Advances in Thermal Profiling for Reflow Process Control

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ABSTRACT

This paper will focus on recent advances in thermal profiling and process control. Several factors are causing a renewed focus on the soldering process. The specter of lead-free electronics assembly has raised concerns with the increased peak temperatures that will be required and the problems higher temperatures will cause for component manufacturers. The continued growth of the CMC (Contract Manufacturing Company) sector and the intense competition in this sector has changed the way electronics are assembled and made optimized equipment utilization critical. And a shrinking pool of skilled labor has brought new problems to the shop floor.

The factors above all raise issues of concern to individuals responsible for quality and productivity in the thermal process. New hardware and software technology will make it possible to both optimize and automatically setup the soldering portion of the SMT line. The paper will include a definition of emerging issues concerning the reflow process, and discuss new technology to manage those issues.

INTRODUCTION

At least three significant issues currently face individuals responsible for soldering processes:

- Lead-free solder will raise process temperatures by 30-50°C. Higher process temperatures will require much more precise process windows.
- A tightening labor market: professional, skilled, and unskilled, will present new challenges to industry managers.
- Outsourcing of a high percentage of SMT assembly to CMC's has created an extremely competitive SMT market requiring optimized process efficiency.

The sum effect of the trends and factors above is that the thermal process, which some manufacturers have neglected in recent years, will again become the object of industry wide focus. Manufacturer's will require both cutting-edge engineering technology and user-friendly operator interfaces. The key to a successful thermal process will be combining the two. All of these factors can be addressed by improved thermal management technology.

THERMAL PROCESS CHALLENGES

The Lead-free Challenge

It is almost certain that lead-free electronic assemblies will be mandatory sometime by 2008 in Europe, and probably will be mandatory earlier in Japan. Currently available lead-free solders have a solidus/liquidous point about 20-50°C higher (depending on the alloy) than the leaded pastes currently in use. The primary challenge lead-free solders will present electronics assemblers with is higher process temperatures. The current thermal process window is a wide one, with the extreme lower limit of Sn63/Pb37 set at 183°C, the eutectic temperature of this leaded solder (a lower limit of 200-205°C is the most common setting), and the high limit at 235°C, which is the maximum temperature that some sensitive components can be exposed to. These high and low process limits provide a Delta of over 30°C—wide enough that a carefully monitored process can be expected to produce low defects and high yield with little fear of defects caused by process drift.

With lead-free assemblies, the process window will shrink dramatically. With Sn/Ag/Cu alloys (217°C liquidus), the window will be cut down by 65% to a Delta of 18°C. Given that few assemblers want to get within 5°C of their control limits, the true process window with Sn/Ag/Cu alloys will be approximately 8°C unless component limits are raised. This very narrow process window is the problem that will confront electronics assemblers making the shift to lead-free production, and the window is unlikely to open wider in the near future (See Figure 1).

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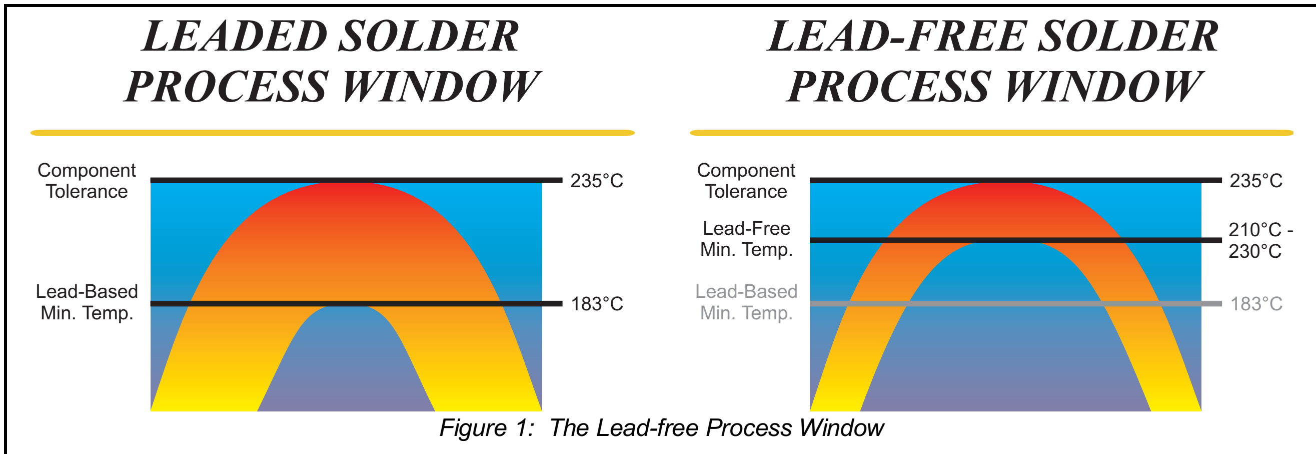

Figure 1: The Lead-free Process Window

The problem of narrow process windows will be further exacerbated by the trend to more complicated assemblies with increased component density. Finding a profile that will reliably reflow these assemblies, especially larger ones which can experience large peak temperature Deltas across the board, has never been easy. Real world production issues like maintaining high throughput and minimizing oven changeover times between production runs also figure into the equation. The Lead-free Challenge will be to find and utilize technology that will allow electronics assemblers to define and maintain optimal thermal processes in the drastically reduced Lead-free process window. The increase in peak process temperatures, combined with the trend to components of decreasing size and robustness, means that precision tools will be required to find profiles that will safely process product at the higher temperatures required by lead-free solder.

Maximizing Human Resources

In an industry that has gone from one engineer per line to one engineer per plant in the last ten years, making sure that scarce engineering resources are used efficiently will be critical. Further complicating Human Resources issues is a booming economy that has produced historically unprecedented employment rates. Employee's frequently job-hop, and high employee turnover wreaks havoc with productivity in a technologically sophisticated industry. New employee's require expensive training, and often it seems that as soon as they are up to speed, they move on to another job. High employee turnover also means a shrinking base of knowledge in CMC facilities. At OEMs, production problems are solved by experienced senior personnel with years of accumulated process knowledge. CMCs often don't have this knowledge base to draw on, especially in regards to specific assemblies. The problem is further exacerbated by the fact OEMs have a limited number of product processes to master, while CMCs are expected to successfully process up to several hundred products a year. This situation has left CMCs in a "Catch-22" situation: experienced personnel drive up production costs; inexperienced personnel can have a negative effect on productivity and product quality. Manufacturing equipment in the Twenty-first Century will need to be "smart" to make the most of diminishing engineering resources and yet user-friendly enough for minimally trained operators.

Contract Manufacturing—The Quest for Efficiency

Approximately 40% of SMT assembly is currently outsourced, and the CMC sector of the electronics assembly market is growing at a rate of better than 20% annually. The key to the growth of the CMC market has been increased production efficiency based on running assembly lines full time at maximum throughput. A competitive edge is maintained by minimizing human resources, and this means that CMCs don't have the luxury of fine-tuning production. Processes must be set up quickly and efficiently in order to keep the lines running, and yet at the same time, quality must be assured. This makes line changeover time a critical factor in maximizing line efficiency.

Another factor that has had a profound influence on the contract manufacturing industry has been the development of the "high-mix" business model. A high-mix assembly facility pursues contracts for small job lots, which generally offer higher profit margins than low-mix, high volume assembly contracts. To take advantage of these higher profit margins, CMCs must have lines and equipment that are flexible enough to be reconfigured as often as

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several times a day. For CMCs, tools to improve process efficiency have become essential. For the thermal portion of the electronics assembly process, tools are now available that can identify robust profiles that process multiple dissimilar products and increase throughput by finding optimal recipes. For “high-mix” production, these tools can dramatically reduce line changeover times for the thermal process.

INTEGRATED PROFILING FOR THE REFLOW PROCESS

The Status Quo

The current method of profiling conveyorized thermal processes is to attach thermocouples to a product, and, using a wireless device or data-logger, run the device and the product through the oven to record the product thermal profile. This is typically done on a regular basis to verify that the oven is working correctly, whenever the oven is changed over, and when a new process needs to be set up. There are several problems with the status quo:

- Profiling is time consuming, and can become even more time consuming if the data is lost, for example, through a bad download, and another profiling run is required.
- Current profiling software is complicated and requires several hours of training to ensure operator competence. Setting up a profiler is also complicated, and has to be repeated for each new oven the profiler is used on.
- Oven setup is a matter of trial and error, with multiple profiling runs being required to find an acceptable profile for new products.

Next Generation Profiler

The next generation profiler features a more robust hardware configuration than profilers currently in use and an all-new software platform. The new configuration guarantees a perfect profile every time with a new wireless download. The next generation profiler provides data in real-time as it passes through the process and simultaneously records the data internally. When the profiler has completed its run through the process, the internally logged profile is automatically wirelessly downloaded, filling in any gaps that may have occurred due to broken transmission of the real-time profile. This new feature ensures that every profile run is a good one, and that it will never be necessary to hold up production to repeat a profile due to data loss.

The new software features minimal initial setup and a radically simplified operator interface that eliminates tedious board mapping. The software is designed to be completely intuitive and require very little training (See Figure 3). It comes with an updateable database of hundreds of popular solder pastes, which allows the operator to automatically

Figure 2: Next Generation Profiler

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select the specs for the paste being used (See Figure 4). A series of screens with clear explanatory graphics steps the operator through the profiling process from beginning to end, and if the profiling is being done with one of the selected ovens that communicate with the software, the software automatically changes the oven setpoints to the approved profile.

Figure 3: Simplified Software Startup Screen

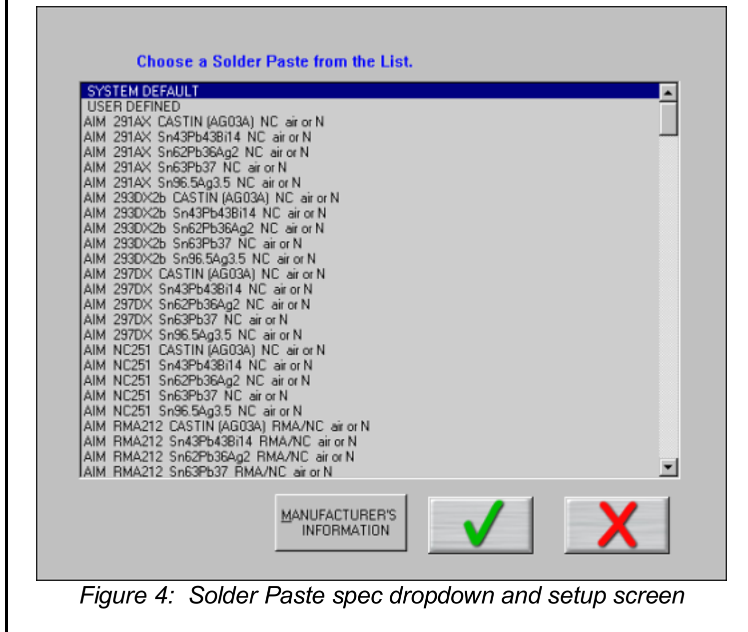

Figure 4: Solder Paste spec dropdown and setup screen

SMART PROFILE PREDICTION

A significantly improved automated prediction tool, available as an option with the next generation profiler, allows users to predict how changes to belt speed and oven setpoints will affect a product profile. The software option can create and evaluate *billions* of potential oven recipes, automatically selecting the recipe that best fits the process window. This automated prediction tool is exponentially more powerful and accurate than any than any tool currently on the market and allows users to find the optimal profile in about a minute. The automated prediction tool is designed to center the profile in a process window designated by the user, who may set limits particular to their processes. An example of this being the sensitive components mentioned in the section on lead-free solders above—if the assembly can't see temperatures above 235°C, the automated prediction tool will find a profile that not only assures it doesn't but will be centered between the high and low limits.

The first automated prediction tool was released in 1997. This technology was capable of formulating over a hundred potential profile recipes per second, evaluating the recipes, and ranking them. One issue with the original automated profiling tool was that it required an expert operator. With a ten-zone oven, there are literally billions of possible combinations of zone setpoints and conveyor speeds. To search all of these would take several days, so the operator was required know enough about thermal profiling to be able to tell the automated prediction tool which range of combinations of zone setpoint and conveyor speed to search in order to get a solution in a reasonable time.

The latest version of the automated profiling tool offers several significant improvements. The improved automated prediction tool is capable of automatically searching the entire range of possible recipes in less than a minute, so operators no longer need to set search parameters. The operator selects the solder paste being used from a drop down menu, adds any non-solder paste related process limits and runs a profile. Seconds after the profile has completed, the automated prediction tool calculates an optimal profile that is custom designed for both the oven and the product. Because the improved automated prediction tool has searched the entire range of possible oven setups, users are assured of finding the best possible profile.

Perhaps the most significant feature of the improved automated prediction tool is that it ranks the profiles it finds using the Process Window

Index (described below). This allows users to compare performance between processes and, more importantly, to be assured that they are using the most robust and reliable profile for a given product that their oven can achieve.

SELF-PROFILING OVEN

For many years the "Holy Grail" for the thermal process has been the "self-profiling oven." Even more revolutionary than the improved automated prediction tool described above is automated self-profiling software that interfaces directly with the oven controller. The improved automated prediction tool will find the optimal profile for a given product, but requires an experienced operator or engineer to do so. The self-profiling oven is the next evolutionary step in thermal profiling, in that it does not require an expert or even experienced operator to profile the oven. This software features a dramatically simplified user interface which will allow a low-skilled operator with one hour's training to set up a profile by merely selecting a pre-profiled product from a menu. The software will automatically change the oven setpoints and conveyor speed, then let the operator know when the oven is ready to run production (See Figure 5).

One key to the self-profiling oven is an interface that allows profiling software to "talk" to the oven controller. The other key is the ability to define a profile's "Process Window Index" which ensures that a profile is the best possible one for a given product. The combination of the simplified operator interface, the profiler/oven controller interface, and the "Process Window Index" allows a low-skilled operator with one hour's training to setup the solder reflow oven better than the most expert operator could previously, and to do it in usually 15 to 60 minutes.

When a new product needs to be profiled, this software will allow a low-skilled operator with one hour's training to setup the solder reflow oven. The operator will not have to understand thermal profiling, or terms such as "peak temperature", "time above reflow", "max slope" etc., or even how to input a zone setpoint temperature or conveyor speed. A series of video animations will show the operator exactly how to complete the profiling process (See Figure 6). The only thing the operator will need to know how to do is attach thermocouples to a PCB, run the PCB through the furnace, and catch it at the other end. The only decisions the operator makes are: which product to run; where to place the thermocouples on the product; and which preset process window to apply to the profile. This revolutionary software utilizes the improved automated prediction software discussed above and will deliver the best profile the oven is capable of. Conventional thermal profiling software runs in the background and is available for an "engineer" so they can input process window limits and view the profiles that have been run by the operator.

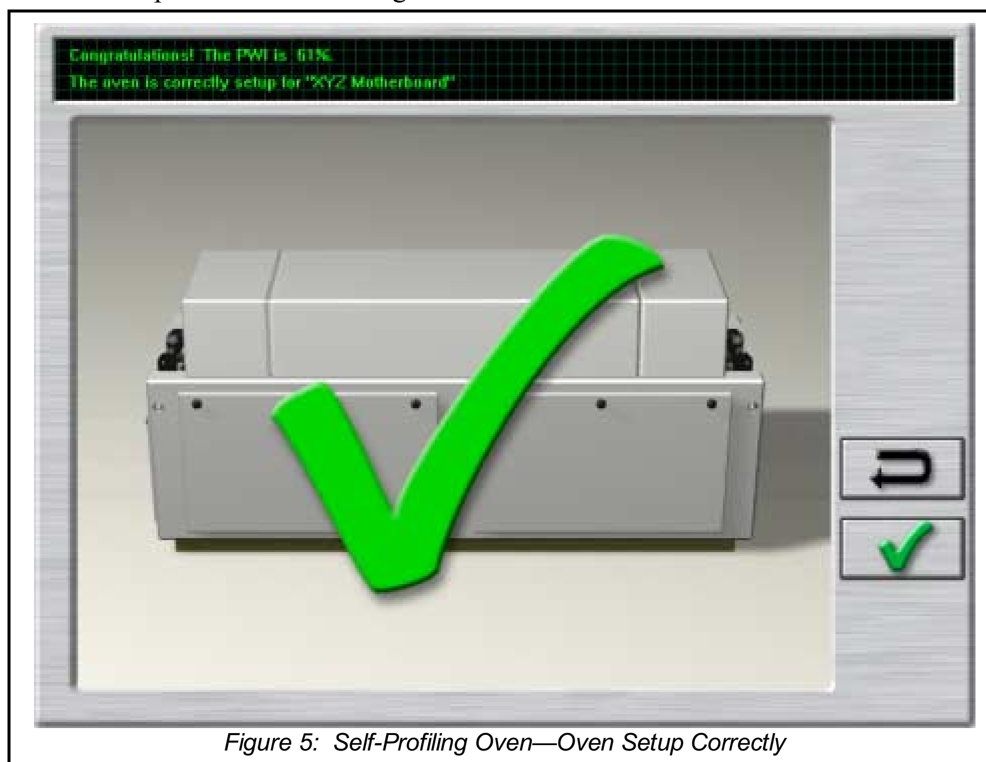

Figure 5: Self-Profiling Oven—Oven Setup Correctly

The key to understanding the revolutionary capabilities of the self-profiling oven is simple. Up until now, the operator has been responsible for controlling the oven. Now, the oven has the intelligence to tell the operator how to set it up, and will not allow the operator to run product if the profile is out of spec. In effect, the self-profiling oven's intelligent system controls the operator.

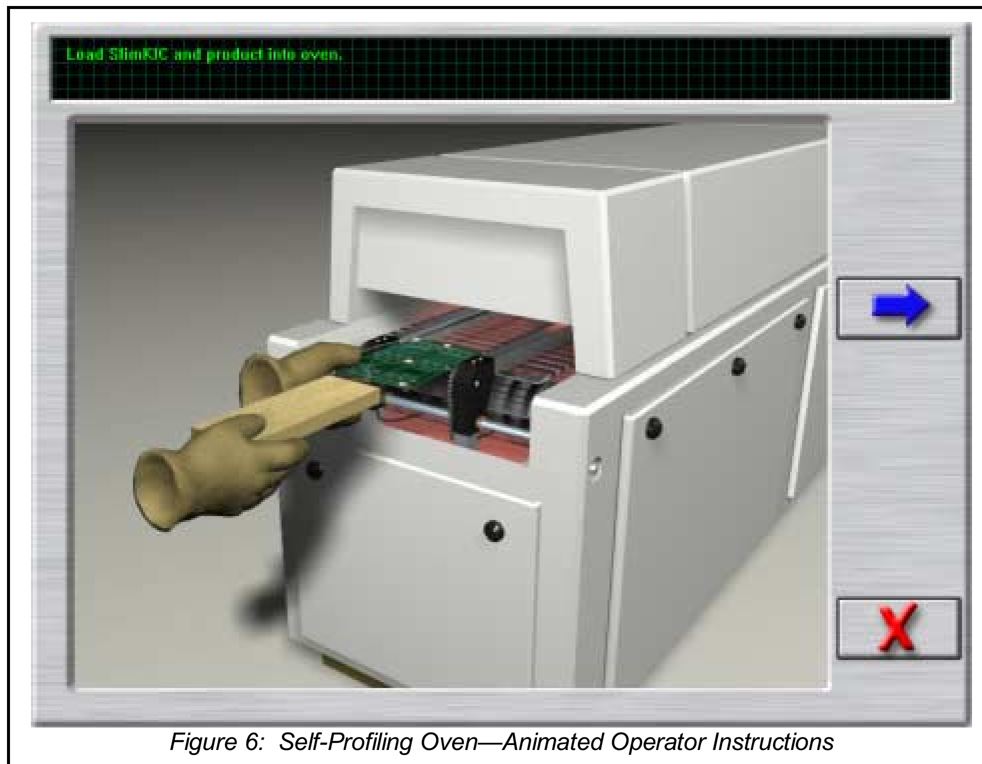

Figure 6: Self-Profiling Oven—Animated Operator Instructions

The Process Window Index

A Method for Quantifying Thermal Profile Performance

The Problem

There is currently no widely accepted method for comparing performance of thermal profiles, and thus, no quantifiable system of ranking thermal process performance. Once a thermal profile has been run, it is judged as being either in or out of spec, and perhaps subjectively judged as being "OK", good, or really good. The "Process Window Index" (PWI) is a statistical method for ranking thermal profile and thermal process performance.

Defining the Process Window Index

The Process Window Index is a measure of how well a profile fits within user defined process limits. 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 Process Window Index 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% 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 below 80%, and profiles with a Process Window Index between 50% and 60% are commonly achieved (if the oven is sufficiently flexible and efficient). The figure below illustrates how the Process Window Index is calculated.

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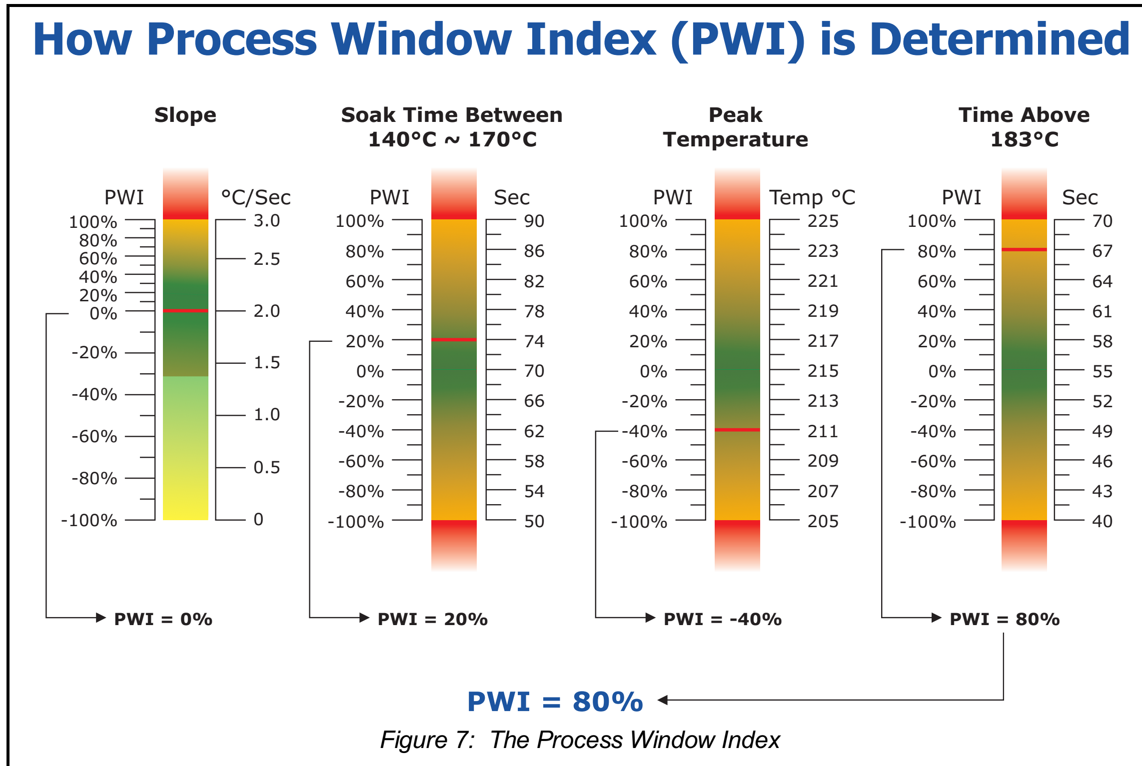

Figure 7: The Process Window Index

Benefits of Ranking Thermal Profile Performance

There are three significant benefits to using the Process Window Index. The first is that profiles can be easily compared, and users can be confident that they are using the best profile their process can achieve. The second is that because the PWI reflects the performance of the whole profile, it provides much better indicator of process capability than tracking a single statistic. The PWI thus provides excellent data for SPC and other QC monitoring programs. Finally, the PWI gives users a simple method for comparing thermal process performance. Comparisons may be made between individual lines on the shop floor, between processes at multiple plants, and between processes using dissimilar equipment. The ability to quantify thermal process performance will give electronics assemblers a means for comparing the performance of their equipment; this will be of value in selecting equipment, for buy off, and for process troubleshooting. (See Table 1, which is the result of testing run on three dissimilar oven configurations.)

The simplicity of the Process Window Index makes its validity as a statistical tool readily apparent, and its adoption as an industry standard clearly offers significant benefits for improving soldering processes.

Table 1: Comparison of Oven Performance with Various Boards—best PWI achieved by each oven for each board expressed as percentage of the Process Window used by the optimal profile achievable on each oven.

Oven		Board Type			
Manufacturer	Model	Motherboard	Cell Phone	Display Adapter	Mainframe
A	X	PWI = 87%	PWI = 62%	PWI = 79%	PWI = 126%
B	Y	PWI = 71%	PWI = 58%	PWI = 61%	PWI = 93%
C	Z	PWI = 33%	PWI = 29%	PWI = 34%	PWI = 58%

Conclusions

Electronics assemblers are currently faced with several serious challenges. The next generation profiler, improved automated prediction tool, and the self-profiling oven software offer CMC's and OEM's tools to meet these challenges and enjoy a multitude of benefits:

Next Generation Profiler:

- Most robust and reliable hardware available.
- Never lose production time because a profile is lost and has to be run again.
- Simplified setup and operator interface—no board mapping.
- Comprehensive solder paste data base.
- Dramatically reduced oven setup and changeover time.

Improved Automated Prediction Tool:

(All of the above and…)

- Improved process efficiency by finding robust profiles that process multiple dissimilar products.
- Increased throughput by finding optimal recipes.
- Optimized profiles to meet the higher peak temperatures required by lead-free solders without damaging sensitive components.
- Find the best possible profile in under a minute.
- Automatic transfer of oven setpoints and belt speed to controller with selected ovens.
- The PWI allows users for the first time to compare thermal profile and equipment performance.

Self-Profiling Oven Software:

(All of the above and…)

- Thermal profiling is vastly simplified, and an optimal profile can be found in by a minimally trained operator.
- All profiling and oven setup tasks are automated for maximum efficiency.
- Rapid changeover—error-proof and completed the instant the oven is stable.
- Fail-safe system—It is nearly impossible to run product in an incorrectly setup oven. (The only way to run product in an oven that is incorrectly setup is gross operator error. It is possible to set the oven up for one product and then run a different product, as there is no method for the self-profiling oven software to determine which product is entering the oven).

New hardware and software tools offer several options for increased optimization and efficiency in the thermal process. The next generation profiler offers real-time profiling with guaranteed first profile success. The improved automated prediction tool guarantees the best possible profile for any product. And the self profiling oven software guarantees rapid and precise oven setup by a minimally trained operator with all potential for error removed. Combined, these technologies are ushering in a new era in thermal process management and control.

If you have any questions regarding this paper or any KIC products, please feel free to contact us at:

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