Indium Corporation Tech Paper

Best Practices Reflow Profiling for Lead-Free SMT Assembly

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ABSTRACT

The combination of higher lead-free process temperatures, smaller print deposits, and temperature restraints on electrical components has created difficult challenges in optimizing the reflow process. Not only are the electronic components and the PWB at risk, but the ability to achieve a robust solder joint becomes difficult, especially if the PCB is thermally massive. In addition, the constant miniaturization of electronic components, hence smaller solder paste deposits, may require the use of smaller particle-sized powders. Both the small solder paste deposits and small particle size result in a large surface area-to-volume ratio that challenges the solder paste's flux to effectively perform its fluxing action. The possible resulting surface oxidation can lead to voiding, graping, head-in-pillow, and other defects. Smaller components are also more susceptible to tombstoning and defects related to solder paste slump.

This paper is a summary of best practices in optimizing the reflow process to meet these challenges of higher reflow temperatures, smaller print deposits, decreased powder particle size, and their affect on the reflow process. It also discusses trouble-shooting of the most common defects in lead-free reflow, such as tombstoning, solder beading/balling, residue discoloration, voiding, graping, and head-in-pillow.

Key words: solder defects, reflow profile, tombstone, solder beads, solder balls, voids, head-in-pillow, graping.

INTRODUCTION

The introduction of higher lead-free process temperatures and a reduction in solder paste deposit volumes require narrower process windows to optimize the reflow profile. Not only are the electronics components and the PWB at risk due to the higher reflow temperatures associated with lead-free processes, the components themselves can restrict the peak temperature that the process can use, making it difficult to achieve a robust solder joint, especially if the PCB is thermally massive. Decreased pad size might also require the solder paste to have solder powder with smaller particle diameters. Both the small solder paste deposits and smaller particle size result in a large surface area-to-volume ratio

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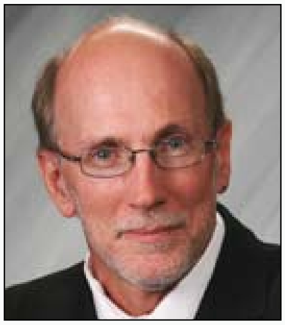

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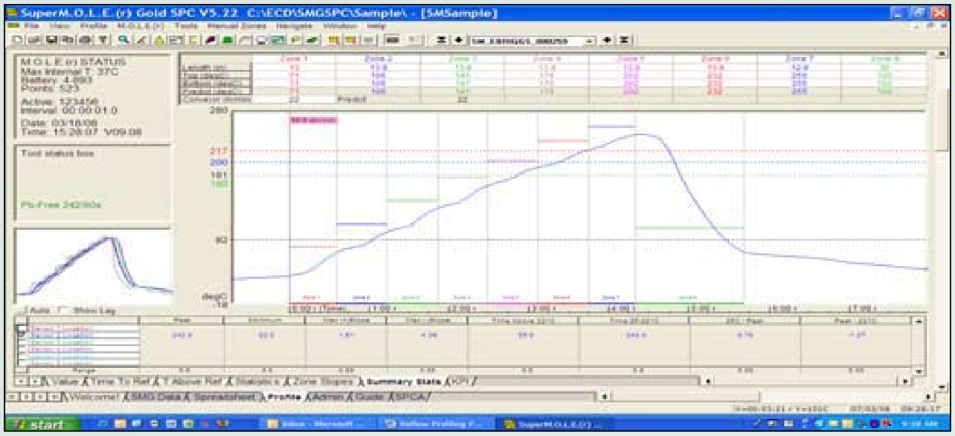

Figure 1 - Ramp-to-peak reflow profile.

Figure 2 - Ramp/soak/spike reflow profile.

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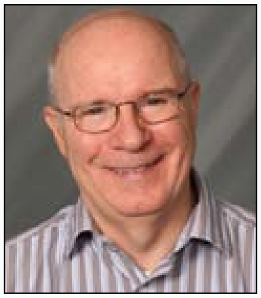

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that challenges the solder paste's flux to effectively perform its fluxing action. The resulting surface oxide can lead to a number of solder defects such as voiding, beading/balling, graping, and head-in-pillow. This paper will discuss techniques to optimize the reflow profile to minimize such defects.

Types of Profiles

The two most common types of reflow profiles are the ramp-to-peak profile, also called ramp-to-spike or tent profile (see Figure 1) and the soak profile, or ramp/soak/spike profile (see Figure 2). A ramp-to-peak profile is a linear ramp to the peak (max) temperature. A soak profile displays some "plateau" within a limited temperature range, before the alloy reflows.

Profile Stages

The SMT reflow profile can be broken down into 4 phases or regions: preheat, pre-reflow, reflow, and cooling.

Preheat

The preheat phase preconditions the PCB assembly prior to actual reflow, removing flux volatiles and reducing thermal shock to the PCB assembly.

The ramp rate is the slope of temperature versus time for the heating portion of the reflow profile. It originates at ambient temperature and ends at the peak temperature. The rate is defined primarily in the preheat phase. A ramp rate of 0.5 – 2.0°C/second is normal and is largely affected by the reflow oven belt speed and the Δ-T (delta-T) between heating zones (ΔT of <40°C is recommended between heating zones). Typically the instantaneous ramp rate will vary as seen in Figure 3. Hence, the maximum ramp rate of 1.61ºC/second, reported in Figure 3, is somewhat meaningless. Most important is the average ramp rate, which is 0.78ºC/second.

Pre-reflow

At the pre-reflow phase, the flux activator (or activator package) removes any existing surface oxide from the component leads and PWB pad finishes, as well as any oxide on the powder particles within the solder paste itself, preparing the surfaces to be joined during reflow.

A temperature "soak," if incorporated, is normally found in this phase. The soak temperature is controlled within a

Figure 3 - Note that the maximum slope (1.61°C/second) does not equate to the average ramp rate (0.78°C/second).

tight range (see Figure 2) for a specified time. This "plateau" in the reflow profile allows the thermal gradient across the PCB to equilibrate prior to reflow. In this way, the entire assembly sees nearly the same reflow conditions (peak temperature and time-above-liquidus) to form consistent solder bonds. Any potential thermal gradient increases as the physical size of the PCB and the diversity of component size increase, so for such large PCBs a soak profile is usually helpful to achieve successful assembly.

Soak profiles are also used to minimize voiding when assembling such components as BGA (ball grid array), LGA (land grid array), SGA (solder grid array), and QFN (quad flat pack, no leads), purging the solder paste of volatile materials, decreasing flux out-gassing, and diminishing the amount/size of voids entrapped in the solder joint upon cooling.

Reflow

The actual reflow of the solder alloy involves the creation of a mechanical and electrical bond through the formation of tin-copper intermetallics.

In forming optimum intermetallics, two critical parameters are involved in the reflow phase: peak temperature and TAL (time-above-liquidus). The peak temperature is generally 20-30°C above the liquidus temperature of the alloy and the TAL is typically 30-90 seconds in order to form effective intermetallics.

Cooling

The cooling phase determines the grain structure of the solder joint. A fine grain structure provides the most reliable mechanical bond. To achieve this structure, a rapid cooling rate as the solder transitions from liquid (liquidus) to solid (solidus) is needed (the first ~50°C of cooling). The limiting factor for the maximum cooling rate is the stress that is exerted on the solder joint if the rate is too fast. This thermal stress, depending on the differences in CTE (coefficient of thermal expansion) of the joining surfaces, can fracture or tear the solder joint. The greater the difference in CTE of the joining materials and the cooling rate, the greater the thermal stress generated. A cooling rate of ~4°C/second is normal. Unfortunately, many ovens lack controls for the cooling zone(s). One method to overcome this is to use the last heating zone(s), if the oven is large enough.

Water-Soluble vs. No-Clean Solder Pastes

At this point, it may be worth discussing the fact that there are distinct differences between water-soluble and no-clean solder paste chemistries and their sensitivity to a soak or a long (total time in oven) type profile. For both types of solder paste, the activator portion of the flux chemistry removes existing surface oxides on the mating surfaces, as well as the powder particles within the solder paste itself. Once removed, other flux chemistry constituents must protect the surfaces from re-oxidation. No-clean chemistries are generally rosin/resin-based materials. Rosins/resins make excellent oxide barriers and protect the "cleaned" surfaces during reflow from re-oxidation. Water-soluble fluxes, on the other hand, contain high molecular weight compounds, such as polymers, which are not as effective as rosins/resins at preventing re-oxidation. Therefore, water-soluble chemistries do not hold up well in elongated reflow profiles, such as soak profiles. If such profiles are used with a water-soluble solder paste, defects such as de-wetting can occur.

Powder Particle Size

Particle size also affects the sensitivity of the solder paste to the reflow profile. As the particle size decreases, the overall area of the surface exposed to oxidation increases. Increased surface oxide challenges the solder paste flux. Under these circumstances, a soak profile especially challenges the capability of the flux to provide an acceptable solder joint.

Troubleshooting

The focus of this paper is the effect of reflow profiling on solder defects. Very often there are more effective and efficient methods of resolving solder defects than optimizing the reflow profile. For instance, it is widely accepted that 60-70% of all solder defects can be traced back to the printer.

With that said, there are certainly instances where fine tuning the reflow profile will benefit. Also note that changing the reflow profile can cause other solder defects.

Figure 4 - An example of tombstoning.

Tombstoning

Tombstoning defects are due to unbalanced wetting forces, generally found when assembling passive components (see Figure 4). In understanding the mechanism for tombstoning, we need to know that there are three forces at work: the weight of chip, the surface tension under the chip, and the surface tension on the side of the chip. From a reflow perspective, unbalanced surface tension, which can result in tombstoning, can be caused by uneven heating, e.g. ground plane or trace, or shadowing from large adjacent components.

To reduce tombstoning, the goal is to minimize the thermal gradient between pads prior to reflow. Minimizing the thermal gradient can be accomplished by slowing the ramp rate from ambient to peak, allowing the PWB assembly to gradually/evenly rise in temperature, or instituting a small soak (often referred to as a shoulder soak) just below the melting temperature of the alloy.

Solder balling/beading

Solder beading occurs when isolated solder paste aggregates are formed under low stand-off components. At reflow, the aggregate melts and emerges from the underside of the component, separate from the solder mass/joint.

Solder balling occurs if the solder paste spatters (small "explosions") during reflow, or if the paste slumps and the flux spreads, carrying away solder particles which cannot reflow back into the solder mass.

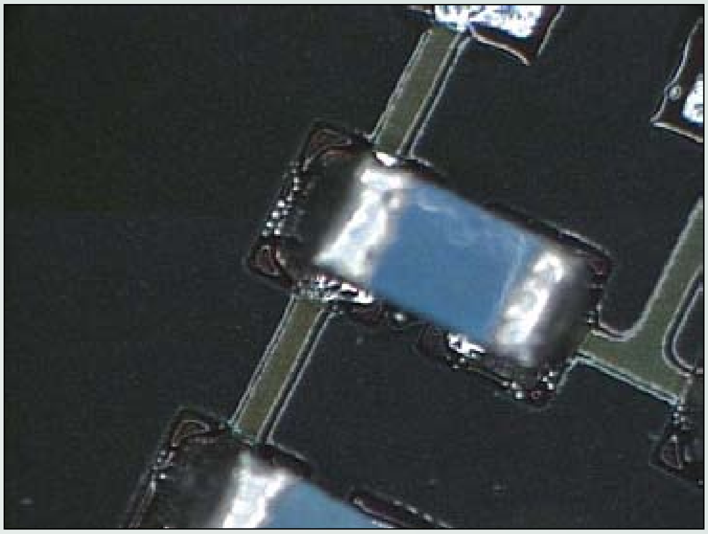

Figure 5 - Solder balling/beading.

A maximum ramp rate from ambient to peak of 1-1.5°C/second is recommended. If the solder paste is heated too quickly, solvents in the flux chemistry vaporize violently creating small explosions, leaving solder balls or paste aggregates (solder beads) isolated from the solder mass with no ability to return to the solder joint. If the ramp rate is too slow, the flux can "run away" (spread out excessively) from the solder paste mass carrying solder particles along with it. A slow ramp rate also increases the oxidation of the solder powder particles inhibiting the coalescence of these oxidized particles.

Residue Discoloration

Residue color is affected by temperature. The higher the peak temperature, the longer the TAL, or the longer the total reflow time, the darker the post reflow flux residue. Since the high tin-containing lead-free solders require higher process temperatures, this concern is more notable in lead-free assemblies. Multiple reflows will also darken the residue. If the assembly is to be cleaned, this can also result in a more difficult residue to remove.

Because the flux residue is affected by temperature, a reflow profile with a shorter TAL, lower peak temperature, faster ramp rate, and no soak provides the best results.

Voiding

Voiding occurs in components such as BGA, SGA, QFN, and LGA and increases with the higher reflow temperatures and greater surface tension associated with the high tin-containing lead-free alloys. Mixed assemblies using a combination of tin-lead and lead-free alloys typically generate more voiding than a totally lead-free assembly, and certainly more so than a totally SnPb assembly.

Pad designs, which include via/micro-via or pads designed for smaller components, such as 01005 and 0.4mm pitch BGAs, increase voiding even further. Smaller pad sizes may require smaller diameter particle solder powders. As powder particle size decreases, the surface area and overall surface oxide increase, demanding more fluxing activity (out-gassing) from the flux chemistry, which results in more voids.

Voiding is affected by the ability of the flux chemistry to effectively (how quickly and how completely) remove surface oxides. It is also affected by flux chemistry out-gassing. The flux solvent is generally vaporized prior to reflow leaving the flux remnant. As the solvent volatizes, the viscosity of the flux remnant increases, making the residue less mobile or difficult to be excluded from the interior of the molten solder[1]. The flux remnant for no-clean chemistries is comprised mostly of rosin/resin.

In the reflow process, a longer profile, longer TAL, and higher peak temperature will produce a less mobile (higher viscosity) flux remnant and greater flux out-gassing rate; however, it also decreases the surface tension of the molten solder.

Conversely, a shorter profile, a shorter TAL, and a lower peak temperature results in a more mobile flux remnant. This slows the out-gassing rate, but also increases the molten solder surface tension. Because of these tradeoffs, there have been mixed results as to which provides the best results. This is because surface finish, pad design (e.g. microvia in pad), can provide different results.

Soak profiles designed to reduce voiding in lead-free assemblies are less effective than soak profiles with SnPb chemistries, perhaps due to the higher peak temperature and higher surface tension of the high Sn-containing alloys. Also, many lead-free flux chemistries contain more rosin/resin in order to provide greater oxidative barriers to compensate for these higher temperatures. Therefore, it is higher in viscosity with more flux remnant. This situation makes reducing voids more difficult. Suppliers' data sheets provide the recommended soak range and length of time based on flux chemistry and the melting temperature of the alloy.

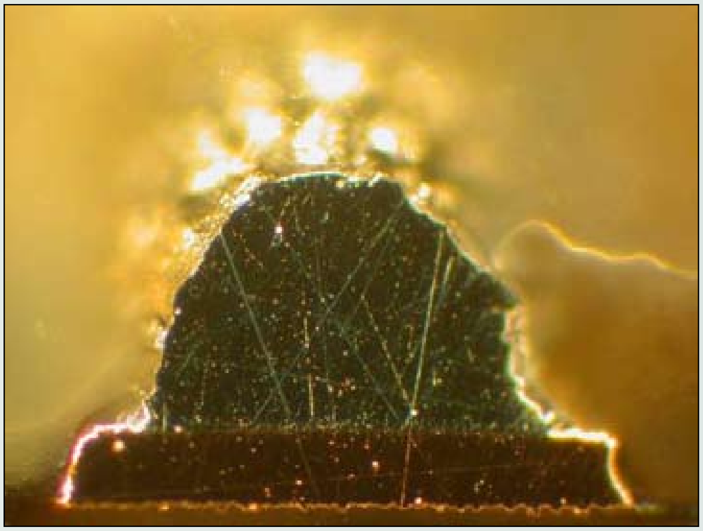

Figure 6 - An example of graping.

Graping

Graping is a phenomenon which appears as un-reflowed solder particles atop the solder mass (see Figure 6). The occurrence of graping has increased due to higher lead-free reflow temperatures, decreased volume of the printed paste deposit, and finer particle size of the powder for the solder pastes required. The combination of these factors puts a lot of "pressure" on the solder paste flux to remove surface oxides. In addition, during the reflow process the flux can "run-away" from the solder powder particles, spreading and pooling around the deposit. The exposed powder particles then become oxidized and with no flux to protect or remove the oxides, these particles do not coalesce into the solder joint.

With the smaller print deposit, the surface area exposed to the reflow oven environment increases in relation to the total amount of solder paste deposited. This decreasing ratio of flux to powder means there is less flux available to remove oxides from the joining surfaces and the solder powder particles within the solder paste itself. This situation can lead to graping.

Graping is much less prevalent in solder mask defined pads, which confines the amount of flux spreading that can occur. Also, resistors are more prone than capacitors to graping. The low stand-off of the resistor can promote the "wicking" away of the flux from the solder particles.

A reflow profile with a slow ramp rate (<1°C/second) can aggravate the graping phenomena. For every degree the temperature increases, the viscosity of the flux decreases. A slow ramp rate allows more time for the solder flux to "run away" from the solder powder particles, forming a larger pool and spreading out at the base of the solder deposit. This exposes the top/outer particles to the oven environment, easily oxidizing them. Increasing the ramp rate (1-1.5°C/second) allows the flux solvent to volatize quickly, increasing the flux viscosity and lowering its ability to "run-away".

Figure 7 - An example of "head-in-pillow" defect.

Head-in-Pillow

Therefore, a ramp-to-peak (RTP) profile with little or no soak, a slow ramp rate of 1-1.5°C/second, and low peak temperature (this may mean extending the TAL slightly) will provide best results.

Head-in-pillow (HiP), a defect seen in BGA components, occurs when the solder sphere on the BGA loses contact with the solder paste and oxidizes during the heating process. This oxidation prevents the solder sphere and solder paste from coalescing (see figure 7). Contributing factors are warping of the BGA component during reflow, co-planarity, poor wetting, excessive oxidation, differences in solder paste and solder sphere alloys, or paste slump. Poor solder paste transfer or insufficient paste deposit volume during the printing process and poor placement can also contribute to HiP.

Conclusion

The required higher peak temperature and higher surface tension of the high Sn-containing lead-free solders, accompanied by the smaller pad size and smaller powder particle size associated with fine feature stencil printing, impose a tremendous impact on the ability of the solder paste flux to provide a good solder joint. Therefore, some understanding of the reflow profile is useful in determining the best method(s) for optimizing the reflow process in these challenging conditions. Very often defects can be traced back to other more important parameters, independent of the reflow process that will have a much more dramatic impact on the solder defect. However, adjustments to the reflow profile can help optimize the process.

To minimize HiP, develop a reflow profile that diminishes oxidation of the joining materials. In addition, a reflow profile that doesn't exhaust the flux chemistry and decreases solder paste slump will also help to minimize HiP. Other process parameters that minimize HiP are: a slow temperature ramp rate, low peak temperature, reduced thermal shock to the component, and minimizing deformation/warping of the PCB or component. If the ramp rate is too slow (<1°C/second), it can increase oxidation of the joining surfaces and also aggravate defects, such as graping. However, a slower ramp rate can help minimize paste slump.

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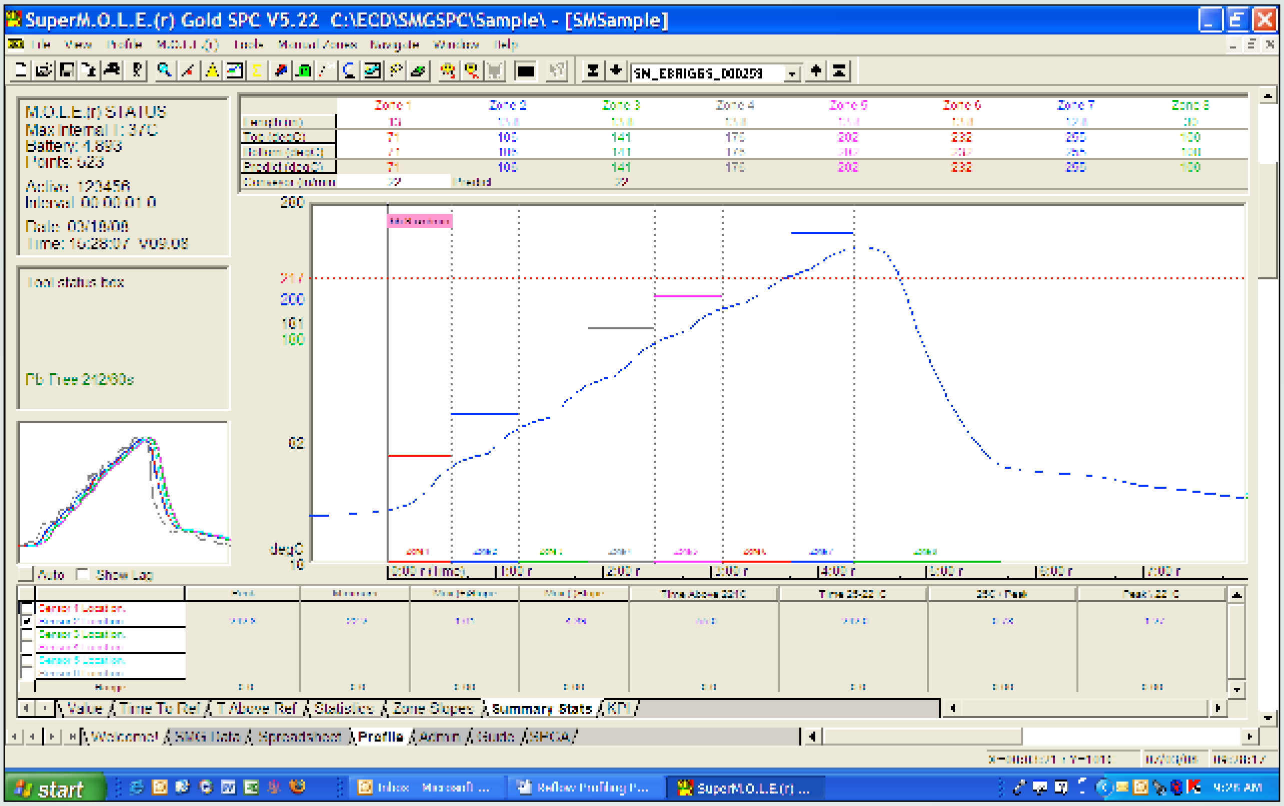

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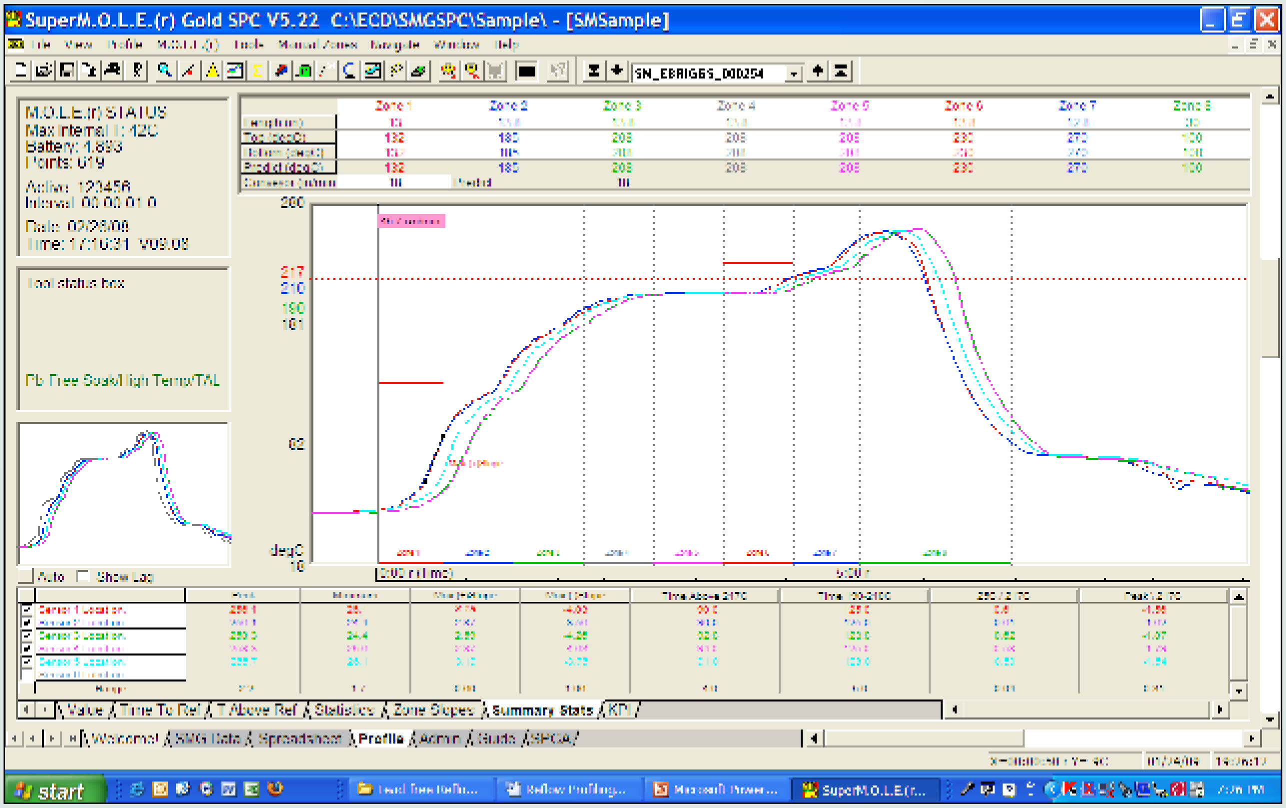

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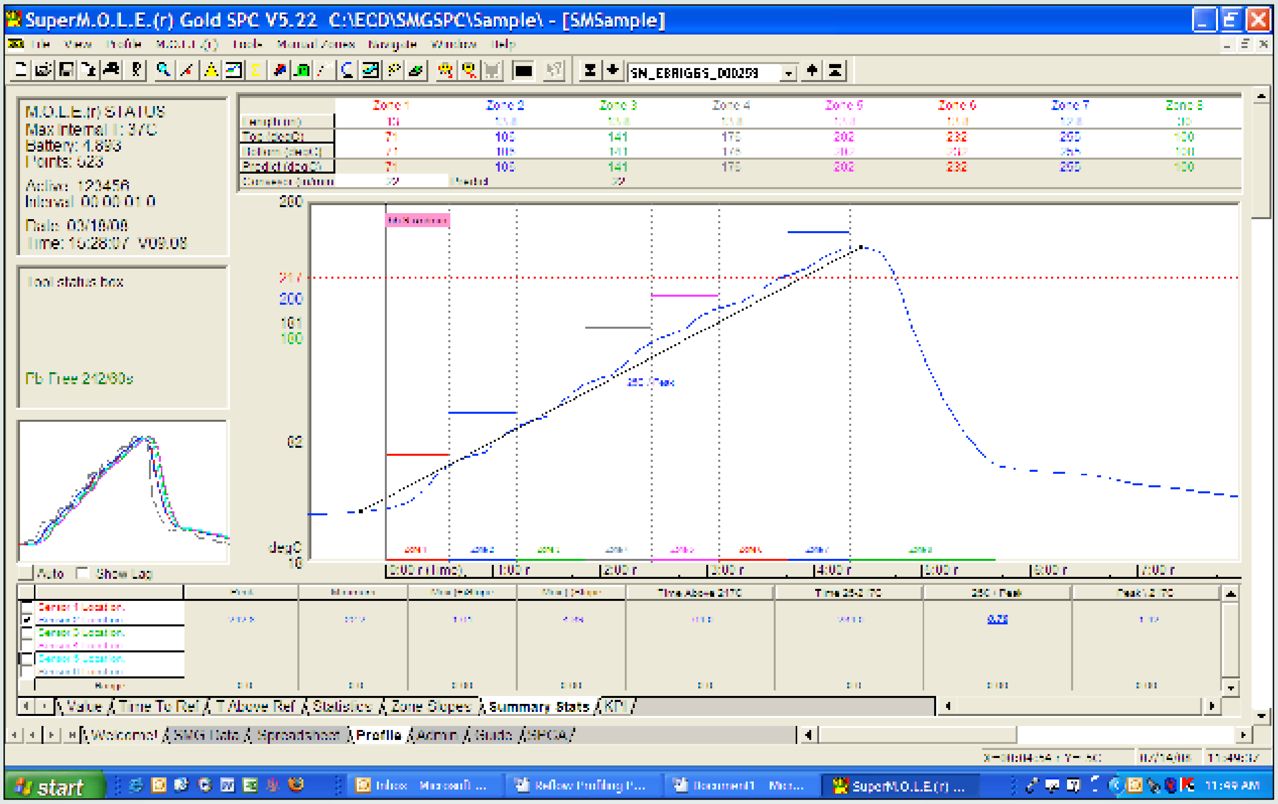
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Figure 3.