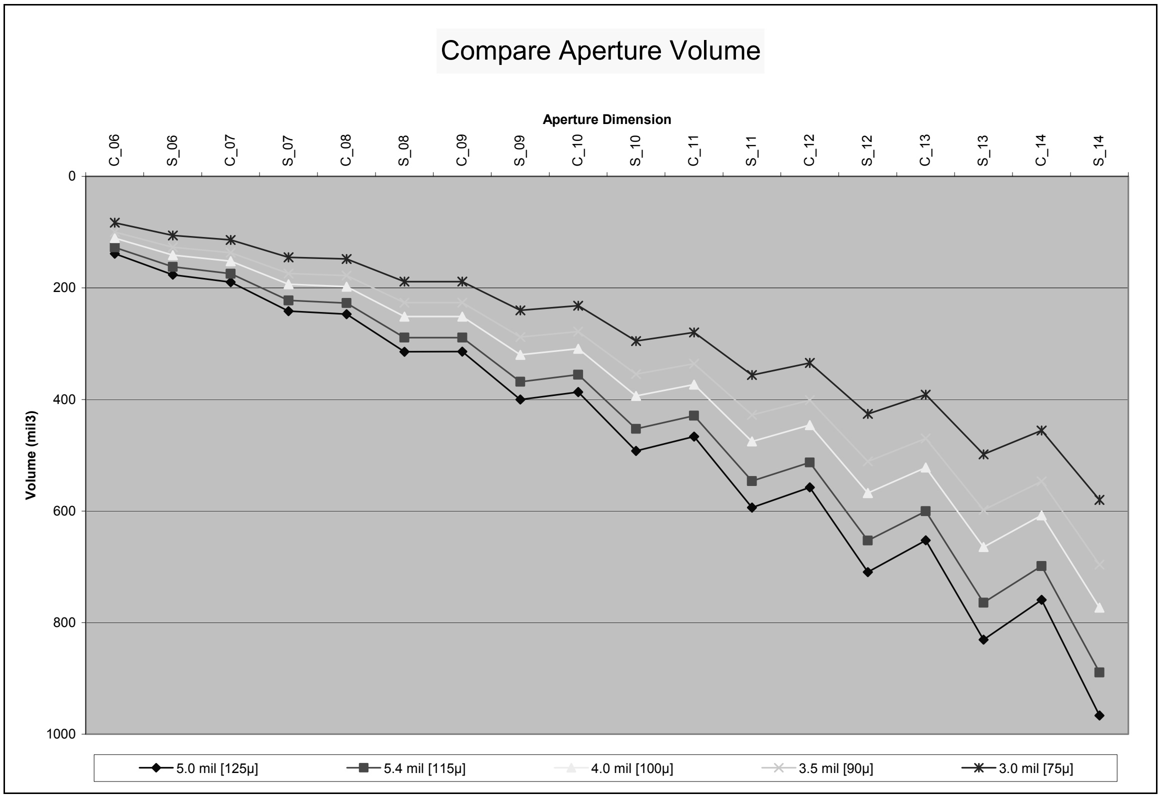


Figure 3. For the same stencil thickness, square apertures have greater volume when diameter of a circular aperture and side of a square aperture are equivalent. Aperture volume can be a similar value for different shapes, or on different stencil thicknesses.

It is common practice for stencil print evaluations to conclude that square apertures tend to have better performance than circular shaped apertures, without clarification whether about performance metric. It could be that square aperture conclusions are unwarily based on volume, and that the circular aperture being compared actually has a smaller volume.

It is important to distinctly clarify within a conclusion about square apertures offering better performance, that volume variation has been considered. Future stencil orders will, therefore, include in that volume variation can be decided by aperture shape for a specified aperture volume.

Circle										
	Diameter (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.330	0.356
	Radius (mm)	0.076	0.089	0.1015	0.1145	0.127	0.1395	0.1525	0.165	0.178
	Diameter (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Radius (mil)	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Circle Area Opening	28	39	50	64	79	95	113	133	154
5.0 mil	Volume mil3 (125μ)	138	190	247	314	387	466	557	652	759
4.5 mil	Volume mil3 (115μ)	127	175	227	289	356	429	513	600	699
4.0 mil	Volume mil3 (100μ)	111	152	198	251	309	373	446	522	607
3.5 mil	Volume mil3 (90μ)	100	137	178	226	278	336	401	470	547
3.0 mil	Volume mil3 (75μ)	83	114	148	189	232	280	334	391	456

Square										
	Length (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.330	0.356
	Width (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.33	0.356
	Length (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Width (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Square Area Opening	36	49	64	81	100	121	144	169	196
5.0 mil	Volume mil3 (125μ)	176	242	314	400	492	594	710	831	967
4.5 mil	Volume mil3 (115μ)	162	222	289	368	453	546	653	764	889
4.0 mil	Volume mil3 (100μ)	141	193	251	320	394	475	568	665	773
3.5 mil	Volume mil3 (90μ)	127	174	226	288	354	428	511	598	696
3.0 mil	Volume mil3 (75μ)	106	145	189	240	295	356	426	498	580

Table A. Calculated values for a (6.0-14.0 mil) range of sizes of both circle and square apertures for five different stencil thicknesses is presented.

Calculated Aperture Area Ratio

In *Table B*, area ratio calculations above two-thirds (0.66) have a green colored background, indicating most solder paste products have acceptable transfer efficiency when aperture area ratio is above two-thirds. Similarly, when area ratio is below one-half (0.50), solder paste print performance commonly has unacceptable transfer efficiency.

The definition of aperture area ratio for is the area of the stencil aperture opening divided by the area of the aperture side walls. A simple calculation shows that area ratio (AR) reduces to diameter (D) of a circle divided by 4 times stencil thickness (t): AR = D/4t. Somewhat surprisingly, results for circular apertures are the same values for square apertures, with D now equal to the side of the square. *Figure 3* demonstrates equivalently defined values for both circles and squares.

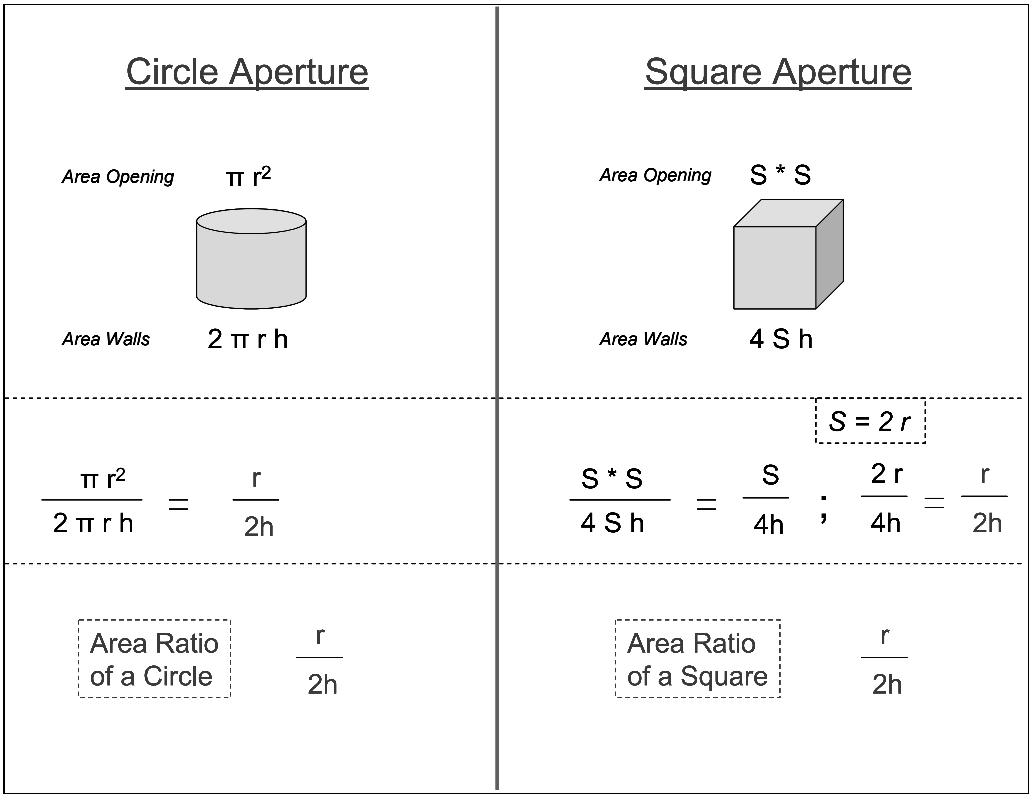


Figure 4. Aperture area ratio is calculated to be the same value when diameter of a circular aperture and side of a square aperture are equivalent.

Circle

	Diameter (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.330	0.356
	Radius (mm)	0.076	0.089	0.1015	0.1145	0.127	0.1395	0.1525	0.165	0.178
	Diameter (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Radius (mil)	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Circle Area Opening	28	39	50	64	79	95	113	133	154
5.0 mil	Volume mil3 (125µ)	0.30	0.36	0.41	0.46	0.51	0.56	0.61	0.66	0.71
4.5 mil	Volume mil3 (115µ)	0.33	0.39	0.44	0.50	0.55	0.61	0.66	0.72	0.77
4.0 mil	Volume mil3 (100µ)	0.38	0.45	0.51	0.57	0.64	0.70	0.76	0.83	0.89
3.5 mil	Volume mil3 (90µ)	0.42	0.49	0.56	0.64	0.71	0.78	0.85	0.92	0.99
3.0 mil	Volume mil3 (75µ)	0.51	0.59	0.68	0.76	0.85	0.93	1.02	1.10	1.19

Square

	Length (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.330	0.356
	Width (mm)	0.152	0.178	0.203	0.229	0.254	0.279	0.305	0.33	0.356
	Length (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Width (mil)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Square Area Opening	36	49	64	81	100	121	144	169	196
5.0 mil	Volume mil3 (125µ)	0.30	0.36	0.41	0.46	0.51	0.56	0.61	0.66	0.71
4.5 mil	Volume mil3 (115µ)	0.33	0.39	0.44	0.50	0.55	0.61	0.66	0.72	0.77
4.0 mil	Volume mil3 (100µ)	0.38	0.45	0.51	0.57	0.64	0.70	0.76	0.83	0.89
3.5 mil	Volume mil3 (90µ)	0.42	0.49	0.56	0.64	0.71	0.78	0.85	0.92	0.99
3.0 mil	Volume mil3 (75µ)	0.51	0.59	0.68	0.76	0.85	0.93	1.02	1.10	1.19

Table B. Aperture area ratio calculations for a variety of stencil thicknesses, diameter of a circular aperture and side of a square aperture are equivalent.

Volume Variation for a Specified Aperture Volume and Shape

Among best practices in optimizing the printing process, it is useful to consider comparison of large and small apertures, square vs. round, not with the same area ratio but with similar or the same volume. This paper taps on a resource available from extensive stencil print measurement data. Within data sets, a significant amount of round versus square aperture has been collected. Realizing value by tapping on the data sets for analytical information is dependent upon the way that data collection is controlled. The four most challenging aspects for controlling print performance trials are the following:

1. controlling entire process & data collection
2. washing the test boards
3. tabulating data
4. information transfer of observations

Stencil Print Data Collection

In order to recall all parameters and effects on solder paste print performance, we have converted a cause and effect or "fish-bone" diagram into a checklist. Using this diagram, variables that contribute to the transfer efficiency are carefully identified for each data set.

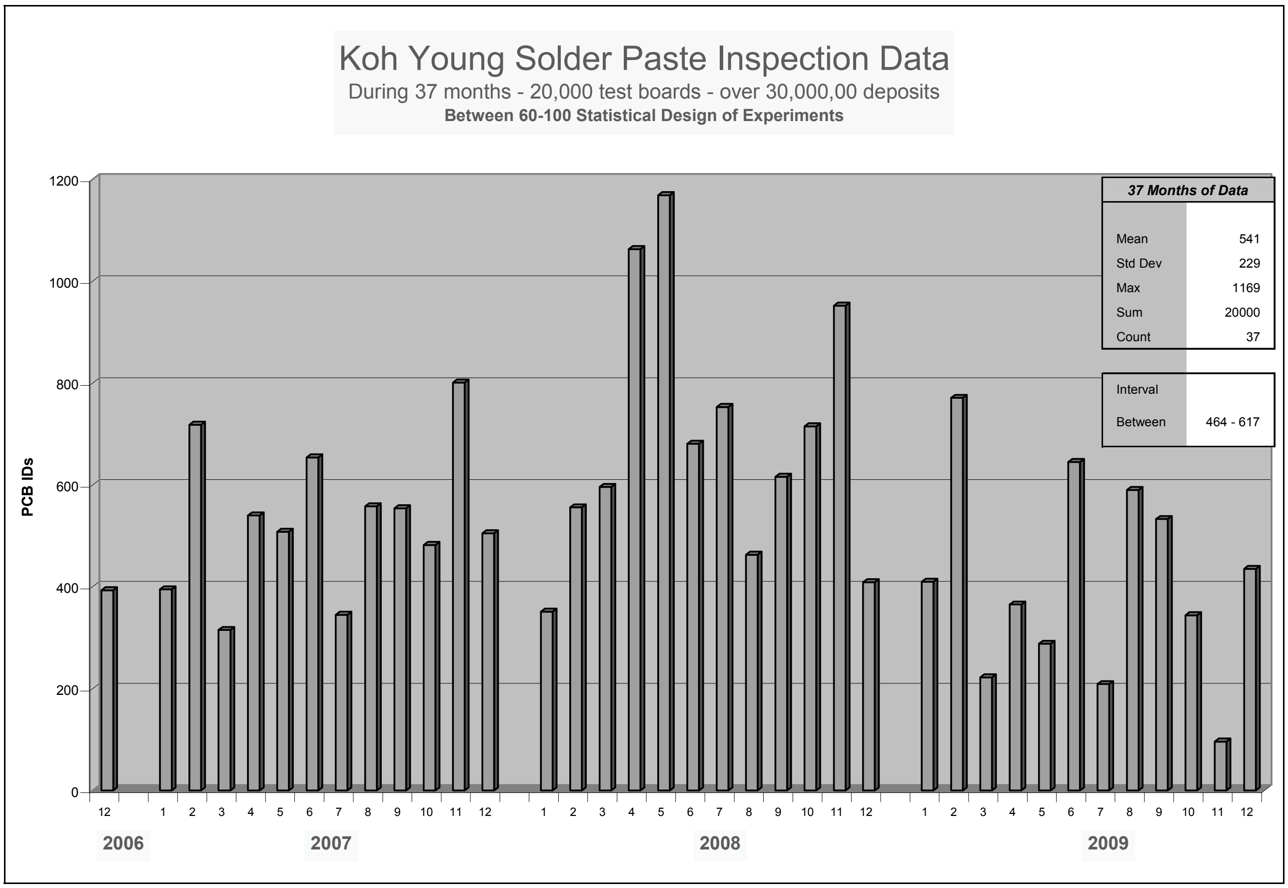


Figure 5. Stencil Print Measurement Data

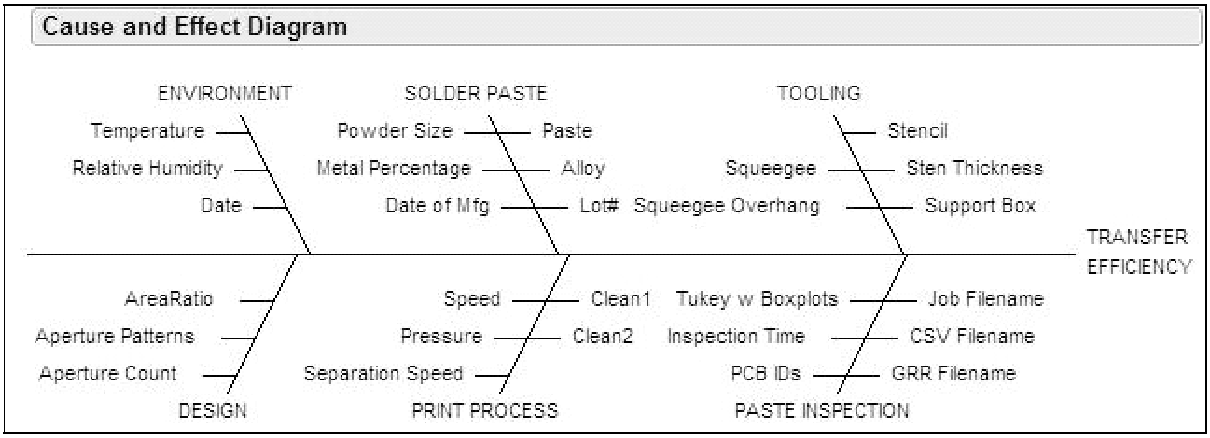


Figure 6. Ishikawa Diagram for Transfer Efficiency

Paste Product Print Trial   Name: ___________

			1
		Paste Product	
		Print Trial	
1	Tooling	Stencil	
2		Squeegee	
3		Support	
4	Print Parameters	Speed	
5		Pressure	
6		Separation	
7	Koh Young Program	Job Filename	
8		CSV Filename	
9		Tukey w Boxplots	
10	Gage R & R	GRR Filename	
11		JPG Filename	
12	Mfg and Design - Printing Attributes	Aperture Count	
13		Aperture Patterns	
14		Stencil Thickness	
15		Area Ratio	
16		Squeegee Overhang	
17		Inspection Time	
18	Reference Info for the Data	Date	
19		Times	
20		Paste	
21		Alloy	
22		Powder	
23		Metal%	
24		Temp	
25		RH	
26		PCB IDs	
27		Clean1	
28		Clean2	
29		DOM	
30		Lot#	
31		Other	

Figure 7. Checklist from Ishikawa Diagram

Measure Variation in Transfer Efficiency

The important metric from the data sets is the measure of variation. A diagram illustrates the level of variation for large, medium and small apertures. The top portion indicates variation in transfer efficiency for any set of relative sizes. It is convenient to routinely report data variation for the transfer efficiency, but for clarifying variation from different stencil thicknesses and shapes, actual volume better shows variation differences. Solder paste inspection systems typically report measurement units as both cubic microns and cubic mils. Due the enormous size of either of these unit values, sharing variation statistics can be difficult, limiting information transfer of observations. The bottom portion indicates variation in actual volume, but the units have been converted from cubic mils to nanoliters. Using this unit can make it especially easy to grasp relative volume variation. Considering that 10% (standard deviation) for transfer efficiency is a typical tolerance limit, reporting relative variation in nanoliters (5.3 – 4.3 – 3.4) would be translated to comparing volume variation tolerance limits of 0.53 nl, 0.43 nl, and 0.34 nl. These are tolerance limits for 0.3 mm pitch CSPs and 01005 components.

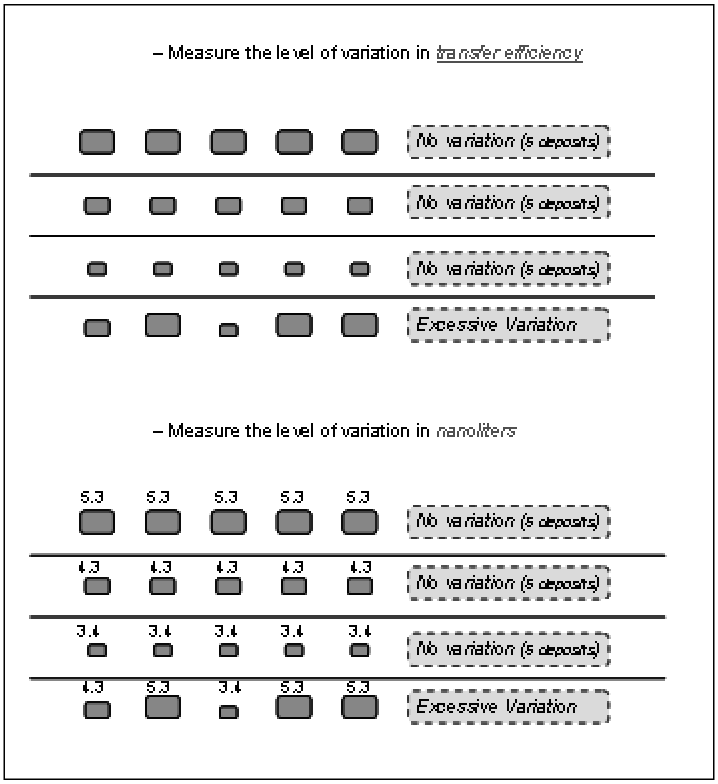


Figure 8. No variation and Excessive variation

The figure below indicates fifteen aperture patterns for which we will show volume variation, but the aperture shape or stencil thickness may vary.

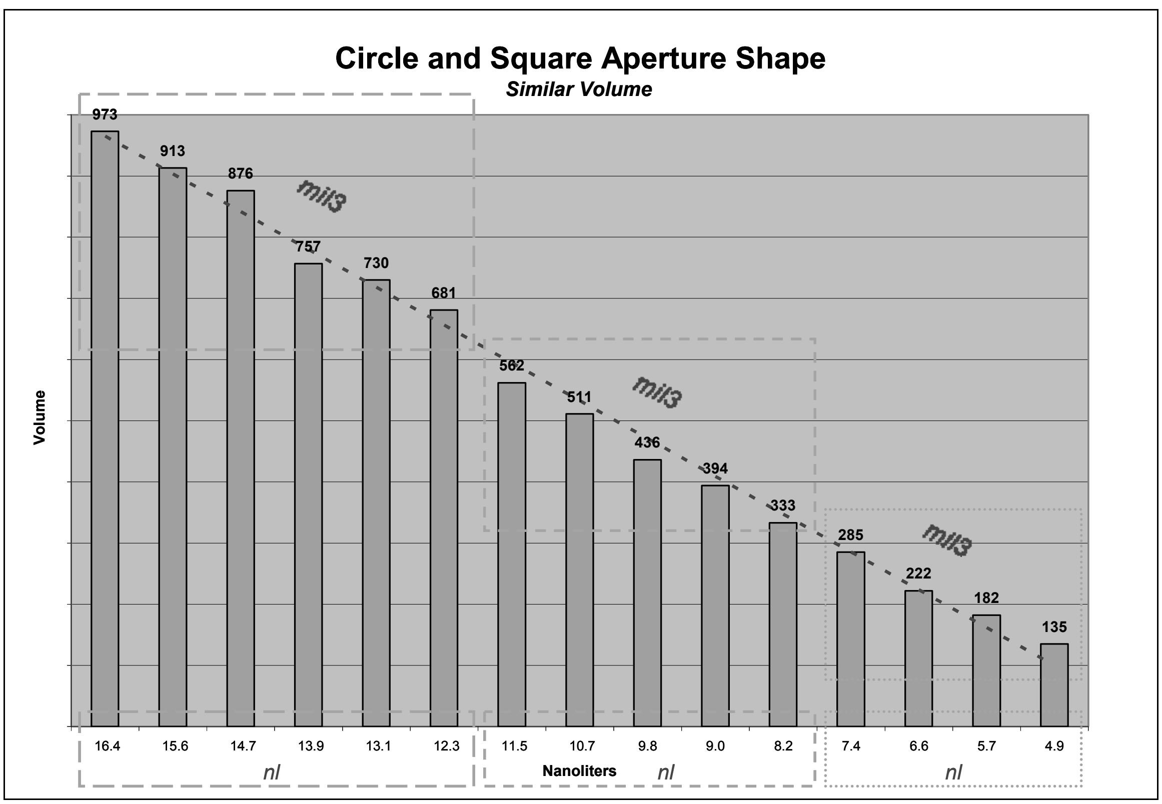


Figure 9. Ranges of aperture volume.

Table Summary – Similar Stencil Aperture Volume

The table below matches up aperture shape, stencil thickness, and aperture area ratio with similar stencil aperture volume calculation. Only non-solder mask defined pads will be presented.

Table C. Stencil Thickness – Circle and Square Shape – Aperture Area Ratio

Volume		Circular Option			Square Option			Third Option		
mil3	nl	Stencil_C	Component ID_C	A.R._C	Stencil_S	Component ID_S	A.R._S	Stencil_3	Component ID_3	A.R._3
973	16.4	4.0-mil	C18_NSMD [0.45]	1.13	4.0-mil	S16_NSMD [0.40]	1.00			
913	15.6	3.0-mil	C20_NSMD [0.50]	1.67	3.0-mil	S18_NSMD [0.45]	1.50			
876	14.7	3.5-mil	C18_NSMD [0.45]	1.25	3.5-mil	S16_NSMD [0.40]	1.11			
757	13.9	4.0-mil	C16_NSMD [0.40]	1.00	4.0-mil	S14_NSMD [0.35]	0.88			
730	13.1	3.0-mil	C18_NSMD [0.45]	1.50	3.0-mil	S16_NSMD [0.40]	1.33			
681	12.3	3.5-mil	C16_NSMD [0.40]	1.11	3.5-mil	S14_NSMD [0.35]	0.97			
562	11.5	3.0-mil	C16_NSMD [0.40]	1.33	3.0-mil	S14_NSMD [0.35]	1.17	4.0-mil	S12_NSMD [0.30]	0.75
511	10.7	3.5-mil	C14_NSMD [0.35]	0.97	3.5-mil	S12_NSMD [0.30]	0.83			
436	9.8	4.0-mil	C12_NSMD [0.30]	0.75				3.0-mil	C14_NSMD [0.35]	1.17
394	9.0	3.5-mil	C12_NSMD [0.30]	0.83	3.0-mil	S12_NSMD [0.30]	1.00	4.0-mil	S10_NSMD [0.25]	0.63
333	8.2	3.0-mil	C12_NSMD [0.30]	1.00	3.5-mil	S10_NSMD [0.25]	0.69			
285	7.4	4.0-mil	C10_NSMD [0.25]	0.63	3.0-mil	S10_NSMD [0.25]	0.83	3.5-mil	C10_NSMD [0.25]	0.69
222	6.6	3.0-mil	C10_NSMD [0.25]	0.83	3.5-mil	S8_NSMD [0.20]	0.56			
182	5.7	4.0-mil	C8_NSMD [0.20]	0.50	3.0-mil	S8_NSMD [0.20]	0.67	3.5-mil	C8_NSMD [0.20]	0.56
135	4.9	3.0-mil	C8_NSMD [0.20]	0.67	3.5-mil	S6_NSMD [0.15]	0.42	4.0-mil	S6_NSMD [0.15]	0.38

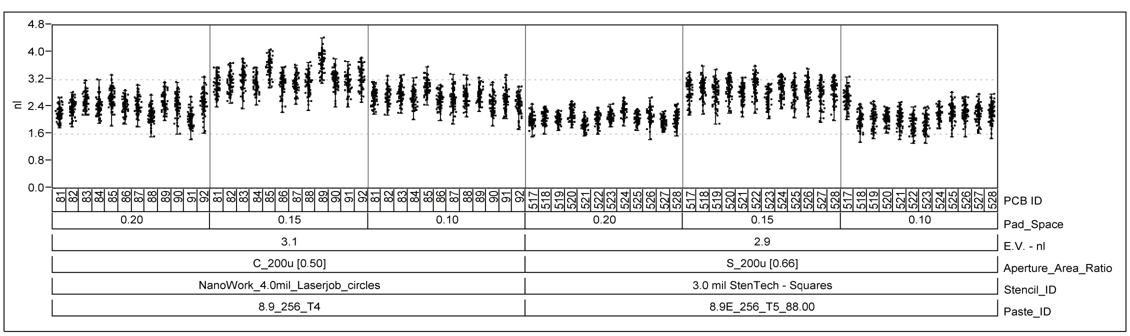
Stencil Printing Process Data – Similar Volume Variability Charts

The data and results are given here in visual format. These figures are actual results from the raw data collected during paste product print trials. The explanation of each figure is focused on the variation present in the data. The outliers are often most interesting because these data points will be the print deposits that simulate inevitable assembly defects.

Volume Variability Chart for 0.30 mm, 0.35 mm, and 0.40 mm Pitch – *190 cubic mil (3 nanoliters)*

Results in this data set are all fairly close, but the least amount of variation is achieved with 0.40 mm pitch square apertures, using a 3.0 mil stencil. Acceptable variation for 0.30 mm pitch circular aperture, using a 4.0 mil stencil, could be expected to be exploited in production. Standard deviation in this data set does not exceed 0.31 nanoliters (19 cubic mil), offering an opportunity for a defect-free stencil print process for miniaturization.

- 8-mil Circles with 4-mil stencil; area ratio is 0.50
- 8-mil Squares with 3-mil stencil; area ratio is 0.66



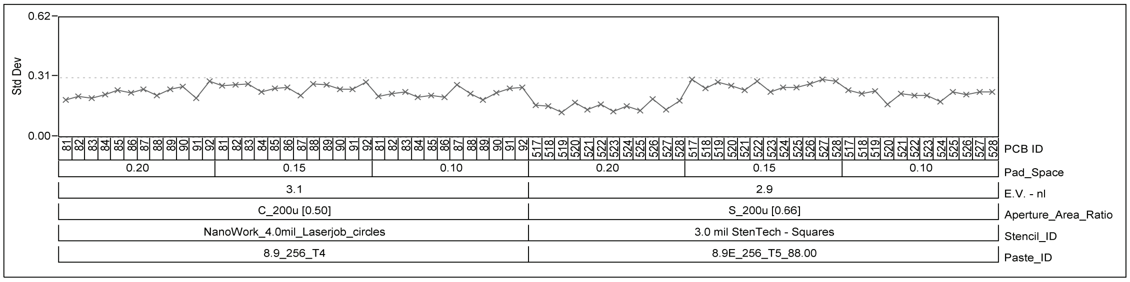


Figure 10. 8 mil Circles and Squares

<u>Volume Variability Chart for 0.35 mm, 0.40 mm, and 0.45 mm Pitch</u> – *300 cubic mil (5 nanoliters)*

Results in this data set are all fairly close, but the least amount of variation is achieved with 0.45 mm pitch square apertures, using a 3.0 mil stencil. Acceptable variation for 0.35 mm pitch circular aperture, using a 4.0 mil stencil, could be expected to be exploited in production. Standard deviation in this data set does not exceed 0.48 nanoliters (30 cubic mil), offering an opportunity for a defect-free stencil print process for miniaturization.

- 10-mil Circles with 4-mil stencil; area ratio is 0.63
- 10-mil Squares with 3-mil stencil; area ratio is 0.82

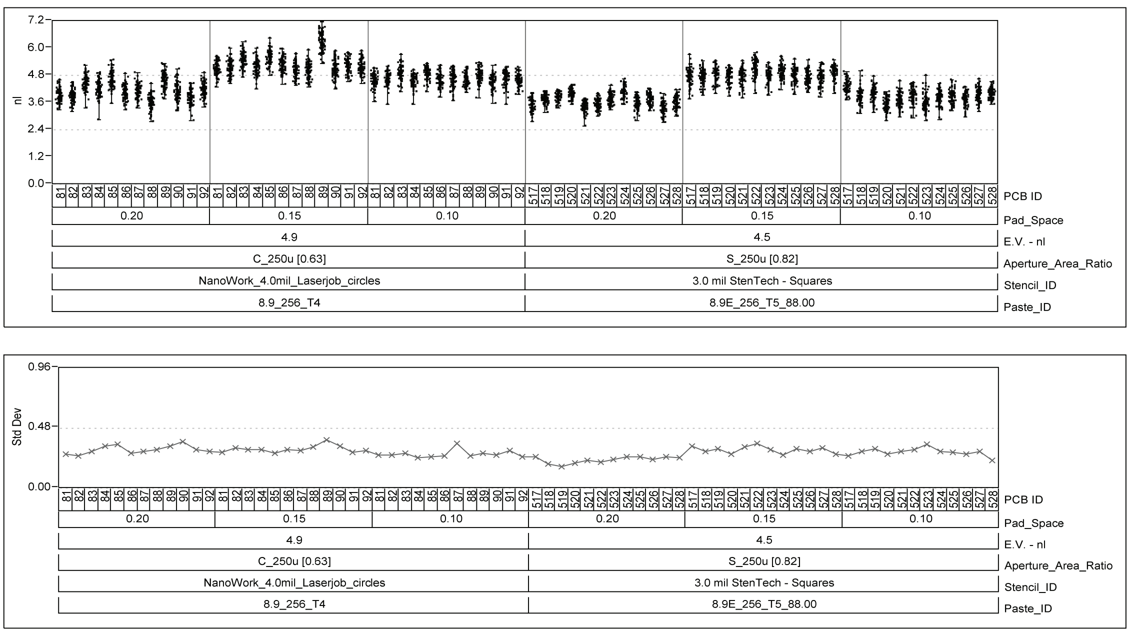


Figure 11. 10 mil Circles and Squares

<u>Volume Variability Chart for 0.75 mm, 0.80 mm, and 0.85 mm Pitch</u> – *750 cubic mil (12 nanoliters)*

Results in this data set are all fairly close, but not only is a lesser amount of variation is achieved with square apertures, using a 4.0 mil stencil, but volume is about 25% less than circular apertures. In terms of transfer efficiency, square apertures (0.88) provide about 100% transfer efficiency, while circular apertures (1.00) are observed to provide greater than 100% transfer efficiency. Acceptable variation for 0.75 mm pitch circular aperture, using a 4.0 mil stencil, has been common in production. Standard deviation in this data set does not exceed 75 cubic mil (1.24 nanoliters), offering an opportunity for a defect-free stencil print process for fine pitch stencil printing.

- 16-mil Circles with 4-mil stencil; area ratio is 1.00
- 14-mil Squares with 4-mil stencil; area ratio is 0.88

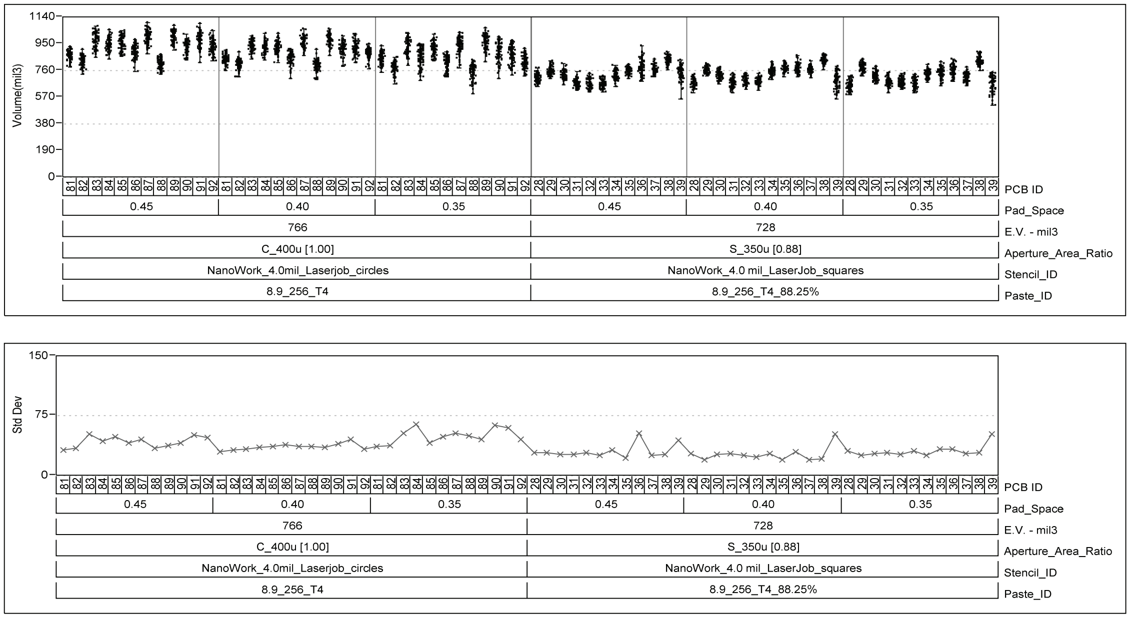


Figure 12. 16 mil Circles and 14 mil Squares

<u>Volume Variability Chart for 0.80 mm, 0.85 mm, and 0.90 mm Pitch</u> – *960 cubic mil (16 nanoliters)*

Results in this data set are all fairly close, and a slightly lesser amount of variation is achieved with square apertures, using a 4.0 mil stencil, but volume is about 25% less than circular apertures. In terms of transfer efficiency, square apertures (1.00) provide about 100% transfer efficiency, while circular apertures (1.13) are observed to provide greater than 100% transfer efficiency. Acceptable variation for 0.80 mm pitch circular aperture, using a 4.0 mil stencil, has been common in production. Standard deviation in this data set does not exceed 96 cubic mil (1.60 nanoliters), offering an opportunity for a defect-free stencil print process for fine pitch stencil printing.

- 18-mil Circles with 4-mil stencil; area ratio is 1.13
- 16-mil Squares with 4-mil stencil; area ratio is 1.00

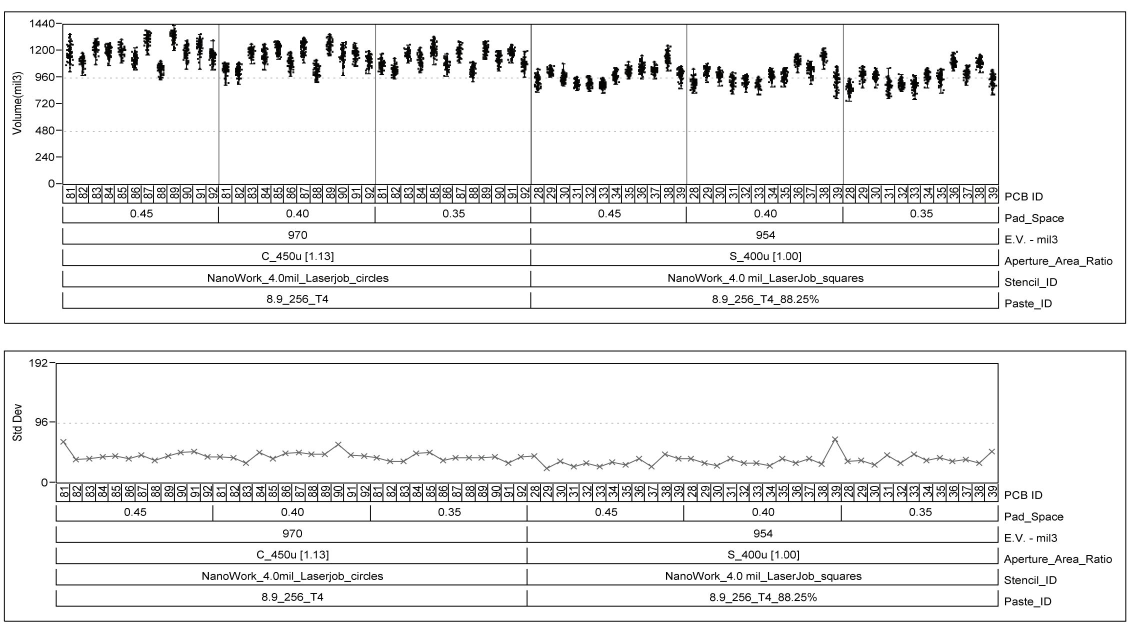


Figure 13. 10 mil Circles and 16 mil Squares

Conclusion – Transfer Efficiency from Similar Volume Apertures

Results between circular and square apertures with the same are all consistently close, and a there is slightly lesser amount of variation is achieved with square apertures, but square aperture volume tends to be about 25% less than circular apertures. In terms of transfer efficiency, square apertures tend to provide closer to 100% transfer efficiency (as area ratio increases from 0.63 to 1.00). Circular apertures are observed to provide greater than transfer efficiency than square aperture for similar aperture volume.

A traditional aperture area ratio barrier (<0.66) can be crossed for both shapes, using setup approaches for detection of an unstable board support system. Acceptable variation for 0.30 mm pitch circular aperture, using a 4.0 mil stencil, could be expected to be exploited in production. Standard deviation in can be controlled so it does not exceed 0.31 nanoliters (19 cubic mil), offering an opportunity for a defect-free stencil print process for miniaturization. Process setup control shows acceptable variation for 0.80 mm pitch circular aperture, using a 4.0 mil stencil, where standard deviation does not exceed 96 cubic mil (1.60 nanoliters). These observations offer an opportunity for a defect-free stencil print process for fine pitch stencil printing and for precision stencil printing for miniaturized electronics assembly

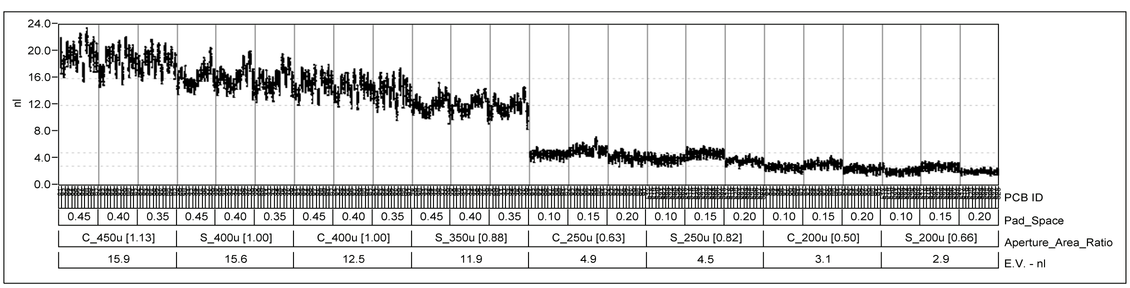
Alternate axis settings can enhance information transfer regarding tolerance level of variation in stencil print results. Using similar stencil thickness for larger apertures with similar volume, axis settings for transfer efficiency allows information to be easily observed. Converting to axis settings to cubic mil for larger and medium sized apertures with similar volume has been shown to be a useful unit for sharing results of print performance differences between circles and squares, especially acceptable tolerance for variation. Axis settings in nanoliters more clearly portray variation results at new low tolerance levels. Consequently, comparisons can be observed more clearly, allowing a more complete appreciation of new variation tolerance levels demanded by 0.3 mm pitch printing, and supporting a need for critical setup approaches.

- 18-mil Circles with 4-mil stencil; area ratio is 1.13
- 16-mil Squares with 4-mil stencil; area ratio is 1.00

- 16-mil Circles with 4-mil stencil; area ratio is 1.00
- 14-mil Squares with 4-mil stencil; area ratio is 0.88

- 10-mil Circles with 4-mil stencil; area ratio is 0.63
- 10-mil Squares with 3-mil stencil; area ratio is 0.82

- 8-mil Circles with 4-mil stencil; area ratio is 0.50
- 8-mil Squares with 3-mil stencil; area ratio is 0.66



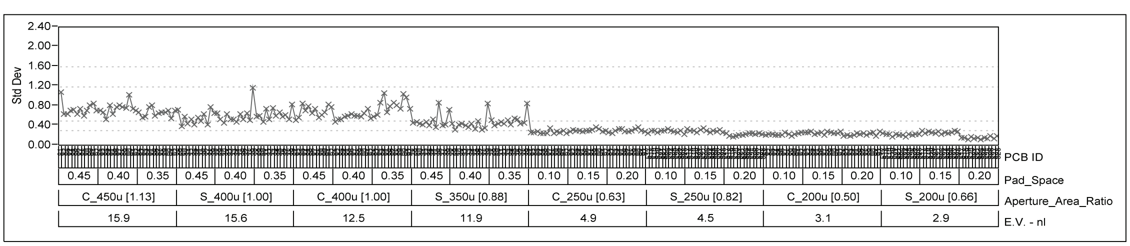


Figure 14. Variability Chart for Volume – Axis Settings in nanoliters.

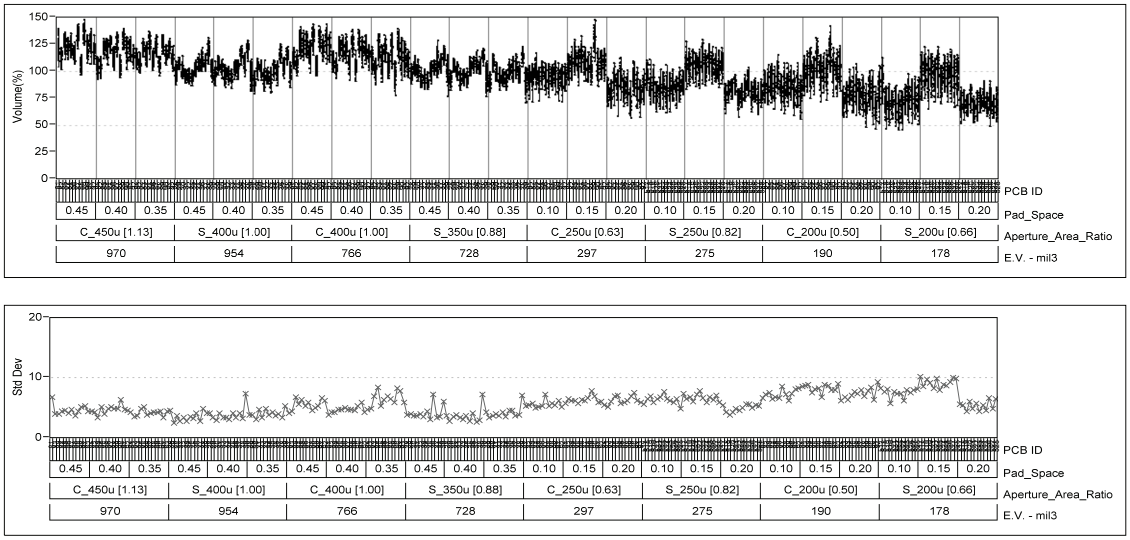


Figure 15. Variability Chart for Transfer Efficiency – Axis Settings in Percentage.

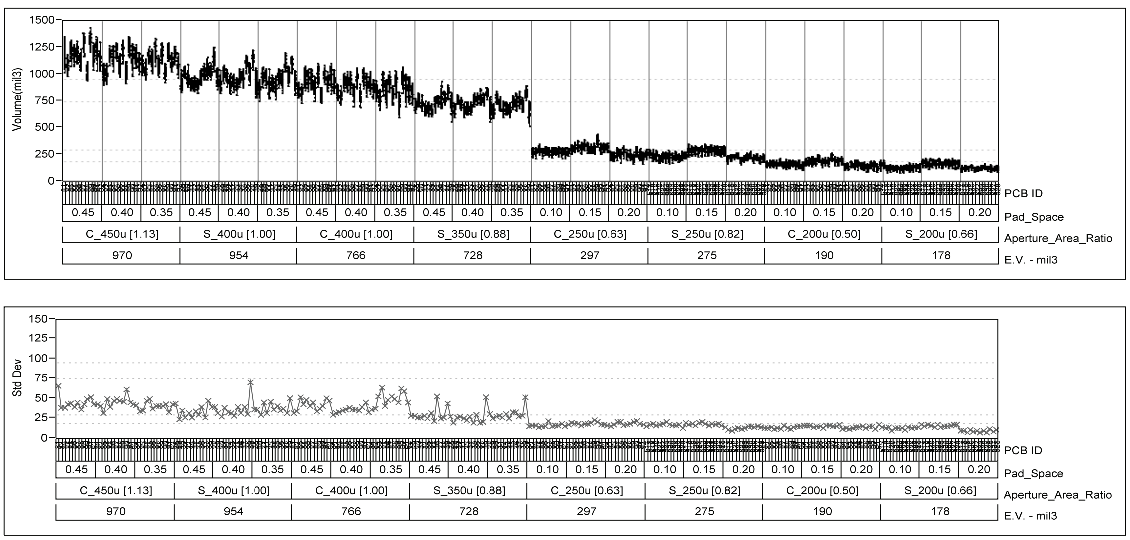


Figure 16. Variability Chart for Volume – Axis Settings in cubic mil.

Courses for Future Development - Transfer Efficiency from Similar Volume Apertures

Application development is underway for better understanding of stencil aperture design for 01005 components and bottom termination components (QFNs). A next step in 01005 and QFN future developments can be to combine inherent advantages of both square and circular aperture shapes – print performance of square apertures with rounded corners for aperture shape needs to be evaluated. Regarding area ratio, aperture size can follow industry standard for stencil aperture area ratio requirement of > 0.66 which continues to be an excellent rule of thumb. In a carefully controlled setup, area ratio range extends from 0.50 – 0.82 with low variation in print performance.

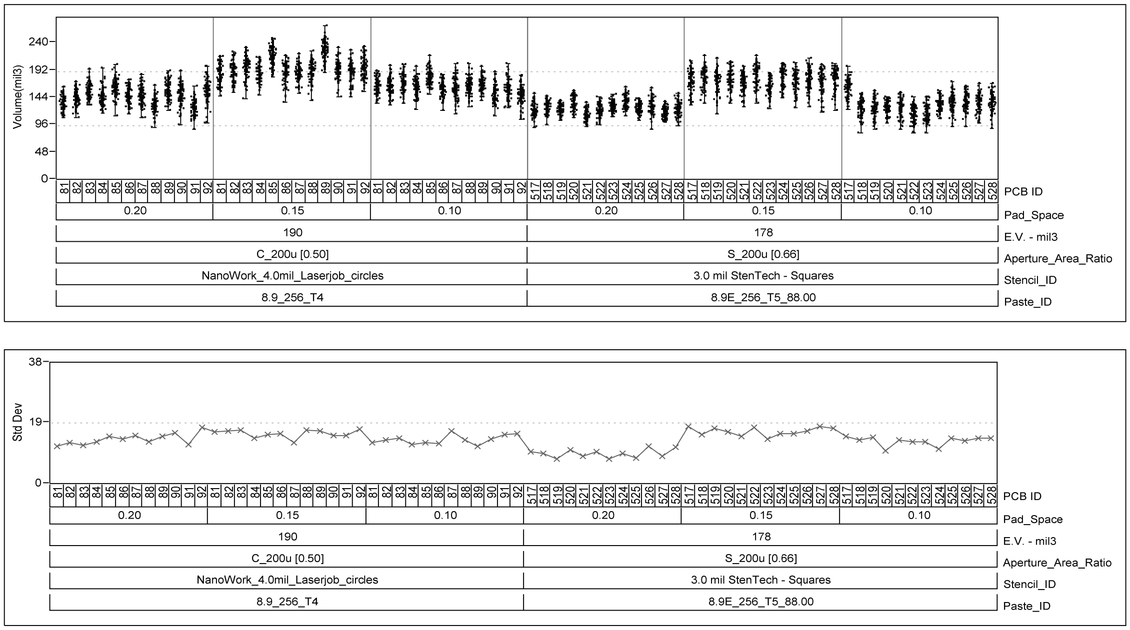


Figure 17. Volume Variability Chart for 0.30 mm, 0.35 mm and 0.40 mm Pitch

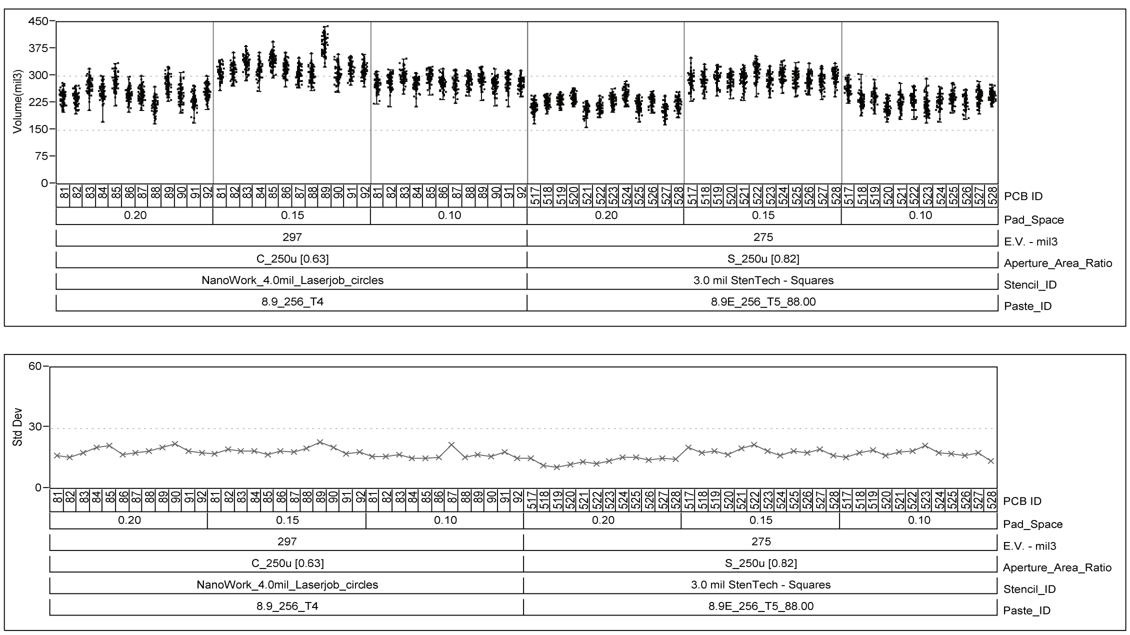


Figure 18. Volume Variability Chart for 0.35 mm, 0.40 mm, and 0.45 mm Pitch

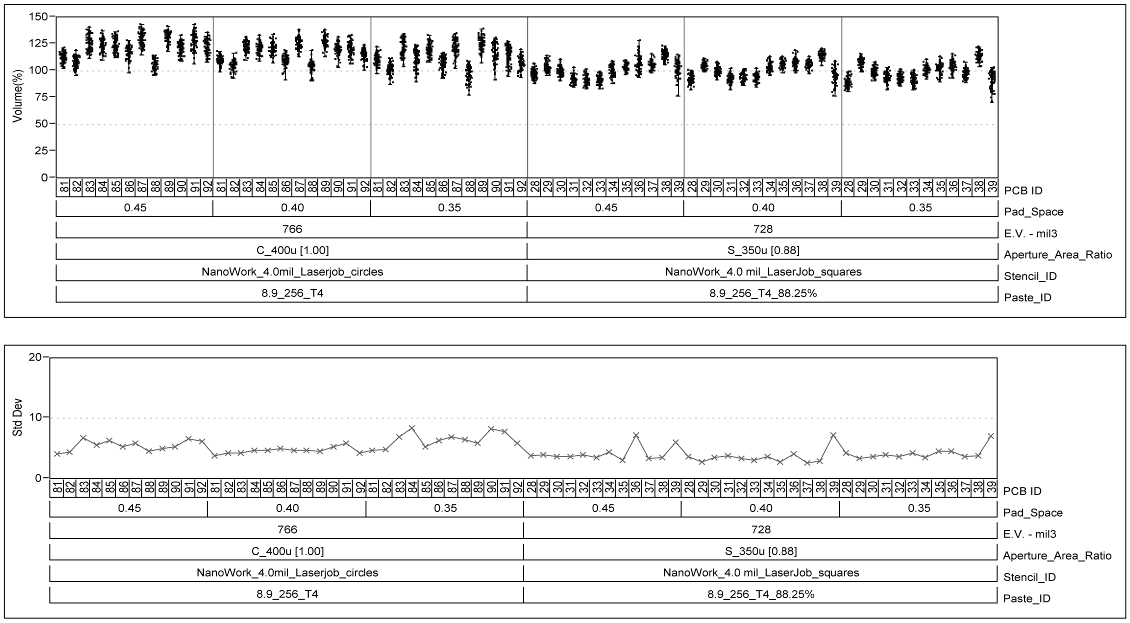


Figure 19. Transfer Efficiency Chart for 0.75 mm, 0.80 mm, and 0.85 mm Pitch

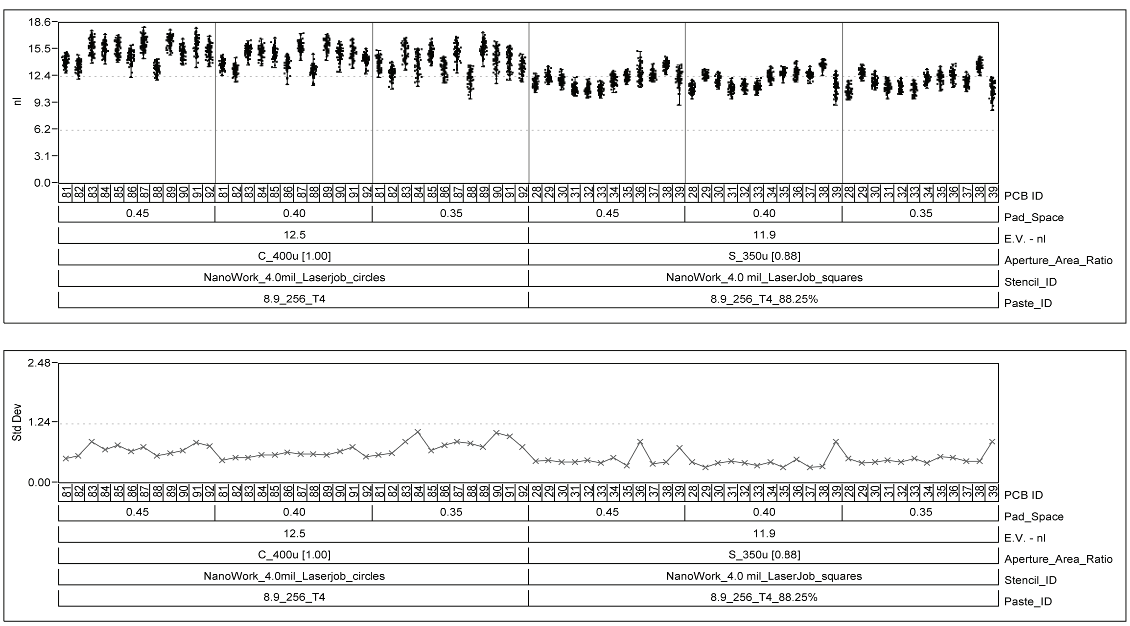


Figure 10. Volume Variability Chart for 0.75 mm, 0.80 mm, and 0.85 mm Pitch

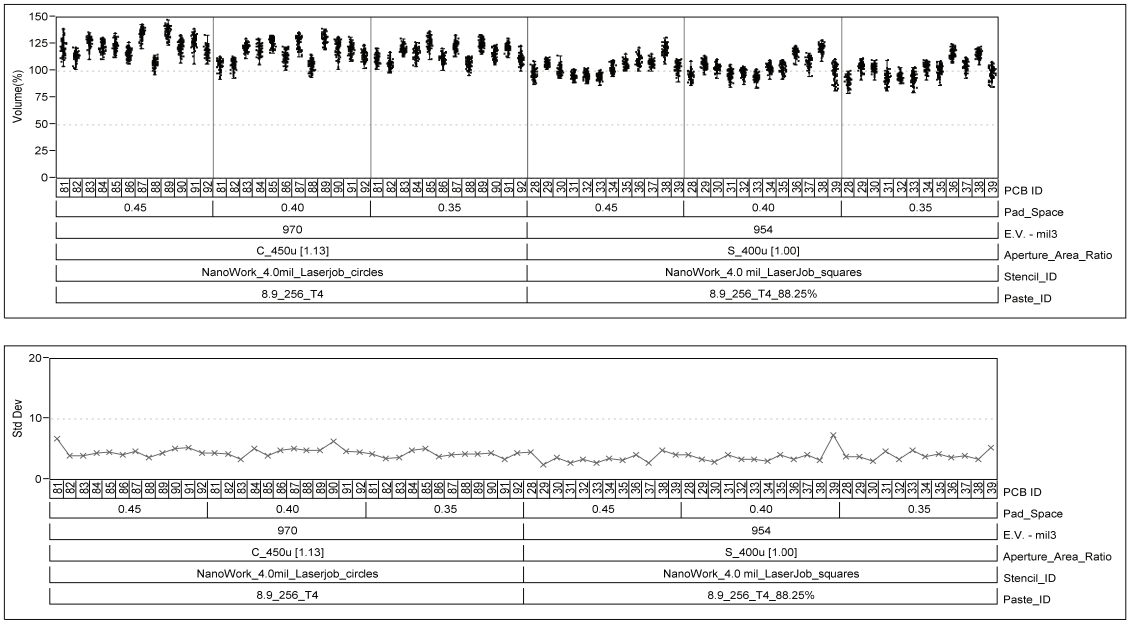


Figure 11. Transfer Efficiency Chart for 0.80 mm, 0.85 mm, and 0.90 mm Pitch

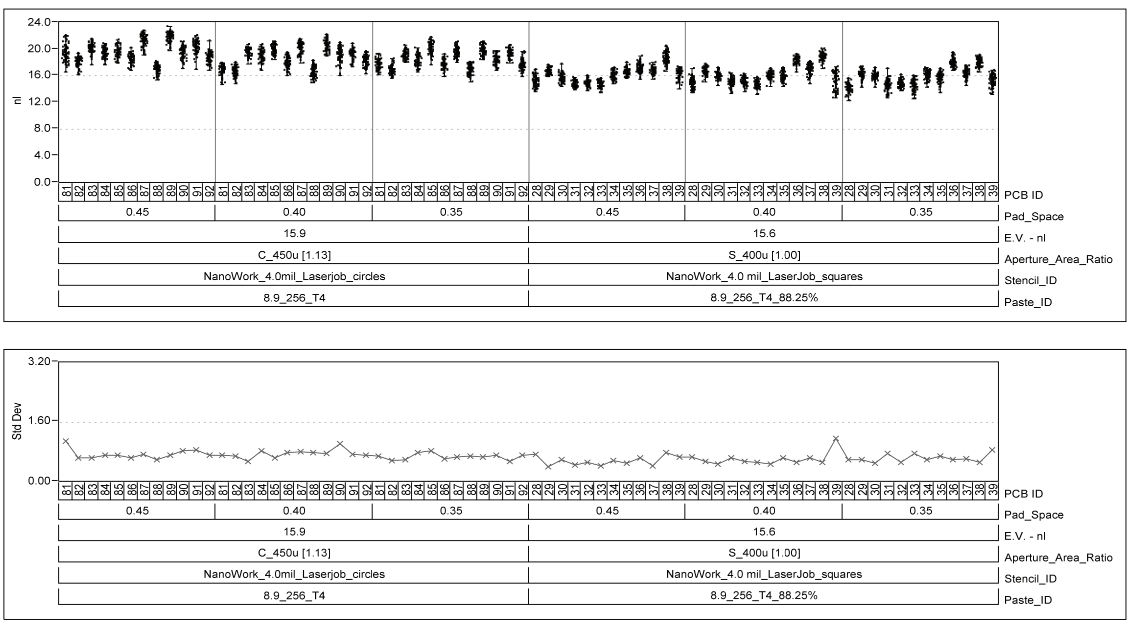


Figure 12. Volume Variability Chart for 0.80 mm, 0.85 mm, and 0.90 mm Pitch

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