Formulation Considerations for Automated Dispensing of Lead Free Solder Paste

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Abstract:

Dispensing solder paste with automated dispensing equipment provides many challenges that must be overcome before a production process can be considered robust. The primary challenge to overcome is the tendency for solder paste to plug in dispensing pumps and needles. This paper outlines the important process parameters that must be determined and controlled for good production robustness, including the selection of valve or pump technology, selection of dispensing needles, selection of solder paste packaging, generic equipment settings, and paste formulation. In particular, the effect and interdependence of solder paste mesh size, % metal content, and alloy of metal is discussed. Many production facilities have overcome these problems, only to have them re-appear when switching to a lead free solder formulation.

This paper will focus on the formulation of solder paste for robust dispensing and how that formulation must be altered when lead free alloys are used. A theoretical model showing recommended % metal content as a function of alloy is presented, with consideration to mesh size and uniformity. This model is then applied to lead free formulations to give the reader an understanding of the formulation for specific alloys as well as a tool for determining this variable for any lead free alloy. An example case study is presented.

Introduction:

Solder paste is dispensed for a variety of applications, but most as an alternative when wave solder or screen printing is not possible. Solder paste can be dispensed on a variety of surface mount applications on printed circuit boards, integrated circuit packages, MEMs devices, and electrical component connectors.

Automated dispensing of solder paste can be trouble free if the paste is formulated correctly, the proper dispensing technology is used, and the equipment is set up properly. Most of the techniques and best practices for dispensing solder paste apply equally to lead free pastes and pastes containing lead. Background necessary to understand dispensing solder paste for all alloys will be given, followed by a discussion of the differences between leaded paste and lead free paste.

Description of Solder Paste:

Solder paste consists of solder powder and liquid flux. The solder powder is specified by the alloy of the metal and the size of the powder particles. Typical alloys contain a combination of lead, tin, silver, bismuth, indium, and other alloys. The alloys are chosen for their physical and chemical properties for a specific application, but the alloy can also affect the dispensability, as will be discussed later. The most important aspect of the alloy that affects dispensability is the specific gravity of the alloy. Table 1.

Typical Solder Alloy Densities	
Alloy Composition	**Alloy SG**
100 Sn	7.3
95 Sn / 5 Sb	7.3
48 Sn / 52 In	7.3
96.5 Sn / 3.5 Ag	7.4
70 Sn / 18 Pb / 12 In	7.9
30 Pb / 70 In	8.2
63 Sn / 37 Pb	8.3
62 Sn / 36 Pb / 2 Ag	8.4
60 Sn / 40 Pb	8.5
40 Pb / 60 In	8.5
42 Sn / 58 Bi	8.6
50 Sn / 50 Pb	8.9
40 Sn / 60 Pb	9.3
60 Pb / 40 In	9.3
30 Sn / 70 Pb	9.7
20 Sn / 80 Pb	10.0
10 Sn / 88 Pb / 2 Ag	10.4
10 Sn / 90 Pb	10.5
5 Sn / 95 Pb	10.8
90 Pb / 5 Ag / 5 In	10.9
92.5 Pb / 2.5 Ag / 5 In	11.0
100 Pb	11.3
1 Sn / 97.5 Pb / 1.5 Ag	11.3

Table 1. Typical Solder Paste Alloys

The size of the powder particles range in size, typically from 5 to 75 microns. Table 2 lists the particle sizes for the industry standard designations of JIS particle size type and ASTM mesh size designations. There are custom formulations also available from some manufacturers.

Type Designation (Joint Industry Standard)	**Mesh Designation (per ASTM-B214)**	**Maximum Particle Size (µm)**	**Less than 1% Larger than (µm)**	**80% Minimum Between (µm)**	**Suggested Needle size**
II	-200/+325	80	75	75-45	**21 or larger**
III	-325/+500	50	45	45-25	**23 or larger**
IV	-400/+500	40	38	38-20	**25 or larger**
V	-500/+635	30	25	25-15	**27 or larger**
VI	-635	20	15	15-5	**30 or larger*** ***30 g. not tested**

Table 2. Solder Powder Particle Sizes

The flux in the solder paste serves several purposes. First and foremost, the flux acts as a an activator to prevent oxidation during reflow. The activators comprise approximately 0.5% of the total volume of the flux. Approximately 75% of the flux is composed of a synthetic resin or nature rosin that serves as a base for the flux. The remainder of the flux is composed of thickening agents, wetting agents, heat stabilizers, and solvents for viscosity reduction. Typical fluxes typically have a specific gravity of 0.94 to 1.05.

Dispensing Technology:

Most automated dispensing of solder paste is dispensed with either a time/pressure system, or with an auger pump.

Time pressure systems consist of a reservoir of material that is pressurized to extrude material through a needle or nozzle. Material flow is governed by the flow equation given in equation 1. The amount of material is controlled by controlling the time of the air pulse and the air pressure. While this type of system is relatively simple, it is subject to viscosity variations. Also, pressure pulsing can cause fluid separation and clogging.

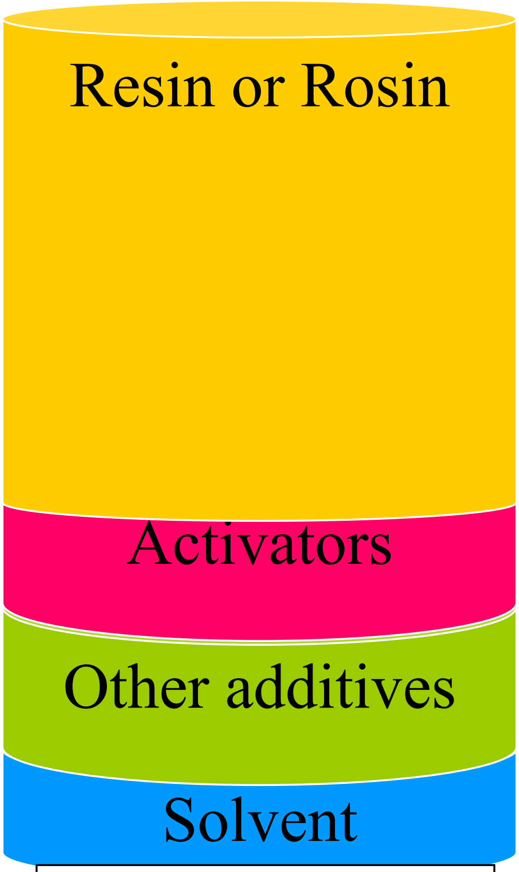

Figure 1. Flux components

$$Q = \frac{\pi d_n^{\,4}}{128 \mu_n l_n}(P_2 - P_3) \qquad (1)$$

Q = Total flow rate
μ = Material viscosity in needle
P2 = Pressure in needle hub
P3 = Pressure at needle outlet
l = Length of needle
d = Inside diameter of needle

Auger pumps use an auger that turns inside a cylinder that is feed from a syringe shown in figure 3. These pumps are similar to the way that plastic extrusion screws on injection molding equipment work. There is a common misconception that these pumps operate on the principle of the Archimedes screw. In fact, the equation that governs the material flow is a complex relationship between the auger screw geometry, feed pressure, fluid viscosity, and nozzle/needle geometry. Equation 2 is the equation that describes the material flow. The constants in the equation are dependant on the screw geometry.

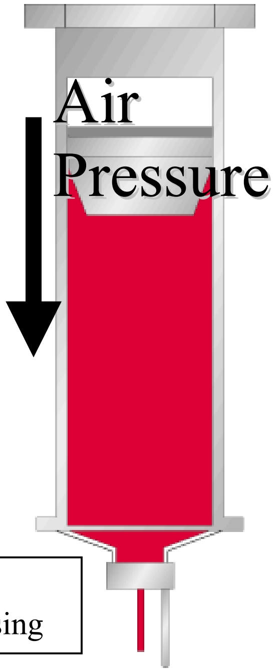

Figure 2. Time Pressure dispensing

$$Q = \frac{C_1 N + \frac{C_2}{\mu_a}(P_1 - P_3)}{\left(1 + \frac{C_2}{C_3}\frac{\mu_n}{\mu_a}\right)} \qquad (2)$$

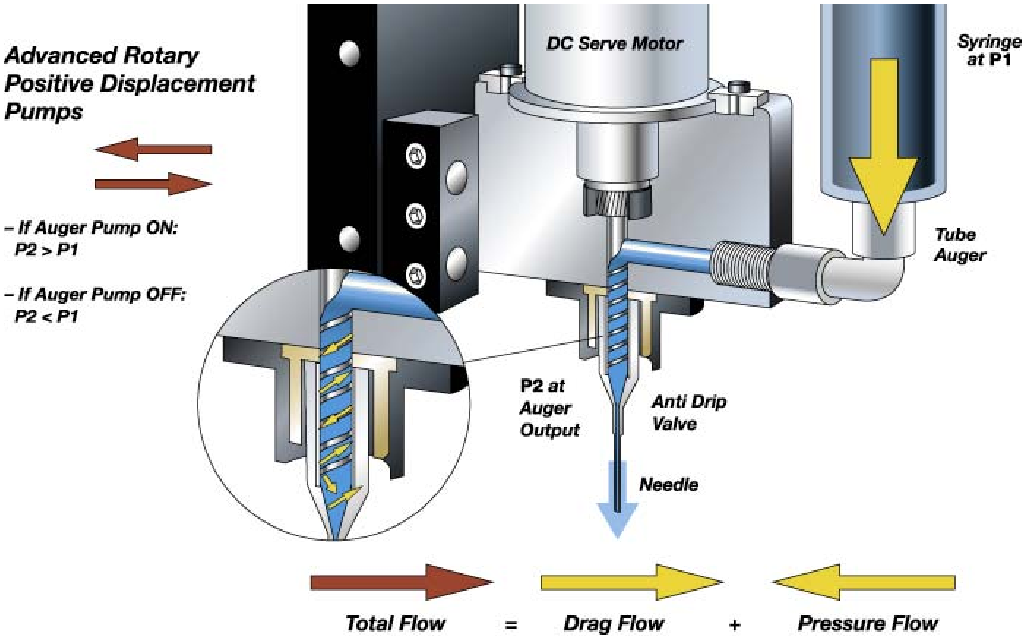

Figure 3. Auger pump dispensing

The advantage of auger pumps with solder paste is that they can be used to extrude very small, accurate amounts of solder in a controlled fashion and are less sensitive to viscosity variations. Auger pumps, too, can be prone to plugging, as will be discussed in the next section.

Typical problems with solder paste dispensing:

Solder paste is a difficult material to dispense in an automated environment. Typical problems include: plugging, dripping or drooling, skipped dots, and inconsistent dispensing. A brief description of the problem and root causes will be given here, although the intricate interaction formulation, hardware, and equipment settings also contribute to this a complex problem. In general, we will be concentrating on those root causes that are affected by changing from a lead type paste to a lead free.

Dripping or drooling is a situation where solder paste does not stop dispensing when the pump or valve dispensing the paste is turned off. Most often, this is cause by air entrapped in the solder paste (either in packaging or mis-handling), causing the fluid to become compressible. Skipped dots and/or inconsistent dispensing can have a number of causes. Some of the most common include:

- Dispense gap problems (between needle and dispensing surface). Dispense gap too small, too large, or changing all can cause problems. A good rule of thumb is to keep the dispense gap between ¼ to ½ of the desired dot size.
- The needle must have a short dwell time before being removed from the board. If this dwell time is too small, the flux may not wet to the board properly.
- The fluid must be stored and handled properly. Exposing the solder paste to extreme heat or cold can change the physical properties of the paste. Exposure to moisture or vibration can also cause a problem.

Solder paste clogging is, by far, the most common problem in automated dispensing and can have a number of causes. Metals used in solder paste are typically soft and easily deformed. Often, the solder paste particles can be welded together through mechanical shearing and pressure. There are two major mechanical sources of this problem. First, the size of the nozzle or needle must be large enough to allow solder particles to pass freely. Table 2 gives some recommended needle sizes for various solder particle sizes. While these recommendations can be exceeded with special needle geometries, these recommendations are "safe" starting points.

Another factor that can cause solder paste to clog is the clearance between the auger pump screw and the cylinder wall. If the particle size is small, the particles can pass between the wall and screw thread without a problem. If the particles are large enough, they will be moved along the auger screw without incident. If the particle size is only slightly larger than the clearance between the thread and the wall, they can be deformed and can cause plugging in the needle. This is illustrated in figure 4. The natural tendency for making small deposits of solder paste is to go to smaller and smaller particle sizes. However, when the particle size is mismatched with the auger screw geometry, problems with plugging can occur. It is possible to dispense dots of solder less than 250 microns in diameter with type IV solder paste as illustrated in figure 5.

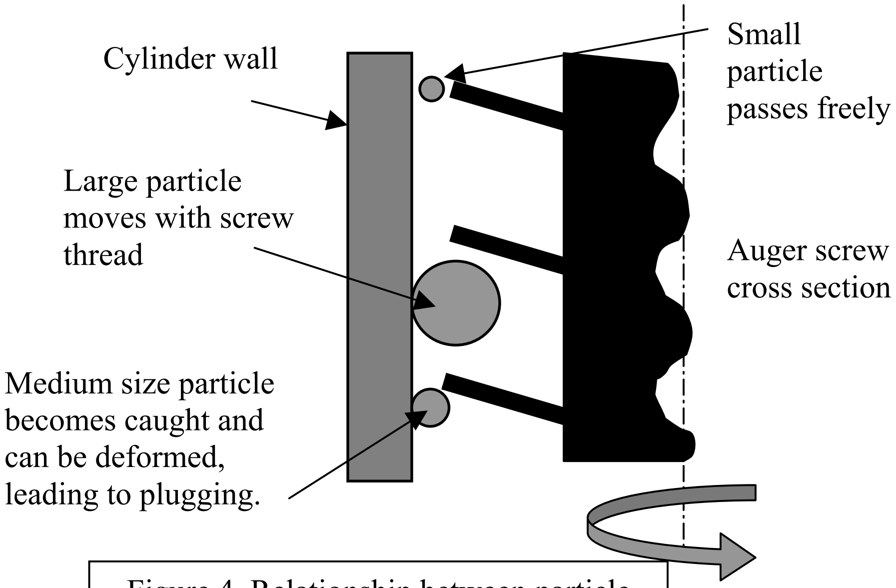

Figure 4. Relationship between particle size and screw geometry

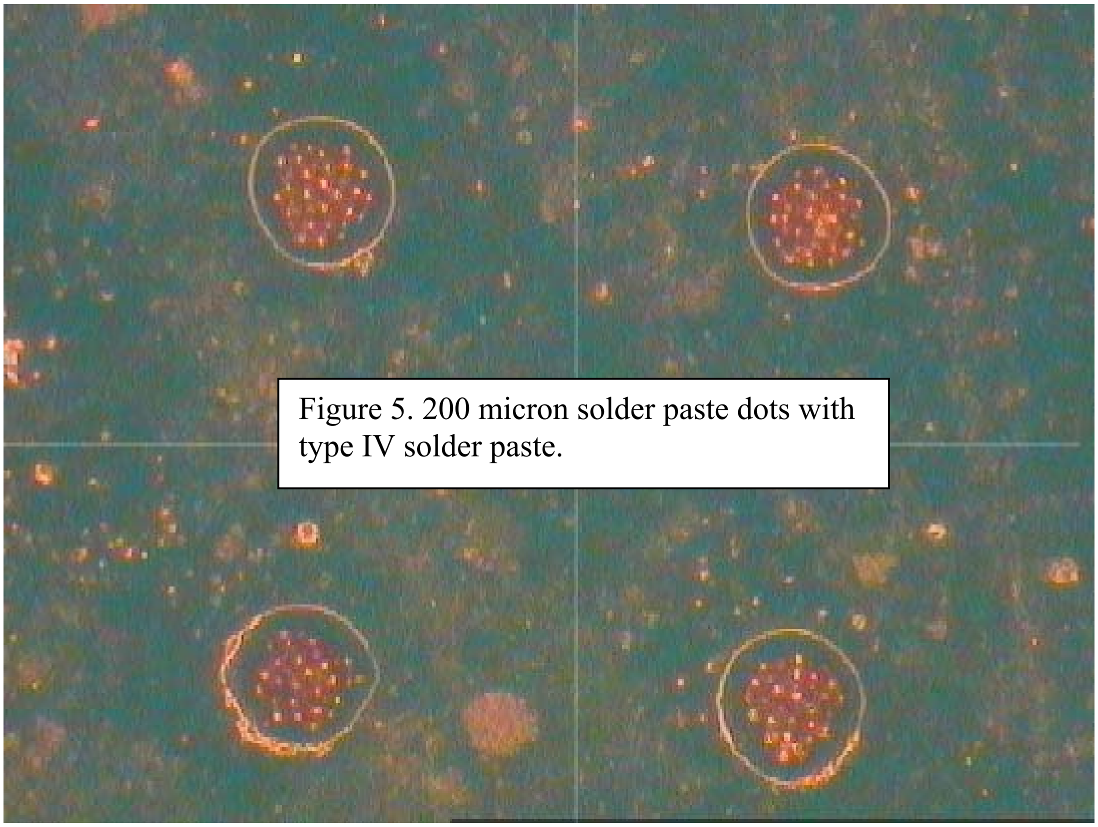

Figure 5. 200 micron solder paste dots with type IV solder paste.

The causes of these dispensing problems can often be linked to one another and often times take several hours to show up. Any process development or process change should be closely monitored to prove long term robustness. A good rule of thumb is to dispense at least 10,000 dots before evaluating the effect of any change.

Formulation of Solder Paste for Dispensing:

The manufacturers of solder paste often recommend formulations that are considered “dispensable grade”, meaning that the flux may be formulated to help lubricate the solder particles, keep them in suspension, and help prevent the solder dot from slumping. In some cases, manufacturers will pay particular attention to the distribution and shape of the solder paste particles to help the material flow. While these factors are important, the most important factor that the user can specify and control is the % metal content.

% metal content is the amount ratio of solder metal weight to the weight of the flux. This makes sense, as it is a convenient way to manufacture the paste. Specified weights of various components are added to the mixture that becomes solder paste.

The mistake that is most often made is not understanding the effect of changing the alloy of the metal and how this effects the dispensability for a given % metal content.

For solder paste to flow, it is important that there is enough flux to fill all the gaps between the solder paste particles. Assuming the solder paste particles to be uniform spheres stacked in a maximum density pyramid, the solder particles fill 74% of the volume, requiring 26% of the volume to be filled with flux. This structure, however, does not allow the material to flow. If the particles were stacked in a cube, allowing some flow, the particles occupy approximately 52% of the volume, requiring 48% flux by volume in the paste. In practice, however, the solder particles are not completely spherical and there is a distribution in the particle size. Empirical tests (see some references listed below) show that approximately 40% solder particles by volume works best in automated dispensing. Some sources list the minimum metal content by weight to be closer to 50% by volume.

In any case, whatever % metal content by volume is the right volume, the trick now, is to convert this % metal content by volume to % metal content by weight so that the paste can be specified from the manufacturer. It is the experience of the author that 40% metal content by volume works well and will be used for the remainder of the discussions.

To make this conversion, we first start by defining the density and volume of the various elements.

% metals by weight to % by volume:

Alloy density*	P_a
Flux density*	P_f
Paste density	P_p
Alloy volume	V_a
Flux volume	V_f
Paste volume	V_p
Weight fraction metals*	α

*Known

Next, we use the principles of conservation of mass and conservation of volume to define the relationships between these variables. The following 6 steps will allow us to compute the ratio of volume of metal to flux for a given paste.

1) $P_aV_a + P_fV_f = P_pV_p$ Conservation of Weight
2) $V_a + V_f = V_p$ Conservation of Volume
3) $P_aV_a/P_pV_p = \alpha$ Fraction of solids by weight
4) $P_p = P_fP_a/(P_f\alpha + P_a*(1-\alpha))$ Use 3) in 2) and solve for P_p
5) $P_aV_a/V_p + P_fV_f/V_p = P_p$ Solve 1) for P_p
6) $V_a/V_p = (P_p-P_f)/(P_a-P_f)$ Use 2) in 5) to eliminate V_p and solve for V_a/V_p

These relationships were used to create the chart shown in figure 6. Here, the relationship between metal content and alloy specific gravity is given for a flux specific gravity of 1 and a constant 40% metal content by volume. Above this line, there will be a higher likelihood of the the paste being too dry and it may plug. Below this line, there will be an increased tendency for the paste to slump and separate.

You can refer to table 1 to get the specific gravity of many common solder alloys. The important thing to note is that as the specific gravity of an alloy drops, the metal content by weight must drop. Why? Lower density material has more volume for a given weight.

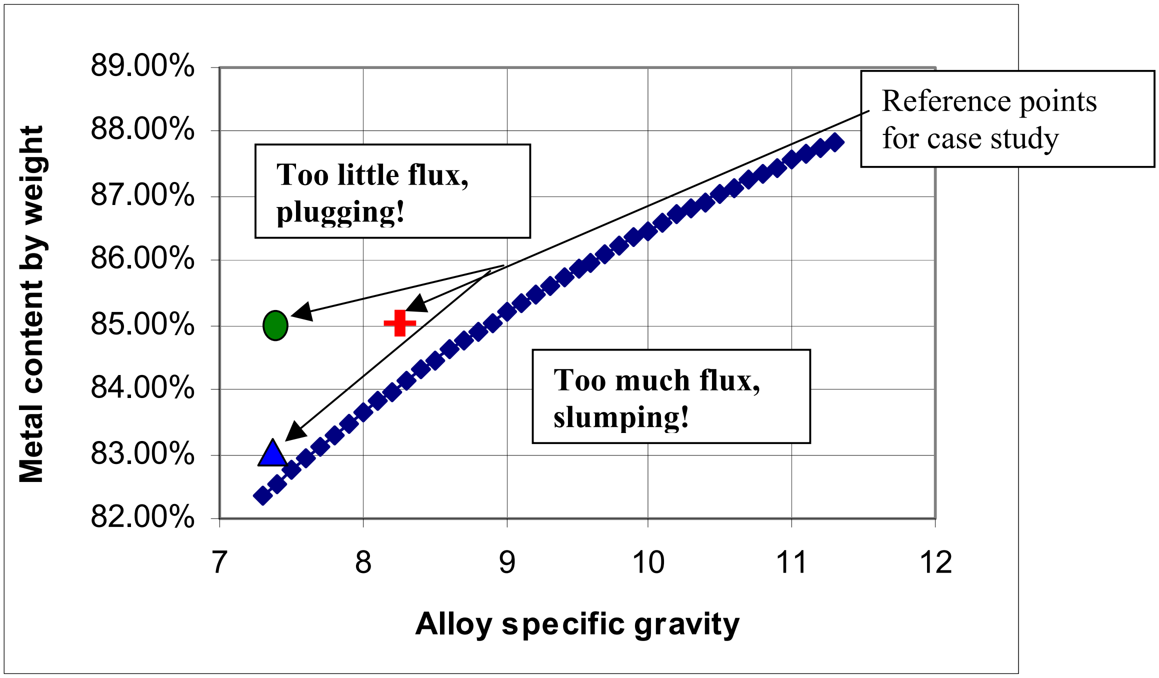

Figure 6. Chart showing the % metal content by weight for various solder alloys, assuming flux with specific gravity of 1 and 40% metal content by volume.

Effects of switching to a lead free alloy:

As shown in the previous section, the alloy of the solder metal is important to getting the correct mixture by weight. Lead, having a specific gravity of 11.3, is one of the highest density metals used in solder. Switching to a lead free alloy usually means replacing the lead with some other alloy of lower density. If this switch is made without adjusting the % metal content by weight, the paste will have too little flux (by volume) and this will most likely lead to dispensing problems, usually plugging of the paste in the pump or needle.

Example Case study:

The following example is a composite example of several real cases, however, the specific company names and material suppliers are confidential. In fact, very similar situations have occurred at multiple production facilities with a variety of suppliers of solder paste.

It is very typical for a production facility to use a standard Eutectic solder paste (37% lead, 63% tin). This solder has a low melting temperature, which is its primary attraction. Referring to chart 1, we find that this alloy has a specific gravity of 8.3. Typically, 85%

metal content will be used with this alloy. Referring to figure 6, this puts them slightly above the 40% volume line, but very close. This point is designated with a red “+” on the chart. There are companies that have years of experience running materials at this operating points.

The drive toward lead free solder is prompting production facilities to switch alloys. Most often, they stay with the same supplier of solder paste and same flux, but change to the alloy to something like 96.5% tin (Sn) and 3.5% silver (Ag). The resultant alloy has a specific gravity of approximately 7.4. This point is shown with a green dot on the chart in figure 6. Here, we see that the formulation is moving further away from the 40% volume line, making the paste more dry and prone to plugging. In fact, anyone following this path run into plugging problems in fewer than 1000 dots.

Applying the principles outlined in this paper, it has been suggested to that the formulation be adjusted to 83% metal content by weight to bring it closer to the 40% volume content. With this minor adjustment, the production line can be brought back on line with little further incident.

Conclusion:

There are many elements to successfully dispensing solder paste in a production environment that apply equally to both leaded and lead free solder alloys. Assuming that a production process has been set up to run a specific alloy containing lead, when this process is converted to a lead free alloy, it is very important to adjust the % metal content of the flux to keep the volumetric ratio of metal to flux constant and get similar dispensing results.

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