The Science Behind Conveyor Oven Thermal Profiling

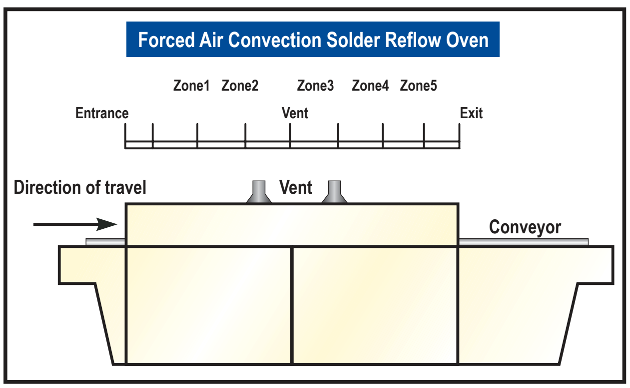
By Philip C. Kazmierowicz, 1992

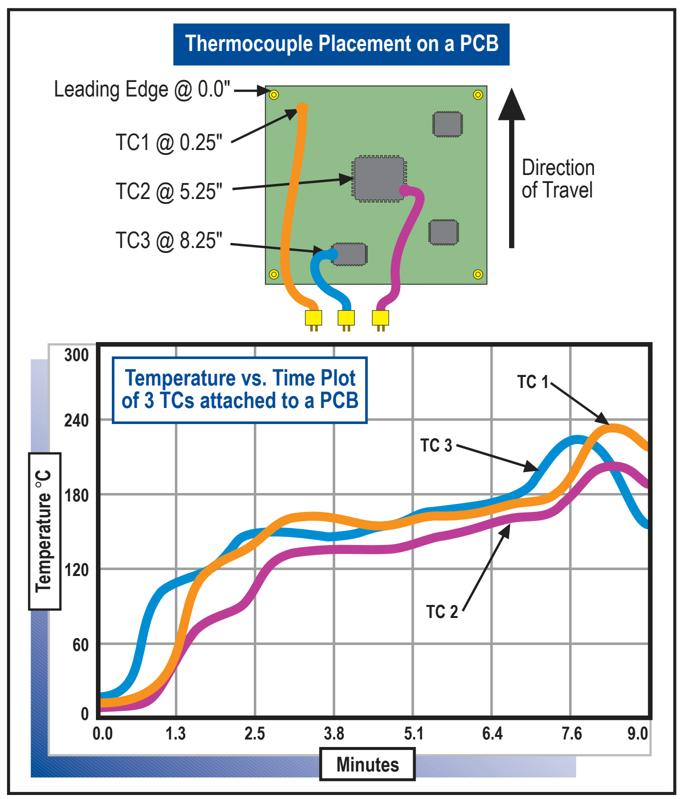
Overview

One of the main problems faced in Printed Circuit Board (PCB) assembly applications is the initial setting up, and the continuing control of the solder reflow process to obtain optimal process yield. To achieve high quality solder joints, all the variables regarding the solder reflow process must be controlled. Understanding how the modern solder reflow oven works and the basic principles of conveyorized heat treatment can ease the job of oven setup, i.e. *Thermal Profiling*.

What is Thermal Profiling

In a typical solder reflow oven, the PCB enters one end of the oven and moves at a constant speed through a series of temperature controlled zones (See Figure 1). Thermal profiling is the process of plotting temperature vs. time of the PCB as it travels through the oven. The PCB thermal profile is determined by temperature, time, and heat transfer rate.



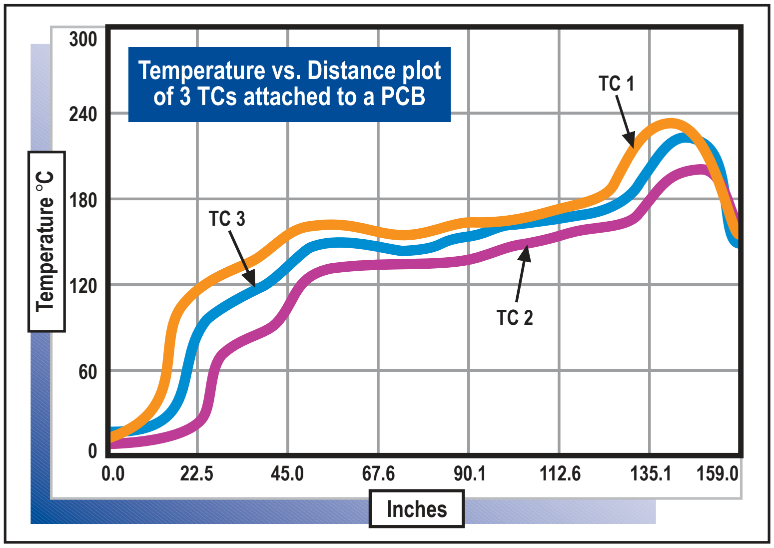


PCB temperature is typically measured by attaching thermocouples to different areas on the PCB. The thermocouples are positioned on the PCB to find the highest and lowest peak temperatures. The highest peak is found near its bare edges and the lowest peak is found at larger components, near the center of the PCB. 30-36 gauge thermocouple wire is used. It is attached to the PCB with Kapton Tape, thermally conductive adhesive, or high temperature solder. Although Kapton tape is the quickest and simplest method of attaching thermocouples to a PCB, this method is not recommended as it often generates serious random temperature errors. Typically, 10-88-2 solder with a melting point of 286°C is the most reliable means of attaching the thermocouples. However, this method requires a sacrificial PCB.

Plotting the PCB Thermal Profile

Figure 2 shows the placement of three TCs on a PCB and a plot of the resulting thermal profiles. Notice that TC2 enters the oven 5" behind TC1, and TC3 enters the oven 3" behind TC2. This separation is typical and causes the resulting temperature vs. time plot to be somewhat confusing.

By plotting the same data as temperature vs. distance, the graph becomes more intuitive (See Figure 3). Here TC2 can be identified as an area of high thermal inertia, and TC1 as an area of low thermal inertia. *Note: These PCB profiles were made in an oven that has been verified to have a consistent temperature across the oven conveyor within ±5°C. Please be aware that many modern solder reflow ovens have cross conveyor temperature uniformity problems that make the resulting PCB profile difficult to interpret.*



Temperature and the PCB Thermal Profile

Two important laws of physics relate the temperature along the oven conveyor to the temperature of the PCB:

- **Law #1:** At a given point in the oven: If the oven temperature is above the PCB temperature, the PCB temperature will rise. IF the oven temperature is below the PCB temperature, the PCB temperature will fall. If the oven and PCB temperatures are the same, the PCB temperature will not change.

- **Law #2:** The greater the difference between the oven temperature and the PCB temperature, the faster the PCB temperature will change.

Note: For simplicity, this paper will ignore heat transfer across the PCB, which can sometimes make a given spot on the PCB appear to violate these laws.

The temperature along the oven conveyor is the *Oven Profile*. The oven profile is primarily affected by the oven zone setpoint temperatures. However, the oven profile is also affected by the air flow inside the oven, by the total thermal mass of the load and its spatial distribution, and by the ambient room temperature.

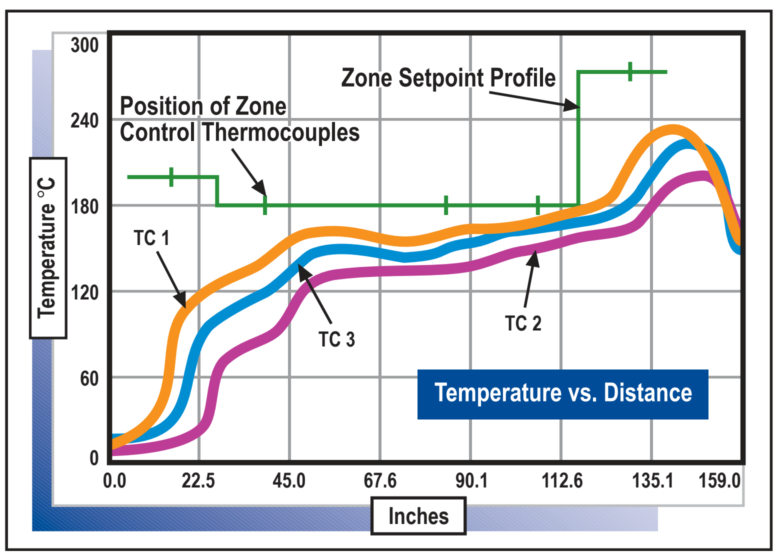
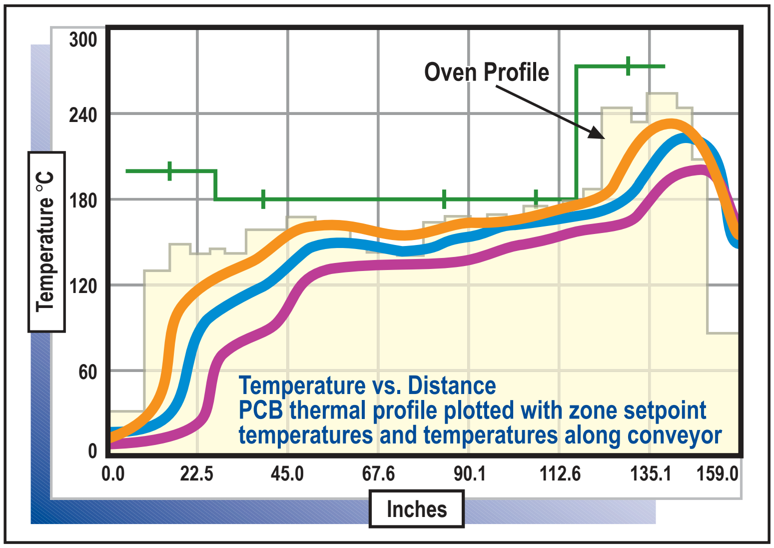


Figure 4 shows the thermal profile of a single point on a PCB. The setpoint temperature of each of the five zones is also plotted. This zone temperature plot cannot be viewed as a plot of the oven profile because from 50°C to 75°C in the oven, the PCB profile would clearly violate the first law. Even though the setpoint temperature is at 180°C, the PCB profile drops from 160°C to 155°C. The first law indicates that the PCB temperature should continue rising.

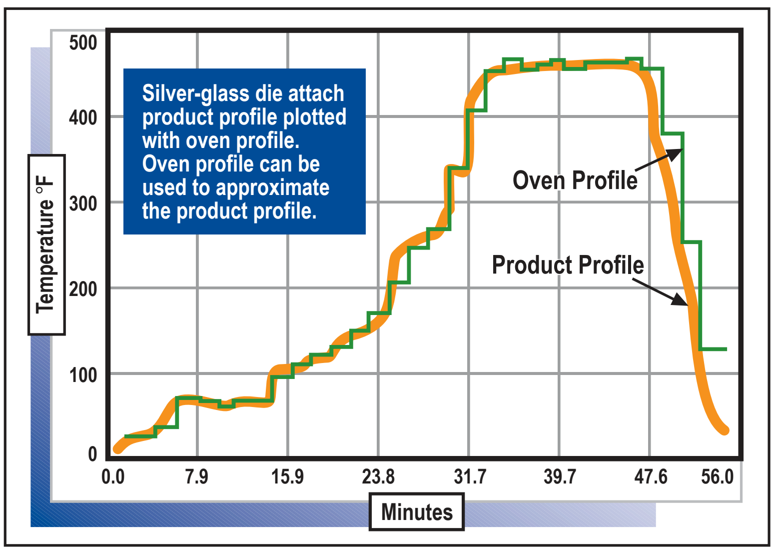
Figure 5 is the same as Figure 4 except a series of steps have been included. The leading edge of each step depicts the placement and temperature of the thermocouple that has been mounted permanently just above the conveyor. Using this series of steps as the oven profile, the PCB profile obeys the two laws very well.



Time and the PCB Thermal Profile

The time that the PCB is subjected to a given oven temperature can be changed by varying the speed of the conveyor. The slower the conveyor speed, the more time the PCB will have to reach equilibrium with the actual oven profile.

In theory, if the conveyor were to move infinitely slowly, the PCB profile would match the oven profile. In practice, there are many conveyor oven processes where the conveyor speeds are so slow that the oven profile is used to approximate the product profile. In the electronics industry, such processes include thick-film resistor firing and silver-glass die attach (See Figure 6).



Heat Transfer Rate and the Thermal Profile

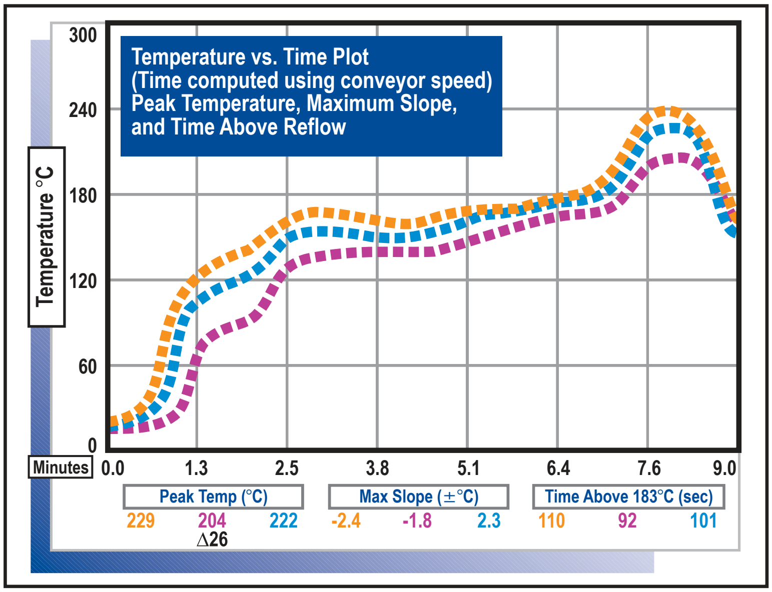
The *Heat Transfer Rate* is a measure of how quickly heat is transferred from the oven to the PCB. The greater the heat transfer rate, the lower the oven temperature required to raise the temperature of a given PCB a given amount in a given time.

As the size and complexity of PCBs increase and the component density becomes less evenly distributed, ovens with a relatively low heat transfer rate begin experiencing problems. These ovens tend to overheat the low thermal mass areas of the PCB in order to insure adequate reflow of the more thermally massive components. Many of the newer oven designs boast a more efficient heating system with a higher heat transfer rate.

The Ideal PCB Thermal Profile

The ideal PCB thermal profile is usually based on a triangle of three factors: peak temperature, maximum slope, and time above reflow temperature.

Figure 7 shows the thermal profile of three locations on a typical PCB. Beneath the graph, *Peak* indicates the peak temperature in degrees C for each PCB location; *Max Slope* indicates the maximum change in temperature in degrees C per second; and *Seconds over 183* indicates the number of seconds each PCB location spends above the reflow temperature of 183°C. Target values for each of the three profile factors are presented below. These target values are based on information from approximately 15 U.S. companies that manufacture surface mounted PCBs.



Peak Temperatures

For a solder with a melting point of 179°C - 183°C, the maximum allowable peak temperature is usually between 220°C and 230°C. The minimum allowable peak is usually between 195°C and 205°C. If the PCB gets too hot, the edges may turn brown. Also, temperature above 230° can cause damage to the internal dies of the SMT components as well as causing intermetal growth formation. If the PCB does not get hot enough, the solder paste will not adequately reflow.

Maximum Slope (Ramp Rate)

The maximum slope is usually measured in °C/second and specifies how fast the PCB temperature is allowed to change. Many components will crack if their temperature is changed too quickly. The maximum rate of thermal change that the most sensitive components can withstand becomes the maximum allowable slope.

In order to maximize throughput, the PCB thermal profile is usually designed to have a maximum slope just under the maximum allowable. For most companies, the ideal maximum positive slope (ramp-up rate) is somewhere between 1.0°C and 3.0°C/second. In vapor phase ovens, a preheat zone brings the PCB up to 70-80°C at 1.0 to 3.0°C/sec., but once the PCB reaches the vapor, the ramp rate often exceeds 5.0°C/sec.

It is unclear why, but the maximum negative slope (ramp-down rate) is often ignored. It would seem that the maximum allowable slope for a given component would be the same whether the part was being heated-up or cooled-down, however, a large percentage of the companies reviewed have profiles with a maximum negative slope that exceeds the specified maximum allowable slope.

This is especially evident in solder ovens that have a short cooling zone at the end of the process which brings the PCB from above reflow to below reflow relatively quickly. As seen in vapor phase systems, it may be that the ramp rate is less critical above certain temperatures.

Time Above Reflow

This is a measure of how long the solder on the PCB is a liquid. Most companies say that they would like to see the solder liquid for between 30 and 60 seconds. However, this seems to be the first leg of the triangle to be compromised and liquid times of 90 to 120 seconds are often encountered on the more massive PCBs. If the solder is above reflow temperature too long, excessive growth of tin-copper intermetallics leads to a tin-depleted and brittle solder joint.

It is unclear exactly why the minimum suggested time above reflow is 30 seconds. Most solder experts say the shorter the liquid time, the better. It may be that with only 3-6 TCs attached to the PCB, there is concern that the coolest spot on the PCB is not being measured. Therefore, by setting the minimum allowable time at 30 seconds, the chances of an unmeasured spot on the PCB not reflowing are minimized. Another possibility is that the solder reflow oven may not always maintain oven temperature during production. Thus, the high minimum reflow time allows a margin of safety against oven temperature drops.

The Production PCB Thermal Profile

Many of the production PCB thermal profiles reviewed did not meet the target value for one of the three factors (peak temperature, maximum slope, or time above reflow). In most cases, it was found that the oven could be adjusted to bring any two of these factors within the target values, but bringing all three within the target values was impossible. ie. if the oven was adjusted to bring the minimum peak temperature up, the maximum time above reflow would be exceeded. Or, if the preheat oven temperature was raised to provide a longer soak and a smaller delta between maximum and minimum peak temperature, the maximum slope was exceeded.

Conventional Profiling Equipment

The original device used to profile conveyor ovens was a strip chart recorder. Using this device, one or more thermocouples were trailed behind the PCB through the oven. The temperature of these thermocouples was plotted in real-time, on calibrated paper as the PCB traveled through the oven.

The strip chart recorder printout of multiple TCs was difficult to analyze. Oven manufacturers then began offering profiling systems that could monitor up to three thermocouples and would display the output on a computer screen. These systems had the advantage of allowing data to be manipulated and analyzed on a computer.

The problems associated with trailing multiple wires through the oven gave rise to the invention of portable, battery powered, thermal profilers that could withstand solder reflow temperatures. These profilers typically monitor three to six TCs and travel with the PCB through the oven. When the portable unit exits the oven, it is plugged into the RS-232 port of a standard PC and the profile data is displayed on the computer screen.

Although a great improvement over the first two methods, the portable profilers have the disadvantage of delayed data. The thermal data is no long displayed as it is collected, thus, there is no way of knowing if the PCB or portable profiler is overheating. If the oven is too hot or the conveyor speed too slow, or if the units become stuck within the oven for any reason, both the PCB and the portable profiling device can be damaged beyond repair. The cost to replace a damaged portable profiling device is fairly high, and the portable profilers cannot be used in higher temperature applications without significant added insulation.

To rectify this, an improved profiling system has been developed. This system packs six thermocouples into a single cable. The cable plugs into a card that mounts in any standard PC, and is trailed through the oven, displaying the PCB temperatures on the computer in real-time as they are collected. These cables come in variations that can withstand up to 450°C, indefinitely.

Portable Thermal Transmitter

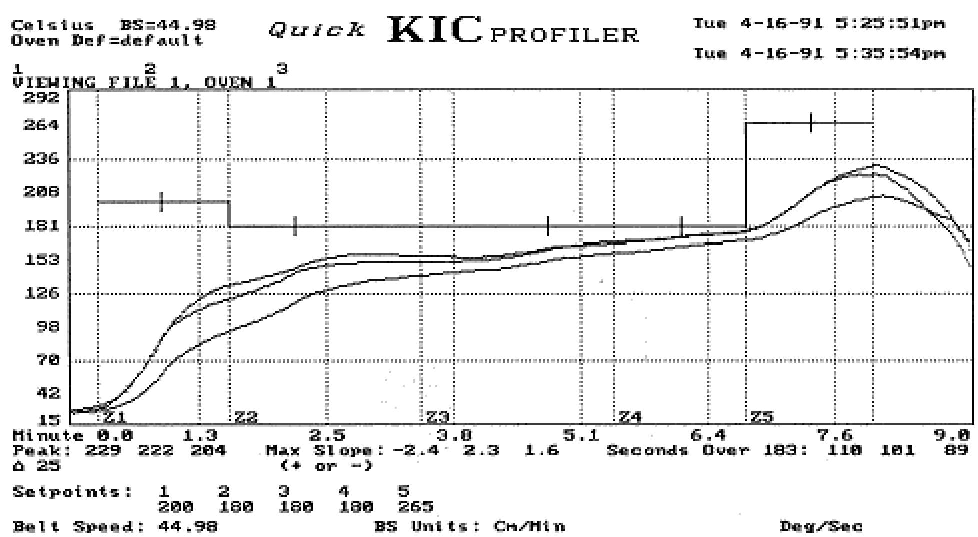
In 1992, a wireless remote thermal transmitter was introduced that incorporates the basic convenience of other standard portable profiling devices, but also provides real-time data collection. This thermal transmitter monitors up to six thermocouples and uses radio waves to send the temperature data back to a remote receiver. The receiver plugs into the user's PC and receives the temperatures as they are collected, alleviating the need to download data after the unit has passed through the oven. This system also has an additional thermocouple readout that continually displays the internal temperature of the thermal transmitter for added safety.

Conventional Profiling Equipment Features

Most conventional profiling systems will monitor the outputs of up to six thermocouples simultaneously. These profilers will display the data on computer screen and print it out on a computer printer. Many of the systems will display and print the data in color which becomes advantageous as the number of thermocouple plots increases.

Most of these profilers provide software features to aid in analyzing profiles for peak temperature, maximum slope, and time above reflow temperature. Figure 8 shows the printed output from a typical conventional thermal profiler.

Figure 8: Printed Output From a Conventional Thermal Profiler



Advanced Thermal Profiling Equipment

In 1989, an advanced profiling system was introduced that is designed specifically for SMT applications. This new profiler offers all the features of the conventional profiling systems with several additional capabilities.

In addition to monitoring six thermocouples attached to the PCB, the advanced profiling system monitors 30 thermocouples placed along the oven conveyor. Two ¼" diameter tubes run the length of the oven and are mounted either above or below the conveyor. Each tube contains 15 uniformly spaced thermocouples. The two arrays of 15 thermocouples are offset from one another in the tubes by one half-pitch spacing, so that the combined array provides 30 evenly spaced thermocouples, spanning the full heated length of the oven (See Figure 9).

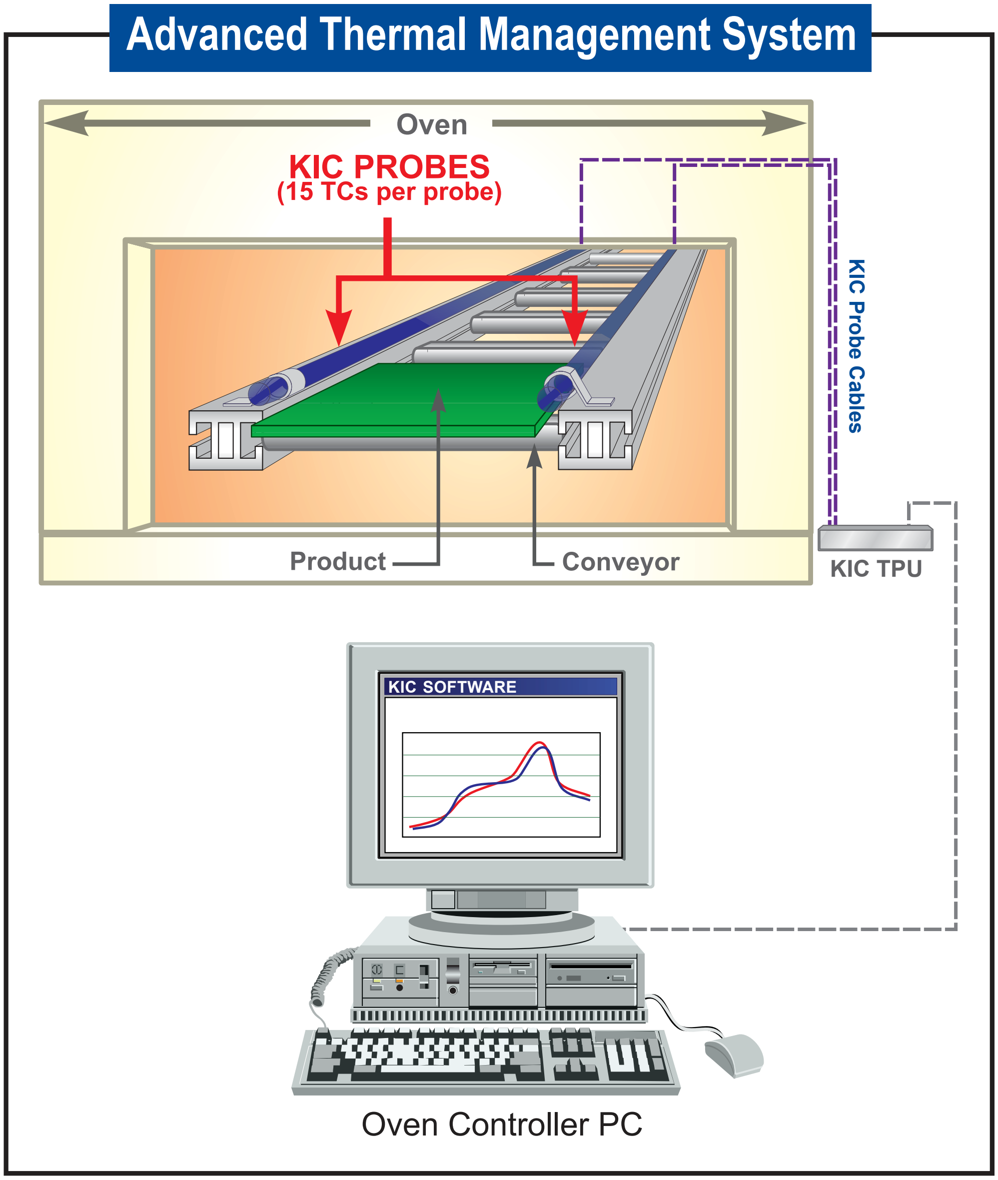
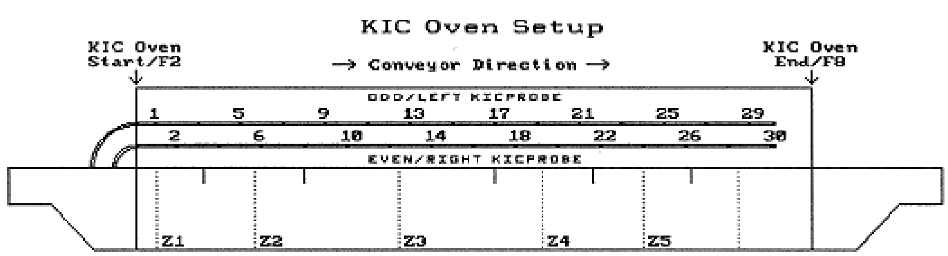


Figure 9b: Oven Setup

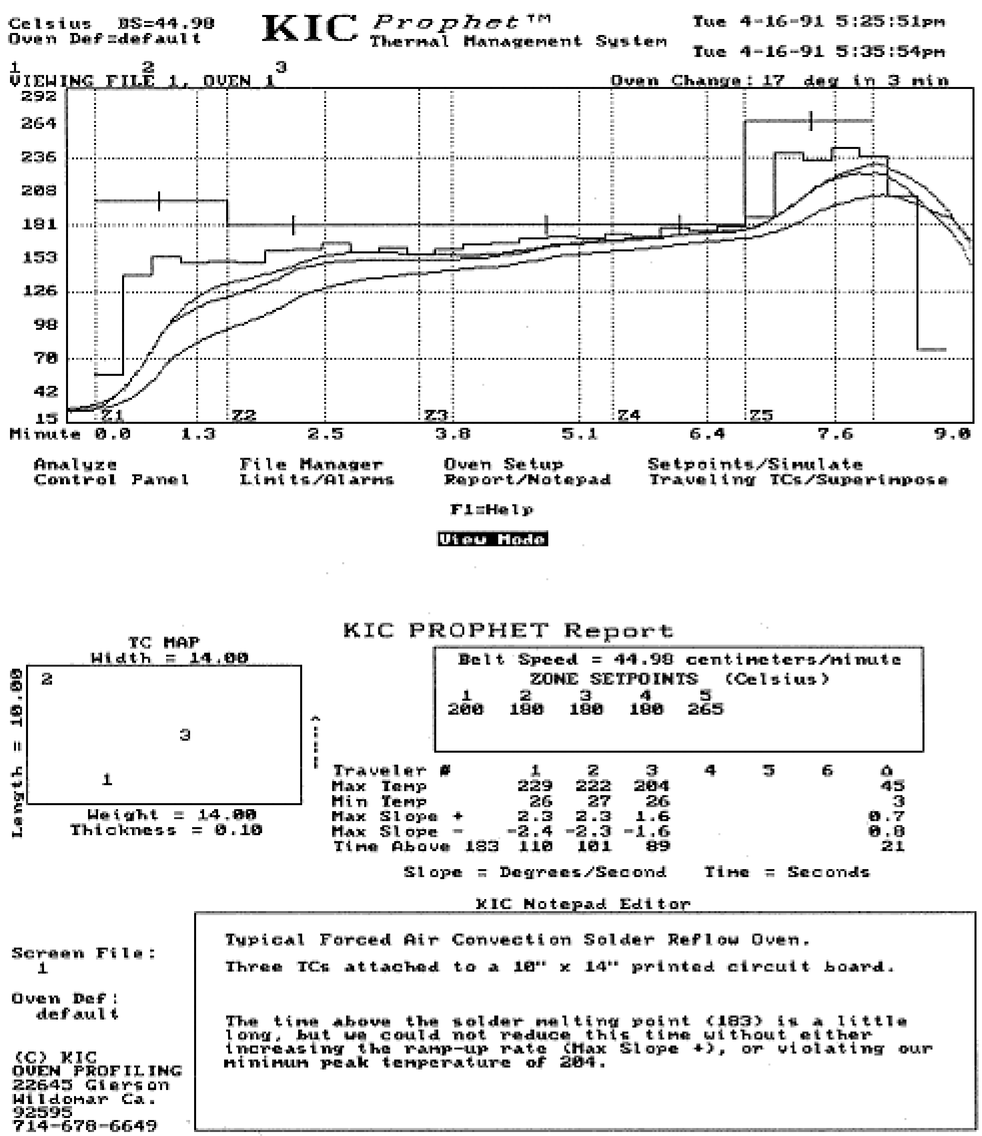


Load Table Length	30.00
Tunnel Length	159.00
Unload Table Length	30.00
Load Table Start to KIC Oven Start	30.00
KIC Oven Start to KIC Oven End	159.00
Probe Feed Point	ENTRANCE
Inches from KIC Oven Start to first KIC TC	4.50
Total Number of KIC TCs	30
KIC TC Spacing	5.00
Oven Number	1
Number of Zones	5

Zone	Tunnel Start to Zone Start	Tunnel Start to Control TC
1	5.00	16.00
2	28.00	39.50
3	62.00	84.50
4	96.00	108.00
5	119.50	131.00
Inches to End of Last Zone		142.00

The outputs of the 30 thermocouples are displayed on a computer screen as a step graph, and updated every five seconds. The graph shows the actual oven temperature along the conveyor (the *oven profile*). Figure 10 shows a picture of the computer screen of one of these advanced systems. Being able to monitor the oven profile in real-time allows the advanced system to provide two special features: profile prediction and 24 hour process monitoring.

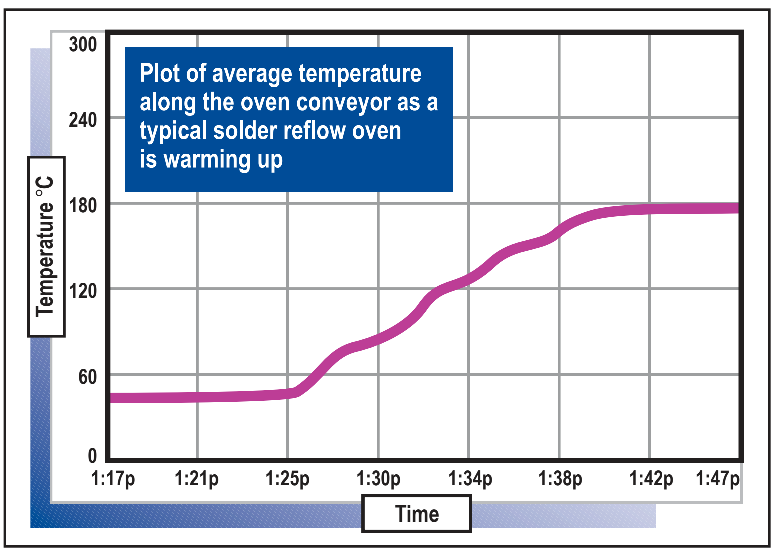
Figure 10: Computer Display of the Advanced Profiling System



Profiling Procedures

Conventional Profiling System vs. Advanced Profiling System

Conventional Profiling System	***Advanced Profiling System***
Using a conventional profiling system, profiling a solder reflow oven for a specific PCB involves the following steps:	Using the advanced profiling system, profiling (with a trailing cable or a remote, real-time thermal transmitter), profiling a solder reflow oven for a specific PCB involves the following steps:
1. Attach the thermocouples to the PCB.	1. Attach the thermocouples to the PCB.
2. Adjust the oven zone setpoints and belt speed to some *first guess*.	2. Adjust the oven zone setpoints and belt speed to some *first guess*.
3. Wait for the oven to stabilize (often some uncertainty here)*.	**3. Wait for the oven to stabilize (the advanced profiler removes uncertainty)*.**
4. Run the PCB through the oven.	Run the PCB through the oven.
5. Analyze the resulting thermal profile.	5. Analyze the resulting thermal profile.
6. Repeat steps 2-5 until the desired profile is achieved.	**6. Adjust the setpoints and conveyor speed on the computer until the desired profile is displayed.**
	7. Repeat steps 2-6 until the desired profile is achieved.
**In step 3, oven stability is typically determined by waiting some arbitrary time, usually 5-30 minutes, after all the zone control thermocouples have reached their setpoint temperature.*	****In step 3, oven stability is determined by waiting until the advanced profiling system shows that the temperature along the oven conveyor is stable. Figure 11 shows a plot of average oven temperature as a typical oven is warming up.***
In this conventional profiling procedure, the time required for each iteration is typically from 15 to 30 minutes. Two to 10 iterations are required, depending upon the skill of the operator and the complexity of the PCB.	With the advanced profiling procedure, the time required for each iteration is still 15-30 minutes, however, only two to three iterations are required, regardless of the skill of the operator or the complexity of the PCB.



Profile Prediction

As shown by the two laws of physics, PCB temperature is directly related to the oven profile. The advanced profiling system integrates a mathematical algorithm that uses the oven profile to relate oven zone setpoints and conveyor speed to the PCB thermal profile. This feature, called *Profile Prediction*, allows the user to change the zone setpoints and/or conveyor speed on the computer and see an instant prediction of the resulting PCB profile. While the conventional profilers take 15-20 minutes to show the user the PCB profile resulting from changes in the oven settings, the advanced profiling system only takes seconds.

Process Monitoring

The advanced profiler is a complete thermal management system that monitors the solder reflow process 24 hours a day. This system shows precisely when the oven is stable and how PCB load affects the oven temperature. It also monitors oven drift during production, triggering a visual and/or audible alarm at the first sign of process malfunction. A key feature of the advanced profiling system is its ability to replay oven profile changes in a fashion that is equivalent to *time-elapse* photography.

It should be noted that several conventional thermal profilers are now offering a version of profile prediction. However, because these devices cannot monitor the real-time **oven** profile, they have two major disadvantages over advanced profiling systems:

1. Since the conventional profiler cannot monitor the stability of the oven, the user must depend on the oven controller to determine when the oven is stable. If oven temperatures are still changing when the PCB is run, then without making any changes to the oven setpoints, the PCB will experience a different thermal profile the next time it is run. Such instabilities are almost impossible to detect without independently monitoring the internal oven temperature.

2. As shown in Figures 4 and 5, the oven setpoint profile does not accurately represent the actual oven profile. If the conventional profilers are depending upon this relationship to make predictions, the accuracy may be reduced to the point where multiple iterations do not converge on the target profile.

Time, effort and *guesswork* can be minimized by understanding three basic items: the variables that are integral to modern reflow ovens; the principles of the basic thermal profiling process; and the types of profiling systems available. This knowledge will translate into a more profitable bottom-line, i.e. less operator time required; higher PCB throughput; and an order of magnitude reduction in improperly reflowed or damaged PCBs.