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Automated SPC for the Reflow Process

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Abstract
This paper will discuss the implementation of real-time automated SPC for the Reflow Process. Topics covered will include: a new statistical method for quantifying the thermal process performance; methods for ensuring that SPC data provides a true representation of process capability; and the value of automated real-time SPC.

To realize the full benefit of an SPC program, it is essential to define and set process specific control limits. SPC programs based on "targets" rather than process specific control limits are not capable of reliably predicting process trends, which is the primary function of an SPC program. Developing a fully functional SPC program requires a sufficient data set on which to project process trends. Another key factor in the success of an SPC program is efficiency. An inefficient method of data gathering and analysis is a guarantee of failure, as a program that consumes excess resources will quickly be abandoned. One method for increasing SPC program efficiency is to focus on key process statistics. A statistical method has been developed that reduces all key process statistics to a single number: the Process Window Index. The calculation of the process Window Index will be defined and its validity as a statistical method for developing Cp and Cpk for the reflow process established.

The continuous and automated gathering of data is essential for successful SPC monitoring of the reflow process. Current methods generally rely on periodic profiling, which disrupts production and provides an inaccurate "picture" of the process. Automated Continuous Monitoring Systems for the reflow process have been developed. These systems can provide a data point for every board processed by calculating a "Virtual Profile". A design of experiment (DOE) will be run to establish that the "Virtual Profile" is a reliable method of continuously gathering data on the reflow process. Experiment methods and results will be included.

Automated SPC for the reflow process offers significant benefits for Electronics Assemblers. Automated SPC provides a significant sales tool for EMS's, as it allows them to prove to customers that their reflow process is in control and that their facility is dedicated to quality electronics assembly. This paper will be of interest to engineers and managers interested in increasing reflow process efficiency and quality.

Introduction
To realize the full benefit of an SPC program, it is essential to define and set process specific control limits. SPC programs based on "targets" rather than process specific control limits are not capable of reliably predicting process trends, which is the primary function of an SPC program. In developing a fully functional SPC program it is essential to gather a sufficient data set on which to project process trends. SPC programs that are based on insufficient data, for example, a single profiling run with a fixture at a set daily or weekly interval, give an inaccurate indication of process capability.

Another key factor in the success of an SPC program is efficiency. An inefficient method of data gathering and analysis is a guarantee of failure, as a program that consumes excess resources will quickly be dropped. The continuous and automated gathering of data is essential for successful SPC monitoring of the reflow process. For most sections of the SMT assembly line, data for process control is readily available. Until now, however, this hasn't been true for the reflow process. Current methods generally rely on periodic profiling, which disrupts production and provides an inaccurate "picture" of the process. An Automated Continuous Monitoring System for the reflow process has been developed that can provide a data point for every board processed.

The Statistical Validity of the Process Window Index
The Process Window Index is a statistical method for ranking thermal profile and thermal process performance. While there are currently statistically valid methods for quantifying pick and place and screen printer performance, there is no widely accepted method for comparing performance of thermal processes, 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, or perhaps just 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 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. Process limits, which provide the "frame" for the Process Window, are usually based on solder paste specifications, though sometimes there are other considerations, such as a thermally sensitive component or assembly. A profile that will process product without exceeding any of the 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 (See Figure 1). 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 less than 80, and profiles with a Process Window Index between 50 and 60 are commonly achieved (if the furnace is sufficiently flexible and efficient). The figure below shows the Process Window Index for the Peak Temperature of a single thermocouple. (See Figure 2) 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.

Note that Figure 3 shows the user designated critical statistics for a single thermocouple. (See Figure 3)

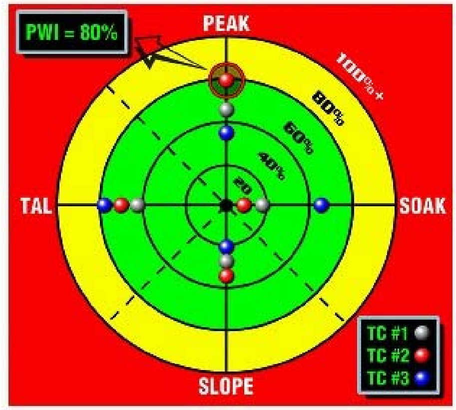

Figure 1 - Process Window Index

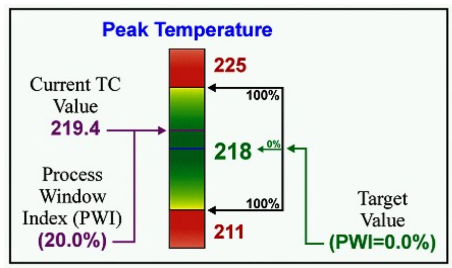

Figure 2 - The Process Window Index (Single Statistic—Peak Temperature of One Thermocouple)

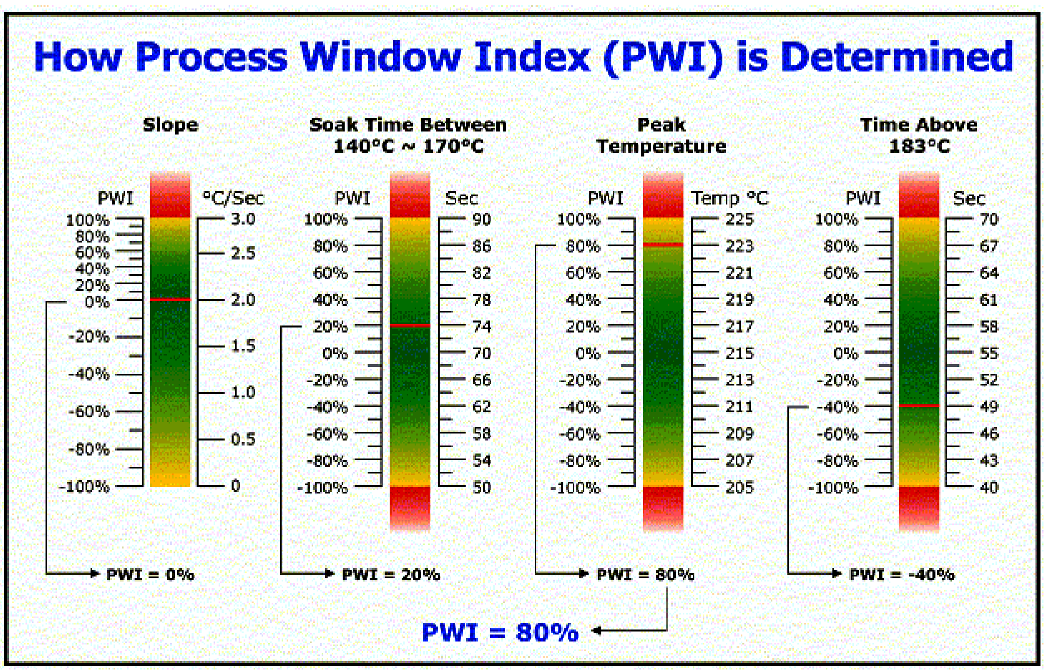

Figure 3 - The Process Window Index (Multiple Statistics for a Single Thermocouple and Final PWI Calculation)

Calculating the PWI

To calculate the Process Window Index, let 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).

Table 1 - Process Window Index Formula

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

Note that the PWI calculation includes all profile statistics logged. ***N*** Thermocouples x ***M*** statistics logged per thermocouple. The profile PWI is the worst case profile statistic (highest percentage of the process window used), and all other values are less.

Benefits of Ranking Thermal Profile Performance

The Process Window Index offers 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 benefit is that the PWI greatly simplifies the profiling process. When used with advanced profiling tools, (e.g. Oven Recipe Search Engine) 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. Finally, 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.

Automated Reflow Management System

Automated Reflow Process Management is based on the following concept: a system is designed to collect product temperatures while simultaneously measuring process temperatures in the furnace at board level at thirty locations. Based on the data collected during a baseline profiling run, process temperatures at board level are correlated with to the actual product temperature. During production, changes in those temperatures can be analyzed through a mathematical model to simulate any changes in the product profile.

Automated reflow management systems that combine continuous SPC charting, line balancing, documentation, and production traceability into one software package have recently been introduced. These systems are designed to feed real-time process data to engineers and managers, allowing them to make critical decisions affecting production costs and quality. They are capable of providing and recording real-time thermal process data for every product, as opposed to the conventional practice of only periodically checking oven performance. SPC charting and the calculation of process Cpk allows the system to automatically catch process drift and prevent potential defects before they happen, rather than discovering actual defects in "Inspection".

The automated reflow management system utilizes thirty thermocouples permanently embedded inside the conveyorized oven/furnace at the process level. The thermocouples are configured in two probes with 15 internal thermocouples inside a flexible stainless steel weave. The probes are installed along the conveyor at product level and run the length of the process. (See Figure 4) Modern automated reflow management systems include more responsive probes than previous thermal monitoring systems. The thermocouple probes need to react quickly to changes in airflow and temperature, which are indicative of changes in temperature experienced by the product. Increasing the sensitivity of the probes reduces system response time to changes in airflow and temperature in the oven, which allows the system to more precisely monitor the changes to the process as a product passes through the oven. This hardware upgrade improves the accuracy of the *Virtual Profile,* which will be verified in the DOE below.

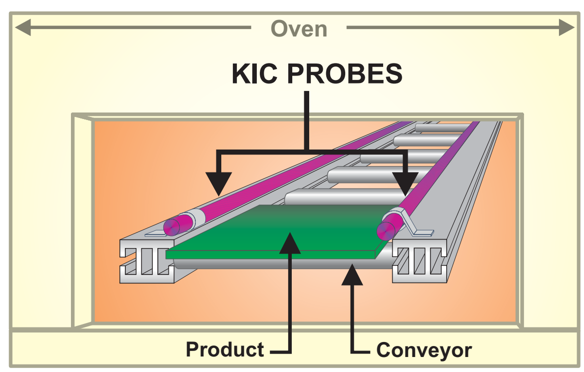

Figure 4 - Thermocouple Probe Location in Oven

The basic functionality of the automated reflow management system is to accurately and automatically collect data on and monitor product passing through the reflow oven. The system automatically and efficiently verifies the profile of every board processed, and this functionality allows the system to provide significant benefits:

1. Eliminate the need for process verification profiles.
2. Provide real-time feedback and alarms for zero-defect production.

3. Completely automate reflow process data collection for product traceability and process documentation.
4. Provide automated SPC charting of the reflow process, and the capability to alarm off variances in process Cpk.

One of the most significant differences between currently available automated reflow management systems and previous real-time thermal monitors is that the new system is a production solution rather than an engineering tool. System software has been designed to be completely intuitive for maximum ease of use. This ease of use means that the process can be monitored with a minimum of human resources, and training costs can be significantly reduced. The automated reflow management system's ability to interface directly with the oven controller on selected models from leading manufacturers offers additional process efficiencies. When setpoints are changed in the software, (e.g. changing over to a previously profiled product), the data can be downloaded automatically to the oven, eliminating the need for separate data entry.

The Virtual Profile

The means for verifying the profile of every board produced is the *Virtual Profile.* The Virtual Profile is established by running a baseline profile of the product with a real-time profiler while simultaneously collecting real-time data from the 30 permanent sensors in oven. The mathematical correlation between the temperatures at product level and the temperatures on the product itself allows the software to accurately simulate changes in the product profile. Once the Virtual Profile has been established, the system goes to monitoring mode with real-time simulation of how the profile of the board is changing based on probe readings. The automated thermal management system monitors and records beltspeed and process temperature variations. Process temperature or airflow cannot change without affecting the product temperature, and the software's algorithms accurately extrapolate changes in process temperature to changes in the product profile. The accuracy of this computer simulation will be established in the DOE below. (See below in DOE section for Virtual Profile images.)

Automated Spc for the Reflow Process

Typically electronics assemblers make every effort to produce assemblies that are identical, but the reality is that there are many variables that come into play, for example: materials, equipment, and operators. If changes occur in any one of these variables, the assemblies may vary from the customer's specifications. Therefore, it is essential that the process is monitored at each step in order to detect process changes.

These changes to a process usually follow a normal bell shaped curve. If the process is normal and stable, a statistical process control (SPC) plan can be put in place to monitor the variation in the process. This variation is represented by the standard deviation (σ), a statistical calculation. From this calculation the upper and lower control limits can be calculated on the bell curve (mean $\pm$ 3 σ). The process is considered out of control when any points for a particular statistic fall outside the control limits. The process engineer must evaluate whether the initial control limits yield an acceptable defect rate. If the defect rate is not acceptable, tighter process control is required.

The use of process performance metrics allows the user to determine the actual process capability. These indexes represent how stable the process is and how centered it is within the specification limits. However, these values are not valid if the process is not in statistical control (Note: from the specification limits on the bell curve process yield can be determined. Any area inside the specification limits of the bell curve represents units conforming to specification. Any area outside the specification limits of the bell curve represents the probability that a defect will occur. This percentage translates into defects ppm.)

What is essential to a successful SPC plan is the ease of use to capture and tabulate the data. The following report details SPC data collection using a software tool to monitor a reflow furnace process. Currently there are two widely implemented methods for tracking reflow process performance: qualifying and establishing machine/oven capability (Cm); or monitoring the capability of the process itself (Cpk). Cpk is the process capability index that takes into account the process shift that often occurs in real life. It is defined as Cpk=(Mean - Closer Spec Limit)/3σ. For the reflow process, machine (furnace) capability is generally monitored through the use of a profiling fixture or a "golden board". Using this method and running profiles at a given interval is done to establish that machine capability remains constant. There are several problems with this method.

1. Running profiles consumes human resources, and, more critically, results in line downtime.
2. This method only provides a "snapshot" of the process. For example, if the procedure is to run a profile with a fixture or a golden board every Monday at 8:00, all the user really knows about their process is that it is in spec on Monday morning. Any variables introduced into the process at any other time of the week will remain undetected.
3. Focusing on machine capability means that true Process Capability (Cpk) is not calculated. Cpk can only be calculated based on process data.

4. This method provides a very limited set of data points. To have a 99% certainty of detecting a one-sigma shift in process (or machine) capability requires a data set of 98 subgroups. To collect this much data running even *daily* profiles would require at least four months. (See Figure 5)

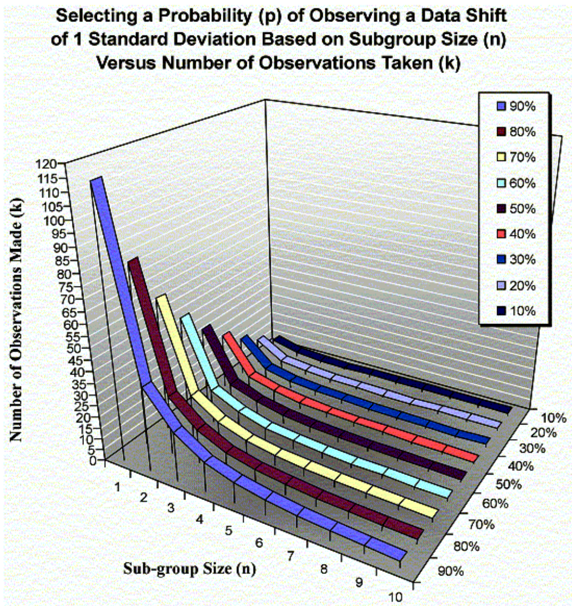

Figure 5 - Sample Size and Certainty of Detecting Process Drift

Continuous monitoring of and ongoing measurement of process capability during production is superior to monitoring machine capability for Process Control, and requires a different approach to generate statistically valid measurement with a high confidence level. This requires data from actual production runs based on measurements taken from a production board rather than a standardized fixture or golden board. Process monitoring must be done in real-time and continuously in order to catch all common causes of variation that are likely to affect the process during normal production.

With an Automated Reflow Management System, real-time process monitoring is vastly simplified, and more importantly, SPC accuracy is maximized. Once a profile has been established within a user defined process window, an automated reflow management system is used to monitor production for that particular board. In the real-time monitoring mode, the system produces a real-time profile chart and a table of key process statistics that is updated every time a board exits the furnace. (See below in DOE section for Virtual Profile images.) On other screens, accessible by tabs, there are Cpk control charts for each statistic, as well as a control chart for the overall Process Window Index (see above) of the product. Data is updated and saved and Process Capability (Cpk) calculated for each board as it exits the oven. For each production board, based on the profile established and the current probe readings, the system produces and records a simulated temperature profile.

Once the virtual profile has been established, the system will automatically begin to gather SPC data when the first board exits the oven. Every time a board exits the oven, the data set is plotted on frequency histograms. Process data is charted for all critical process specs: peak temperature, soak time, time above liquidus, etc. The data is plotted on *real-time control charts* and *Process Capability* (Cpk) is calculated for each specification. The overall Process Window Index (PWI) is charted, providing a *Real-time Cpk for the entire process*. Any process drift outside of control limits will bring an immediate alarm. The process engineer also has the option of setting a warning limit on the Cpk. Real-time Cpk tracking enables the system to flag an out of control process before the furnace has produced a single defect.

Design of Experiment

The objective of this study was to validate an automated reflow management system on a reflow furnace. The goal was to ensure that the software's calculated profiles matched actual thermocoupled profile results for boards loaded into the furnace.

The test vehicles were small consumer products (See Figure 6). Thermocouples were placed on the bottom right and top left corners across the board. The Reflow Furnace was configured with 10-heated and 2-cooling zones. The furnace was also configured with frequency controllers, which ensured tight process control. The frequency controllers in each of the zones ensure that there is no heat transfer loss at higher temperatures in the convection furnace. An automated reflow management system was utilized to develop the profile, collect data, and monitor the process.

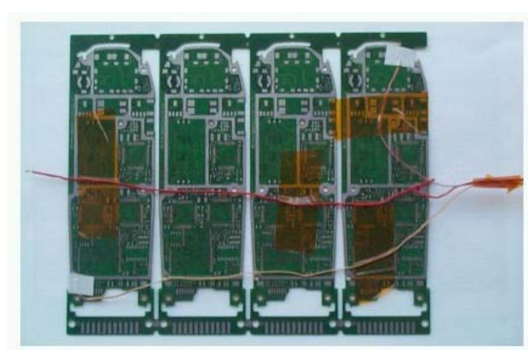

Figure 6 - Test Vehicle 45 Grams

The following $Sn_{62}Pb_{36}Ag_{02}$ solder paste criteria were used to develop the profile and monitor the process performance.

- Maximum ramp rate 2 °C/sec
- Soak Time 0 - 60 seconds between 150 - 170 °C
- Time above liquidus (179 °C) 30 - 90 seconds
- Peak Temperature 204 - 224 °C
- Maximum Cooling Rate 4 °C/sec

The recipe set points utilized to develop these profile criteria for the test vehicle are found in Table 2. Once the profile for the consumer product was developed using an oven recipe search engine (See Figure 7), a virtual profile was established under a loaded condition in the furnace (See Figure 8). In order to validate that the virtual profile represented an actual thermocoupled profile of a board, a design of experiment test plan was put together (Table 3). The test plan simultaneously ran virtual and actual profiles and compared the PWI results using hypothesis testing (Analysis of Variance – ANOVA).

Three trials were run under loaded conditions to simulate real-world production. This validation capability is included in the software and the Verification Profile can only be run when the virtual profiling is run in the live mode (See Figure 9).

Table 2 - Optimal Furnace Set points

Zone	Temp °C
1	80
2	100
3	120
4	140
5	160
6	164
7	179
8	223
9	220
10	223
Belt Speed (ipm)	38

Table 3 - DOE Test Plan: One –Way Classification Analysis of Variance

Treatment	Observed PWI Responses	Total
Actual Profile	X_{11}, X_{12}, X_{13}	T_1
Virtual Profile	X_{21}, X_{22}, X_{23}	T_2

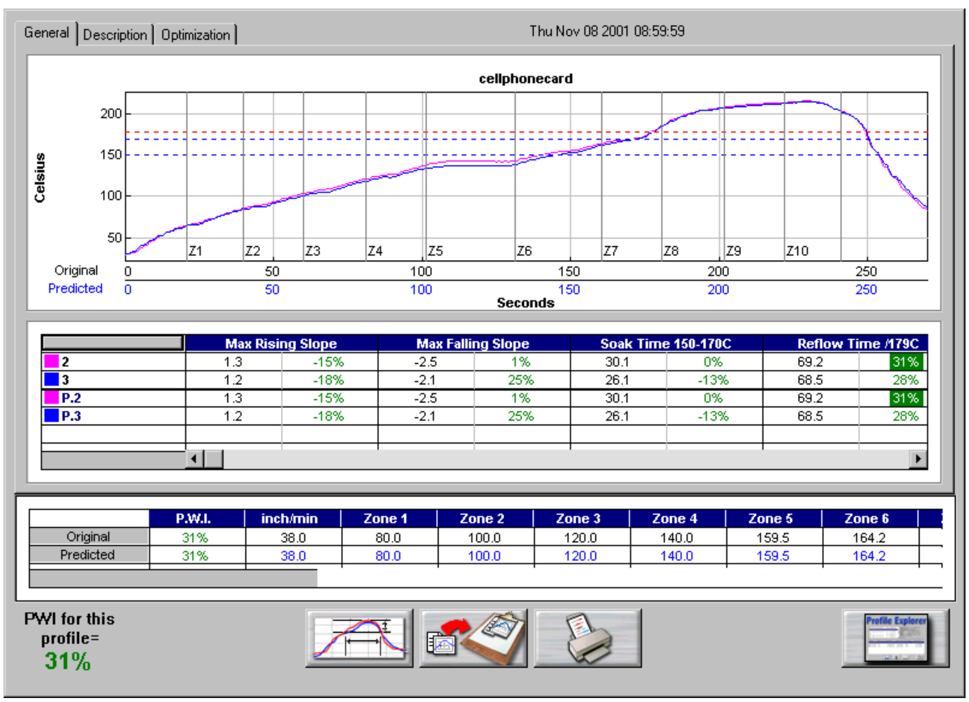

Figure 7 - Actual Profile

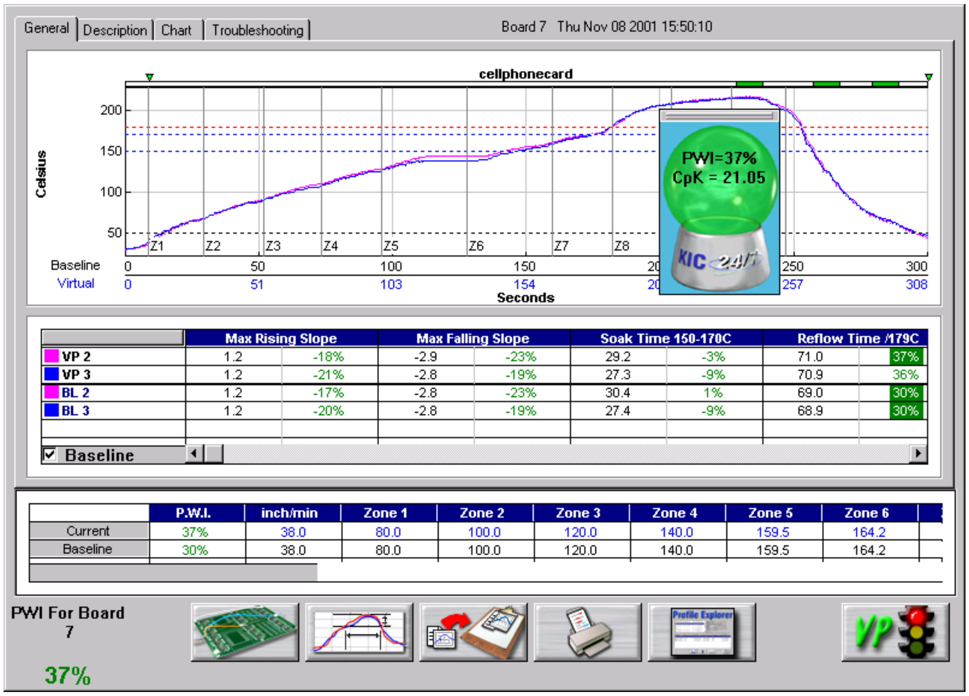

Figure 8 - Virtual Profile

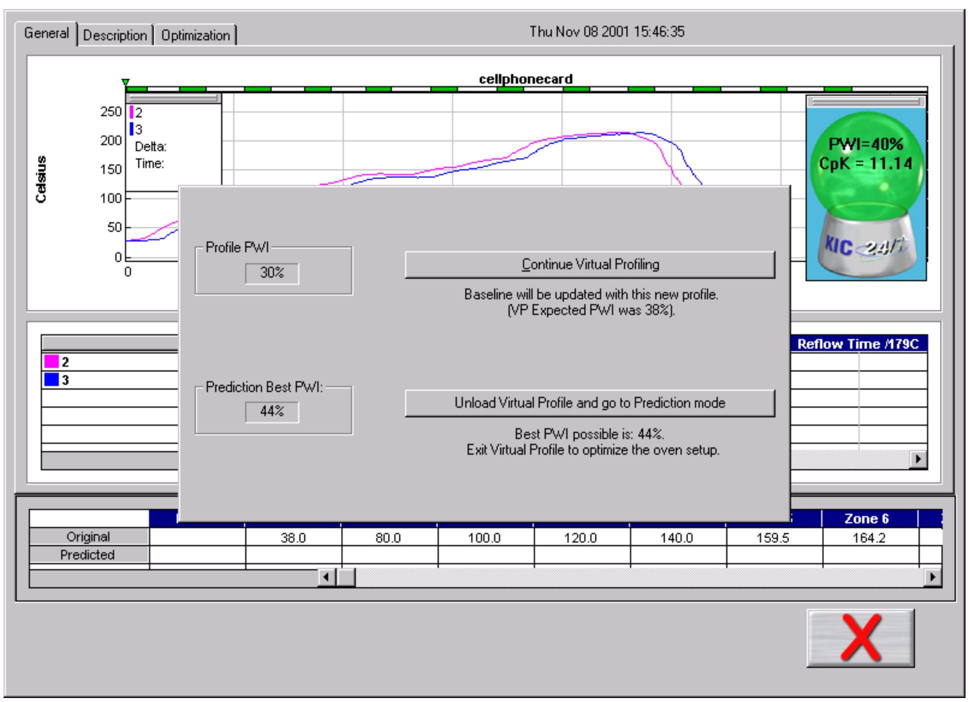

Figure 9 - Verification Page Dialogue Box

Results

The original product profile created by the oven recipe search engine demonstrated a peak temperature delta of 1.2 °C in the reflow zones. This parameter is critical because if the temperature is too high components can be damaged and if the reflow temperature observed at the solder joint is too low the solder does not reflow and produce good solder joints.

The time above liquidus demonstrated the highest PWI for all the process specifications: 69.2 seconds in a range of 30-90 seconds. Too long a time above liquidus could lead to embrittlement. The Process Window Index (PWI) achieved while developing the profile was 31%. The DOE PWI test results are shown in Table 4.

Table 4 - DOE One-Way Classification ANOVA of PWI Results

Treatment	Observed PWI Responses	Total
Actual Profile	34, 33, 30	97
Virtual Profile	35, 31, 35	101

Prior to the DOE seventeen boards were run through the system and a virtual profile was calculated for each as it exited the furnace. After five boards went through a Cpk value was calculated (This is the minimum sample required to calculate Cpk). All the critical statistics had a Cpk greater than 1.33 (See Figure 10) indicating that furnace performance was exceptionally stable. Next, we began the DOE tests. For Trial One thirty boards were run and a virtual profile was validated. The virtual profile for board number 30 showed a PWI of 35% (See Figure 10). The actual product profile for board number 30 was 34% (See Figure 11). These validation tests were repeated by running two verification profiles of thermocoupled boards in the furnace under loaded conditions. The virtual profile for Trial Two (the virtual profile that was validated was board number 33) had a PWI of 31%. (See Figure 12). The actual product profile (simultaneously run with a real-time profiler) had a PWI of 33%. (See Figure 13). For the Third Trial the virtual profile for Board 19 showed a PWI of 35% (Figure 14) and the actual product profile for board 19 demonstrated a PWI of 30%. (See Figure 15). In all tests the PWI proved to be statistically equivalent for the virtual and actual product profiles (See Table 5), thus, providing the conclusion that there is not a difference between the means of the virtual and actual profiles. The Cpk all were well above 1.33, which indicates the process and furnace performance were exceptionally stable.

Table 5 - ANOVA Table Test Results Comparing Virtual and Actual PWIs

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Test Statistic
Treatments	2.7	1	2.7	.56
Error	19.3	4	4.8	
Total	22	5		

Note: rejection that the means are equal for the different treatments occur when F-Test Statistic > $f_{\alpha,r-1,N-r}$. Since the F-Test Statistic (.56) was less than $f_{.05,1,4}$ (7.71) it is sufficient to assume that the virtual profile and actual product profile are fair representations of each other.

Figure 10 - Process Control Charts for Test 1

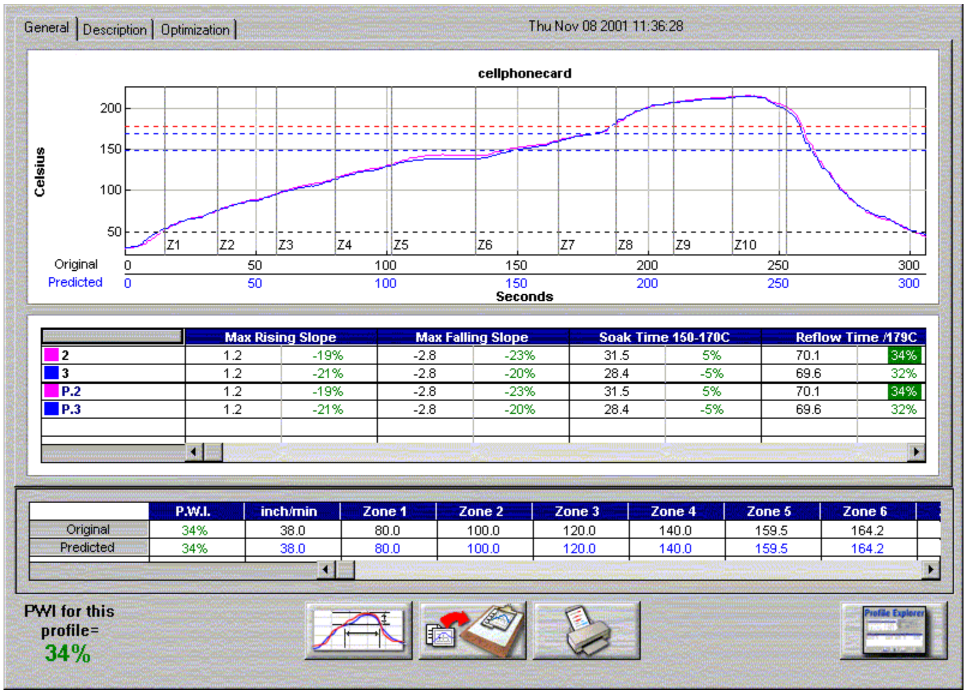

Figure 11 - Validation Profile for Board 30 Test 1

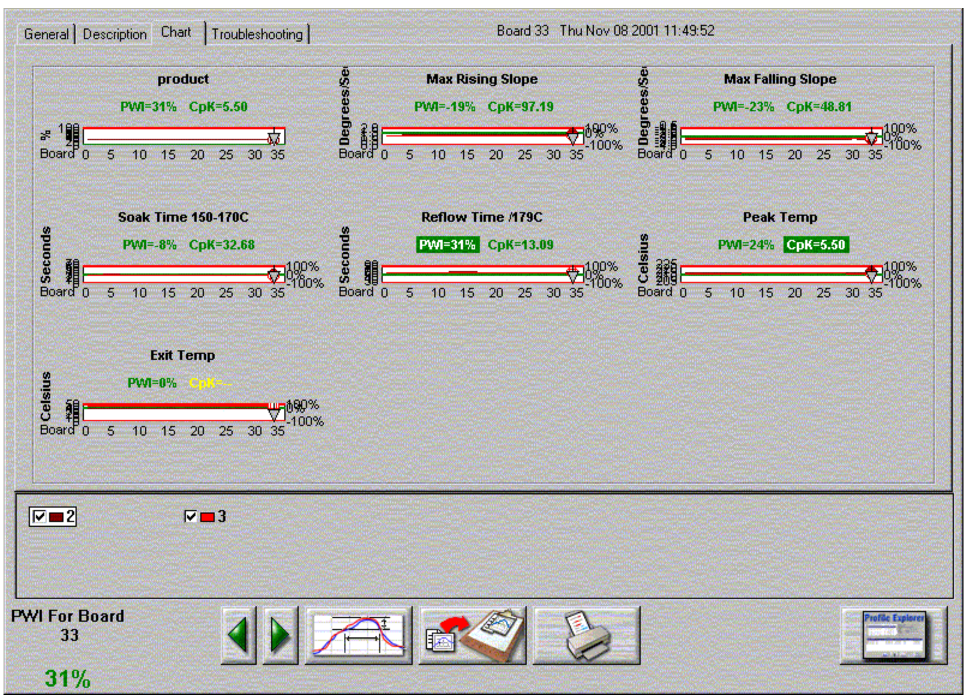

Figure 12 - Process Control Charts for Test 2

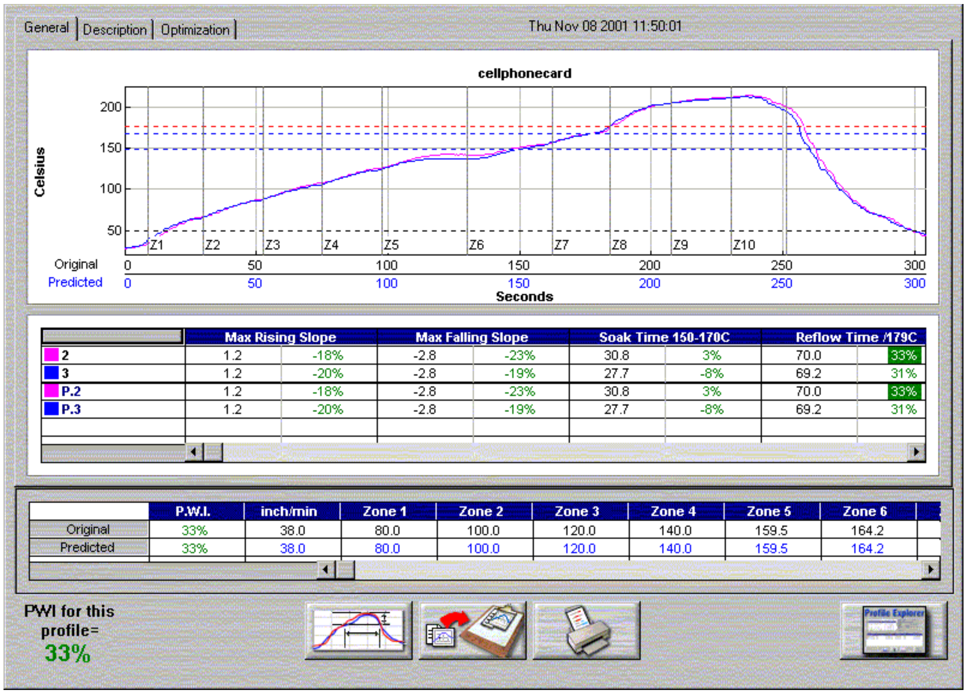

Figure 13 - Validation Profile for Board 33 Test 2

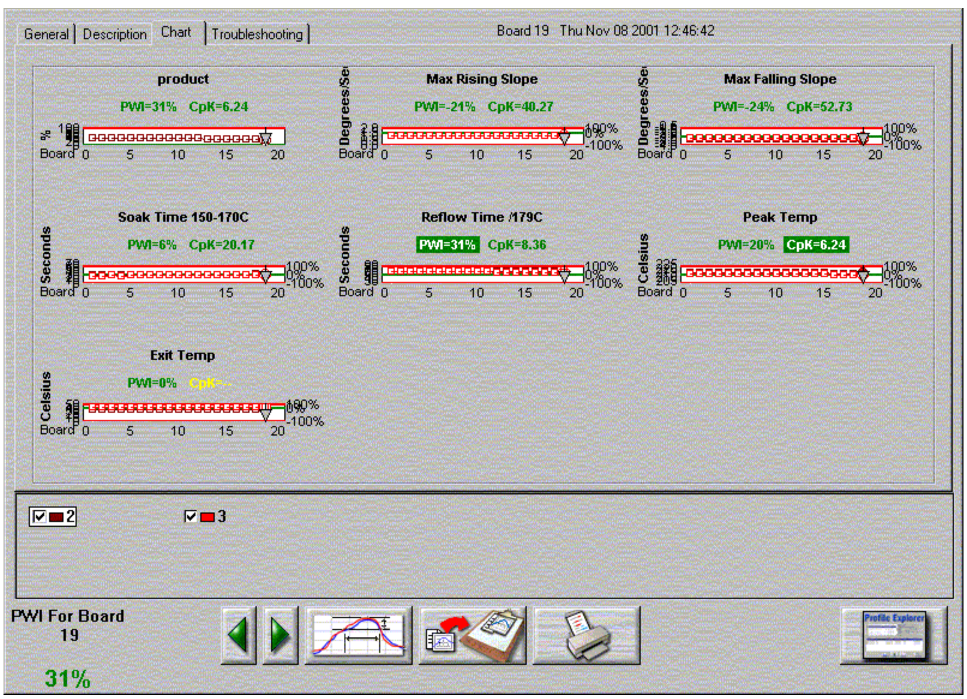

Figure 14 - Process Control Charts for Test 3

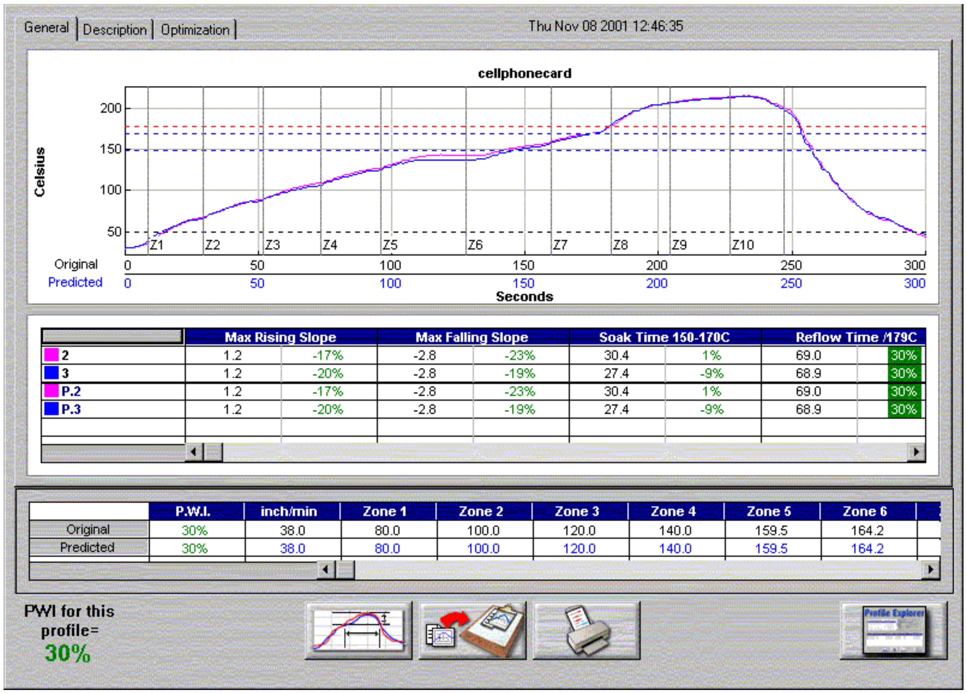

Figure 15 - Validation Profile for Board 19 Test 3

DOE Conclusion

The automated thermal management system demonstrated that the virtual profile algorithm is very accurate. If there is a drift in the process, the software allows profile verification to confirm the drift. The software demonstrated the tight process control of the furnace. The control charts and Cpk values at each instance of time indicate how reliable, repeatable and capable the furnace performance is. The chart page allows the operator to monitor for any process drifts immediately so unnecessary production costs are not generated. The operator can then notify the engineer so that he or she can evaluate the situation with a built in troubleshooting screen to determine a root cause and rectify the situation immediately. The Cpk index allows the operator to measure real process capability and determine if process shifts are occurring. The Cpk index allows the operator to compare one furnace's performance to another or furnace performance from day to day. The Cpk values obtained these trials were well above 1.33. This was due to the fact the furnace demonstrated tight process control. The sigma for each statistic was very small and the process was well centered with the help of the optimized profile developed using an oven recipe search engine software algorithm. In addition, the statistic range each parameter measured is wide. As the engineer's tighten their process variation, they can bring in the specification limits for each of the process factors and hence, the values will decrease.

Conclusion

The ultimate objective for any electronics assembler is to improve manufacturing efficiency to achieve higher quality at a lower cost. To improve and assure quality, continuous real-time monitoring of the process and a proactive SPC system are required. The method for achieving this is to use advanced technology for process development and control. An automated reflow management system provides a valuable tool for measuring process performance. This technology allows users to maximize efficiency, minimize costs, improve yields, and improve product quality.