Optimization of Stencil Apertures to Compensate for Scooping During Printing.

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ABSTRACT
This study investigates the scooping effect during solder paste printing as a function of aperture width, aperture length and squeegee pressure. The percent of the theoretical volume deposited depends on the PWB topography. A typical bimodal percent volume distribution is attributed to poor release apertures and large apertures, where scooping takes place, yielding percent volumes <100%, while SMD apertures and apertures near PWB features that raise the stencil yield percent volumes >100%. This printing experiment is done with a concomitant validation of the printing process using standard 3D Solder Paste Inspection (SPI) equipment.

The data collected from the SPI equipment included the solder paste volume, printed area, solder paste height and x-y offset printing. The volume data for each aperture width exhibits a Gaussian distribution, with the mean and standard deviation changing as a function of aperture width. For small apertures poor release is observed, while the reduction of the solder paste volume for large apertures is attributed to the appearance of the scooping effect at 0.070” aperture width. The Gaussian distributions, when analyzed separately, indicate that the printing process for each aperture width is under control yielding C-pk greater than 1.33 (DPMO <63), with USL and LSL set at ±20% from the mean volume.

We also investigated the release of apertures with and without round corners. The former exhibited better solder paste release.

INTRODUCTION
The current design of printed wired boards (PWB) to meet the demand of higher pin count, higher density, small size packages and mixed component pad sizes creates a PWB topography that yields considerably different solder paste volumes (~40% difference) for apertures of the same size depending on the components, pads, vias and labels around it, the thickness of the traces that connects them, whether they are solder mask defined (SMD) or not, if the printing is parallel or perpendicular to its narrow side, etc. This variation of the solder paste deposits during printing can affect the reliability of the solder joints and customers are requiring contract manufacturers to place a tight control on the solder paste volume across all the PWB pads, especially on expensive and difficult to rework components (e.g, BGAs, QFNs/BTCs, etc.). Numerous experimental and theoretical studies have been done to optimize the solder paste stencil printing parameters [1]-[4].

A statistical measure of how accurate is the solder paste volume controlled is the C_{pk} of the percent of the theoretical volume deposited. This statistical measure depends on the Upper Specification Limit (USL) and Lower Specification Limit (LSL) used in the calculation. For instance, Figure 1 below shows an ideal Gaussian volume distribution with a mean of 100% and a 7.5% standard deviation (sigma). The C_{pk} for the USL and LSL set at ±15% from the mean, a 2 sigma level process, would be 0.67, which translates in a process yield of 95.45% (Process fallout of 45500 Defects Per Million Opportunities, DPMO). However, if the USL and LSL for the process were ±30%, a 4 sigma level process, the C_{pk} would increase to 1.33, which translates in a process yield of 99.9936% (Process fallout of ONLY 63 DPMO). A C_{pk} of 1.67, a 5 sigma wide limited process, is equivalent to a process fall out of 1 DPMO. We will be focusing on a 4 sigma level process or better, i.e., a C_{pk} equal or greater than 1.33. It is obvious that the C_{pk} also increases if the standard deviation decreases while the USL and the LSL stay the same.

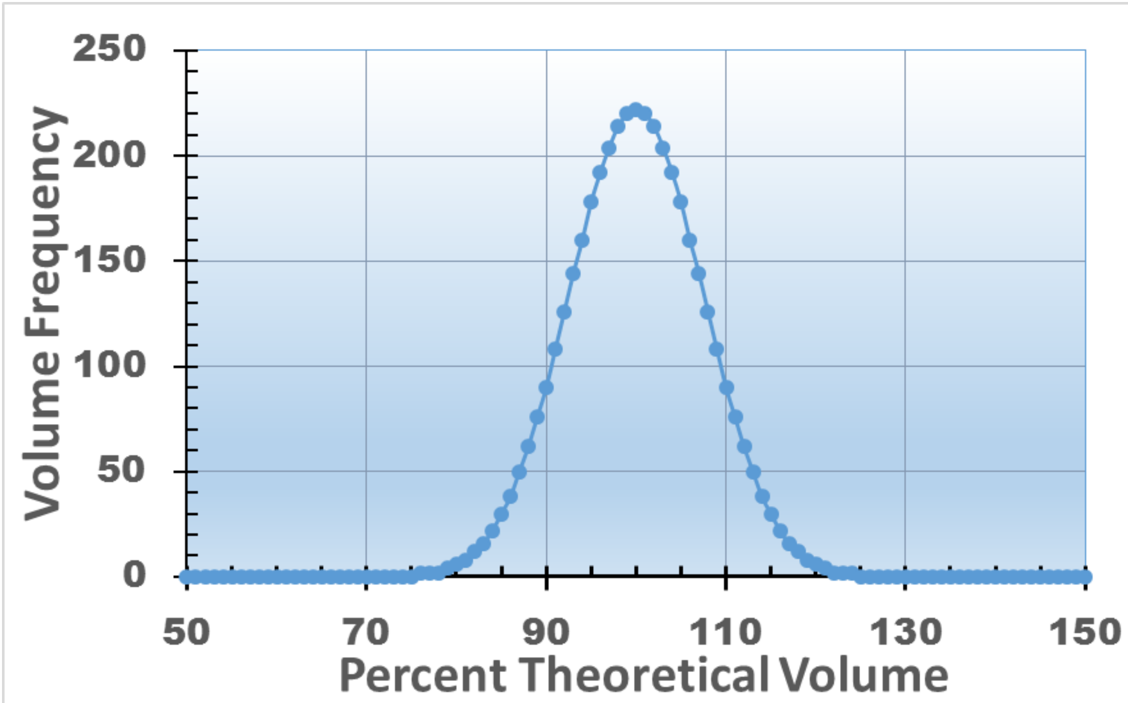

Figure 1. Volume Gaussian distribution with a mean of 100% and a 7.5% standard deviation.

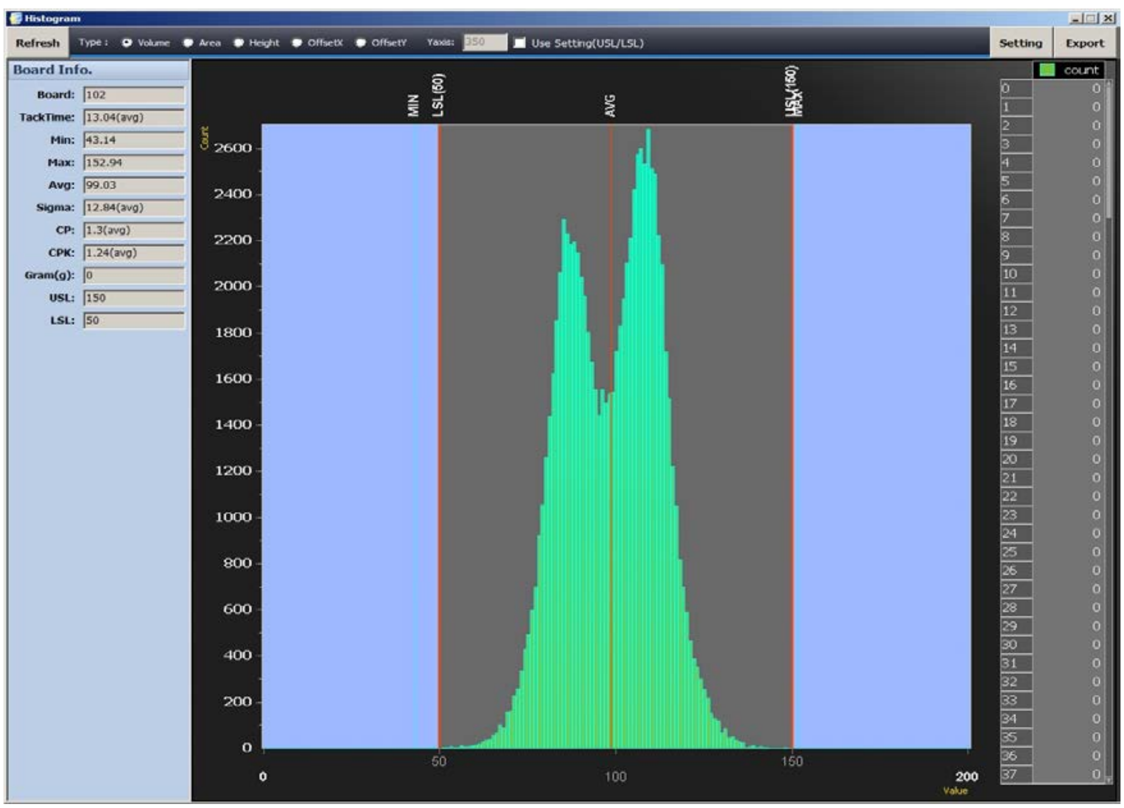

Figure 2. Typical solder paste percent volume histogram. The parameters of the graph are discussed below.

Figure 2 above shows a typical solder paste volume histogram. It corresponds to 102 PWBs of the same assembly from customer “ANYONE” inspected by our production SPI equipment. The graph shows an average volume of 99.03% and a 12.84% standard deviation. When the USL and LSL are set at 150% and 50%, respectively, the C_{pk} of ALL the data is only 1.24, less than what a 4 sigma level process requires.

Despite wide process specification limits and a $C_{pk}<1.33$, the assembly did not exhibit any solder joint defects related to solder paste volume. Was the printing of the PWBs under control or were we just lucky not to obtain any defects? Or will the defects show later in the field due to a questionable reliability? In this paper we will show that the paste printing process of the assembly in the above histogram was in control, we just need to pay attention to the way the data is analyzed.

EXPERIMENTAL

The statistics requirement, strictly speaking, to calculate the C_{pk} of a measurement, the solder paste percent of the theoretical volume in this case, is to print the same pad as many times as required (hundreds) to obtain a statistically meaningful distribution of measurements of the solder volumes on that pad. This would be not practical since it would be time consuming and expensive due to high cost of operator and equipment time. Instead we designed a 5.25”X5.25” PWB with 16 1.0”X1.0” groups of identical pads. Different groups of pads were separated by about 0.325”. The distance from pad to pad is 0.018”. All the pads were not SMD except U7, U8, U27 and U28. The solder mask opening is 0.002” larger than a given pad all around it. The PWB does not have any vias or traces connected to any pads to avoid any PWB topography that could cause a bias on the solder volume on the pads. The picture in Figure 3 shows one of the 12 PWBs used in this solder paste printing experiment.

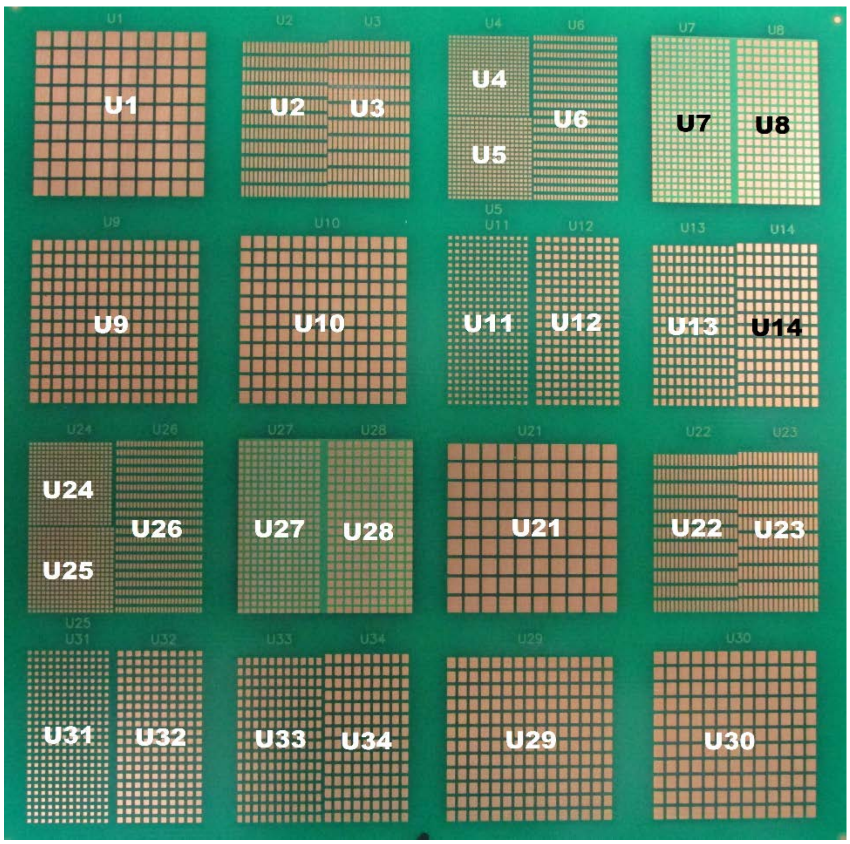

Figure 3. Picture of one of the 12 PWBs used in this printing experiment.

The pads of the PWB are squares or rectangles as described in Table 1. The pads are 0.002” larger than the stencil apertures in Table 1 to have a 0.001” printing gasket around each pad. The pads of U7, U27, U8 and U28 are solder mask defined.

TABLE I. Stencil aperture dimensions, number of apertures at each reference designator and their Aspect Area ratio (AAR).

Reference Designator	Aperture width (inches)	Aperture length (inches)	Paste Volume (cubic mils)	Number of apertures	Aspect Area Ratio (AAR)
U1, U21	0.090	0.080	36000	90	4.24
U2, U22	0.065	0.013	4225	220	1.08
U3,U23	0.075	0.018	6750	160	1.45
U4	0.014	0.014	980	400	0.70
U5	0.016	0.016	1280	361	0.80
U6	0.030	0.010	1500	500	0.75
U7, U27 (SMD)	0.020	0.020	2000	300	1.00
U8, U28 (SMD)	0.030	0.030	4500	200	1.50
U9, U29	0.060	0.045	13500	180	2.57
U10, U30	0.070	0.055	19250	143	3.08
U11, U31	0.020	0.020	2000	300	1.00
U12, U32	0.030	0.030	4500	200	1.50
U13, U33	0.040	0.025	5000	176	1.54
U14, U34	0.050	0.035	8750	126	2.06
U24 (R C)	0.014	0.014	911.32	400	0.74
U25 (R C)	0.016	0.016	1211.32	361	0.85
U26 (R C)	0.030	0.010	1431.32	500	0.78

The stencil was a 304 grade stainless steel 0.005” thick. The stencil was coated with a nanofilm to enhance the solder paste release from the stencil. The apertures for U24, U25 and U26 are squares with round corners using a radius of 0.004”. The stencil was laser cut with a 0.00025” tapered edge on the bottom side, i.e., a 2.9 degree angle.

The experiment was done using a Sn63/Pb37 Type 3, water soluble, solder paste. The printing speed was set at 25 mm/sec. The separation speed and separation distance were 15 mm/sec and 3 mm, respectively. Two different pressures were used, 1.0 and 0.75 kg/inch of squeegee length. The squeegee was 8 inches long. The printing was done perpendicular to the aperture widths with a 60^0 angle squeegee. A SMT carrier fixture made out of 0.25” thick production pallet material was used to keep the PWB flat and avoid any flexing of the PWB during the solder paste printing. The paste volumes were inspected using a production SPI machine and the results discussed in the next section.

RESULTS AND DISCUSSION

Figure 4 below shows the solder paste volume measurements of 18 prints in black squares. A commercially available solder paste inspection (SPI) equipment was used to measure the solder paste volume, area, height and x-y offset. The PWB was designed to have each 1.0”X1.0” group of solder paste deposits measured with a single field of view by the SPI equipment. The 5400 volume measurements had an average of 88.87% of the theoretical aperture volume and a standard deviation of 2.83%. If we set the USL and LSL at ±20% from the average volume we obtain a C_{pk} of 2.37, equivalent to a process fallout of less than 1 DPMO. The yellow dots are the results of a Gaussian distribution fit using 5400 volumes, with the mean and the standard deviation as the only fitting parameters. The best fit yielded a mean of 88.5% and a standard deviation of 2.69%.

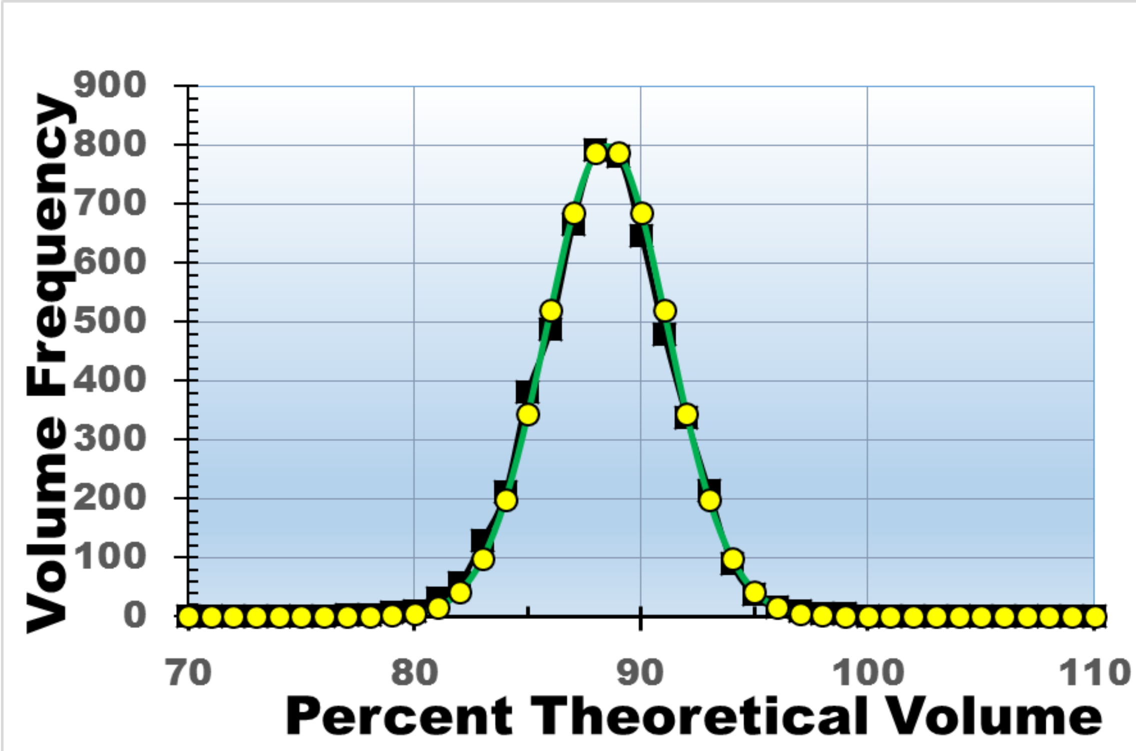

Figure 4. Solder paste printing results of U11, 300 apertures 0.020"X0.020". The data, black squares, represents 18 prints using a squeegee pressure of 1.0 Kg/inch. The yellow dots are from a Gaussian distribution fit to the data.

Figure 5 below shows the solder paste average volume of the Gaussian distribution fit to the data as a function of aperture widths for two different squeegee pressures. The green squares are the average volumes for 1.0 kg/inch pressure and the red triangles are the averages measured at 0.75 kg/inch pressure. It can be seen that the small width apertures exhibit a low average solder paste volume attributed to their low AAR. U4 (0.014" squares) data had an average volume fit parameter of 83.8%. The average fit parameter increases as the square aperture side increases from 0.014" to 0.030" (the AAR increases from 0.70 to 1.50). It should be mentioned that green squares data (not shown for clarity) should be next to the red triangles in the red ovals. The two red triangles in the red oval for aperture width of 0.030" are the average volume fit parameter for the U6 and U26 data. They exhibit low average volume because the length of their apertures is 0.010", with an AAR of 0.75. The black dotted curve is a parabola fit to the shown green squares to be used as a guide to the eye.

We should mention that the only fitting parameter for the parabola was its y-axis intercept set at 76%. The trend of the solder paste volume shows that it maximizes for an aperture width of 0.050" and starts to decrease at an aperture width of 0.060". The decrease of solder paste volume average for aperture widths greater than 0.060" is attributed to scooping. The insert of Figure 5 shows a picture of a 0.090"X0.080" aperture solder paste deposit printed from top to bottom. It shows the thinning of the solder paste height on the top edge of the pad. The other two red triangles in red ovals are the average volume fit parameters for the 0.040"X0.025" and 0.075"X0.018" apertures. They have AARs greater than 1.4, i.e., have good solder paste release and do not exhibit scooping due to the narrowness of the apertures.

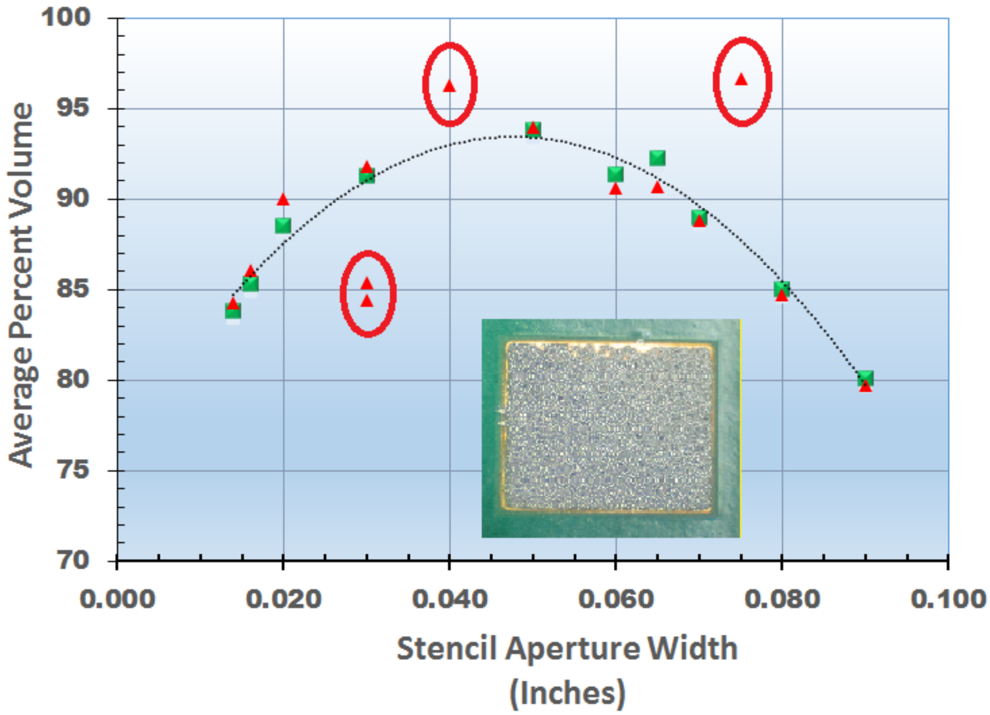

Figure 5. The mean percent volumes for different aperture widths for 1.0 kg/inch (green squares) and 0.75 kg/inch (red triangles) squeegee pressure. Poor release for small apertures yielded low solder paste volumes, while solder paste scooping results in low volumes for apertures wider than 0.070”. The black dotted line is a parabola fit to the green squares. The insert shows a picture of U1 that exhibits scooping on the top edge of the pad.

It can also be inferred from Figure 5 that each pad size has a different average, from 80% to 97%, that depends on its dimensions. Actually, the highest volume averages, 110%, were obtained for the U8 and U28 SMD pads (not shown in the graph). It is reasonable to have a higher volume average for a SMD pad since the stencil is higher than the pad level by the thickness of the solder mask, about 0.001”. The average of ALL the data is 91.47% with a standard deviation of 6.00%. The standard deviation widens because the individual average for each pad centers at different percent volumes. This is a 4 sigma level process or better for a USL and a LSL set at least ±24.0% from the average, i.e. greater than 111.5% and less than 71.5%, respectively.

If we had included traces, vias, silkscreen and other kinds of topographic features that a regular PWBs have, like the one that yielded the data from Figure 2, we would have a greater standard deviation. That would require wider USL and LSL for the process to be a 4 sigma level process.

Going back to the data in Figure 2, we can think of the bimodality of the percent volume data due to two independent sets coming from low percent volume apertures and high percent volume apertures. The low percent volume peak can be attributed to poor release apertures and large apertures where scooping of the solder paste takes place. The high percent volume peak corresponds to SMD pads, pads with wide traces, pads near tented vias, or pads near any feature that could raise the stencil, allowing the dispensing of a higher solder paste volume than the theoretical aperture volume.

Figure 6 below shows a two Gaussian distribution fit to the data of Figure 2. The low peak fit is shown in orange triangles and high peak fit in red squares. The sum of the two distributions is shown in black circles. The volume average of the low peak fit is 87.3% and 108% for the high peak. Their standard deviations fit parameters were 6% and 5% respectively. If we use the same LSL and USL that we used before to analyze the data (50% and 150% respectively), the C_{pk} for the low peak is 2.01, while the C_{pk} for the high peak is 2.37. This indicates that the process was under good control, with a DPMO of less than 1.

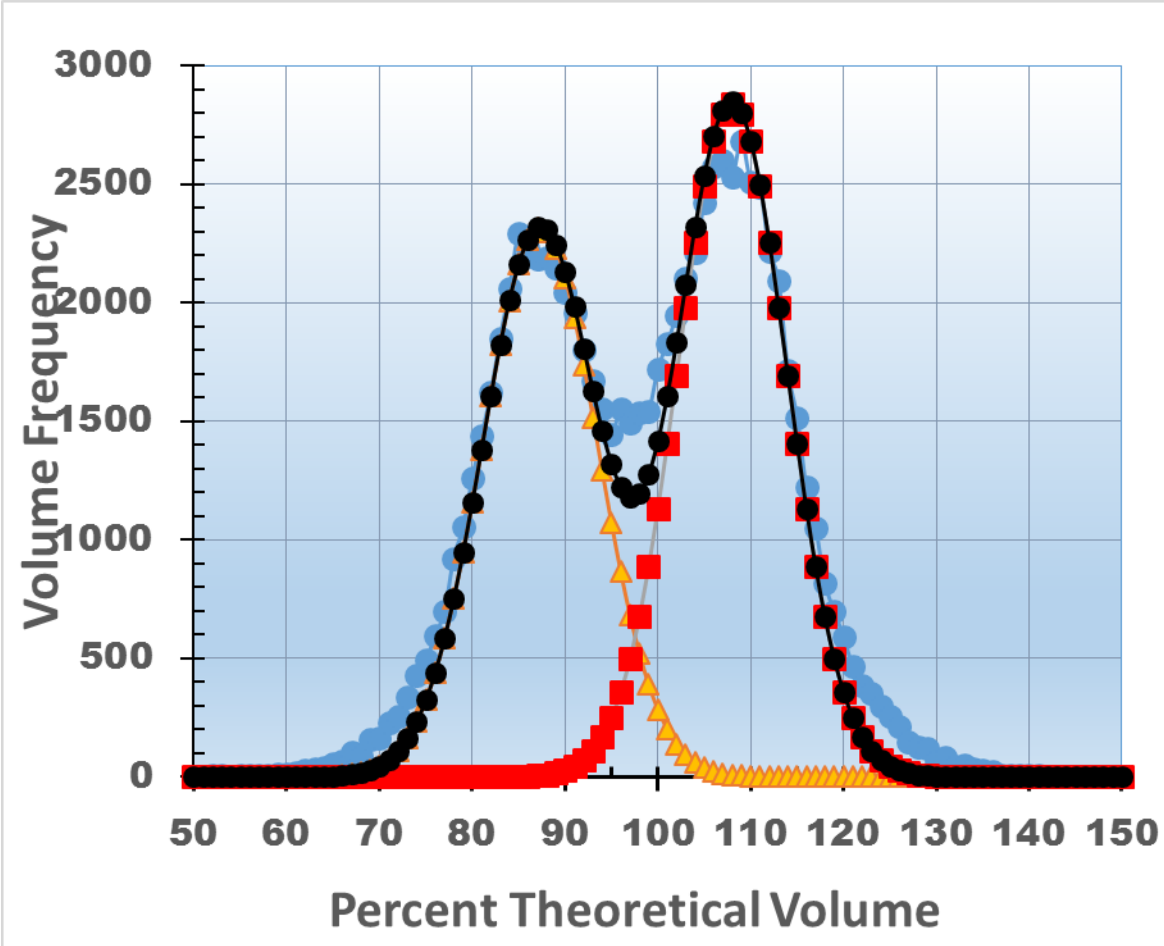

Figure 6. Two Gaussian distribution fit to the bimodal data of figure 2 (Blue circles).

CONCLUSIONS

The SPI volume data should be analyzed by individual pads. However, the analysis can be simplified by grouping the data into different groups (e.g., low percent theoretical volume pads and high percent theoretical volume pads) and then fitting each group of data to a Gaussian distribution to determine its mean and standard deviation. The solder paste printing process is bimodal by nature. The LSL and USL for the SPI equipment should be determined from specified absolute solder paste volumes that yield reliable solder joints. The limits can be tighter for critical components and should be analyzed separately.

The stencils apertures should be designed to be in the 90%-100% solder paste percent release volume, whenever possible. If apertures smaller than 0.025"X0.025" are present, they should be oversized to compensate for their lower solder paste release and be able to meet their absolute specified solder paste volume. Small apertures will shift the overall mean percent volume below 100%, making the LSL lower.

Similarly, apertures that are 0.060"X0.60" or larger will shift the overall mean percent volume below 100%, as the onset of solder paste scooping was observed at around aperture widths of 0.060". These large apertures should be avoided. A good Rule of Thumb from this observation is to split the apertures whenever a pad is greater wider than 0.060" to avoid the scooping effect. For example, if a pad is 0.115"X0.250", it would be wise to have a 2X3 window pane with a 0.010"-0.015" gap between apertures.

REFERENCES

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[4] R. Farrell and C. Shea: "*Stencil and Solder Paste Inspection Evaluation for Miniaturized SMT Components*". Proceedings of SMTA International, October 2013.

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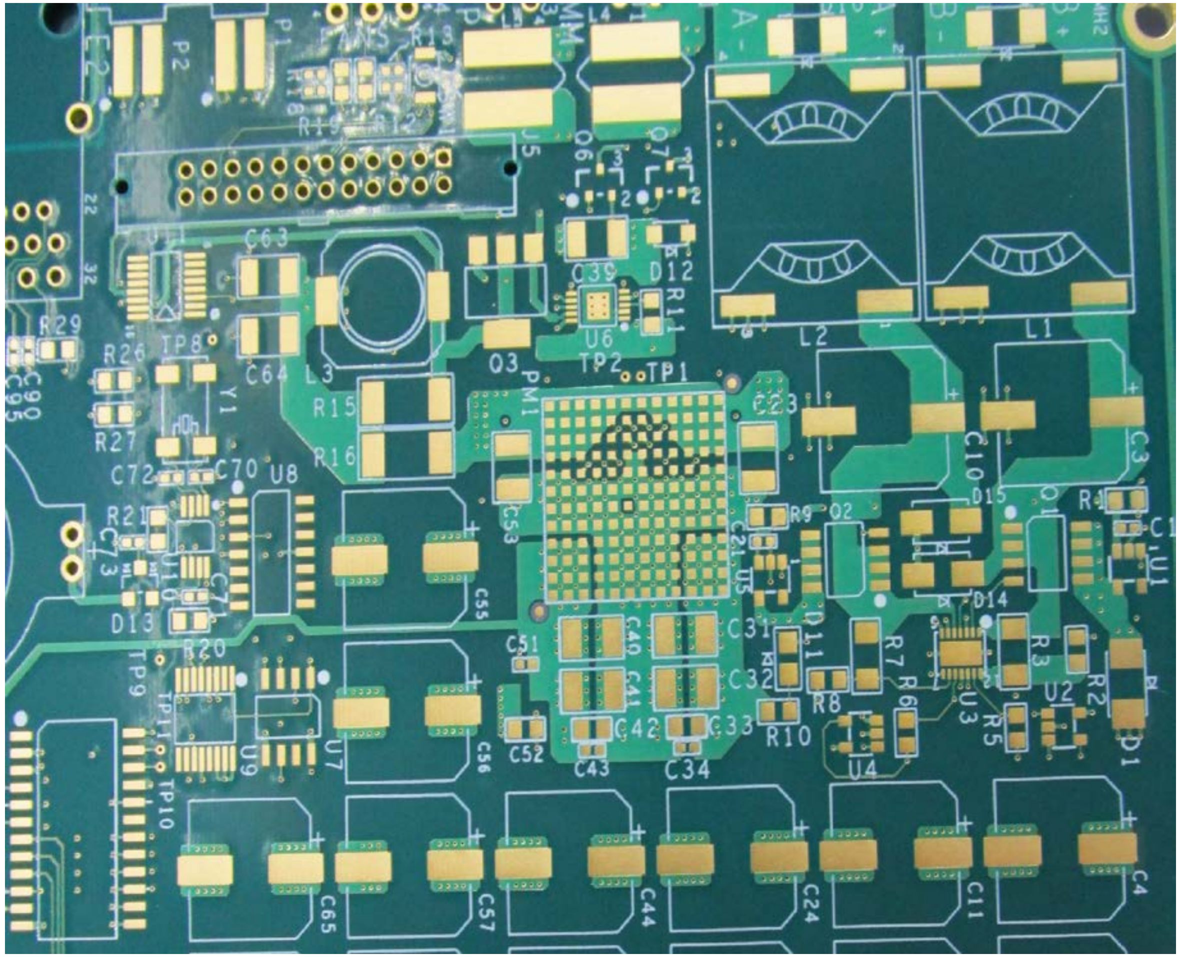
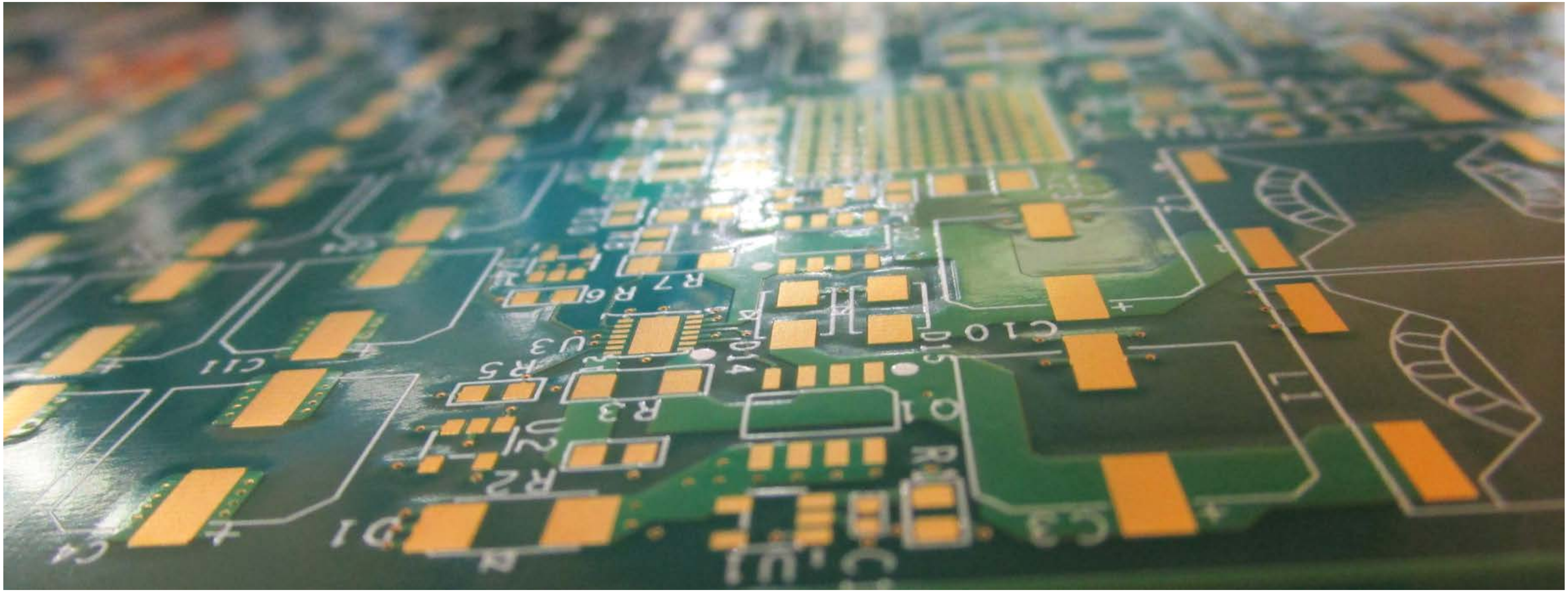
Top view of a typical PWB

- SMD pads
- NSMD pads
- Thick traces
- LGA
- Fine pitch ICs
- Small chip SMT components
- Large SMT components
- Etc.

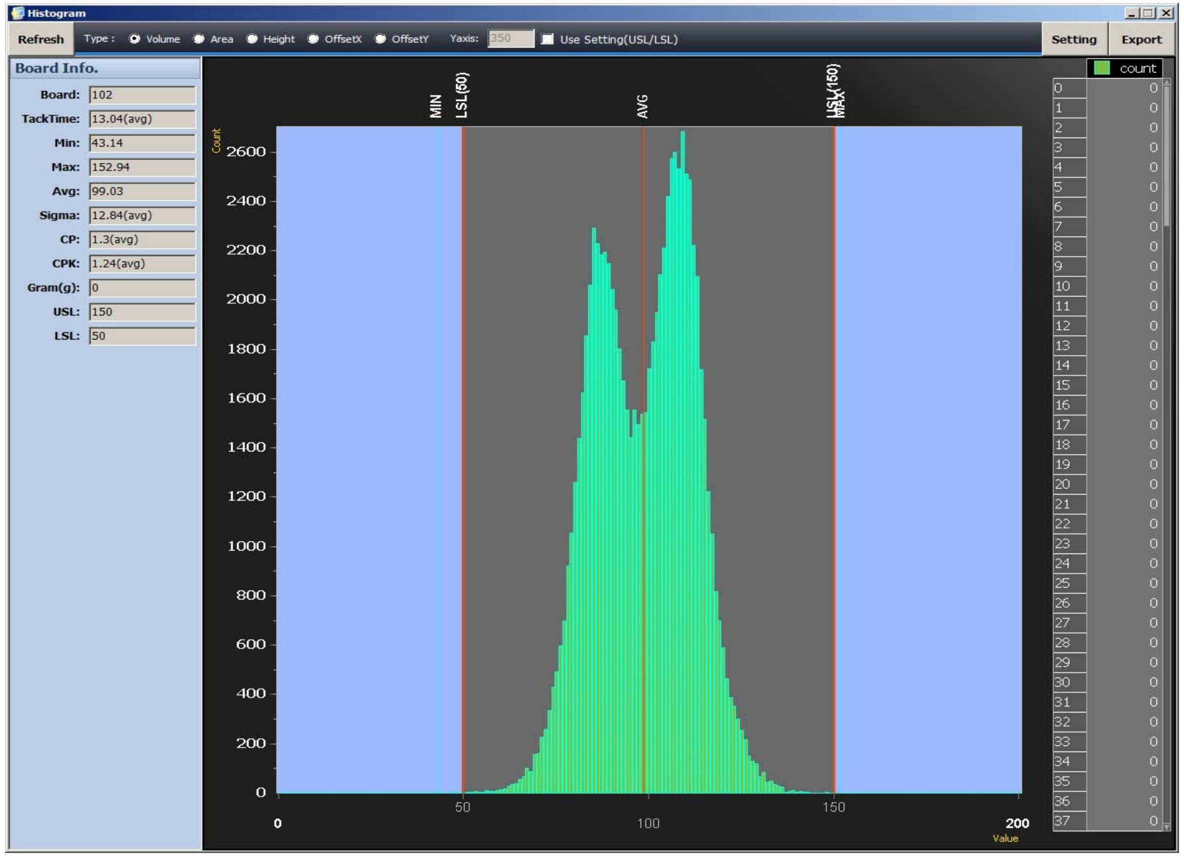


Typical topography of a PWB



Typical solder paste percent volume histogram.

- μ = 99.03%
- σ = 12.84%
- LSL = 70%
- USL = 130%
- C_{pk} = 0.75, 23765 DPMO
- LSL = 50%
- USL = 150%
- C_{pk} = 1.24, 134 DPMO



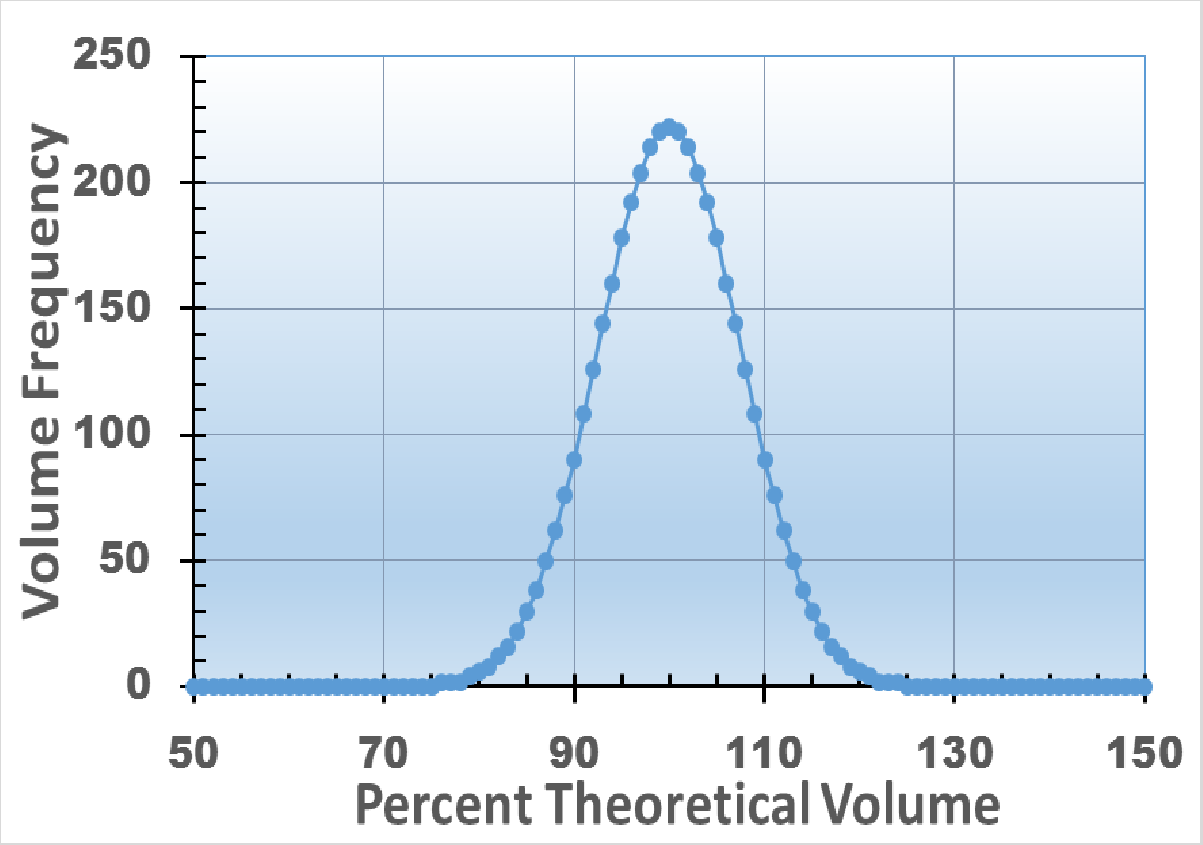
Process Capability Index and Process Fallout

C_{pk}	Sigma Level (σ)	Process Yield	DPMO
0.33	1	68.27%	317310
0.67	2	95.45%	45500
1.00	3	99.73%	2700
1.33	4	99.9968%	63
1.67	5	99.9999%	1

Ideal Volume Gaussian distribution

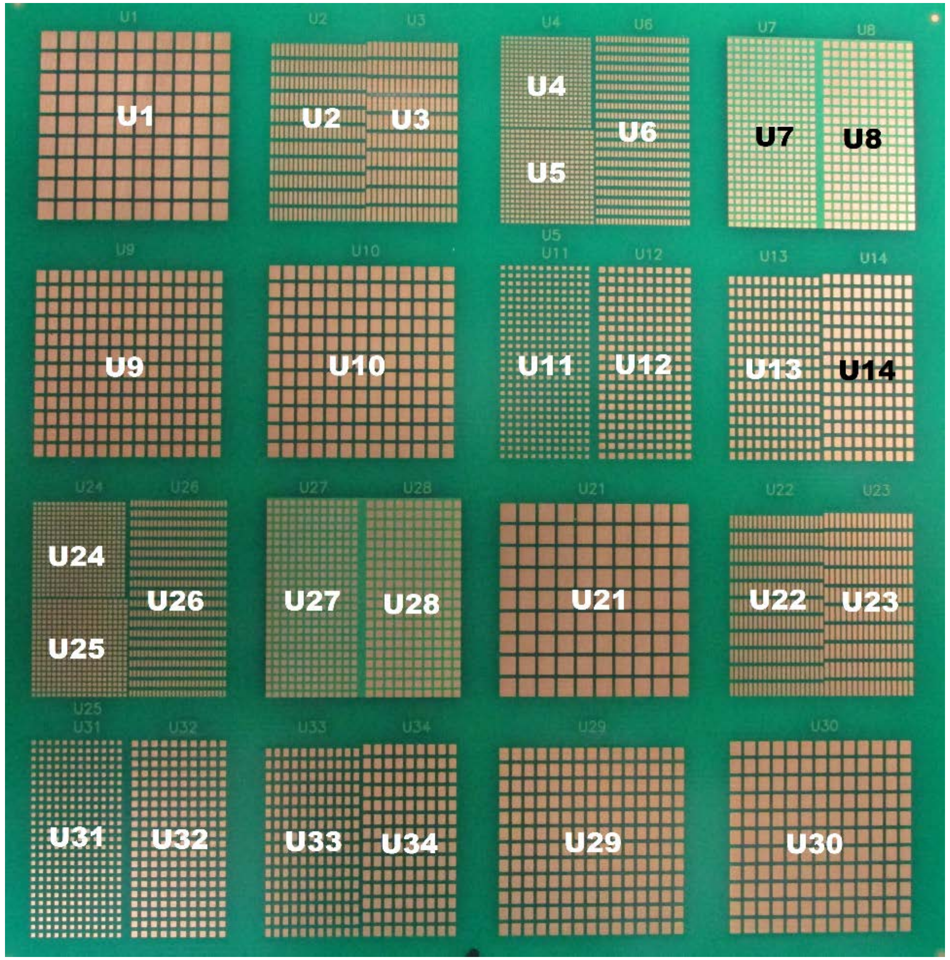
$$g(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

- μ = 100%
- σ = 7.5%



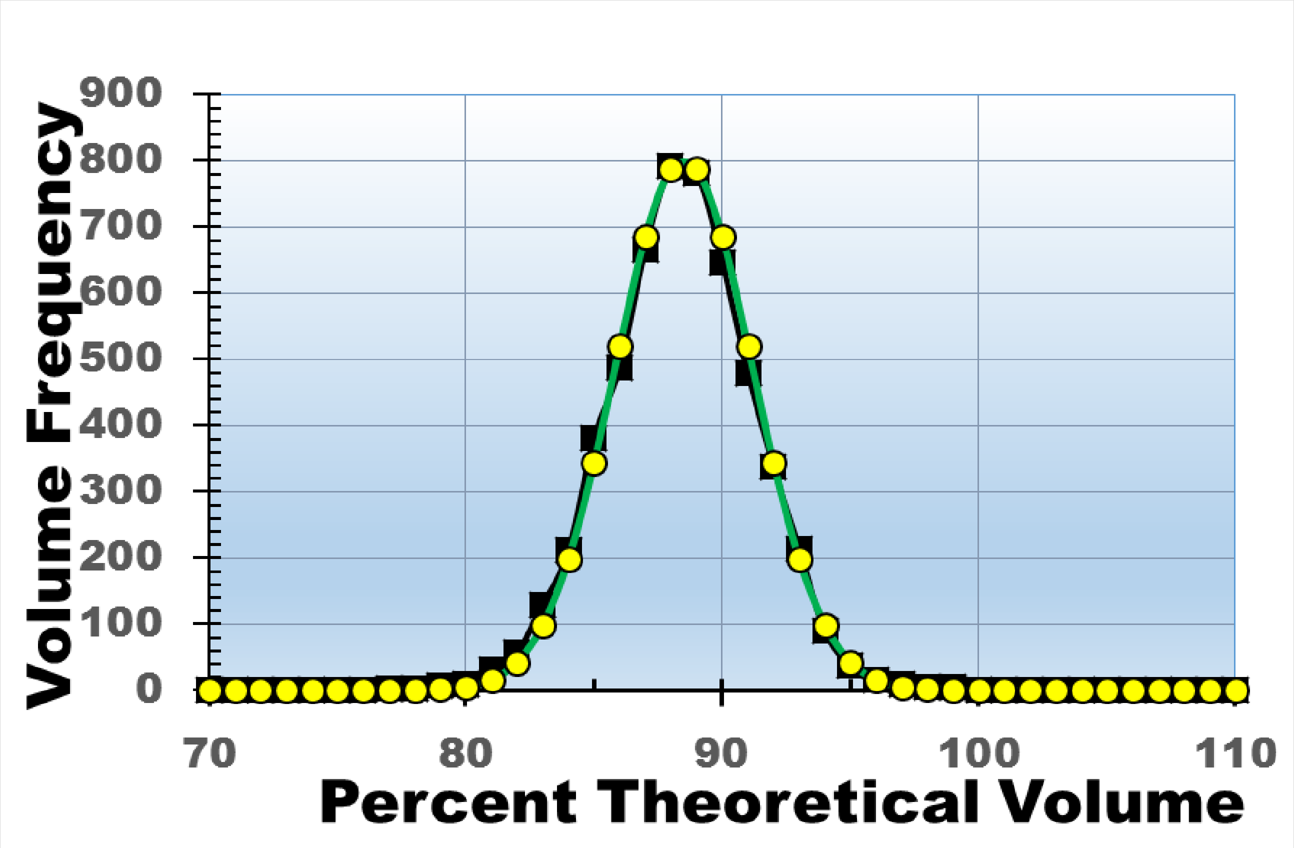
Test PWB used in this printing experiment

Reference Designator	Aperture width (inches)	Aperture length (inches)	Paste Volume (cubic mils)	Number of apertures	Aspect Area Ratio (AAR)
U1, U21	0.090	0.080	36000	90	4.24
U2, U22	0.065	0.013	4225	220	1.08
U3,U23	0.075	0.018	6750	160	1.45
U4	0.014	0.014	980	400	0.70
U5	0.016	0.016	1280	361	0.80
U6	0.030	0.010	1500	500	0.75
U7, U27 (SMD)	0.020	0.020	2000	300	1.00
U8, U28 (SMD)	0.030	0.030	4500	200	1.50
U9, U29	0.060	0.045	13500	180	2.57
U10, U30	0.070	0.055	19250	143	3.08
U11, U31	0.020	0.020	2000	300	1.00
U12, U32	0.030	0.030	4500	200	1.50
U13, U33	0.040	0.025	5000	176	1.54
U14, U34	0.050	0.035	8750	126	2.06
U24 (R C)	0.014	0.014	911.32	400	0.74
U25 (R C)	0.016	0.016	1211.32	361	0.85
U26 (R C)	0.030	0.010	1431.32	500	0.78



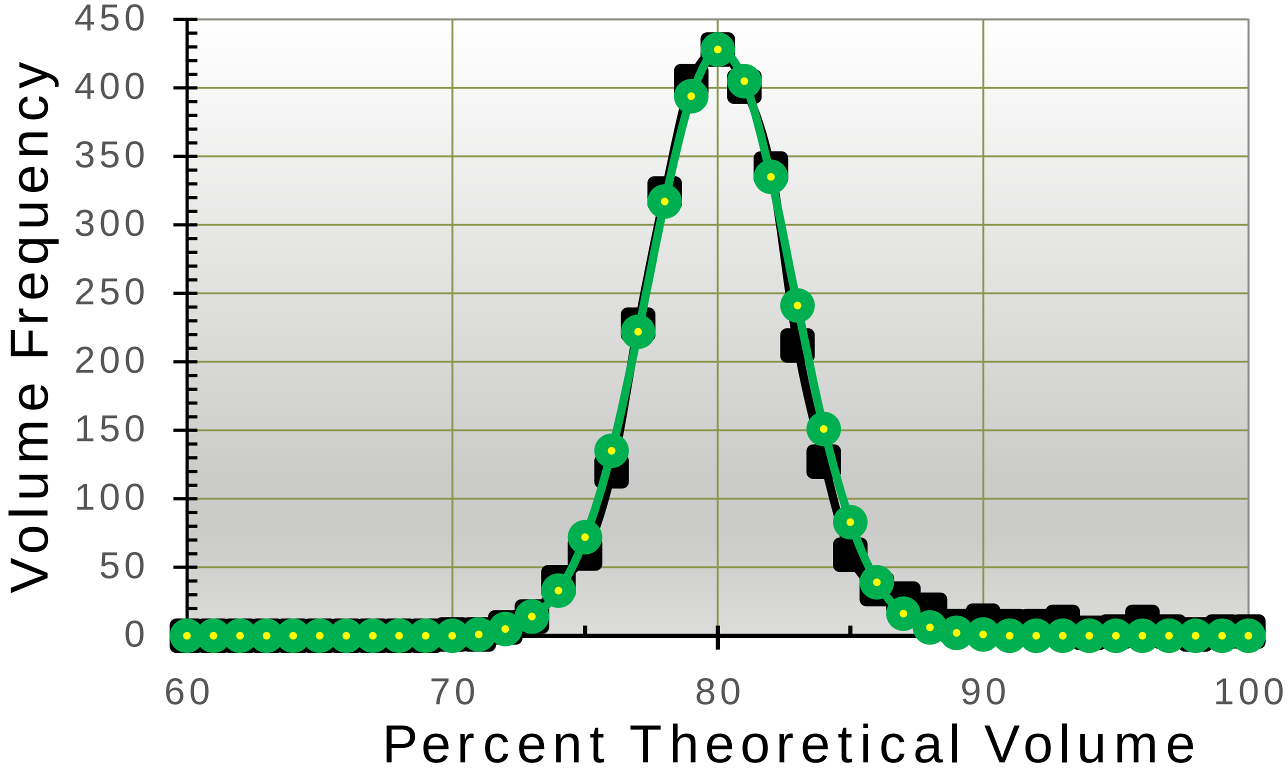
Percent Volume distribution for U11: 0.020”X0.020”

- N = 5400
- µ measured = 88.87%
- σ measured = 2.83%
- µ fit = 88.5%
- σ fit = 2.69%



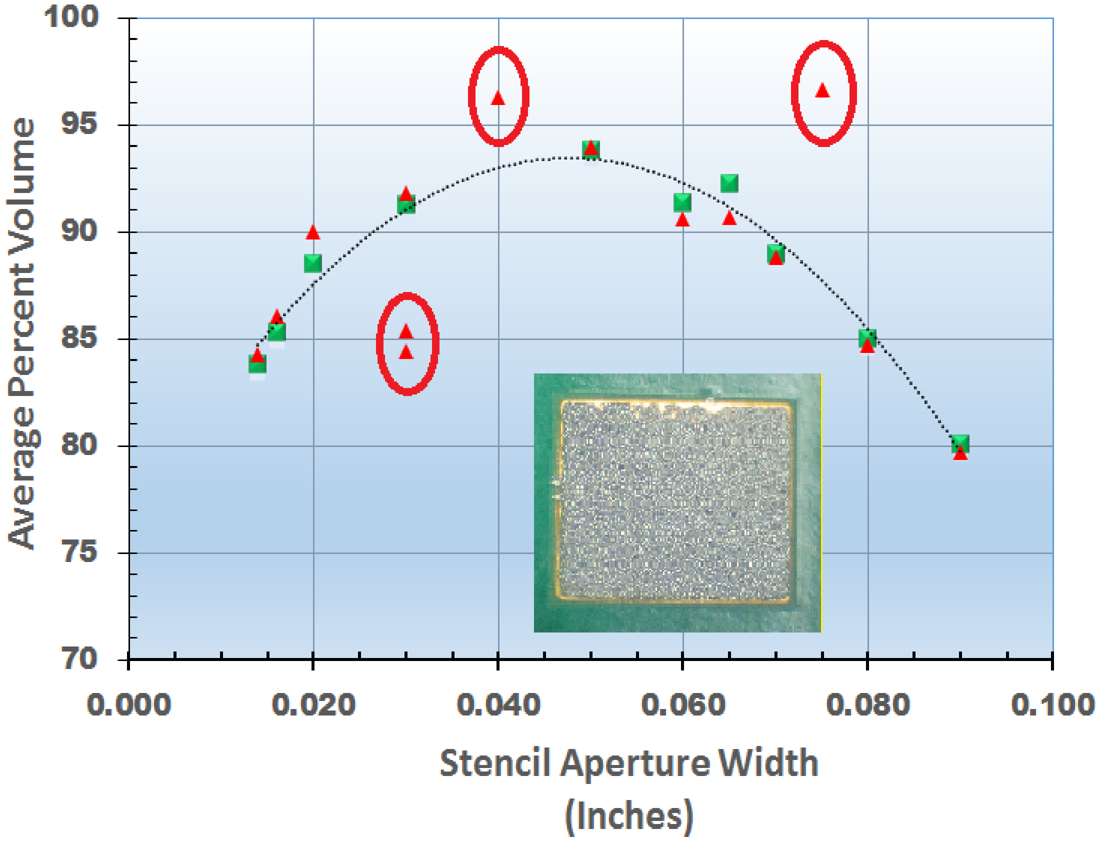
Percent Volume distribution for U1 and U21: 0.080”X0.090”

- N = 2900
- μ_{measured} = 80.88%
- σ_{measured} = 3.463%
- μ_{fit} = 80.1%
- σ_{fit} = 2.7%



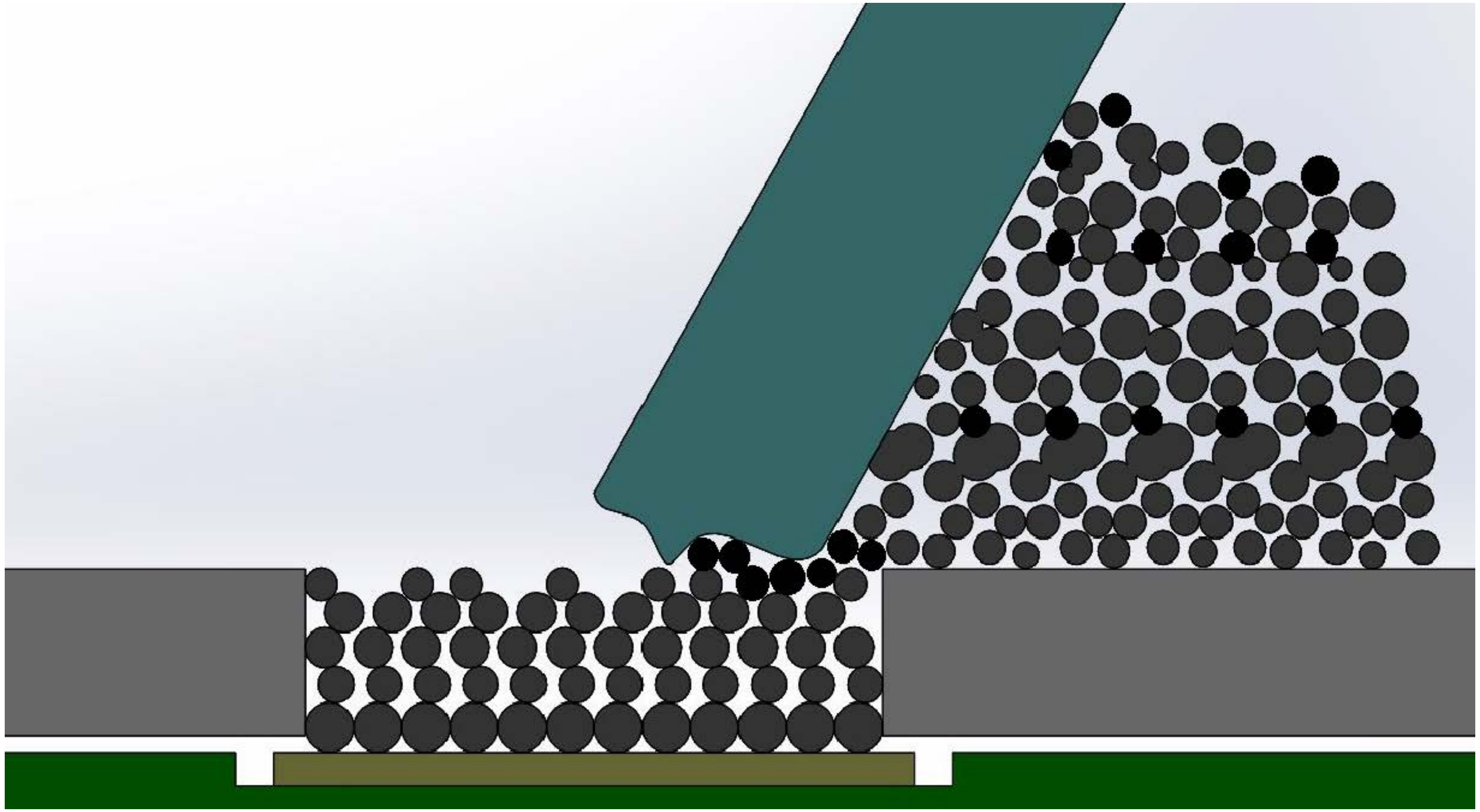
Mean percent volume for 1.0 kg/inch and 0.75 kg/inch

- Low volume for small apertures
- Maximum at 0.040”-0.060”
- Decrease for W > 0.060” (scooping)
- 0.030”X0.010” AAR = 0.75
- 0.040”X0.025” ARR = 1.54
- 0.075”X0.018” ARR = 1.45



Solder paste shaving/scraping during printing

- Type 3 particle size is 25-45 μm.



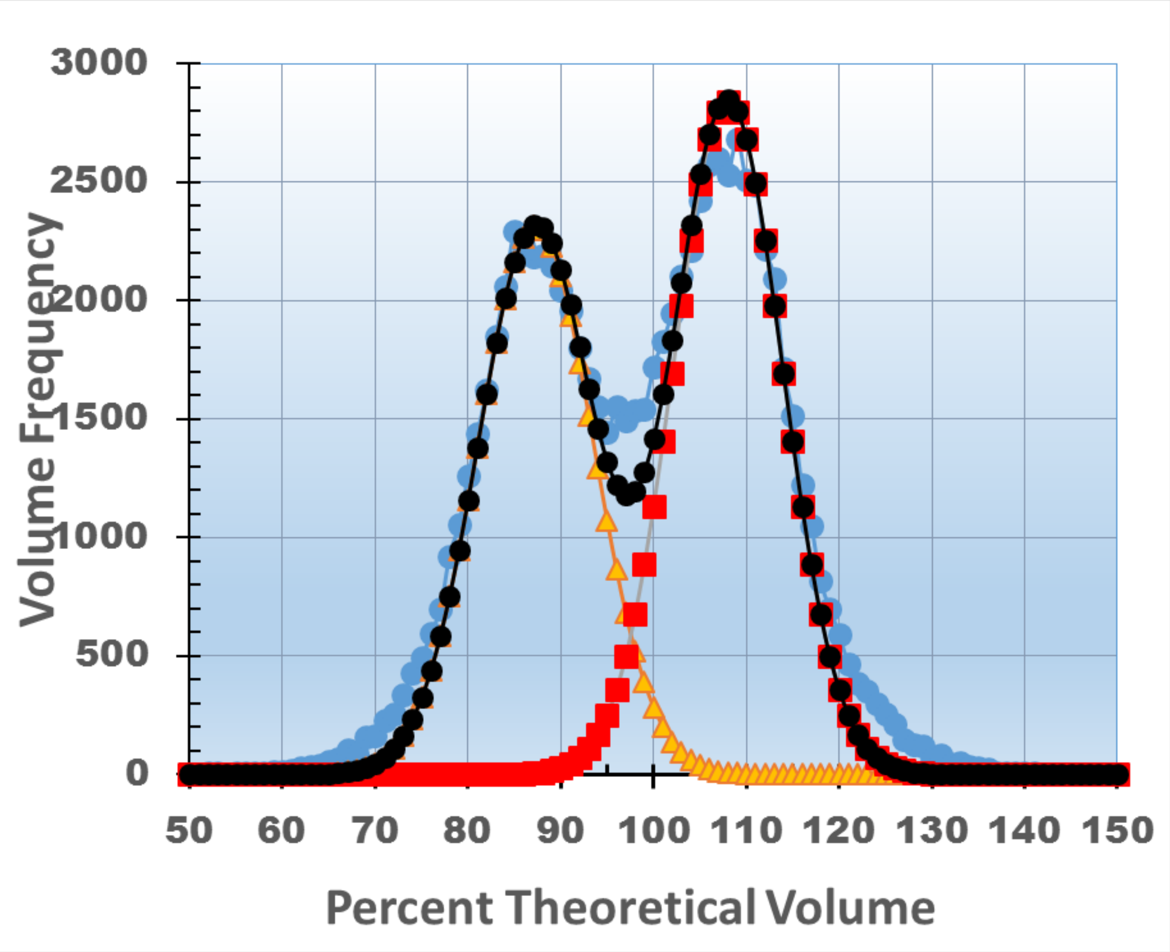
Two Gaussian distribution fit to bimodal data.

Low Peak:

- μ measured = 87.3%
- σ measured = 6.0%
- C_{pk} = 2.01

High Peak:

- μ measured = 108.0%
- σ measured = 5.0%
- C_{pk} = 2.37



Conclusions:

- SPI data should be analyzes by individual pads.
- The analysis can be simplified by grouping the data.
- The LSL and USL should be based on volumes that yield good solder joints.
- These limits can be tighter for critical components. Analyze separately.
- Small apertures (below 0.025”X0.025”) should be oversized, if possible.
- Avoid apertures larger than 0.060”X0.060” to avoid scooping.
- For example, a 0.115”X0.250” should be split into a 2X3 window pane with 0.010” gap between apertures.