Hybrid Drying Technology for In-line Aqueous Cleaning of Lead-Free Assemblies

Dirk Ellis
Speedline Technologies
Camdenton, MO

Abstract

The use of high velocity, heated air to remove residual water has become the predominant method for drying printed circuit boards in the in-line aqueous cleaning process. As lead-free circuit boards become more complex and component spacing decreases, the effectiveness of direct blow-off drying is greatly diminished. Adding blower power or slowing process speed will improve drying performance, but increase operating cost, and may decrease throughput.

This paper describes a new approach to drying circuit board assemblies that significantly reduces the cost of ownership of an aqueous cleaning system. Drying performance is increased through a hybrid drying process that reduces energy input, exhaust requirements and sound levels. The combination of high temperature blow-off and convection brings the flexibility to tailor drying performance to fit the product's drying requirements.

Introduction

The advantages of performing post assembly cleaning are well documented. As the industry pursues lead-free initiatives, the importance of cleaning becomes more and more evident. Process residues are considerably more difficult to clean because of higher reflow temperatures and the complexity of flux formulations that are currently being used. Higher reflow temperatures, while necessary for proper intermetallic formation, bake flux residues, making them harder to clean from a board's surface. While the newer flux formulations have been designed to improve wetting, stencil life, printability and solderability, little regard has been given to cleanability.

Residues left from these newer flux formulations create a "plastic-like" shell over the flux residue. Many of these shell-like layers can form depending on the amount of flux that is present and the rate of thermal activation. Faster ramp-to-spike profiles will be more apt to create this plastic shell, where the outer layer is hard or skinned over and the inner portion is softer or liquid.

To effectively remove this material, the shell must be penetrated using thermal and/or chemical energy, and the underlying layers removed with the subsequent high-energy impact of forced spray nozzles. Once the visible residue is removed, cleaning chemistry can start the more difficult task of removing any remaining residues, especially from under low stand-off components. Low surface tension chemistries used in conjunction with a parallel flow to the board help to pierce through the flux residue. Once completely cleaned, rinse water can then flush all remaining chemistry and contaminants off of the board's surface.

If these newer flux residues are allowed to remain on the PCB, then the chance for electrochemical problems increases. When left in sufficient quantities along with moisture from an insufficiently dried PCB, these residues can lead to dendritic growth, corrosion and possibly tin whiskering. Dendritic growth has always been an issue to the reliability of circuit boards. What is less understood is the impact of lead-free specific contaminants and phenomena combined with ever-decreasing component spacing. Until (and unless) this is understood, cleaning of lead-free assemblies is an important and prudent process.

Problem Statement

Drying printed circuit boards is a critical and expensive aspect of an in-line cleaning process. The importance of drying is determined by the post cleaning process requirement. In-circuit test, conformal coating and underfill are demanding processes and their success depends on good drying. Test failures can often be attributed to wet boards and rework and scrap are costly. Conformal coat failure and underfill voiding can be caused from moisture trapped under components. This is especially true for PBGA where "popcorning" is the leading cause of delamination, open solder joints and component warpage. Electrochemical migration promoted by trapped moisture may be a major contributor to failure during final test, or worse, in the field.

Design History

Today’s complex PCBs present a challenge to completely and totally dry in an in-line cleaning process. Blind connectors, through hole and blind vias, processor flip chips, micro BGA, LCC, encased relays and flush mounted chips all create locations for water to hide. Often traditional high velocity air knives cannot completely remove this water and evaporation is the only remaining means. Mechanical stripping of gross amounts of DI water from the PCB via high velocity blowers is accepted as the most efficient and economical means in the cleaning industry. Typically 80 to 95% of the water is removed in the first dryer blow-off module. This is heavily dependent on the complexity and the mass of the PCB. This stripping can be accomplished using many different designs of blower and air knife combinations.

Blowers used today in most in-line cleaners are classified as high velocity. These are generally belt driven with rotating blower head speeds of 18,000 rpm and intake temperatures limited to 50°C. Another type of high velocity blower is the regenerative blower. These blowers are direct drive, operate at 3500 rpm and can produce outlet temperatures of up to 115°C. Both of these high velocity blowers achieve similar discharge pressures and flow rates with the same brake horsepower. Therefore, the main advantage is in the ability to recirculate high temperature air by the regenerative blower.

How much better is 100°C vs. 65°C air for water removal? From a mechanical standpoint, there is no difference, but raising the board temperature results in significantly quicker evaporation. Detail A in Figure A shows a board temperature of 33°C vs. 53°C giving a 20°C advantage to the 100°C heated air. The 65°C air actually drops the board temperature 27°C from the 60°C final rinse water, while the 100°C air only drops 7°C. The evaporative cooling effect is therefore minimized by the higher temperature air.

There are several types of air knife designs; round tubes with slots, tear-drop shapes with adjustable width slots, coherent jet manifolds and compressed air manifolds. These air knives have outlet velocity values from 20,000 to 30,000 feet/minute. Ideally, a “systems approach” should be taken to matching air knives to a particular blower. By measuring electrical current draw and air flow, an optimization curve can be drawn to maximize performance. Variables such as knife length, diameter, length and type of ducting and width of the air slot will all factor in to the performance curve.

Cleaning Process and System Considerations

In-line cleaning is a thermal process from beginning to end. Time is the critical component during this thermal process. When looking at the thermal profile through the cleaner with hybrid drying, it will closely resemble a ramp-soak-spike reflow profile as shown in figure 1. The importance of the soak time in a reflow profile aids the activation of the flux to clean oxidation from the pad and component. The ramp and soak time in the cleaner begins in the prewash module. The importance of the soak time in the cleaner profile is to increase board temperature and soften flux residues. Good flow coverage by the prewash nozzles causes the temperature of the board to rise quickly and initiate chemical dissolution. These thermal and chemical energies work to start the flux residue removal process. The prewash module is typically powered by the wash module pump, so as the board leaves the prewash and enters the wash module, its temperature is maintained and the soak continues.

With thermal and chemical energies constantly working in the prewash and wash modules, the next important energy to add is mechanical. Lead-free residues can be very hard and require high impact forces to be removed. Vee shaped spray nozzles produce smaller droplets at high pressure and have very little mechanical energy at the PCB level. Coherent (solid stream) nozzles maximize the impact energy on the PCB and break up layers of lead-free residue. The more coherent nozzles, the quicker the residues can be removed and the faster the in-line conveyor can run.

Drag-out management of wash chemistry is a very important step following the wash module. This chemical isolation (wet isolation) module does not play as important of a role in the cleaning soak profile, but is critical in keeping the cost of ownership down in the in-line cleaning process. The isolation strips wash chemistry from the board and returns it to the wash tank using air knives specifically designed to not dry the chemistry and residues on the board. A low flow rate of pre-rinse water dilutes these residues and is followed by another set of air knives. These air knives remove remaining wash water before entering the recirculated rinse module.

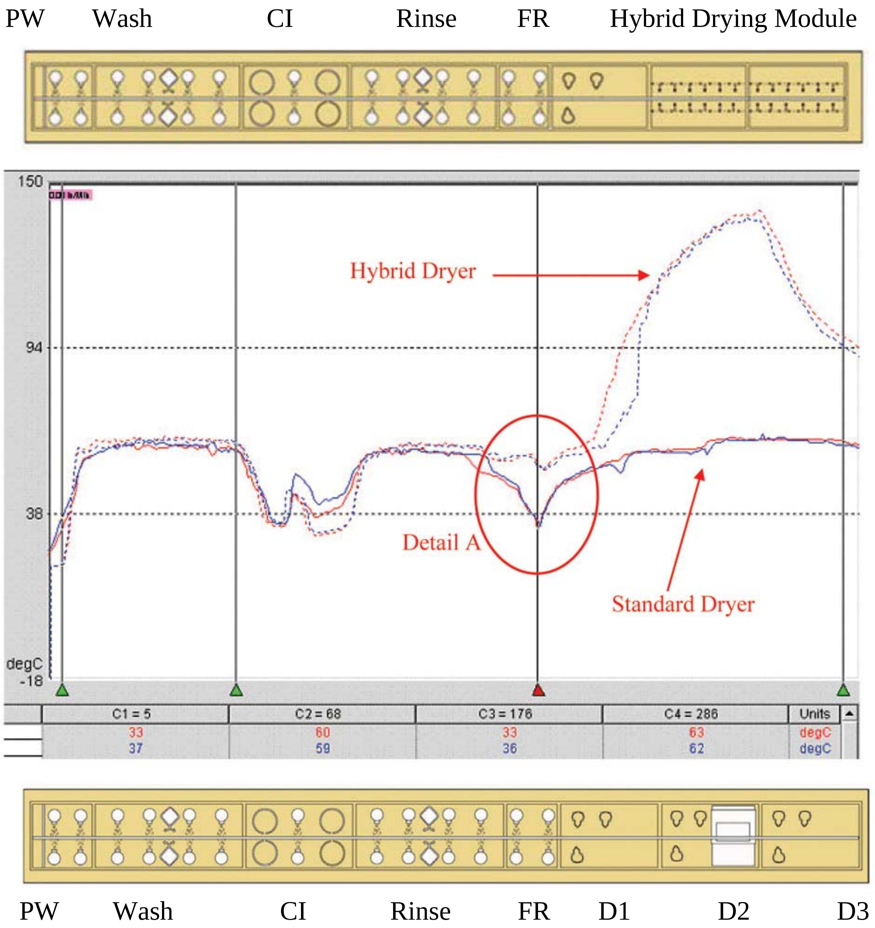


Figure 1. In-line cleaning thermal profile

The recirculated rinse module provides gross rinsing of the PCB with typically 1 to 2 M ohm quality deionized (DI) water. To reduce operating cost, the rinse water is typically recycled through a closed-loop system and returned to the final rinse at 3 to 18 M ohm. Resins used in the closed-loop tanks have a temperature limit of 60°C, so this dictates the rinse module maximum operating temperature to 60°C. The thermal soak continues while all remaining residues are flushed from around and under surface mount components. A combination of vee jet flooding nozzles and coherent nozzles act together to accomplish this task.

The last section of the soak process in the cleaning profile is the final rinse module. The final rinse is an integral extension of the dryers and most important to the preparation of a properly cleaned and dried board. Ultra high purity DI water (2 to 18 M ohms or 0.25 to 0.03 ppm Total Dissolved Solids) is used at a rate of 3 to 5 gallons/minute to flush any remaining ionic residues from the PCB. DI water absorbs ions aggressively, which is very effective in pulling any remaining, potentially harmful contaminants off the PCB. A certain amount of evaporation is going to occur in all in-line drying sections. The higher the quality of final rinse water, the better chance that nothing ionic in nature will be left behind as the water evaporates from the PCB.

The final reflow section analogy is spike, where the TAL (Time Above Liquidus) is important to ensuring all components are completely soldered during the reflow profile. As in the cleaning process with hybrid drying, the TAB (Time Above Boiling) can be the key to a complete and successful cleaning process. As previously stated, cleaning is a function of time (and temperature). With high quality final rinse water (low conductivity), an extended TAB value will facilitate faster evaporation and hence, faster drying process time.

Methodology

To measure the effectiveness of hybrid drying technology versus standard drying technology, four different PCBs were chosen with difficult drying challenges. All boards were cleaned prior to initial pre-dry weighing to eliminate any residues. Precise initial and final weights were taken on each board to three decimal place accuracy to determine weight loss or gain. These weights were measured after running at 1, 3 and 5 feet per minute (fpm) through three different dryer configurations.

Dryer configuration 1, as shown in top of figure 1 has a hybrid dryer using a 15 hp regenerative blower with high temperature (set point 105°C) and high velocity air through tear drop shaped air knives. This module is followed by two high temperature (set point 149°C) convection heating zones. Figure 2 represents the schematic of a high temperature module. Each convection zone is powered by a 3 hp direct drive blower and two 6 kW heaters. Dryer configuration 2, which is shows at the bottom of figure 1 has a 15 hp blower with additional side air knives followed by a 10 hp blower with two radiant heater panels, and the last module has a 15 hp blower. All set point temperatures were 70°C. Dryer configuration 3 was identical to dryer configuration 2 with the exception of adjustable compressed air nozzles that were directed at difficult-to-dry connectors.

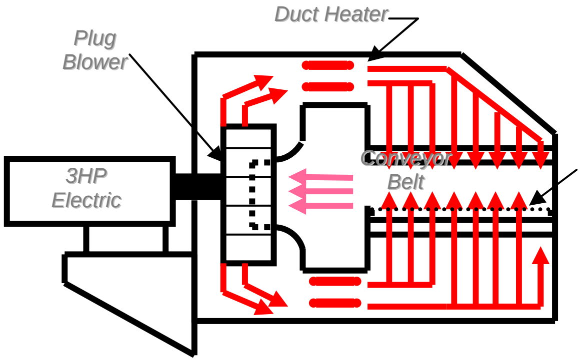


Figure 2. High temperature convection heating zones

To measure the energy input to each dryer configuration, current readings (in amperes) were taken on each blower and heater at steady state. Duty cycles for the heaters were monitored using a data logging computer connected to the heater SSR. Exhaust measurements were taken on each dryer configuration. Additionally, a sound pressure meter was used to take readings on all the dryer configurations.

Some PCB devices like LEDs have maximum temperature limitations and others may have limitations in terms of rate of heat rise (°C/sec). The design criterion to achieve complete drying without board damage is a major benefit of this hybrid drying technology. Using conveyor speed and temperature control of the two convection drying zones, a thermal profiler can be used to develop proper settings to meet these temperature limitations of sensitive components.

Data Analysis

The drying comparison graph for test board 1, shown in figure 3 indicated better drying results at all conveyor speeds using the dryer configuration 1, hybrid drying. Figure 4 shows result from various dryer configurations. 1 foot per minute (fpm) and 3 fpm both removed over 0.5 grams of ambient weight in the board resulting in negative numbers.

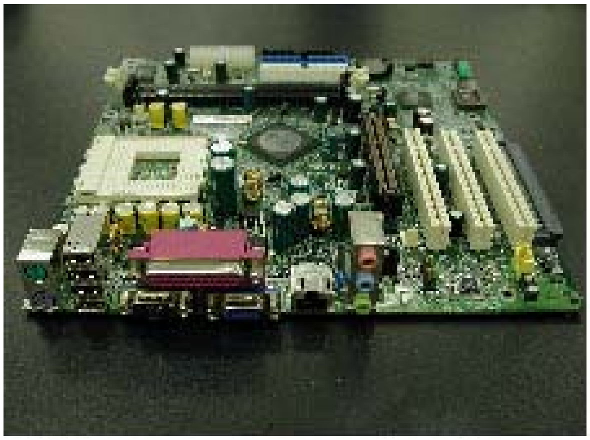


Figure 3. Test Board 1

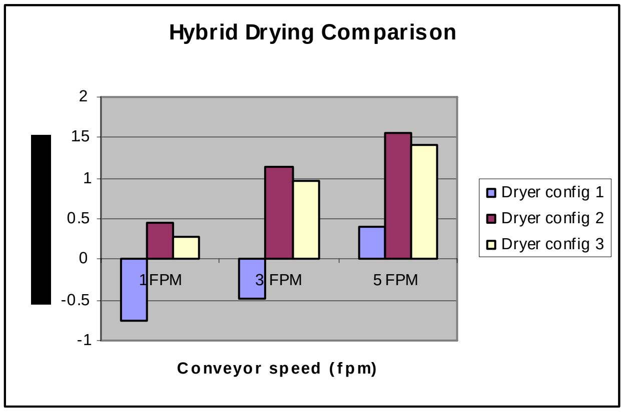


Figure 4. Hybrid drying comparison for test board 1

All dryer configurations for test board 2 were able to remove ambient moisture weight resulting in all negative numbers. This is one of the few boards that yielded better results with dryer configuration 2 and 3. Figure 5 and 6 shows the test board 2 and drying result comparison for test board respectively.

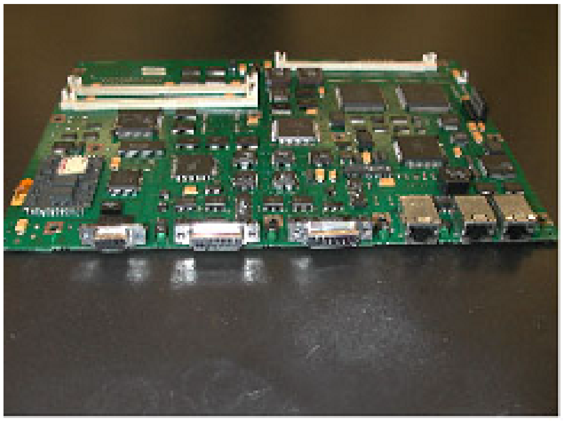


Figure 5. Test Board 2

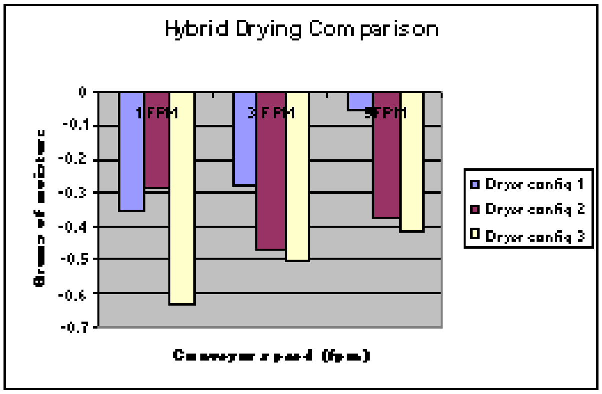


Figure 6. Hybrid drying comparison for test board 2

Test board 3 graph shows ambient moisture weight loss for conveyor speeds of 1 and 3 fpm, while 5 fpm showed weight gain for all dryer configurations. This is shown in figure 7 and 8.

Figure 7. Test Board 3

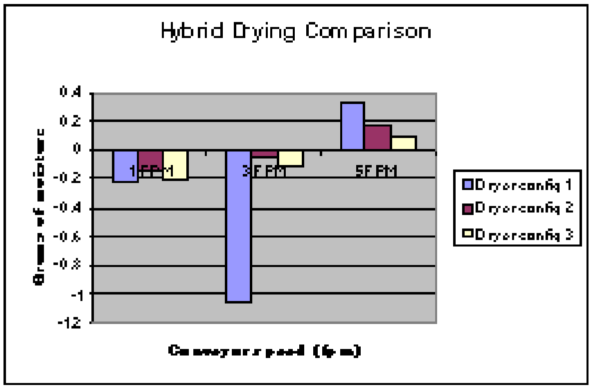


Figure 8. Hybrid drying comparison for test board 3

Test board 4, figure 8, had almost identical results of test board 3, figure 9. Conveyor speeds of 1, 3 and 5 fpm showed ambient moisture weight loss for the hybrid dryer. Conveyor speeds of 1 and 3 fpm showed ambient moisture weight loss and a weight gain at 5 fpm.

Figure 8. Test Board 4

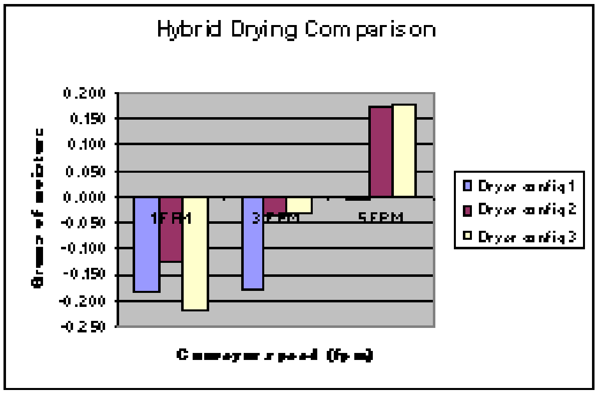
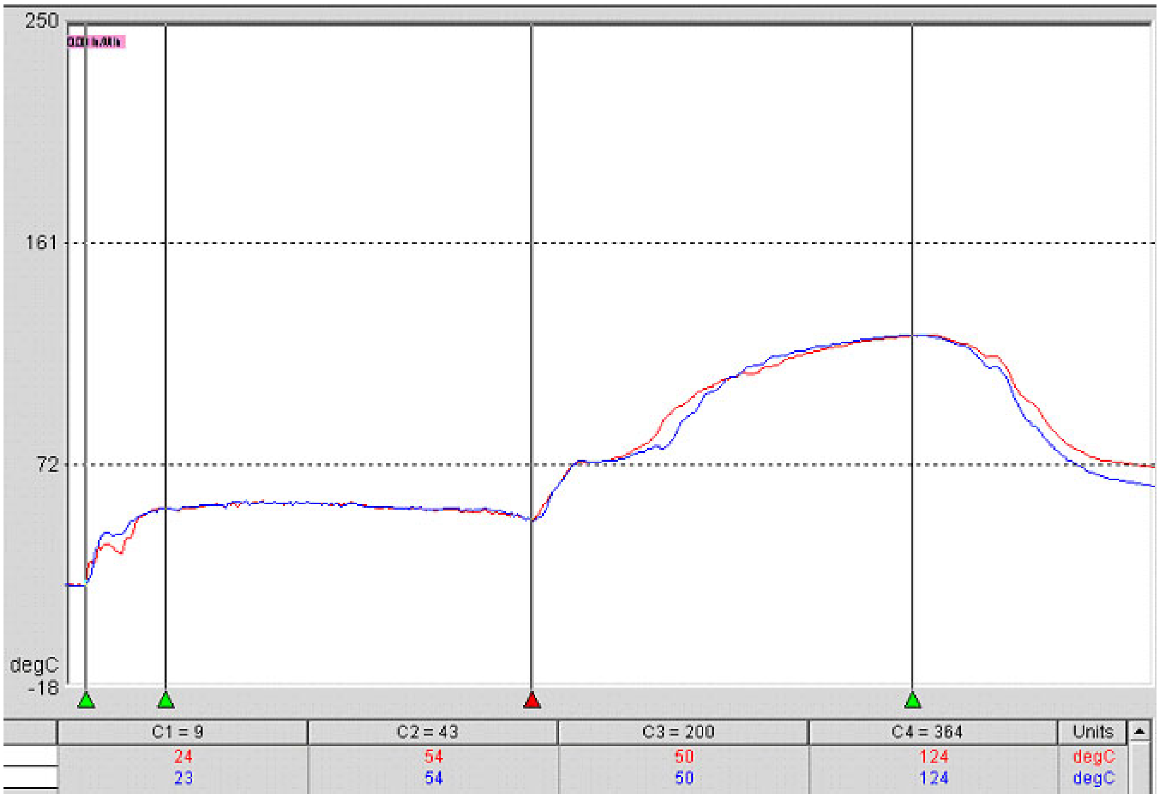


Figure 9. Hybrid drying comparison for test board 4

Cost of Ownership Benefits

Current draw (in amps) readings were multiplied by the operating voltage and the power factor to obtain the kW usage for each drying configuration. The duty cycles for all heaters were multiplied by the kW usage to obtain the actual consumption. Heaters used in the first convection zone of the hybrid dryer section had a 44% duty cycle while the heaters in the second convection zone only ran a 6% duty cycle. The hybrid drying section is well insulated to help keep these duty cycles low, resulting in an overall energy efficient design. The hybrid dryer zones operate at 29 kW, while the dryer configuration 2 and 3 operate at 38 kW. Some in-line cleaners offer a two dryer configuration that operates with two 15 hp blowers and two radiant heater panels. This configuration's energy consumption would equal the hybrid dryer consumption at 29 kW. The exhaust measurements for each dryer configuration are significantly different. The hybrid dryer only requires 800 cfm versus the 2400 cfm of the dryer configuration 2 and 3. This results in two-tiered savings. First, less heated or cooled make-up air is required in the cleaner's operating environment. Second, less fan horsepower is required for the exhaust system.

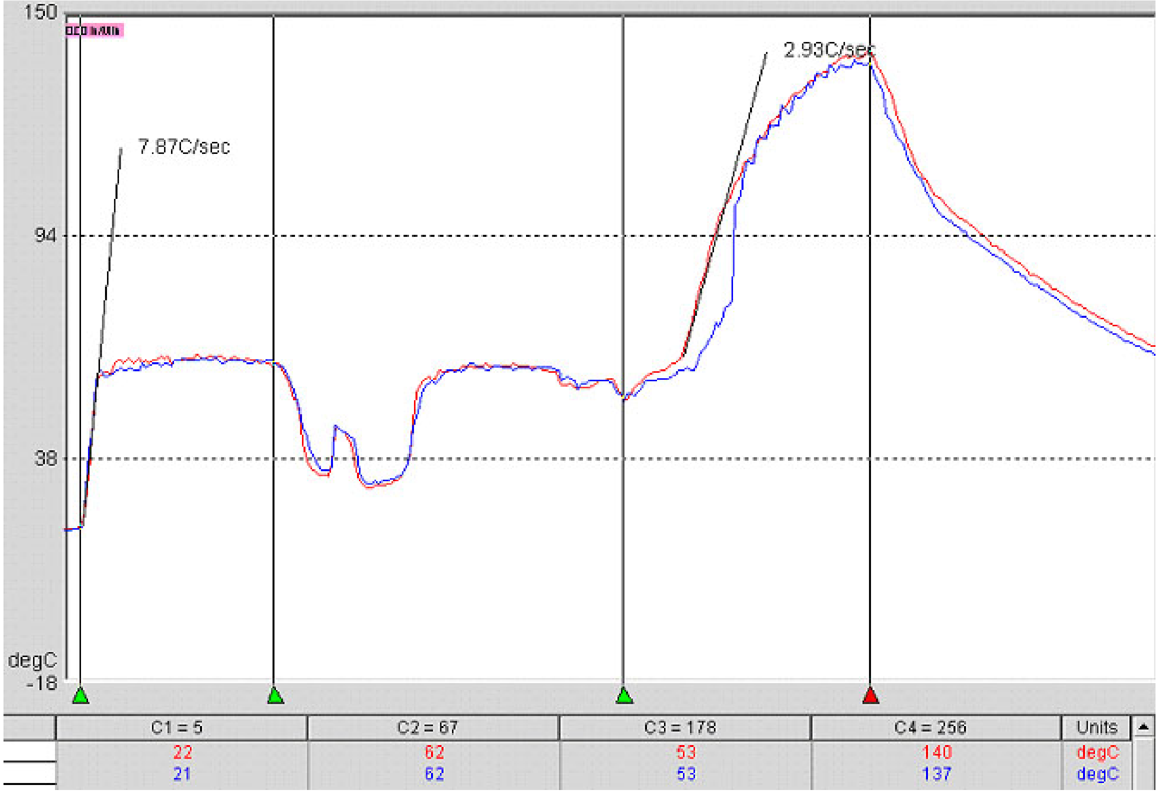


	C1 = 9	C2 = 43	C3 = 200	C4 = 364	Units
	24	54	50	124	degC
	23	54	50	124	degC

Figure 10. Thermal profile through the rinse, final rinse and hybrid dryer

Thermally Sensitive Board Benefits

Figure 10shows a thermal profile through the rinse, final rinse and hybrid dryer. The PCB has a low melting point solder that needs to be kept below 128°C during the drying process. This profile was achieved using a conveyor speed of 2 fpm, a set point of 100°C for the high temperature blow-off zone, 120°C for the first convection zone and 140°C in the second convection zone. The peak temperature achieved in the profile was 124°C, safely 4°C under the solder melting point of 128°C. This process is repeatable for every board processed.



C1 = 5	C2 = 67	C3 = 178	C4 = 256	Units
22	62	53	140	degC
21	62	53	137	degC

Figure 11. Thermal profile through the entire cleaner

Figure 11 is a complete thermal profile through the entire cleaner. As the PCB enters the prewash module of the in-line cleaner, the board goes from ambient to 62°C. This is a surprising 7.87°C/sec rate of heat rise. The ramp rate of the board entering the hybrid dryer is 2.93°C/sec. This ramp rate was created by using the maximum temperature settings and is easily reduced by lowering the set points of each of the hybrid dryer zones or increasing the conveyor speed.

Conclusion

The data has shown that hybrid drying can provide many benefits to the drying of PCBs. High velocity air typically removes up to 95% of water during the first past. In order to achieve reasonable throughput, remaining water must be evaporated. The use of high temperature high velocity air up to 115°C is a proven way to maintain board temperature from the final rinse to the convection zones increasing the evaporation rate. This enables dryer boards at higher conveyor speeds with controllable board temperature constraints. Hybrid drying can also provide economic benefits in everyday operating cost when compared to conventional dryer configurations.

Follow-up Research

Can rapid evaporation carry more residues away in water vapor or precipitate them out and leave them behind? For years it has been thought that evaporation leaves residues in solution behind. No matter what the drying technology, water is always evaporated. An experiment was conducted for this paper with inconclusive results due to initial bare board contamination. Further testing will be conducted to analyze this hypothesis using an inert substrate that will eliminate these difficulties and help isolate only the flux residues.