Increasing Reflow Process Efficiency and Yield with Automated Reflow Setup

Philip C. Kazmierowicz, KIC Thermal Profiling
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Abstract

Several factors are causing a renewed focus on the reflow soldering process. The probability of lead-free electronics assembly becoming widespread has raised concerns about the increased peak temperatures that will be required and the problems higher temperatures will cause for component manufacturers. Increasingly dense assemblies and the continuing reductions in assembly size have complicated the thermal process. The continued growth of the EMS sector and the intense competition in this sector has changed the way electronics are assembled, and a shrinking pool of skilled labor has brought new problems to the shop floor. New research on the thermal process indicates that reflow process performance can be significantly improved.

This research has been facilitated by the discovery of a method for evaluating and ranking profile performance. The Process Window Index ranks profiles as to how well they fit a user-defined process window, which is usually determined by the solder paste specification and the most thermally sensitive component. Over 3000 profiles of a broad spectrum of boards were developed and run on multiple ovens in the course of this research. The research focused on the potential for improving equipment utilization and increasing line uptime by automating the reflow setup process. A further aspect of the research is the capability to dramatically reduce required operator training through the use of smart technology. This is significant for the soldering of both lead-free and high-density electronic assemblies.

The increasing density of electronic assemblies, the coming of lead-free electronic assembly, and the overall search for greater efficiencies are all issues of concern to individuals responsible for quality and productivity in the thermal process. New software technology will make it possible to setup and maintain the reflow portion of the SMT line with significantly improved efficiency.

This paper will include a discussion of new technology to manage the issues listed above and the results of extensive testing of the new technology.

Introduction

The introduction of Automated Reflow Setup Systems offers electronics assemblers an opportunity to make significant improvements to their thermal processes. Significant issues confront electronics assemblers:

- Higher process temperatures and tighter process windows required by lead-free processes
- A tightening labor market: professional, skilled, and unskilled.
- The extremely competitive EMS market.

These issues are sufficiently well known in the industry to preclude the need for more detailed discussion. The sum effect of these issues is that the thermal process, which some assemblers have neglected in recent years, will become the object of industry wide focus. All of the issues above can be addressed with improved thermal management technology.

The Status Quo

The decades old conventional method of managing conveyorized thermal processes is to profile the oven by attaching 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.

The conventional method of profiling allows for numerous inefficiencies that are unacceptable in the modern manufacturing environment.

Automated Reflow Setup Software

Automated Reflow Setup Software has been developed to address the inefficiencies endemic in the conventional method of thermal management. This package needed to contain:

- Next generation user-interfaces
- Oven Recipe Search Engine
- Direct communication with oven controller software
- “Smart” technology to automate the oven setup process

Next Generation User Interfaces

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. It comes with an updateable database of hundreds of popular solder pastes, which allows the operator to automatically select the specs for the paste being used (See Figure 5). A series of screens with clear explanatory graphics and animated instructions steps the operator through the profiling process from beginning to end.

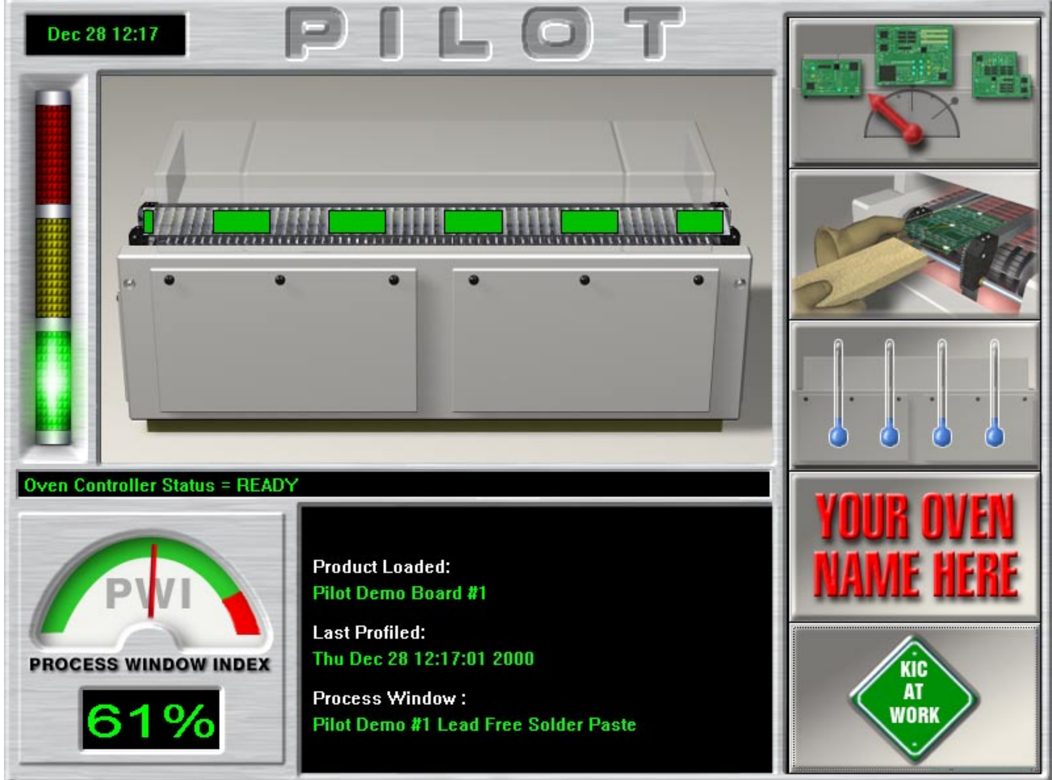

Figure 1: Simplifed Interface

Oven Recipe Search Engine

A new Oven Recipe Search Engine predicts how changes to belt speed and oven setpoints will affect a product profile. This tool creates and evaluates *billions* of potential oven recipes, automatically selecting the recipe that best fits the process window, as specified by the Process Engineer. The Oven Recipe Search Engine is designed to center the profile in the process window, and will find the optimal profile in about a minute. The tool also has the capability to find oven recipes that maximize conveyor speed.

Perhaps the most significant feature of the Oven Recipe Search Engine 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.

Automated Reflow Setup Software

The Automated Reflow Setup Software is the next evolutionary step in reflow process management, in that it does not require an expert or even an experienced operator to setup the oven. This software will allow a low-skilled operator with a few minute's training to setup an oven for an previously setup process by merely selecting a pre-profiled product recipe from a menu. The software will then automatically change the oven recipe (oven setpoints and conveyor speed) and let the operator know when the oven is ready to run production.

However, loading the correct oven recipe for a previously setup product is a fairly rudimentary task. Determining the correct oven recipe in the first place is the real trick, and the Automated Reflow Setup Software allows an unskilled operator to do this with only about an hour's training. The operator does not have to understand thermal profiling, or terms such as "peak temperature", "time above reflow", "max slope" etc., or even zone setpoint temperature or conveyor speed. A series of video animations shows the operator exactly how to complete the oven setup process. The only things the operator will need to know how to do are: attach thermocouples to a PCB, run the PCB through the oven, 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 Oven Recipe Search Engine 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, view the profiles that have been run by the operator, and view the resulting oven recipes developed by Oven Recipe Search Engine.

One key to the Automated Reflow Setup Software is an interface that allows the software to "talk" to the oven controller. The other key is the ability to calculate a profile's "Process Window Index", which ensures that an oven recipe is the best possible one for a given product. The combination of the simplified operator interface, the profiler/oven controller interface, the new Oven Recipe Search Engine, and the Process Window Index allows a low-skilled operator with about one hour's training to setup the solder reflow oven.

The key to understanding the revolutionary capabilities of the Automated Reflow Setup Software is simple. Up until now, the operator has been responsible for controlling the oven. Now, the Automated Reflow Setup Software has the intelligence to setup the oven with an optimal profile, and will not allow the operator to run product if the profile is out of spec. In effect, the Automated Reflow Setup Software's intelligent system controls the operator.

Following a definition of the Process Window Index, this paper will focus on two experiments run to verify the Automated Reflow Setup Software's capabilities.

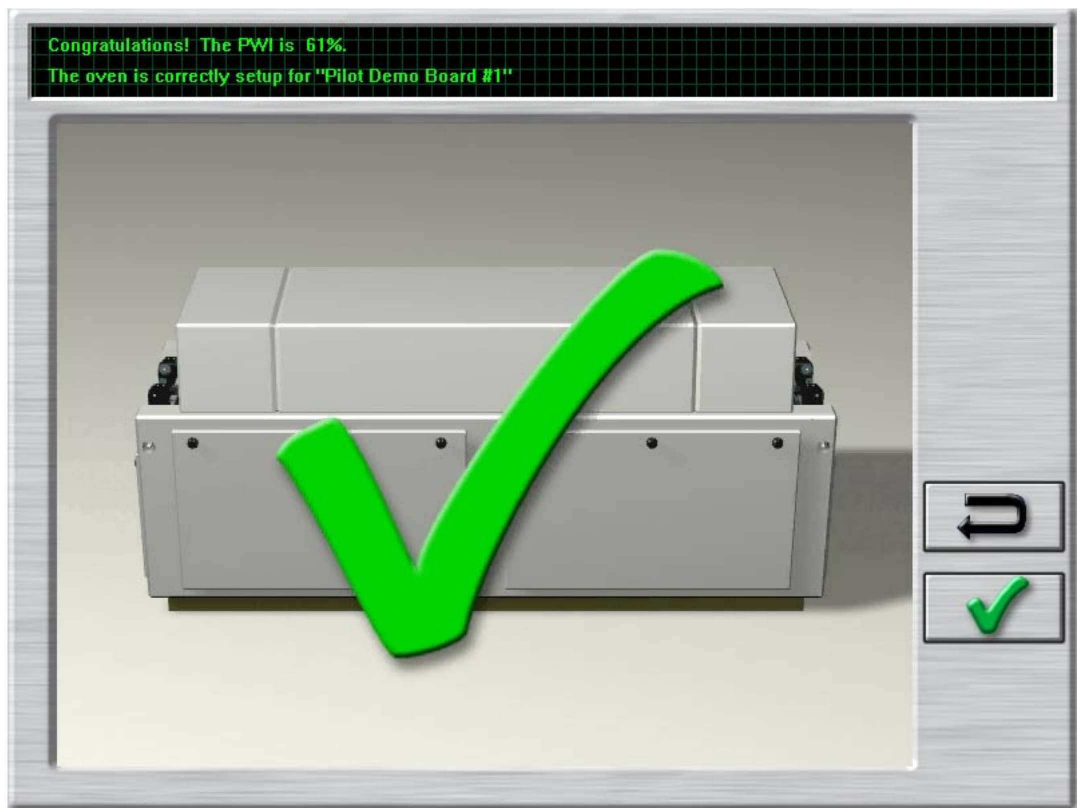

Figure 2: Automated Reflow Setup Software—Oven OK

The Process Window Index: A Method for Quantifying Thermal Profile Performance

Currently there is 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 is a statistical method for ranking thermal profile and thermal process performance.

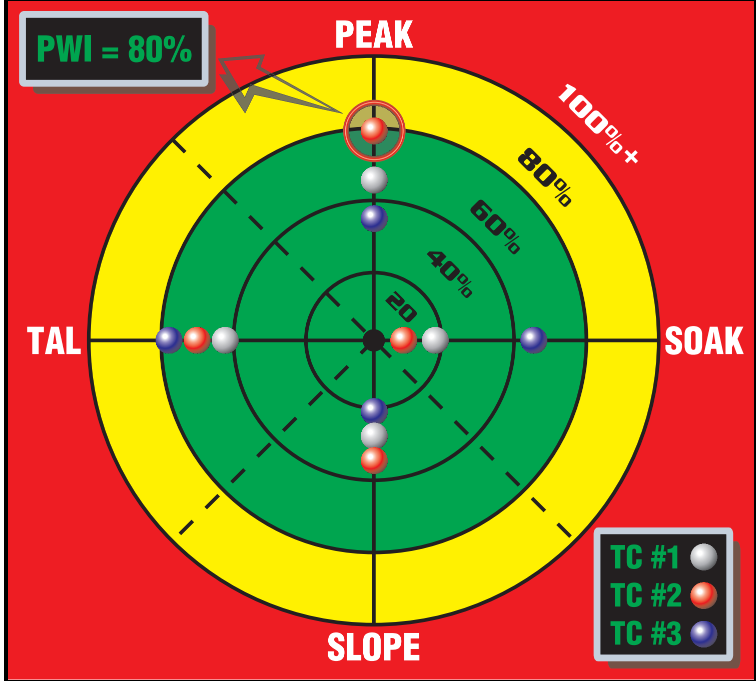

Figure 3: PWI Conceptual Diagram

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 below 80%, and profiles with a Process Window Index between 50% and 60% are commonly achieved. The figure below illustrates how the Process Window Index is calculated.

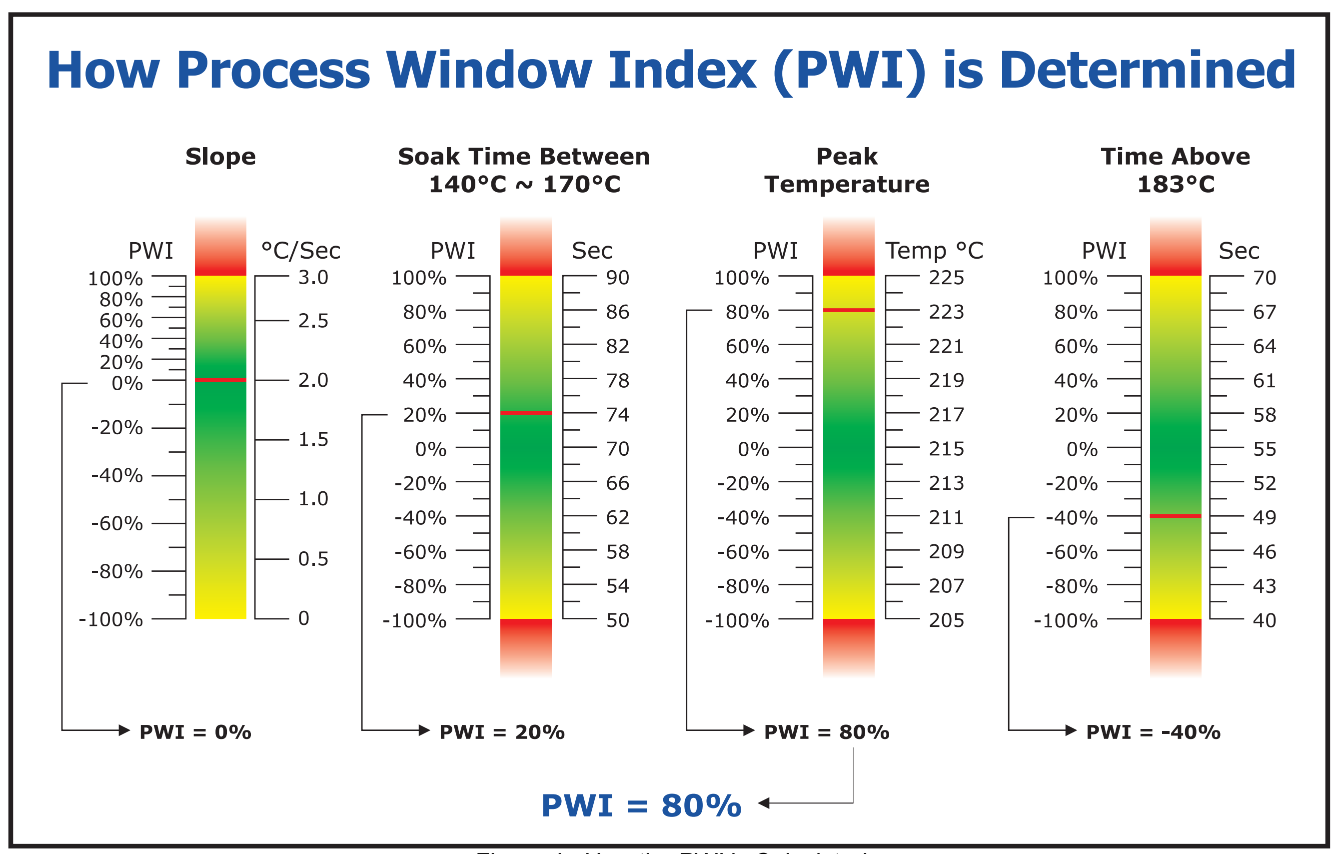

Figure 4: How the PWI is Calculated

The simplicity of the Process Window Index makes its validity as a statistical tool readily apparent, and that it clearly offers significant benefits for improving soldering processes. The Process Window Index offers users three 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. 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.

Test 1: Establishing Minimum Training Requirements

A significant issue with the current method of reflow oven setup is the complexity of oven controller and profiling software. A typical controller or profiling package requires an amount of training comparable to learning Excel or Word, with dozens of screens, dialogue boxes, and features, and operators have to learn two programs.

The Automated Reflow Setup Software significantly reduces amount of training required for an operator to successfully setup and profile a reflow oven. A single program handles both profiling and oven setup tasks, and in a facility with multiple types or brands of ovens, it is possible to have a single operator interface for all reflow ovens. The interface screen only presents 5 buttons: Load the oven recipe for a previously profiled product; Setup the oven for a new product; Load the oven cool down recipe; Go to the oven controller software; and Go to the automated oven setup software. The last two buttons are protected (engineers only), so operators really only have three buttons to worry about. Pressing any one of the three buttons takes the operator through a series of clearly defined steps in which the software tells the user exactly what to do and when to do it.

The goal in developing the Automated Reflow Setup Software was to create a program that a new hire with no SMT experience could master in hour. To test whether the software met this goal an experiment was designed. Temporary workers were hired for a half day, given as much training as they required and then asked to setup the oven for three different boards. The temp agency was instructed to send their least qualified workers. (Among these workers were one who had never used a computer and one that didn't know how to use a mouse or how to measure with a ruler.) The amount of time required to train the temporary workers to a point where they were confident with the software was tracked.

A total of six temporary workers were trained on the software and then had their performance evaluated. Although this is not a large enough number to give the test statistical certainty, the consistency of the test results indicates that they are valid. The temporary workers' education level and computer experience was tracked. Four of the six test subjects had some college (under 60 semester units) and two had high school diplomas. The four subjects with some college all had some computer experience (word processing, Internet, email) and one had experience with database and graphics software. Of the two subjects with high school diplomas, both said they had been introduced to computers in high school, but one said she had never used one. Computer experience was rated on a scale of 1-30, with 1 being none and 30 being professional technician level proficiency (Excel, some database and networking experience, etc.) The high score was 17, followed by 14, 12, and 11 (all subjects with some college). The two subjects with high school diplomas were both ranked as ones. It is interesting to note that though we requested temporary workers with no computer experience, the agency was only able to provide two.

Each subject was hired for four hours. At the test facility, each subject was given a brief overview of the SMT assembly and reflow processes. They were introduced to the Automated Reflow Setup Software, shown how to attach thermocouples a PCB with aluminum tape, and then asked to setup the oven for 3 three boards of varying size and density. Variables tracked during the experiment included: time per profiling pass; time to get each board in spec, final PWI of the profiled board; number of profiling passes to get a board in spec; and total training time. Total training time was defined as the amount of training it took until the subject felt confident they could operate the software without supervision or assistance.

On average it took one hour and fifteen minutes to train an individual who was unfamiliar with reflow procedures to a point where that they are able to profile boards and setup the oven with the optimal recipe. The range of the training times was one hour to one hour and forty-six minutes. As can be seen for the table below, subjects with some college and computer experience were all trained in under an hour and fifteen minutes. The one subject requiring an hour and forty-six minutes to train, as mentioned above, did not know how to use a mouse or how to measure with a ruler.

For the sample of six subjects, it took an average of 18 minutes per profiling pass, with a range from 14-23 minutes. Average time to get a board in spec was 36 minutes, with a range of 29-49 minutes. Average number of profiling passes to get a board in spec was 2, with a range of 1.8-2.33. Average final PWI was 48.14%, with a range 38.60-59.95%.

A question may be raised by some readers why there was a variation in the final PWI's achieved. This occurs because of the Automated Reflow Setup Software's Target PWI feature. As soon as an Oven Recipe is found that brings the PWI of the resulting PCB profile at or below the Target PWI (as set by the process engineer), the Automated Reflow Setup Software declares the process correctly setup. This occurs, even if the Oven Recipe Search Engine can find a significantly lower PWI. Depending on the complexity of the PCB, the size of the Process Window, and the number of PCBs that have been previously setup, it can take between one and 5 profiles to reach this limit. For example: if the Target PWI is set at 70%, and the software finds an initial profile with a PWI of 68%, it will stop searching, even if the Oven Recipe Search Engine finds a recipe that will reduce the PWI to 25%. However, if the initial profile has a PWI of 72%, the best recipe found by the Oven Recipe Search Engine will automatically be used and a second profile will be required. This feature was designed to save setup time, and a process engineer always has the option of setting the Target PWI to 0%, which effectively forces the Automated Reflow Setup Software to run until the Oven Recipe Search Engine cannot find a better oven recipe.

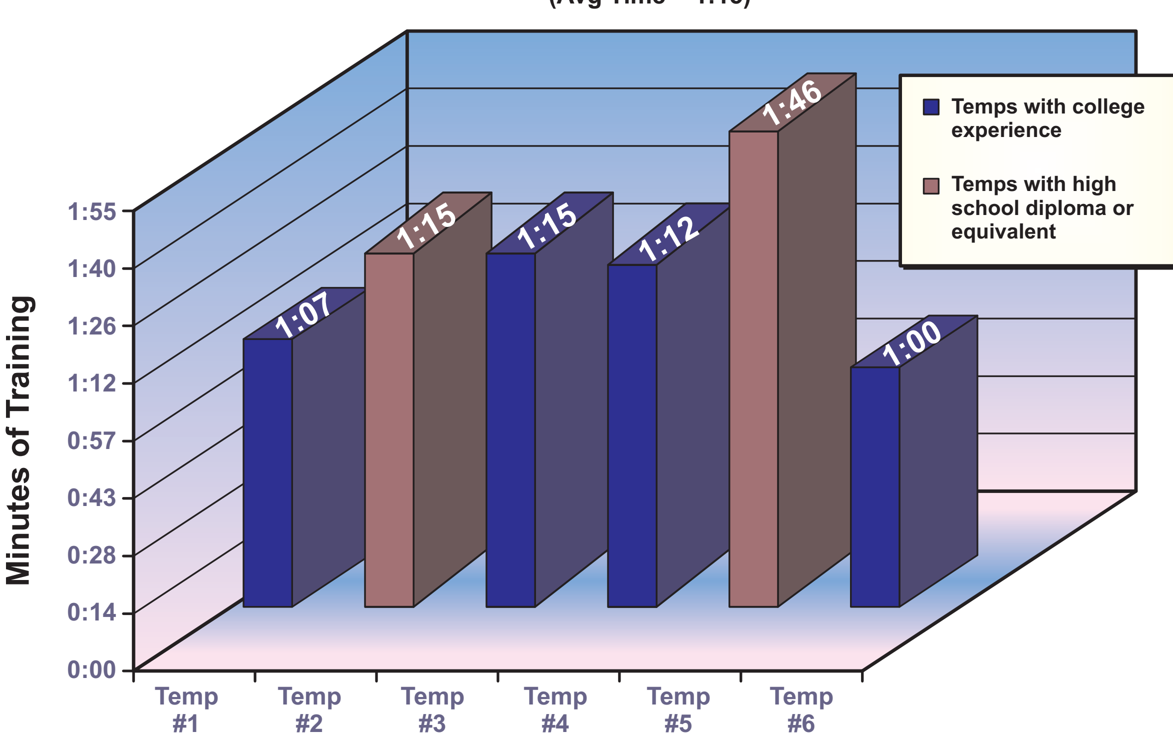

Table 1: Results of Training Test

When the session had been completed, subjects were asked to rate the ease of use of the Automated Reflow Setup Software on a scale of 1-10 (Extremely Easy-Extremely Difficult). Five of the six subjects rated the software a 1 (Extremely Easy) while the final subject ranked it a 3 (Easy). In a further test of the software's user-friendliness, a temp who worked with the self-profiling oven software for 4 hours was asked to train another temp who is unfamiliar with profiling. Without any assistance, the former temp—trained nearly three months prior—was able to train the unfamiliar temp within 1:20, and the unfamiliar temp successfully setup the oven for five different test boards.

Test 2: Self-Profiling Oven Software Capability

A second test was conducted to baseline the Automated Reflow Setup Software's capabilities. One of the software's most significant benefits is the ability to rapidly find the optimal oven recipe a given oven is capable of delivering for a given board. The procedure is as follows:

1. Operator names the board
2. Operator selects the process window (solder paste spec) for the product.
3. Operator weighs and measures the board.
4. Based on the information the operator has entered, the software searches the database of previously setup boards and finds the best first guess oven recipe.
5. Oven is automatically set to best first-guess recipe.
6. Software shows the operator how to attach thermocouples to the board.
7. Software verifies that the oven is stable.
8. Software tells operator to turn profiling unit on.
9. Software verifies thermocouples are attached correctly.
10. Software tells operator to put the board and profiling unit in the oven.
11. Profile is displayed in real-time. Operator is prompted to remove board and profiling unit from oven when profile is completed.
12. The PWI for the profile is calculated.
13. If the PWI is above the Target PWI, the oven settings are automatically changed to the best recipe found by the Oven Recipe Search Engine and we repeat the process starting at Step 7.
14. If the PWI is below the Target PWI specified by the process engineer, the oven is ready to run product. (Target PWI for this test was set at 70%.)

It is important to note that the Automated Reflow Setup Software has a "smart" capability that allows it to learn the oven's characteristics. The more boards that have been setup on an oven, the smarter the system gets. It learns the oven's characteristics and improves the results from the Oven Recipe Search Engine, thus decreasing the number of profiling runs it takes to find the optimal oven recipe.

At the process engineer level (password protected) the Automated Reflow Setup Software can be directed to focus the Oven Recipe Search Engine to minimize the PWI (most stable process), or to maximize conveyor speed (highest throughput). An additional feature allows users to direct the Oven Recipe Search Engine to only change setpoint temperatures, only change beltspeed, or to search changes to both. This feature is valuable for line balancing.

This experiment will define the Automated Reflow Setup Software's capabilities. The experiment will start with an empty database, so the software will have to "learn" the oven. The oven will be setup for five dissimilar boards and the time to find an optimal profile for each board will be tracked, as well as the quality of the final profile as indicated by the Process Window Index. Test boards varied from very light cell phone boards to a 13"x12" motherboard. After the oven was setup for the initial five boards, three new boards of varying size and density were run to determine how rapidly the system can find optimal profiles once it has characterized the oven.

The experiment was run through four iterations:

- One with the Oven Recipe Search Engine set to the minimize PWI function with a typical leaded solder paste specification.
- One with the Oven Recipe Search Engine set to the minimize PWI function with a lead-free solder paste specification.
- One with the Oven Recipe Search Engine set to the maximize throughput function with a typical leaded solder paste specification.
- One with the Oven Recipe Search Engine set to the maximize throughput function with a lead-free solder paste specification.

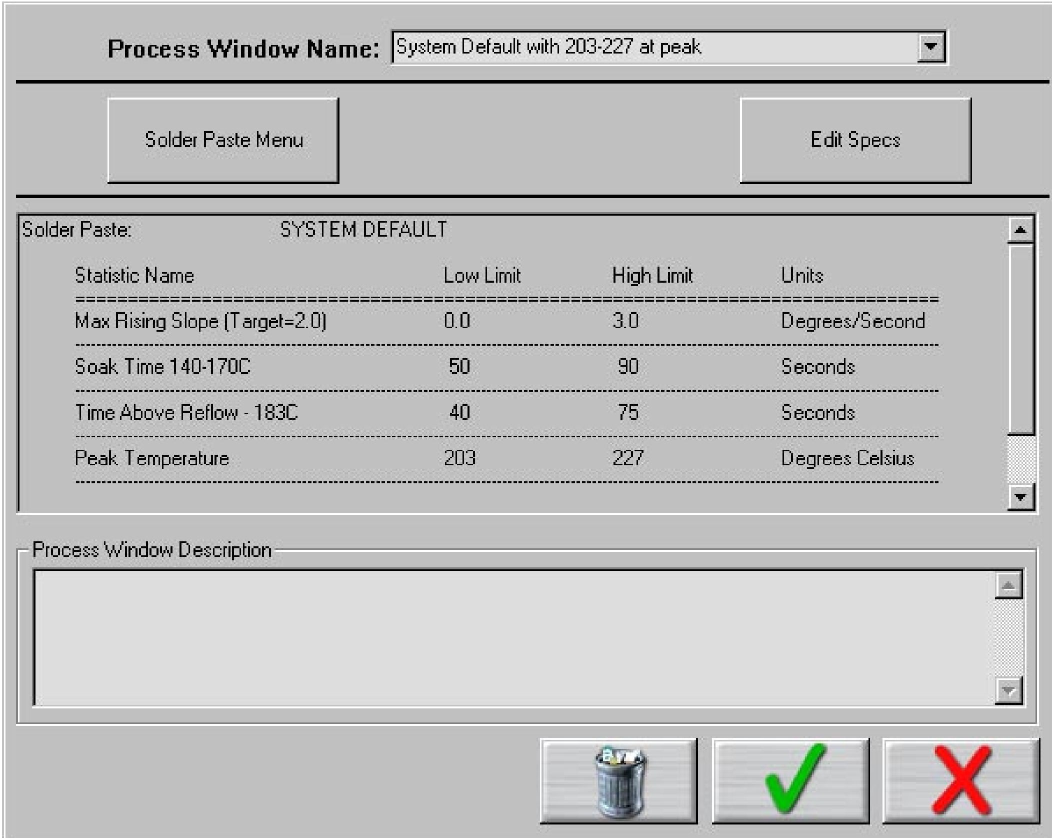

Figure 5: Lead-based Solder Paste Spec

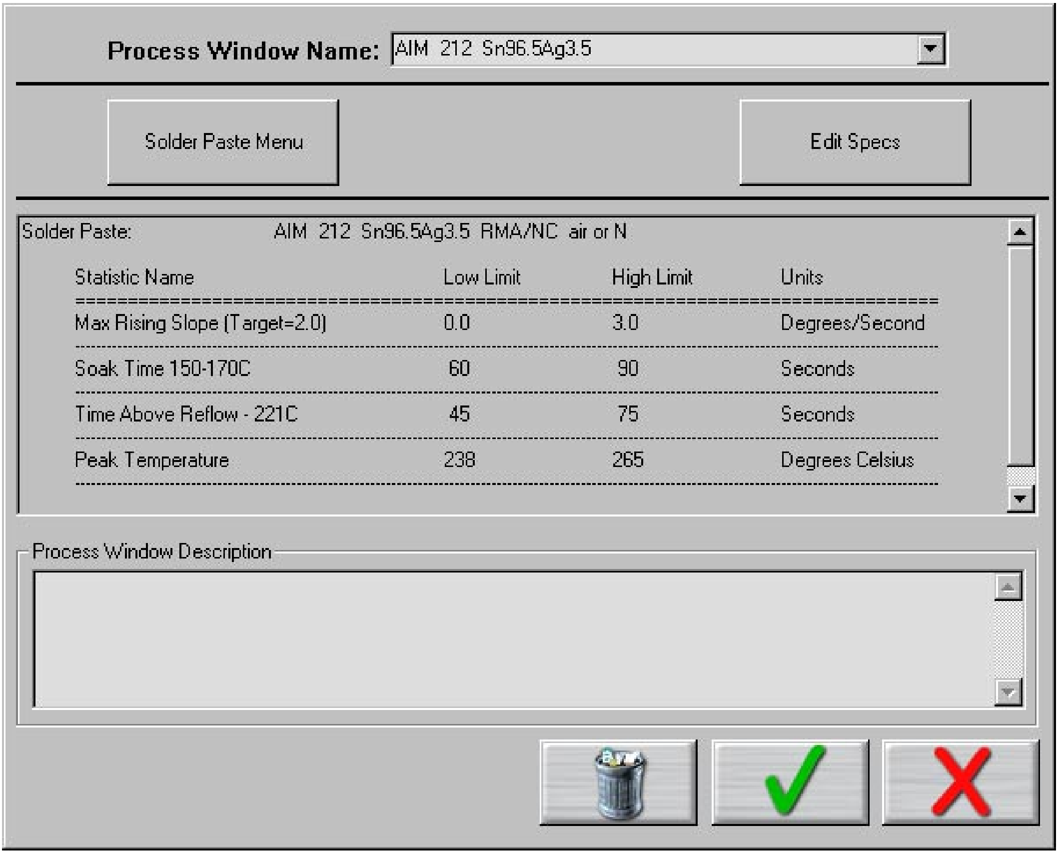

Figure 6: Lead-free Solder Paste Spec

To simplify the discussion, this paper will focus on the first iteration: the search set to the minimize PWI function with a typical leaded solder paste specification. Following the discussion of the results of the first experiment, overall findings from the complete experiment will be revealed.

Test boards were marked to ensure consistent thermocouple placement. Thermocouples were attached with aluminum tape. In the first iteration of the experiment, results were as follows:

- Board 1 took 4 profiling runs and 46 minutes to achieve a PWI of 76.9%.
- Board 2 took 2 profiling runs and 27 minutes to achieve a PWI of 71.4%.
- Board 3 took 2 profiling runs and 25 minutes to achieve a PWI of 34.4%.
- Board 4 took 1 profiling runs and 13 minutes to achieve a PWI of 63.8%.
- Board 5 took 2 profiling runs and 31 minutes to achieve a PWI of 51.0%.

Note that Boards 1 & 5 are large boards with high mixes of components (Board 1—13"x12", Board 2—11.2"x8.3"). For Board 1, when the Oven Recipe Search Engine had an empty database, it took 4 profiling runs to find an optimized profile for the board. With only four board profiles in the database, the Oven Recipe Search Engine was able to find an optimal profile for Board 5 in only two profiling runs (31 minutes). As it can take 2-4 hours to find an adequate profile using the status quo profiling method, reducing reflow process setup time by 400-800% is a significant achievement.

The functionality indicated by the initial test runs above was confirmed by setting up the oven for three additional boards.

- Board 6 was setup in a single profiling run (16 minutes) and achieved a PWI of 36.2%.
- Board 7 was setup in two profiling runs (22 minutes) and achieved a PWI of 56.0%.
- Board 8 was setup in a single profiling run (16 minutes) and achieved a PWI of 65.0%.

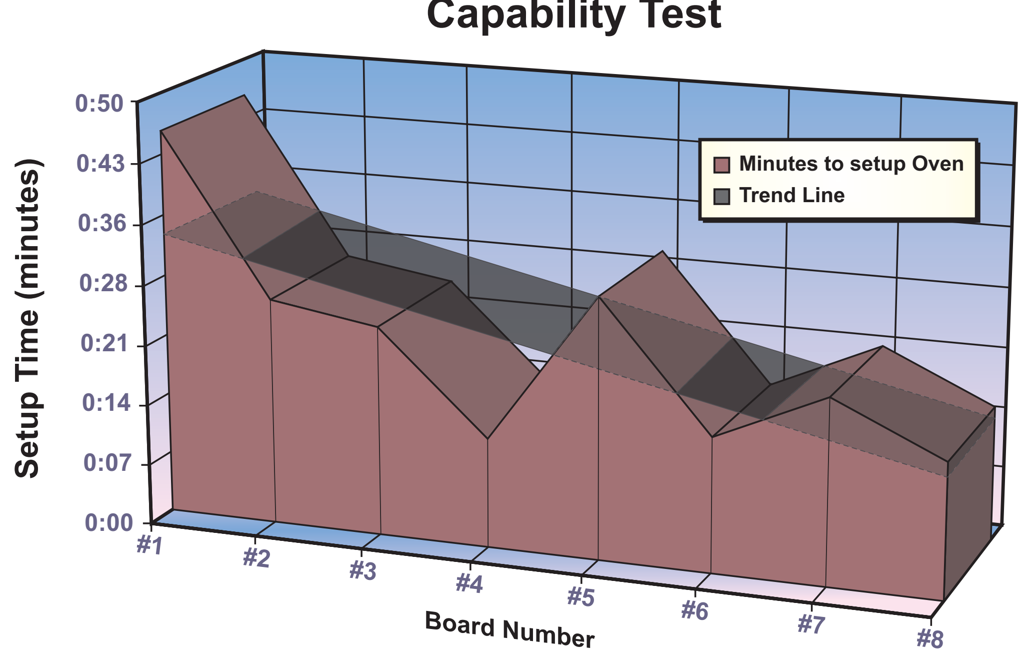

Table 2: Results of Capability Test

These results were confirmed through all four iterations of the experiment. Average time to find the correct oven recipe for a board while building the database was 26.0 minutes; average time with five boards in the database was 21.0 minutes. Average runs required to profile a board while building the database was 2.2; average runs with five boards in the database was 1.3. Average final PWI achieved for 32 profiles (eight boards x four iterations) was 55.84. A PWI of 55.84 is indicative of an extremely robust profile that will be unlikely to drift and will consistently provide the highest quality solder joints.

Another confirmation of the Automated Reflow Oven Software's capability can be found by comparing the results of the Minimize PWI iterations to the Maximize Conveyor Speed iterations (Table 3).

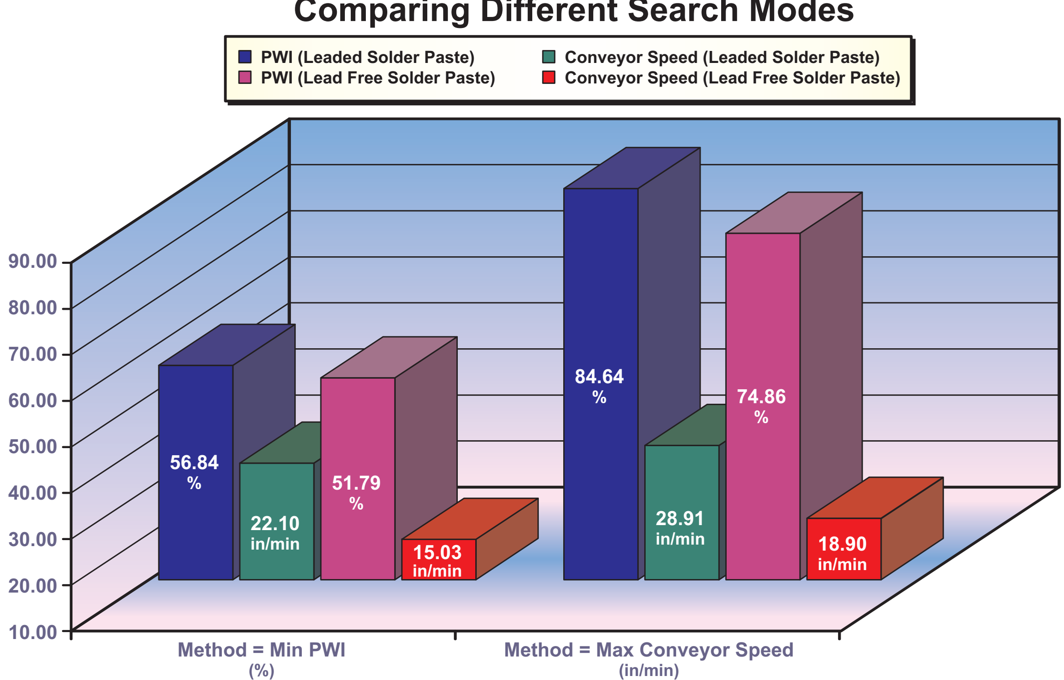

Table 3: Comparison of Minimize PWI Results to Maximize Throughput Results

As can be seen in Table 3, for both standard and lead-free solder pastes, when told to Minimize PWI, the Automated Reflow Setup Software found profiles that were very robust. When asked to Maximize Conveyor Speed, the Automated Reflow Oven Software was able to significantly increase conveyor speed (especially for the standard paste), though at the cost of an increased PWI. The ability to make a trade off between maximizing throughput and minimizing PWI is an option that will prove valuable to many users.

Conclusions

Automated Reflow Setup Software offers contract manufacturers and OEM's tools to meet the challenges of the current market and enjoy a multitude of benefits. As established by the tests above, this technology's capabilities include:

1. Virtually instant training. Reflow process setup is vastly simplified, and a minimally trained operator can find an optimal profile. Anyone can setup a reflow process with this software.
2. Rapid reflow process setup, which means better equipment utilization and improved line uptime—which goes directly to the bottom line.

Other benefits of Automated Reflow Setup Software include:

- Optimized profiles—better profiles than are achievable by the most experienced process engineer.
- Simplified setup and operator interface—no board mapping.
- Comprehensive solder paste database.
- Increased throughput.
- Optimized profiles to meet the higher peak temperatures and tighter process specifications required by lead-free solders without damaging sensitive components.
- The PWI allows users for the first time to compare thermal profile and equipment performance.
- 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 Automated Reflow Process Software to determine which product is entering the oven.)

The bottom line is that the Automated Reflow Process Software is simple, fast, and it works. It brings the reflow process up to a level of automation the screen printers and pick and place machines have enjoyed for years and is a significant step towards the goal of completely automating SMT production.

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