Thermal Profiling in the Twenty-First Century

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Abstract

In the opening years of the twenty-first century at least three significant issues will be faced by individuals responsible for soldering processes:

- Lead-free solder will require much more precise process windows.
- A tightening labor market: professional, skilled, and unskilled labor, will present new challenges to industry managers.
- Outsourcing of a high percentage of SMT assembly to CMCs will continue to produce an extremely competitive SMT market requiring optimized process efficiency.

Lead-free Solder: It is almost certain that lead-free solders will be mandatory by 2004 for companies exporting their products to Europe. In Japan, the electronics industry will voluntarily remove lead from 50% of new assemblies by 2002. Currently available lead-free solders have a solidus\liquidus point between 20-50°C higher than the leaded pastes currently in use. This increase in peak process temperature, combined with a decrease in the size and robustness of components, will make new profiling technologies critical. Older reflow ovens will have difficulty developing the precise profiles required, and precision tools will be required to find profiles that will safely process products 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, ensuring that scarce engineering resources are used efficiently will be critical. Hiring skilled and even unskilled labor is already difficult in today's tightening domestic labor market. Internationally, finding qualified plant personnel is also a key factor in the productivity equation. Manufacturing equipment in the twenty-first century will be increasingly user-friendly and networked for remote monitoring to make the most of diminishing human resources.

Outsourcing: It is estimated that 30-40 percent of electronic assembly is currently outsourced. This means tough competition among CMCs and a brutal emphasis on the bottom line. Profitable CMCs will be distinguished from those whose lines they acquire by their use of tools which:

- Improve process efficiency by finding robust profiles that process multiple dissimilar products.
- Increase equipment utilization by increasing throughput with optimized profiles.
- Reduce production disrupting pass-through verification profiles.

The consequence of the trends and factors discussed above will be that the thermal process, which some manufacturers have neglected in recent years, will again become the object of industry-wide focus. The need for real-time profiling and process optimization will be greater than ever. Manufacturers will require both cutting-edge engineering technology and user-friendly operator interfaces. The key to successful thermal profiling in the twenty-first century will be combining these elements.

Introduction

As the millennium approaches, engineers responsible for soldering processes will be faced with several significant challenges. Use of lead-free solders will be mandated in Europe by 2004 and will require much more precise process windows. A tightening labor market of professional, skilled, and unskilled workers will present new challenges to industry managers. Electronics assemblers will be required to create processes that can be monitored by unskilled operators in less developed countries. The continuing outsourcing of a high percentage of SMT assembly to CMCs has created an extremely competitive SMT market that requires optimized process efficiency. All of these factors can be addressed by improved thermal profiling technology.

- Advanced thermal management systems make it possible to develop optimized profiles to meet the higher peak temperatures required by lead-free solders without damaging sensitive components, provided the oven is sufficiently flexible and stable.
- Advanced thermal profiling software features tools that can improve process efficiency by finding robust profiles that process multiple dissimilar products. The advanced automated prediction tool allows increased throughput by finding optimal recipes.
- Advanced thermal management software with a simplified user interface increases operator competence, eliminates potential errors, and significantly reduces training expenses.

Lead-free Electronic Assembly

It is almost certain that lead-free electronic assemblies will be mandatory by 2004 for companies exporting their products to Europe, and probably will be mandatory for the Japanese market as well. 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 lower limit set at 183°C, the liquidus temperature of leaded solders, and the high limit at 235°C, which is the maximum temperature that some sensitive components can see. These high and low process limits provide a Delta of over 50°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 the Bismuth alloys favored by Japanese assemblers (206-213°C liquidus), the window will shrink by half, to a Delta of 22-29°C. Using the more reliable 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. 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.

It is widely acknowledged that the component sector is lagging behind assemblers, soldering materials, and soldering equipment in being prepared for the shift to lead-free assemblies. Component manufacturers are faced with a three-part challenge: they must remove lead from their products; they must develop leads that are compatible with lead-free solders; and eventually they will need to develop components with higher temperature tolerances. The first two tasks must be completed in order to successfully assemble products which meet the European standards. This leaves the question as to whether component manufacturers will be able to raise their temperature tolerances in the short term. In the longer term, the question will be whether raising the process temperature limits of components will be economically justifiable or even necessary.

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 allows 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 accurate real-time monitoring of the thermal profile will become critical. Precision tools will be required to find profiles that will safely process product at the higher temperatures required by lead-free solder and insure that the process does not drift outside its narrow process window.

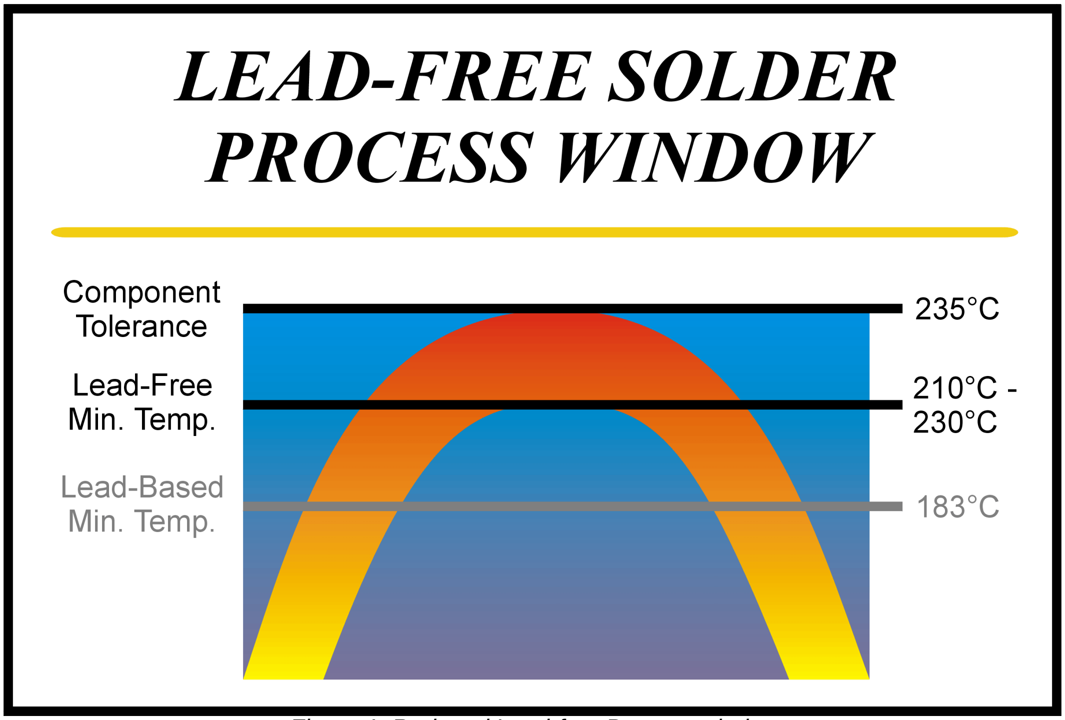

Figure 1: Reduced Lead-free Process window

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. Hiring skilled and even unskilled labor has become difficult in a tightening domestic market. Internationally, finding qualified plant personnel is also a key factor in the productivity equation. Manufacturing equipment in the twenty-first century will be increasingly user-friendly and networked for remote monitoring to make the most of diminishing human resources.

One solution to diminishing human resources will be the virtual factory. The virtual factory uses sophisticated process control and modeling software to monitor production on an entire assembly line. For the thermal process, the key to establishing a virtual factory is a real-time thermal manager. This system allows the remote viewing of data from either an individual oven or multiple ovens at any given time and will have the capability to display multiple ovens on the production floor in a single snapshot window. The ability to access any or all ovens on the production floor greatly reduces the time engineers need to be away from their desks. The information from the output folder on the corporate Intranet can also be accessed externally via an Internet website established for this specific purpose.

The effect internal distribution of real-time thermal process data has on production costs and quality control cannot be overstated. With qualified engineering staff difficult to come by, many companies are running lean on engineering and support staff. Being able to access data remotely eliminates the engineer's need to constantly jump up and go out to the shop floor to view each process. The internal distribution of data from the thermal manager via the Intranet allows users to maximize the value of scarce engineering resources. Time spent efficiently by engineers means a better bottom-line for any facility.

The external distribution of the thermal process data to a CMC's customers via the Internet facilitates increased customer satisfaction. Customers can have individual web sites on a corporate Intranet, which they can access through the firewall with a personal password. Within their respective sites, they are able to view work in process and real-time quality data collection showing both in-process inspection and test yields. Their ability to dial in and check on their particular product at anytime, from anywhere, assures them that they are getting a quality product that is being built to their specifications.

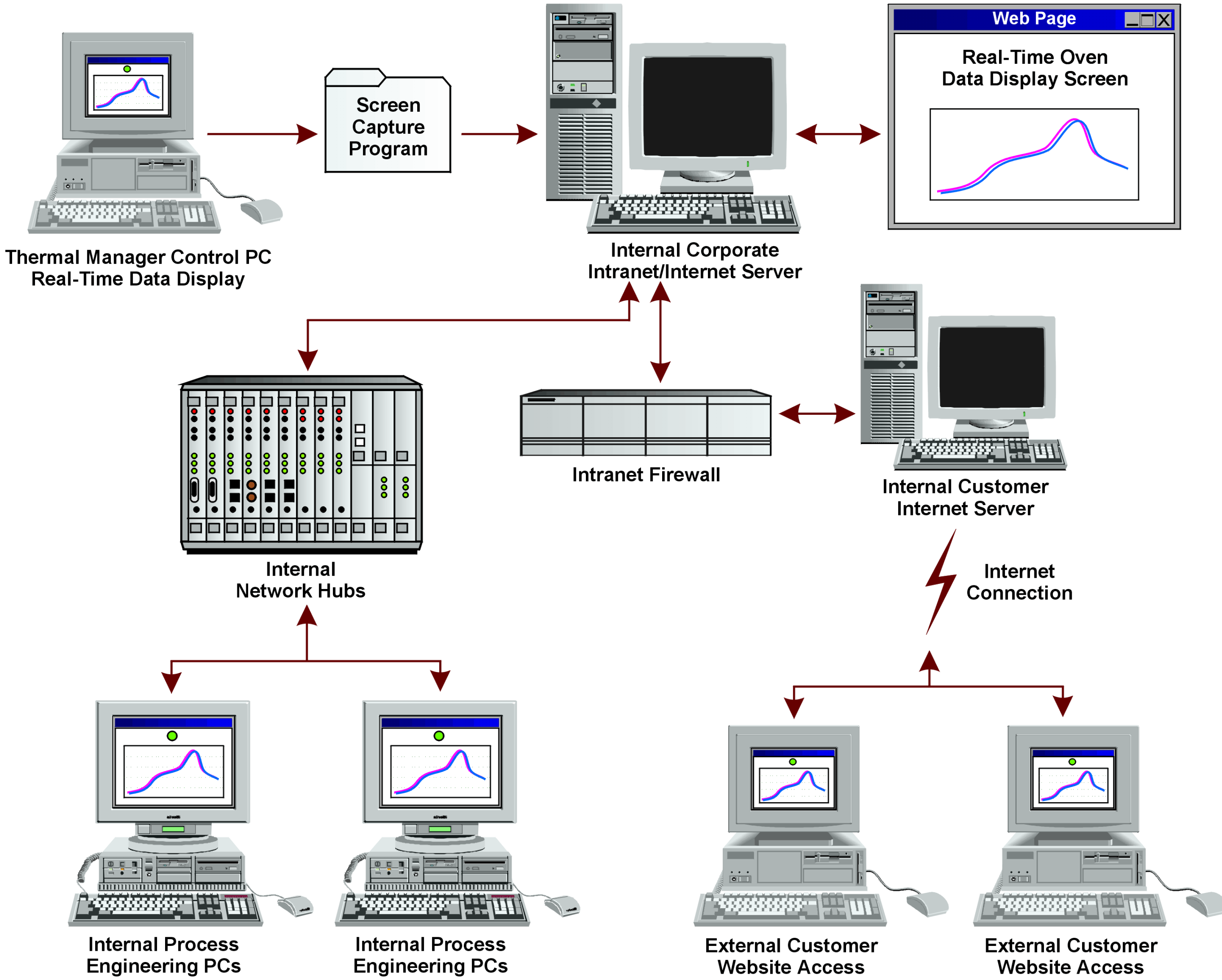

Figure 2: Networking Process Data

Contract Manufacturing—The Quest for Efficiency

Approximately 30-40% of SMT assembly is currently outsourced, and the CMC sector of the electronics assembly market is currently 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. OEM's generally had lines dedicated to a single product, and these lines were run based on demand for product—when demand fell off, the line stopped running. Dedicated lines allowed production engineers the luxury of fine tuning their processes, and once a line was dialed in for its dedicated product, all that was required was to monitor the line's performance. This was generally done by monitoring the quality of the product coming off the line and performing preventative maintenance at specified intervals. Dedicated lines allowed OEM's to assure the quality of their product, but the downside was that expensive capital equipment and human resources were often idled.

Contract Manufacturers have taken advantage of the inefficiencies of dedicated lines by developing highly flexible lines that run job lots of product. When one job is completed, the line is immediately shifted to the next job. Competition in the CMC industry is fierce and profit margins slim. A competitive edge is maintained by minimizing human resources, and this means that CMC's 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.

Further complicating the Contract Manufacturer's task 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 employees 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 OEM's, production problems are solved by experienced senior personnel with years of accumulated process knowledge. CMC's often don't have this knowledge base to draw on, especially in regards to specific assemblies. This situation has left CMC's in a "Catch-22" situation: experienced personnel drive up production costs; inexperienced personnel can have a negative effect on productivity and product quality.

For CMC's, 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.

Thermal Profiling for the Twenty-first Century

The Status Quo

The current method of profiling conveyorized thermal processes is to attach thermocouples to a product, and, using a wireless device, run the device and the product through the oven to record the product thermal profile. This is called "profiling the oven," and is typically done on a regular basis: monthly, weekly, or as often as once a shift, to verify that the oven is working correctly. The oven must be verified regularly because it has been demonstrated that even in modern forced air convection ovens, there are times when the product thermal profile is no longer within specifications, even though the oven controller indicates that nothing has changed.

Next Generation Profiler

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.

The new SlimKIC 2000 introduces cutting-edge profiling. It features an even more robust hardware configuration than the original SlimKIC and an all-new software platform. The new configuration guarantees a perfect profile every time with a new wireless download. Not only does the SlimKIC 2000 profile in real-time as it passes through the process, but the profiler 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 a second profile.

Figure 3: SlimKIC 2000

The KIC 2000 software, which is a key component of the SlimKIC 2000, features no setup and greatly simplified profiling. No longer do users have to measure their oven and it's zones. The software maps the oven after in the course of the profiling runs, and all users have to do is input their current beltspeed. Another significant feature of this software is its radically simplified operator interface. The software is designed to be completely intuitive and require very little training. The software comes with an updateable database of hundreds of popular solder pastes, which allows the operator to automatically select the spec.s for the paste that they are using. 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 communic ate with the KIC software, the software automatically changes the oven setpoints to the approved profile.

Figure 4: KIC 2000 Software Startup Screen

KIC Navigator

A powerful option available with the SlimKIC 2000 is the *KIC Navigator,* which allows users to predict how changes to belt speed and oven setpoints will affect a product profile. In the automated mode, the Navigator will create and evaluate *billions* of potential product profiles, automatically selecting the profile 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 a matter of minutes. 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 be the sensitive components mentioned in the section on lead-free solders above—if the assembly can't see temperatures above 230°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. With selected oven manufacturers, the profiling software can communicate with the oven controller. Zone setpoints and beltspeed are automatically exchanged between the profiling software and the oven controller, eliminating any potential for data entry errors.

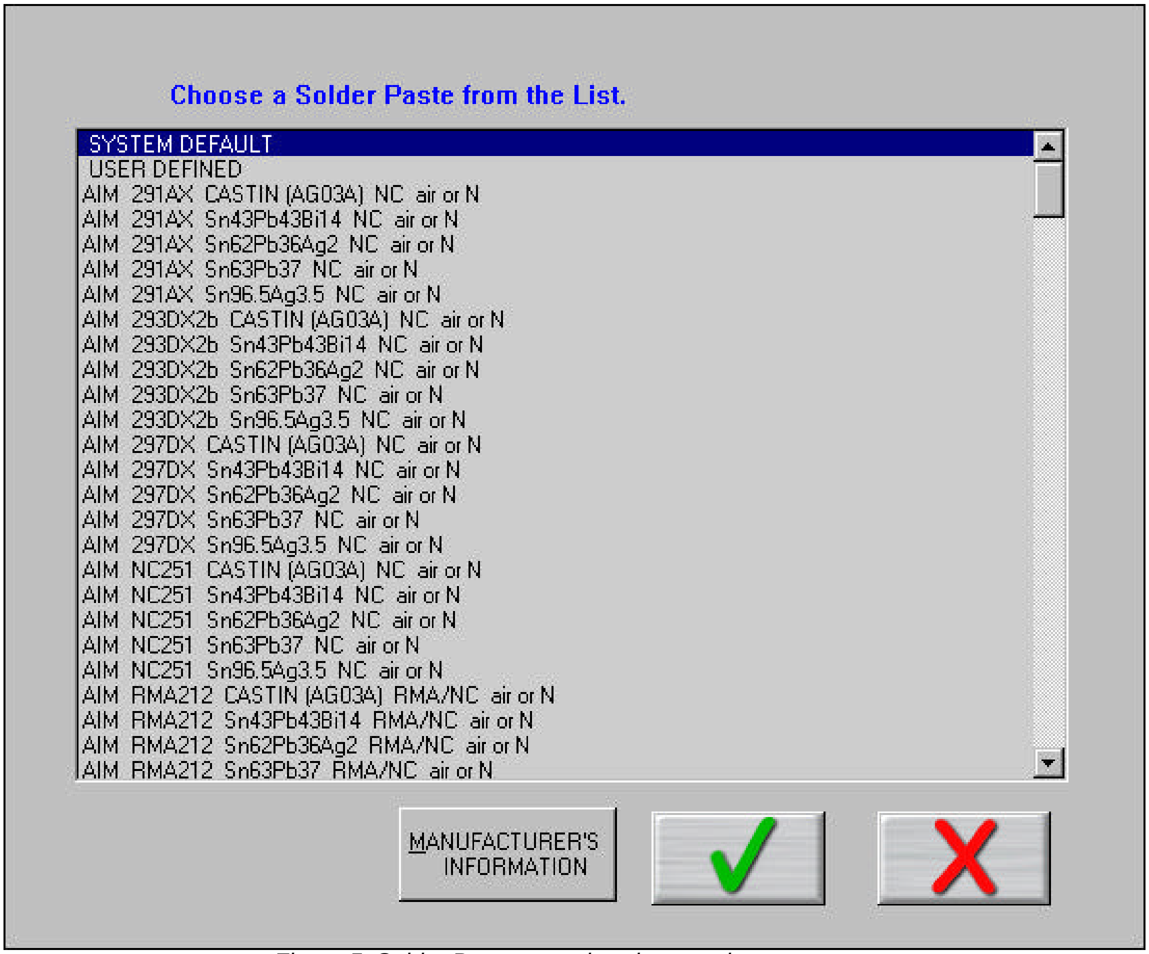

Figure 5: Solder Paste spec dropdown and setup screen

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. This tool was capable of finding optimum oven setups that would yield a profile in the center of the process window, as well as the recipe with the highest possible conveyor speed to maximize throughput. With the automated prediction tool, users were able for the first time to know that they had found an optimal thermal profile for a given product.

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 release 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 software package also includes a comprehensive database of solder paste specifications, including specs for the new lead-free solder pastes from all major manufacturers. The operator selects the solder paste being used from a drop down menu, enters any non-solder paste related process limits, runs a profile, starts the automated prediction tool, and in seconds has an optimal profile that is custom designed for both the oven and the product. A pass through profile is run to confirm that the oven settings are correct and then the oven is ready for production. 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 KIC Navigator 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.

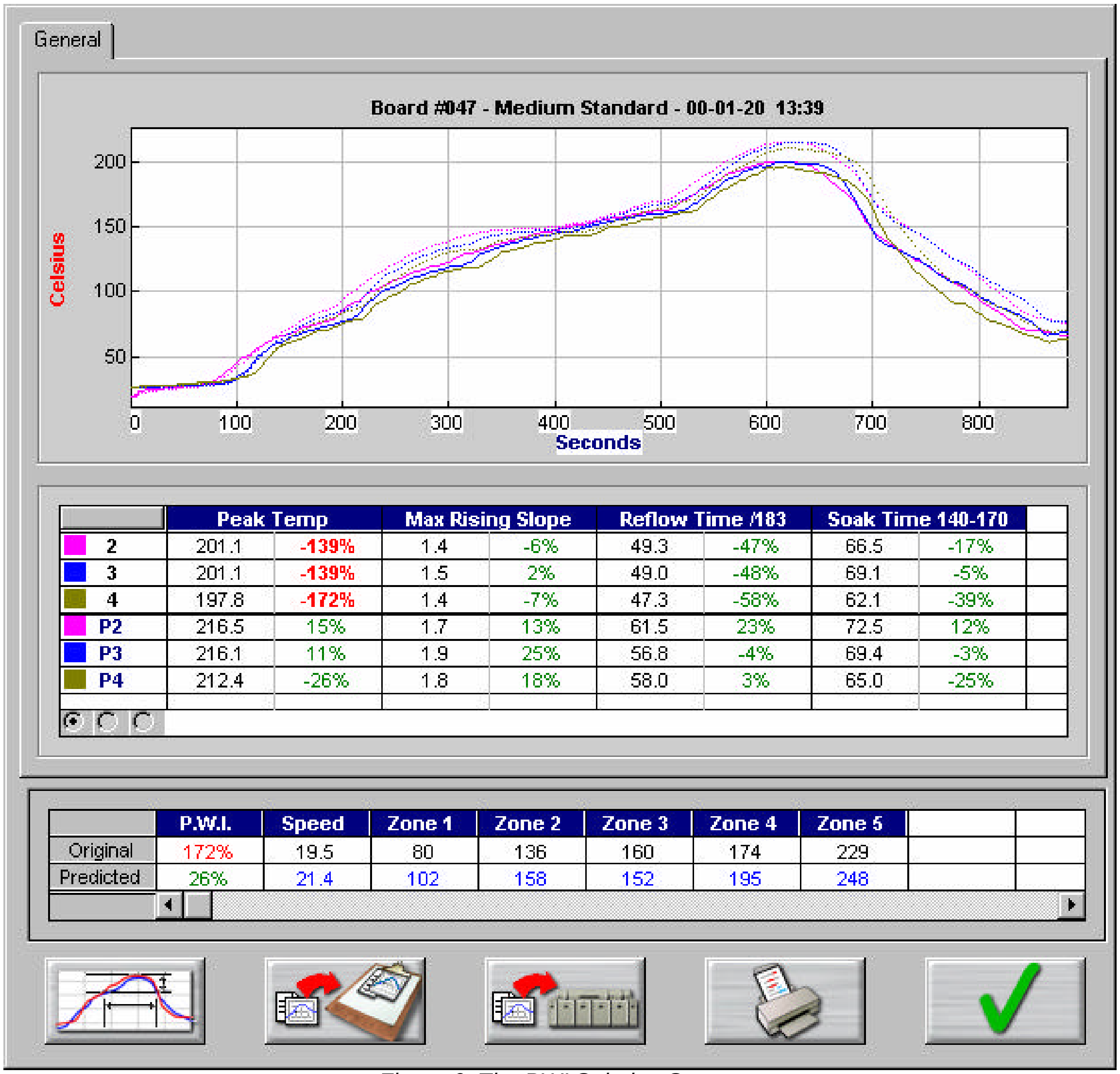

Figure 6: The PWI Solution Screen

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”. Efforts to track process performance for SPC or QC generally focus on a single, or a small group, of profile statistics, for example, peak temperature of one or two thermocouples on a golden board. The Process Window Index is a statistic 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 shows the Process Window Index for the Peak Temperature of a single thermocouple. The Process Window Index for a complete set of profile statistics would be calculated as the worst case (highest number) in the set of statistics.

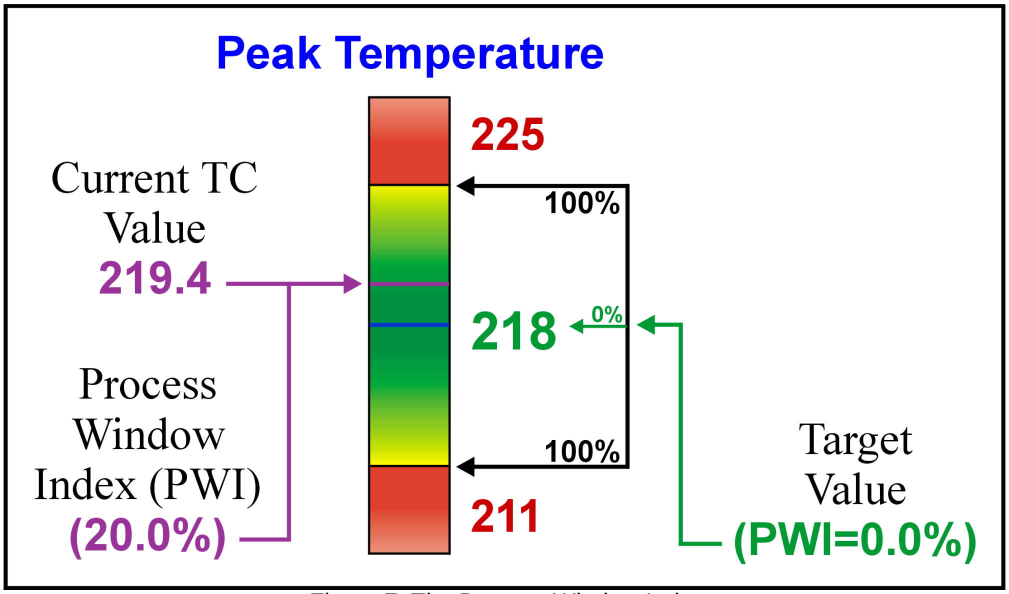

Figure 7: The Process Window Index
(Single Statistic—Peak Temperature of one Thermocouple)

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.

Table 1: Process Window Index Formula

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

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.

Benefits of Ranking Thermal Profile Performance

The analysis of thermal profiles with the Process Window Index offers four significant benefits. 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. Before the PWI was available for profile analysis, comparing profiles was subjective, and users could never be certain they had the best profile for their product. The PWI provides an excellent opportunity for process improvement and it's use is a significant step towards Zero-defect Production.

The second benefit is that the PWI greatly simplifies the profiling process. When used in advanced profiling tools, all profile statistics are reduced to a single number (the PWI) that even the most inexperienced operator can understand. This means significant savings in terms of training costs and a reduction in defects caused by operator error. It further means that in a few minutes, an inexperienced operator can setup an oven with the optimal profile, a job that formerly could take an experienced engineer hours.

The third benefit 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 while simplifying data gathering and reducing process monitoring costs.

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 soldering equipment. This will be of value in selecting equipment, for buy off, and for process troubleshooting.

Table 2 (below) is the result of a series of tests comparing oven performance using several sizes of PCBs. Each board was profiled in the given oven, and then an automated profile prediction tool was used to find the optimal profile for that board in the given oven. After the oven setpoints were changed and the oven stabilized, a second profile was run to confirm that the predicted PWI had been achieved. The table below shows that there is significant variation in oven performance between various makes and models. In this test, Oven C had more zones than Ovens A and B, and performed better, as would be expected.

Table 2: Comparison of Oven Performance — Best Achievable PWI

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%

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.

Conclusions

The twenty-first century will present electronic assemblers with several serious challenges. The state-of-the-art SlimKIC 2000 and KIC Navigator offer CMC's and OEM's a tool to meet these challenges and enjoy a multitude of benefits:

- Advanced thermal profiling software features tools that can improve process efficiency by finding robust profiles that process multiple dissimilar products and allow increased throughput by finding optimal recipes.
- The Navigator option makes it possible to develop optimized profiles to meet the higher peak temperatures required by lead-free solders without damaging sensitive components.
- Never lose production because a profile is lost and has to be run again.
- A tightly controlled thermal process can significantly reduce solder joint defects and the expensive rework associated with them.
- Advanced thermal profiling systems make it possible to develop optimized profiles to meet the higher peak temperatures required by lead-free solders without damaging sensitive components, provided the oven is sufficiently flexible and stable.
- Thermal profiling is vastly simplified, and an optimal profile can be found in minutes by a relatively untrained operator.
- The PWI allows users for the first time to compare thermal profile performance, and equipment performance.

The thermal process, which some manufacturers have neglected in recent years, will again become the object of industry-wide focus. The need for real-time continuous monitoring and documentation of processes will be greater than ever. Manufacturers will require both cutting-edge engineering technology and user-friendly operator interfaces. With the SlimKIC 2000 and the KIC Navigator option, electronics assemblers will be able to meet the challenges of the new millennium by increasing efficiency, maximizing human resources, and achieving unprecedented levels of process control.

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