Optimizing Your Reflow Profile for Maximum Productivity and Profitability

Bjorn Dahle and Ronald C. Lasky, Ph.D., PE
Indium Corp.
Medway, MA

Introduction
Successful reflow soldering is a key to productivity and profitability, yet many assemblers may be using a nonoptimized reflow profile.

Years ago, when IR ovens were the norm and solder pastes were relatively unsophisticated, initial reflow profiles were developed (Figure 1). These profiles were called "*ramp to dwell – ramp to peak*." Since then, IR technology has bowed to the superior capabilities of convection technology, with its dramatically different heating mechanisms. Additionally, solder paste formulation technology has evolved significantly in the same time.

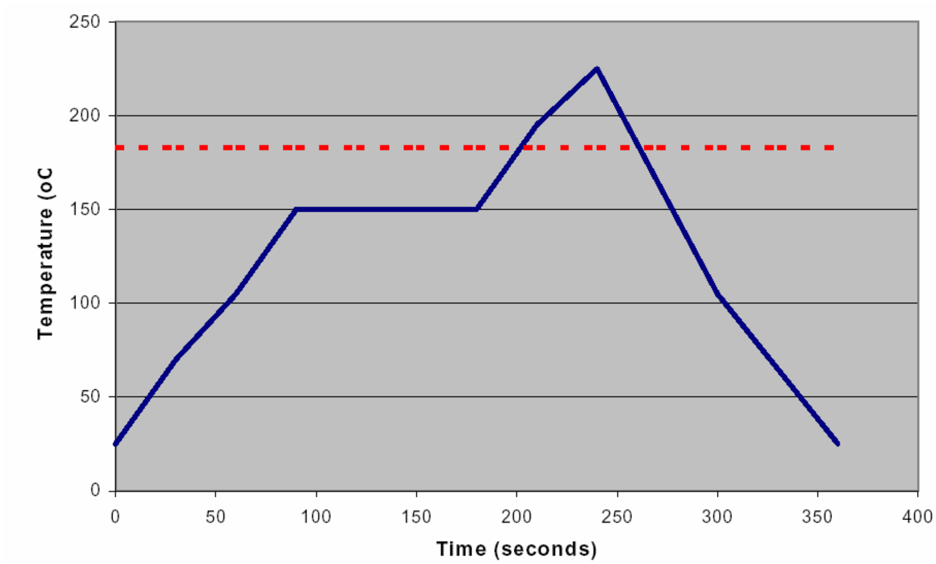

Figure 1 - The "Ramp to Dwell-Ramp to Peak" Reflow Profile that was Initially Developed for IR Reflow Ovens

Recent work by Lee[1] indicates that these IR reflow profiles are not optimum for convection ovens and modern solder pastes. Through the analysis of defect mechanisms, his work reveals that a gentle ramp to about 175°C, and a very gradual rise above liquidus, followed by a ramp to a peak temperature of 215°C will result in the highest yields. An example of the "Lee Profile" is shown in Figure 2. When one considers that almost all ovens used in SMT assembly are convection ovens, this distinction in reflow profiles is very significant.

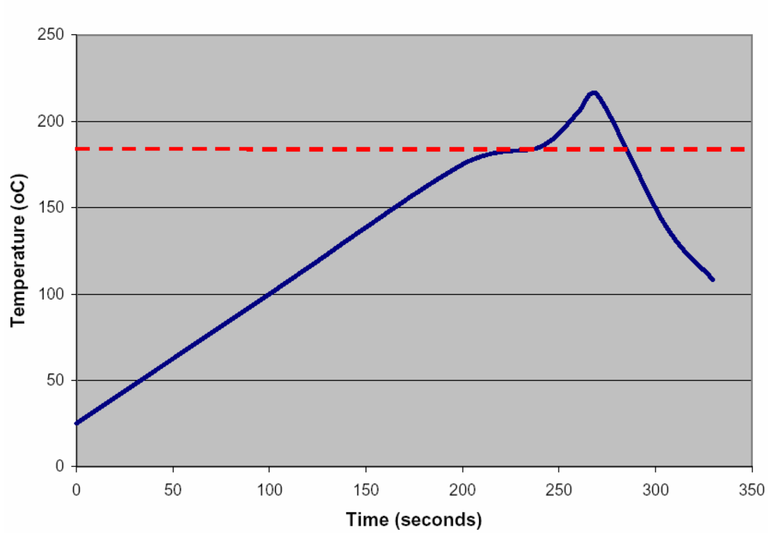

Figure 2 - The Optimized "Lee" Reflow Profile

In order for a reflow oven to achieve the Lee profile, the user must select the appropriate oven setups. Since a modern reflow oven is designed to support literally hundreds of millions of different setups, modern process setup tools are needed to identify the best combination of zone temperatures and conveyor speed. This process optimization needs to take place quickly in order to minimize production downtime. This paper will discuss the tools and techniques available to help you achieve process optimization via reflow profile improvements. Initially, however it will review the analysis that resulted in the Lee Profile.

The Science behind the Lee Profile

As mentioned earlier, the ramp to dwell ramp to peek (RDRP) profile was developed for infra-red (IR) reflow ovens. This technology tends to heat unevenly and in some respects more slowly than convection ovens. Consequently the dwell, usually at 140 to 160°C, was developed to assure as even as possible heating with IR technology in the solvent evaporation and flux activation stages of the reflow process. The ramp to peak was then employed to minimize the time above liquidus (TAL) and the possibility of singeing components. When IR technology was deployed, 0402 passives, ultra-fine pitched PQFPs, BGAs, CSPs, and other "high tech" components were far in the future. Unfortunately, each of these now dominant technologies has a problem with the RDRP profile. Many of the failure mechanisms, common today with these components, can be traced to the use of the RDRP profile.

Tombstoning

Tombstoning is a phenomenon in which uneven melting of the solder paste causes the surface tension of the melted solder to lift the passive as shown in Figure 3.

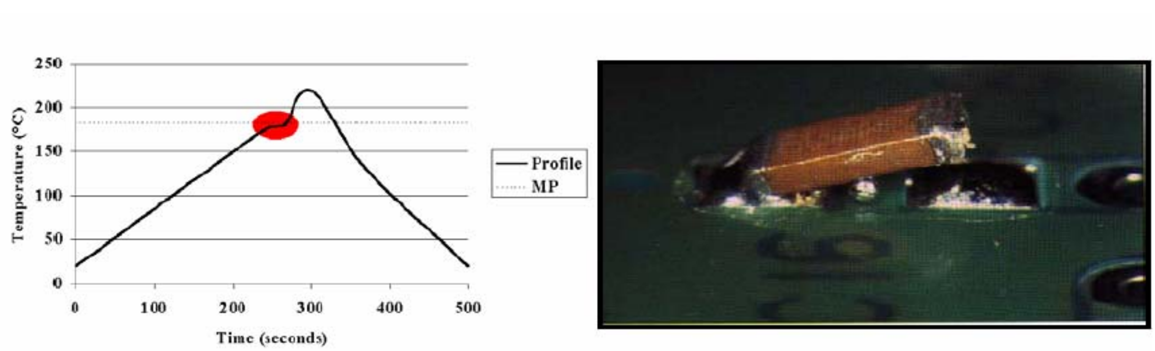

Figure 3 - The Uneven Melting Caused by the RDPR Profile can Produce Tombstones. The Lee Profile has a Brief Dwell as the Oven Passes Through the Melting Point of the Solder to Minimize this Failure Mode

This failure mode is almost unavoidable with RDPR. As the RDPR profile goes from the soak temperature of 140 to 160°C, it shoots straight up to the peak reflow temperature. This fast temperature rise from below to above liquidus will often cause the solder paste at one end of a passive to melt before the paste at the other end. The surface tension of the melted solder will cause the passive to tombstone. The Lee Profile minimizes tombstoning by establishing a brief dwell as the profile goes through liquidus. This dwell allows for more even temperatures as solder paste at the component leads goes through liquidus. This profile melts the solder paste at both ends of the passive simultaneously, hence minimizing tombstoning.

Wicking

Wicking occurs when the leads of the components become significantly hotter than the PWB pads during reflow. Since solder flows to where the temperature is highest, opens can result as seen in Figure 4.

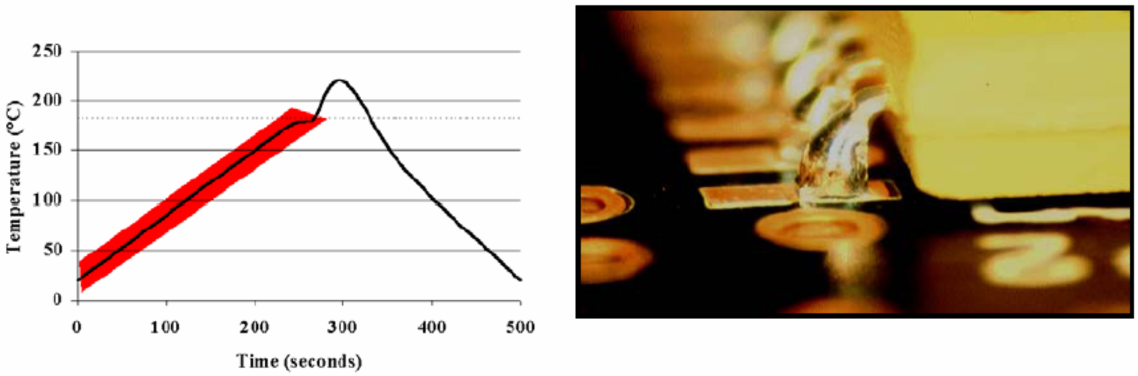

Figure 4 - If the Component Leads become much Hotter than the Pads, Wicking can Result Causing Opens

The RDRP profile typically ramps from 1-2°C/s from its dwell. This high ramp rate and the lack of a dwell at liquidus can result in the leads being much hotter than the pads. Wicking will then often follow. The Lee Profile's more gentile heating rate of 0.5 to 1.0°C and a brief dwell at liquidus help to minimize such wicking.

Solder Balling

Solder balling is an all too common phenomenon today. The RDRP profile is often the culprit. Its rapid ramp rate can cause the solvents to escape so rapidly that spattering of the paste occurs. In addition the long time at a relatively high dwell temperature can result in oxidation. The combination of these two mechanisms can create solder balling. The spattering disperses the solder paste and the oxidation prevents coalescence of the melted solder into the solder joint. The Lee Profile's gentler ramp rate minimizes spattering and the lack of a long dwell reduces oxidation. Therefore, the Lee Profile has a strong tendency to minimize solder balling. (See Figure 5.)

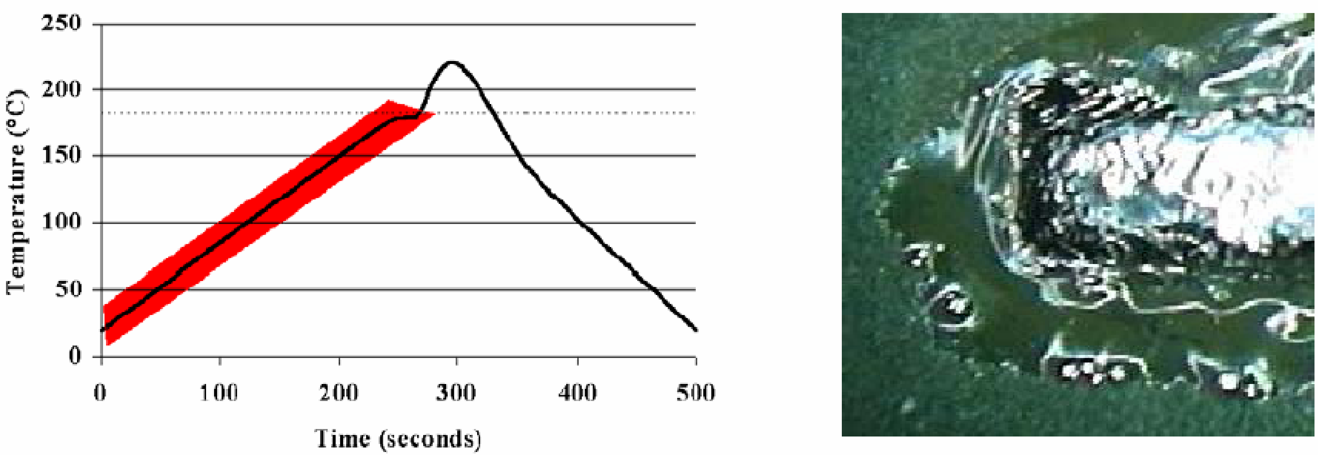

Figure 5 - The Gentle Ramp Rate and Lack of a Long Dwell, Tends to Minimize Soldering Balling in the Lee Profile

Hot Slumping – Bridging

Hot slumping occurs when the solder paste is at too high a temperature for too long a time. Hot slumping can lead to solder bridging. The long dwell of the RDRP profile can result in hot slump. The gentle ramp of the Lee Profile minimizes this failure mode as the solder paste is exposed to high temperatures for a shorter time. (See Figure 6.)

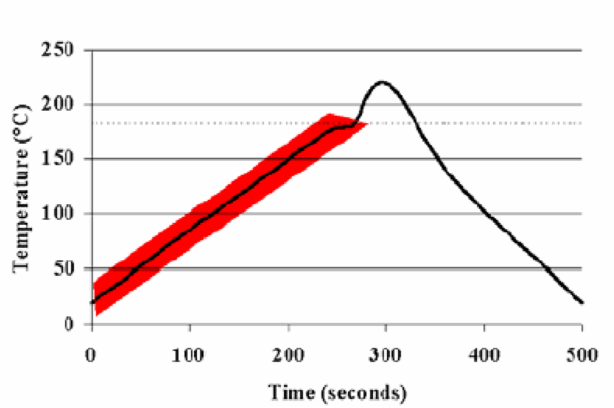

Figure 6 -The Long Dwell at High Temperature can cause Hot Slumping or Even Bridging in Reflow - The gentle Ramp of the Lee Profile Minimizes this Effect

Poor Wetting

The RDRP profile can expose the solder paste and leads and pads to excessive temperature and time. This can cause oxidation which results in poor wetting. The Lee Profile minimizes the time at high temperatures, reducing the chance of excessive oxidation, making good wetting more likely. (See Figure 7.)

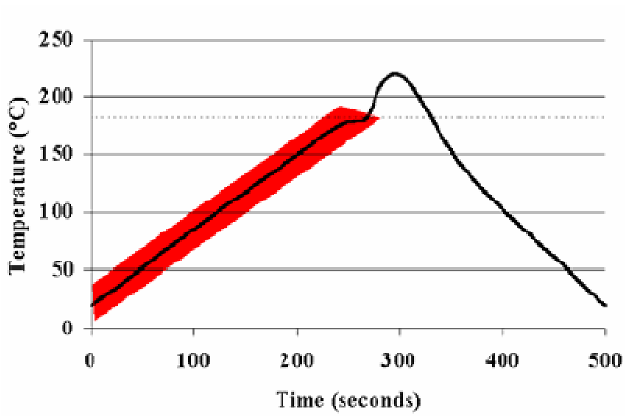

Figure 7 - Poor Wetting can be the Result of Exposure to High Temperature for Excessive Time

Voiding

The combination of oxidation and the flux remnant being too viscous can result in voids. A viscous flux remnant is not able to move through the molten solder an escape through the surface. The longer times at high temperatures that the RDRP profile provides can cause oxidation, as previously discussed. However, this profile can also drive off too much solvent and leave a viscous flux remnant. The shorter time at higher temperatures, provided by the Lee Profile, minimizes the oxidation and leaves the flux remnant fluid enough to flow to the surface of the molten solder, minimizing void formation. (See Figure 8.)

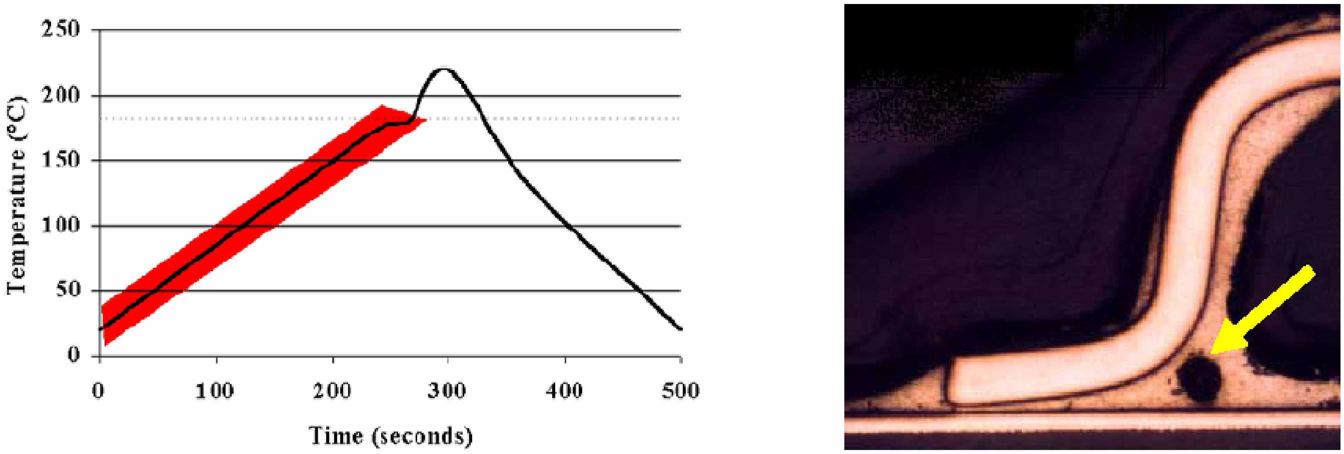

Figure 8 - The Shorter Time at Higher Temperatures in the Lee Profile, Minimizes Oxidation and Leaves a fluid Flux remnant, thus Minimizing Voiding

Excessive Peek Temperature & Time Defects

Peek temperatures that are too high can result in charring of components. The combination of high peek temperature or excessive time above liquidus (TAL) can also create intermetallics that are too thick, resulting in reliability concerns. The Lee Profile recommends an absolute peak temperature of 228°C, but encourages the user to strive for 215°C as a target peak temperature. The Lee Profile minimum TAL can be as short as 30 seconds. Some RPRD profiles suggest peak temperatures of 235°C and minimum TALs of 45 seconds. These types of profiles can cause charring of components or form intermetallics that are too thick. (See Figure 9.)

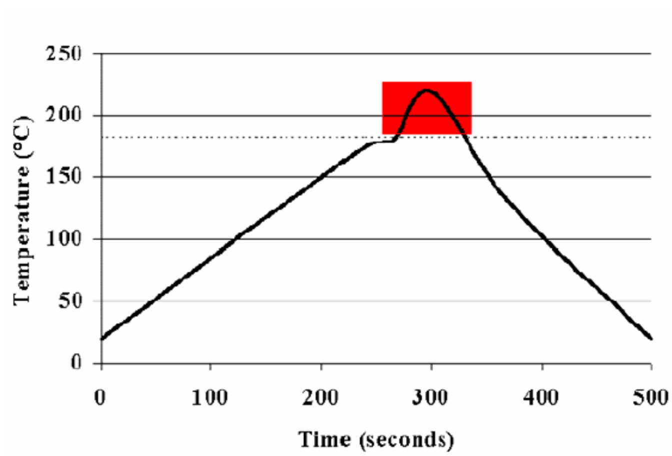

Figure 9 - The TAL and Peak Temperatures should be such as to Minimize Damage to Components and the Creation of Intermetallics that are too Thick

Tools to Verify and Control the Lee Profile

To achieve the higher yields described above, it is not sufficient to simply select any oven recipe that provides an inspec profile. A smaller subset of oven recipes, those that yield a profile that conforms to Lee profile specifications, needs to be identified. For example:

- From room temperature, ramp at 0.5-1.0°C/s to 175 +/- 3
- Ramp at <0.25°C through 183° but for less than 45 seconds
- Ramp to peak (target 215°, range 208°-228°) with TAL 30-90 seconds
- Ramp down 2-4°C/s.

While this is clearly more challenging and time consuming than using a conventional "trial and error" approach to oven set-up, there are currently new software driven technologies that make this easy and fast. Such technologies typically take the form of a "***recipe search engine***" approach.

Recipe Search Engine

A modern reflow oven typically has between 5 and 12 independently controlled temperature zones. The conveyor speed represents yet another variable. Since each of these variables can operate in a wide range, the technician is faced with literally billions of alternative oven setups. Only a small percentage of the possible oven setups will yield an in-spec process, and only a fraction of those setups will conform to the Lee specification. (See Figures 10-13.)

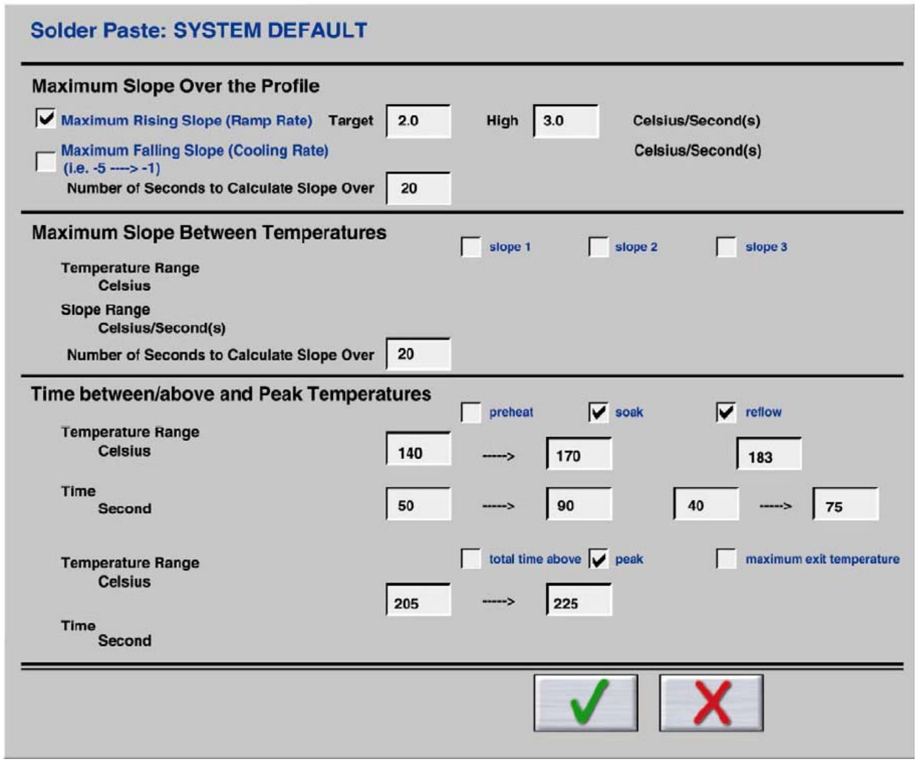

Figure 10 - "Recipe Search Engine" with a Typical 63/67 Solder Paste Process Window Specification

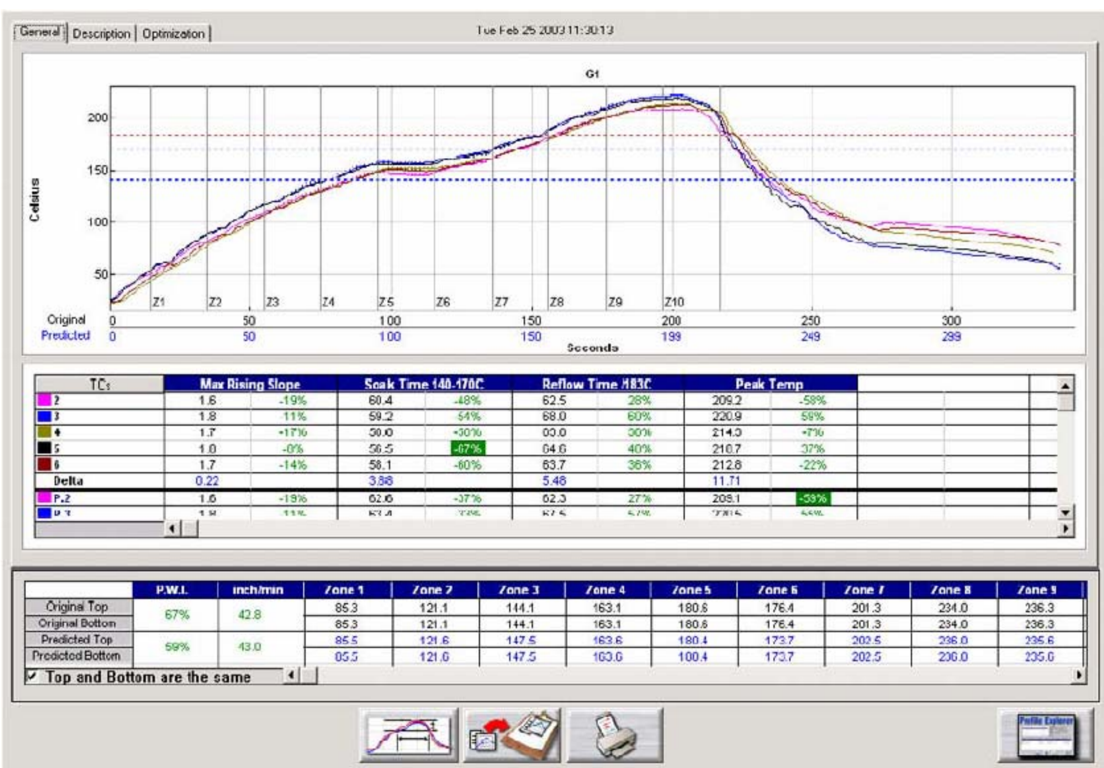

Figure 11 - A Typical 63/37 Solder Paste Profile Optimized by an "Oven Recipe Search Engine"

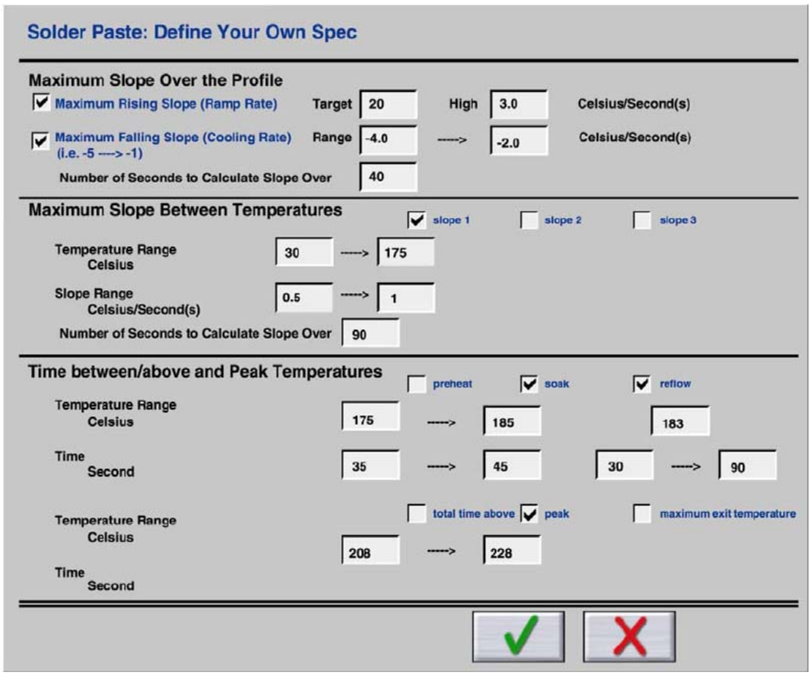

Figure 12 - The Lee Profile Process Window Specifications

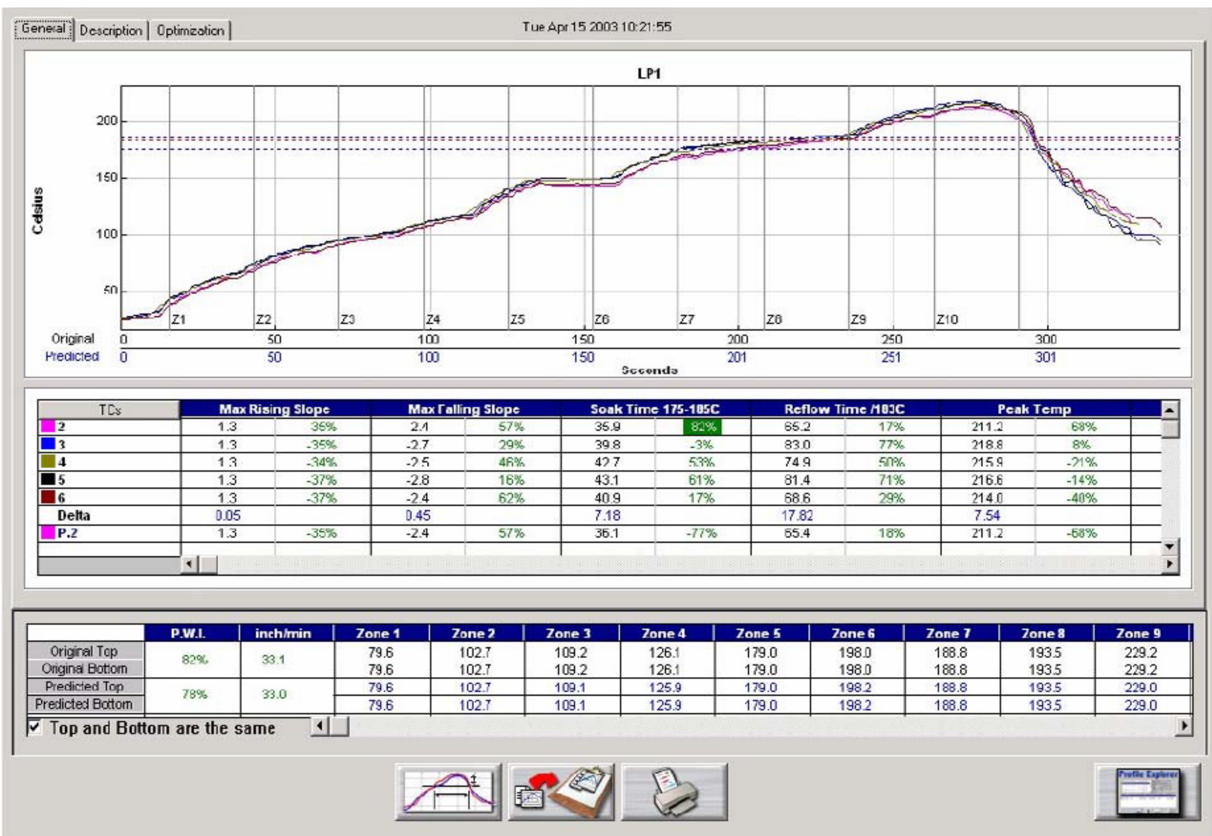

Figure 13 - The Same Product that was Previously Optimized for a Typical Process Window (in Figure 11) is Shown Optimized for the Lee Process Window

A recipe search engine works in the following manner:

The Lee profile specifications are entered to define the required process window. The technician runs a profile to measure the time versus temperature on the relevant PCB or part in the current oven setup. The software now has information on the relationship between the oven settings and the resulting profile. An automatic computer simulation routine is then initiated. The software makes a small incremental change in one of the variables (an individual zone temperature or conveyor speed), simulates the new profile that would result from such a new oven setup, and determines how well this profile fits the Lee process specifications. This "fit" is mathematically calculated using the Process Window Index (PWI) concept. The PWI assigns a single number which represents each profile's fit to the process specifications. Any number less than 100% is in spec, and more than 100% is out of spec. A PWI of 0% represents the very center of the process window. (See the sidebar for how to calculate the PWI).

This procedure is repeated billions of times in a matter of seconds, and the Oven Recipe Search Engine selects the optimum recipe. Typically within 60 seconds, the optimum oven recipe is displayed, ready for downloading to the oven control system. The process engineer decides the criteria for the optimum oven recipe. They typically fall into one of three categories, or a combination of them all:

1. The oven recipe that positions the profile towards the center of the Lee specifications.
2. The oven recipe with the fastest conveyor speed that still yields a profile within the Lee specifications.
3. An oven recipe that eliminates, or minimizes, the oven changeover time. (The search engine will attempt to find an acceptable profile by searching exclusively on different conveyor speeds, rather than temperatures. While it may take from 5 to 30 minutes for an oven to stabilize on new temperature settings, changes in only the conveyor speed may be reached in a few seconds).

In other words, rather than the conventional "trial and error" approach, the technician or engineer can now specify the requested process window (the Lee profile specification), allowing modern software simulation and today's common computer power to select the appropriate oven recipe – all in a matter of a few seconds. This offers manufacturers the best of both worlds: they can reap the superior benefits of the Lee profile while improving setup time and costs.

Defining the Process Window Index

The Process Window Index (PWI) is a measure of how well a profile fits within user-defined process limits (see Figure 14). This is done by ranking process profiles on the basis of how well a given profile "fits" the critical process statistics. A profile that will process product without exceeding any of the critical process statistics is said to be inside the Process Window. The center of the Process window is defined as zero, and the extreme edge of the process window as 99%. A "Process Window Index" of 100% or more indicates that the profile will not process product in spec. A "Process Window Index" of 99% indicates that the profile will process product within spec, but it is running at the very edge of the Process Window. A "PWI" of less than 99% indicates that the profile is in spec and tells users what percentage of the process window they are using. For example, a PWI of 70% indicates a profile that is using 70 percent of the process spec. The PWI tells users exactly how much of their process window a given profile uses, and thus how robust that profile is. The lower the PWI, the better the profile. A PWI of 99% is risky because it indicates that the process could easily drift out of control. Most users seek a PWI of <80%, and profiles with a Process Window Index between 50% and 60% are commonly achieved (if the oven is sufficiently flexible and efficient).

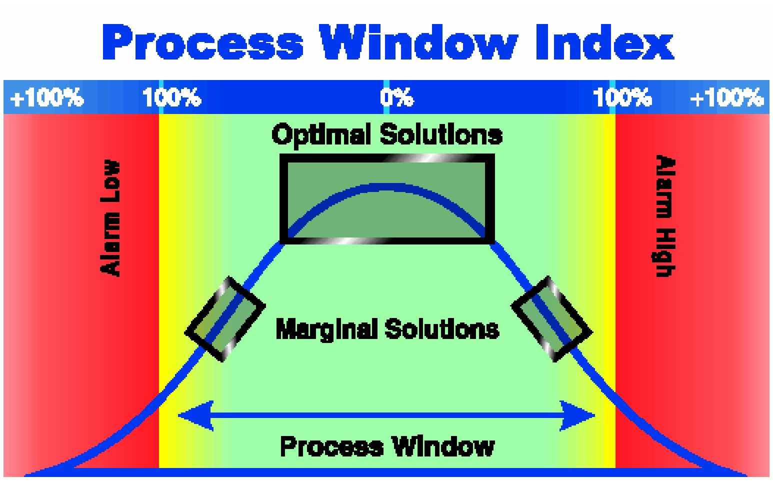

Figure 14 - Process Window and PWI

Figure 15 shows the Process Window Index for the Peak Temperature of a single thermocouple. The Process Window Index for a complete set of profile statistics is calculated as the worst case (highest number) in the set of statistics. For example: if a profile is run with six thermocouples, and four profile statistics are logged for each thermocouple, then there will be a set of twenty-four statistics for that profile. The PWI will be the worst case (highest number expressed as a percentage) in that set of profile statistics. Note that Figure 16 shows the user designated critical statistics for a single thermocouple (See Figure 16).

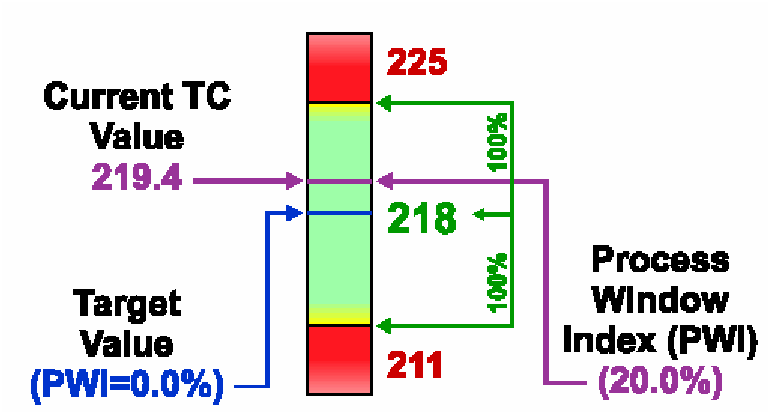

Figure 15 - The Process Window Index (Single Statistic—Peak Temperature of One Thermocouple)

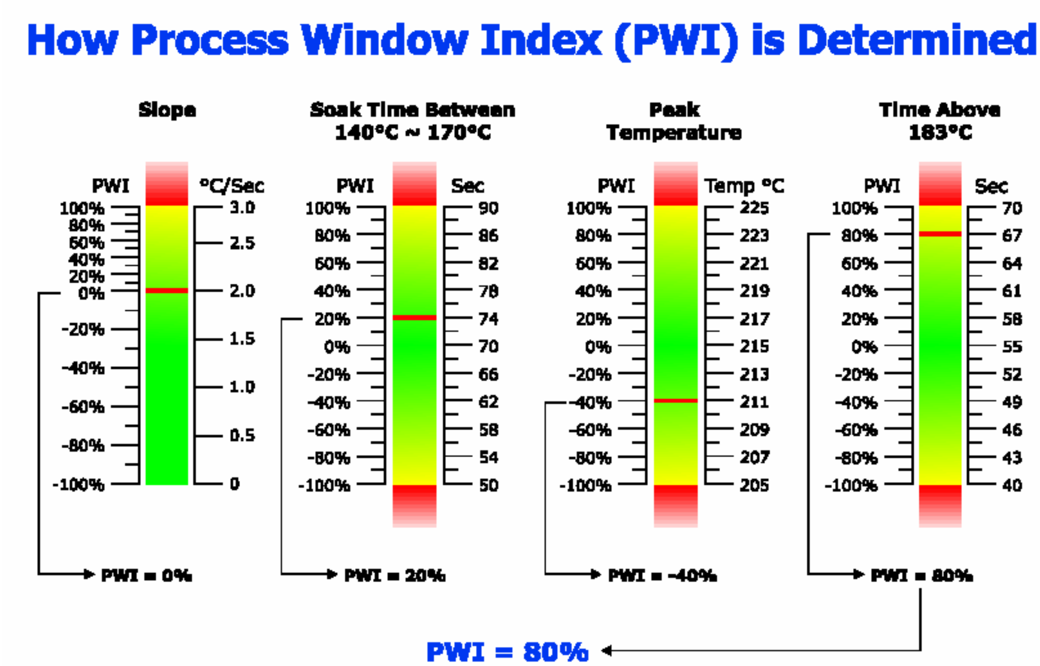

Figure 16 - The Process Window Index (Multiple Statistics for a Single Thermocouple and Final PWI Calculation)

Calculating the PWI

To calculate the Process Window Index: i=1 to N (number of thermocouples); j=1 to M (number of statistics per thermocouple); **measured_value**$_{[i,j]}$ is the $[i,j]^{th}$ statistic's value; **average_limits**$_{[i,j]}$ is the average of the $[i,j]^{th}$ statistic's high and low limits; and **range**$_{[i,j]}$ is the $[i,j]^{th}$ statistic's high limit minus the low limit.

Thus, the PWI calculation includes all thermocouple statistics for all thermocouples. The profile PWI is the worst case profile statistic (maximum, or highest percentage of the process window used), and all other values are less. (See Figure 17.)

$$\mathbf{PWI} = 100 \times \underset{N,M}{\overset{i,j=1}{\mathrm{MAX}}}\left\{ \left| \frac{(\text{measured\_value}_{[i,j]} - \text{average\_limits}_{[i,j]})}{(\text{range}_{[i,j]} \div 2)} \right| \right\}$$

Figure 17 – Process Window Index Formula

Conclusion

With so many changes occurring in our technology, our markets, our customers, and our competition, it is critical to continually refresh our efforts at process optimization. Implementing the latest proven tools and techniques frequently and effectively is the surest way to remain competitive.

Reference

1. N. C. Lee, *Reflow Soldering Processes and Troubleshooting*, pg. 239, Newnes, 2002 Boston.