

**SMT Line Improvements for High Mix, Low Volume Electronics Manufacturing**

by

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## Abstract

This work covers two major projects aimed at increasing quality and efficiency on a high mix, low volume surface mount electronics production line. Specifically the installation of a ten zone reflow oven and an enhanced changeover method for SMT pick and place machines. A full description of these projects is presented along with rationales and background on their real world implementations. The transition from a five to ten zone reflow oven represents many opportunities for reflow soldering quality improvements. Specifics about the enhanced profiling abilities gained with the longer oven are explored and results from the oven installation are presented. To increase SMT line efficiency various changeover methods are discussed. The “hot swap” method, a somewhat new and unknown setup strategy, is explored in detail. Results from an implementation of the “hot swap” changeover method are discussed. Additional productive enhancements to the strategy are proposed.

## Acknowledgements

This work would have not have been possible without the support and guidance provided by a few individuals. I would like to especially thank Dr. John Evans for providing me with this opportunity. I fully believe the opportunities he has given me over the past two years will affect me for a lifetime. I would also like to thank Tom Devall. Throughout this project he has provided me with great direction and assistance. I must also mention Dr. Richard Sesek and Dr. Chase Murray who have helped me when needed and given me continuous support. I also want to acknowledge the opportunity afford by CoachComm. Without their agreement, none of this work would have been possible. Lastly, I want to sincerely thank Namo Vijaykumar, without his aid and friendship this work would be far form complete.

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## Chapter 1: Introduction and CoachComm Background

### 1.1 The Business

CoachComm is a sports communications technology company located in Auburn, AL. The company was founded in 1991 by Peter Amos. CoachComm designs, manufactures, and sells secure wireless communication systems. The company began marketing to football teams; supplying the communications equipment needed to facilitate communication between sideline and press box coaching staff. The company has also found applications for its technology in other industries and is preparing to release a 900MHz variant of one popular 2.4GHz product. A fair amount of growth is expected over the next few years as a result. The company also provides sports target video products. These products are specifically tailored for use by high school and college coaching staff. Their main use is in practice video review and in creating highlight reels for player recruitment. Over the past few years the company has seen a huge amount of market growth. In addition the company has introduced 3 new major products since 2008.

### 1.2 Manufacturing

CoachComm has been manufacturing their electronics assemblies in house for roughly 8 years. They currently produce seven different product families which require over 30 distinct electronic assemblies. CoachComm operates a full surface mount technology or SMT electronics manufacturing line which includes a solder paste printing machine, two component placement machines, and a reflow oven. These machines are currently in a series configuration in the order listed. Though CoachComm does not manufacture any of their unit's housing, they

do assemble the units at the same location. The facility also includes a full service repair and service center. The entirety of the manufacturing operation is housed in a large warehouse behind the company's offices. In addition to manufacturing, the warehouse contains some offices, the stockroom, and the shipping department.

### 1.2.1 Manufacturing Issues and Project Setup

At the onset of this project CoachComm was facing a number of production issues. These challenges were mostly related to quality and efficiency on the surface mount electronics assembly line. The company had experienced solid growth over the past few years and was expecting this trend to continue into the foreseeable future. This sustained increase in demand was beginning to put increased pressure on the company's already taxed manufacturing operation. If production efficiency could not be increased, CoachComm was faced with the possibility running Saturday's on a regular basis. Adding to these issues was the recent transition of the majority of the company's assemblies to lead-free solder. This switch was having dramatically negative effects on the quality of the reflow soldering operation. Consequently, any increases in production efficiency or demand volume caused greater amounts of rework. At the onset of the project, it was clear that both quality and efficiency solutions would need to be implemented in a concerted manner. This would be no simple task as the company's wallet was tight and many industry standard solutions for these production issues would not be fiscally responsible. A comprehensive understanding of CoachComm's production process and corporate environment would be necessary to ensure the success of any improvement projects.

A production improvement team was assembled to see these tasks through. The team consisted of the production supervisor, manufacturing engineer, chief operations officer, and director of IT. The majority of the project work was performed by myself and Namo Vijayakumar, another graduate student working at the facility. I personally conducted all of the research. However, Namo assisted me greatly in setting the profiles, taking data on boards, repairing the new oven, and getting it into the production line. The production team aside from Namo and myself largely functioned as a support and approval team. Throughout this work it was important to ensure the continued support of this student project by diligently working on the CoachComm's most high priority assignments.

At the beginning of this work at the facility it was made clear that the installation of a new reflow oven and working to reduce setup time on the electronics manufacturing line would be the two highest priority projects. The installation of a new reflow oven was something which the company had desired for quite a while. A connection made possible by Dr. Evans ensured that such an oven could be procured within the companies budget constraints. The decision to work specifically on reducing changeover times for line production was based on some data collected as part of a previously completed senior design project at the facility. The senior design project pointed out that CoachComm was spending 2 to 3 days per month of production time performing line changeovers. No production assembly was possible during downtime. This data was verified and it was proved that downtime due to changeovers was an area ripe for improvements. The rest of the senior design project was somewhat flawed and the solutions it offered were proved poor at best. However, it did point out the area of changeovers as a good place for improvements and this was made one of the top priorities for me to look at in my time at the company.

## Chapter 2: Literature Review

### 2.1 Surface Mount Electronics

Surface mount technology, SMT, electronics assembly is the predominant form of electronic circuit construction worldwide today [1]. A completed surface mount electronics assembly has three main ingredients: the printed circuit board or PCB, solder paste, and the functional electrical components which must be connected. The PCB is a complex rigid assembly of many layers. The top and bottom of the PCB are covered in metal contacts. All of the functional electronic components will be attached to these pads. A tangled highway of copper runs through the interim layers of the PCB, making all the necessary connections between the electrical components. Solder paste is a mixture of flux and tiny solder particles which due to its tackiness will hold the components on the board during assembly. During reflow soldering the paste will be heated until it becomes a liquid; once cooled it serves as the both the physical and electrical connection between the functional components and the PCB. The electrical

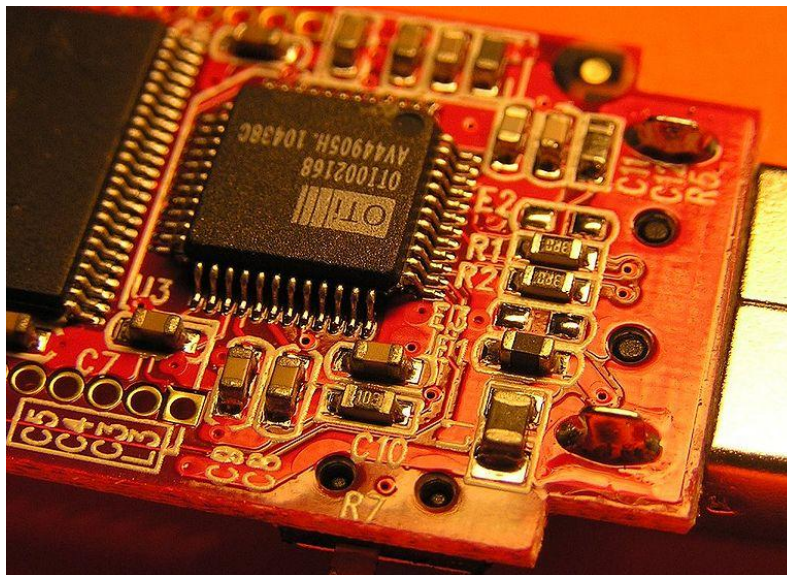


Figure 1 – USB Flash Memory Assembly Wikipedia

components are the pieces of the assembly which facilitate and determine its function. These include integrated circuits, capacitors, resistors, switches, and a variety of other important components. Figure 1 is a photo of a completed SMT electronics assembly. This particular assembly is a USB flash memory drive.

The SMT production process generally consists of three distinct steps: solder paste printing, component placement, and solder reflow [2]. At the beginning of the SMT production process, the bare printed circuit board enters the solder paste printing machine. After some processing the board emerges with solder paste deposits precisely aligned on its surface interconnect pads [3]. Next, the PCB enters the component placement machine. In this processing step the board is populated with the electrical components necessary for its function. To finalize the product, the entire assembly is carried through a reflow oven [4]. This oven raises the solder paste above its melting temperature and secures the components to the board. The improvements discussed in this work deal with component placement and reflow. As such they will be explained in greater detail [1].



**Figure 2 - SMT Processing Steps**

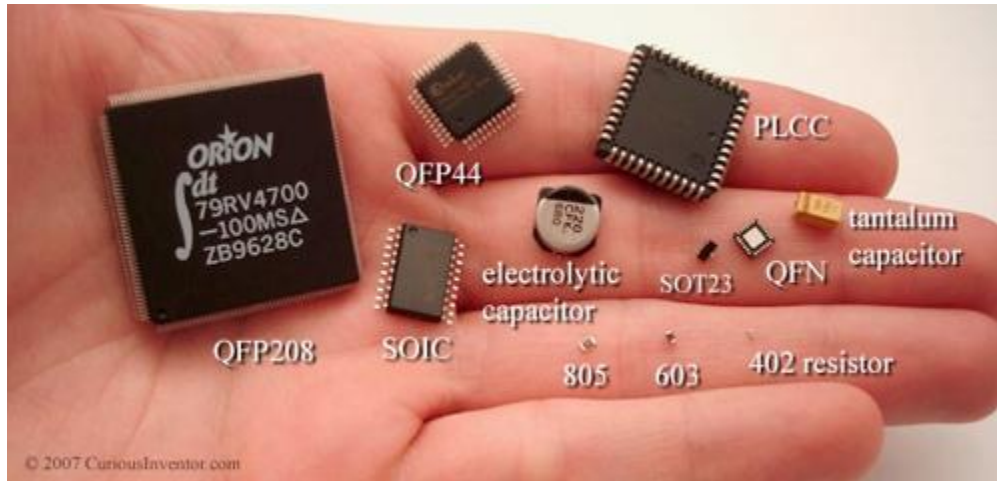
### 2.1.1 Component Placement

Component placement is a highly complex process that must be completed flawlessly for the final assembly to function correctly. During component placement, all of the functional electronic components must be precisely placed at their specific locations. It is not uncommon

for a single assembly to have tens or hundreds of passive devices which are 0.4mm x 0.2mm in size or smaller. The reflow and solder paste printing steps of the SMT production process are completed on a per panel basis. One cycle of a given machine will complete the entire board. In contrast, during component placement each component must be placed on the board individually. In almost every case component placement represents the process bottleneck [5]. Consequently, “The placement machine is the most important piece of equipment required for surface mounting. It absorbs the highest capital investment, and it also determines the overall economy of manufacturing” [1]. All these factors have created great profit potential for new procedures designed to increase component placement speed. The byproduct of this is a highly competitive market with a stratified landscape of component placement machines. Approaches to component placement vary widely between machine vendors and even between models from the same manufacturer. However, there are some unifying characteristics which are shared between almost all placement machines.

Irrespective of the approach being taken to component placement, there are certain unwavering aspects of these machines. All component placement machines contain: one or more placement heads, a board stop or circuit board table, a tooling carrier, and component feeder mounts. Circuit boards enter the machine and are lifted or stopped onto a table. Next, utilizing a vacuum nozzle these machines sequentially pick up components one at a time from a tray or feeding device of some sort. The components are then individually inspected, aligned, and placed on the PCB. The placement machine is equipped with several nozzles of various materials, sizes, and shapes. Each of these nozzles is suited for a particular type of component and the machine has a tooling carrier to hold nozzles which are not currently mounted to the

placement head. Another unifying characteristic between these machines is the delivery method of the components which they place.



**Figure 3 – Various SMT Electronics Packages - Electronics-lab.com**

As the image above illustrates, SMT components come in a variety of shapes and sizes. Resultantly, parts vendors use many different bulk packaging methods for parts delivery. A component placement machine must be able to handle all the various packaging forms of the parts being used in a given SMT assembly. Figure 4 and Figure 5 show two of the major component delivery methods. A tape and reel system can hold from 100 to over 20,000 components. Before placement, the reel must be loaded onto a specialized component feeder which pulls back the protective leader tape, advances the part carrying tape a precise amount, and presents the part for pickup by the machine nozzle. The waffle tray is delivery method popular with larger components. The use of a waffle tray necessitates careful, sequential picking of the SMT parts by the machine head. Besides tape and reel and waffle trays, bulk magazine feeders are also available [2]. Tube feeders were more popular with through hole electronics and are somewhat antiquated, but still seen on manufacturing floors. There are other delivery methods, but in general the bulk of parts today come as tape and reel. Though all SMT parts are



Figure 5 – Waffle Tray – Topline.tv



Figure 4 – Tape and Reel - techon.nikkeibp.co.jp

delivered in a similar manner and component placement machines operate on the same principles, many machine variations still exist [1].

The pursuit of increased throughput has driven vendors to develop an array of diverse placement machines. Some authors have categorized these different component placement machines [6], [7], [8], [9]. Ayob went so far as to create 5 distinct categories of placement machines [7]. Among these categories are machines which move the PCB table and feeder bay, allowing the placement head to remain stagnant and rotate at high speed. Other machine types contain multiple placement heads or even multiple production bays to handle mirrored assembly of multiple boards at once. On the other end of the spectrum are semi-automated placement machines for prototyping and small scale assembly. Though many machine styles exist, this work has dealt only with two variants of the very popular gantry style component placement machine.



### 2.1.1.1 Gantry-Style Placement Machines

Almost every placement machine vendor offers a variation of the popular gantry style machine. Figure 6, below, shows a Universal Advantis General Surface mount, GSM, placement machine. This gantry style machine is one of the two I worked on as part of my setup time reduction effort. Inside, there is a rail running front to back on each side of the machine. The placement head is mounted on a horizontal rail attached at each end to these side rails. The center rail may move front to back on the side rails allowing movement along the X axis. The head itself can move laterally along its rail on the Y axis. Movement on the Z axis is facilitated by the placement head itself. Grunow described these machines as operating in a gantry system as a result of the gantry style movement of the placement head [10]. Salonen's work is more pointed at classifying such machines as 'gantry style' [6]. Aside from the internal movement of

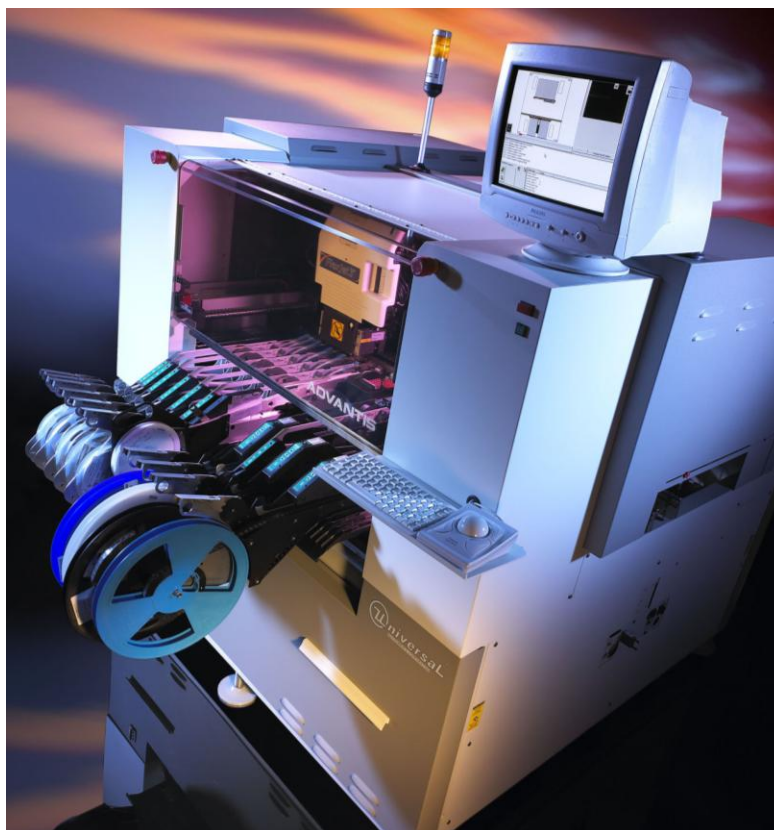


Figure 6 - Universal Advantis GSM - pcb007.com

the head, the physical configuration of gantry style machines is often similar.

In the case of the GSM machine shown in Figure 6, the outside of the machine is essentially symmetrical; with the front and back each containing slots for up to 35 feeders for a 70 feeder total capacity at any one time. In almost all machines there will also be an internal rack which stores nozzles while they are not mounted to the placement head. Functionally, the PCB enters on a conveyor from the upstream side of the machine. It is then lifted slightly and locked into place at the center of the machine by pneumatic fingers. During one machine cycle, the placement head is then tasked with moving to the feeder bays, picking up components, and placing them back on the PCB. Before the components are placed, they may be inspected with a camera or by another automated inspection system to ensure proper alignment. The number of components which may be picked and placed in one cycle is determined by how many spindles the placement head contains. The spindle is the attachment point of the vacuum nozzles. In most cases, it is also the part of the head which allows Z axis movement. Figure 7 shows a 6



Figure 7 - Six Spindle Placement Head - Panasonic



Figure 8 - Rotary Head - Universal Instruments

spindle placement head on a gantry style machine. This style head is well suited for placing any type of surface mount components. Figure 8 shows a 30 spindle rotary placement head; this style is also employed in gantry style machines. It can place small components at a much higher rate than the traditional head. However, larger components can substantially slow the head down. An additional downfall is that some oddly shaped and large components cannot even be placed by the spindle rotary placement head [11].

### 2.1.2 Reflow Soldering

After all the components have been successfully placed onto the printed circuit board, reflow soldering is the next step in the SMT production process. Up until this point the tacky nature of the solder paste has held the components temporarily on their pads. The goal of reflow solder is to evenly heat the assembly past the liquidus point of the solder alloy. Once the solder is cooled a strong mechanical connection to the board will exist. It is essential to heat the board in an even and controlled manner to yield a consistent, quality product. At the same time process engineers must ensure no components on the board are overheated or damaged due to extreme temperatures. Reflow soldering occurs most often in a common convection reflow oven. The reflow oven work provided herein has been centered around this type of oven. Though nitrogen, vapor phase, and even infrared ovens exist, the proceeding information is tailored to standard reflow ovens. Recently the move to lead-free solder has necessitated some changes in reflow soldering ovens. The main transition has been the lengthening of reflow ovens to give process engineers greater control over the reflow process. The move to lead-free solder has been very demanding not only on the equipment itself, but on the reflow process in general. A PCB built

using lead-free solder necessitates a much tighter reflow processing window than in an identical tin-lead solder assembly[12]

#### 2.1.2.1 Solder Pastes

Today there are a great number of solder paste variants available. Each specific paste is targeted to meet the goals of a given manufacturing situation. Solder paste is made up of cleaning flux and a metal alloy which will actually create the electrical/mechanical connection. The flux in the solder paste helps make the paste tacky so that it can hold components through the assembly process. During reflow, flux is activated and cleans any oxidation from the surfaces which are to be soldered. After reflow, fluxes can require cleaning or be “no clean.” Among those requiring cleaning some are water soluble while others require more harsh cleaners. In this work I have only dealt with “no clean” flux based solder paste. To reduce production steps, manufacturers usually choose a “no clean” flux unless their particular process requires a more stringent cleansing. In general the major selection criteria for a solder paste is not the flux, but the metal alloy.

Presently electronics manufacturers have a large pool of solder alloys to choose from. The diverse landscape of options is largely a product of the move to lead-free solders. The low eutectic melting point, small price, high availability, and good mechanical joint strength of the tin-lead solder alloy had made it the choice of electronics manufacturers since the mass adoption of electronics. Joe Fjelstad asserts that “Over the decades, tin lead solder has likely made hundreds of trillions of solder joints.” [13] However, in the 1990’s, pressure was mounting on the electronics industry to move away from tin-lead solder [14]. The harmful effects of lead on

the nervous system were very well understood at this point and the potential of lead leeching into groundwater from electronics in landfills was seen viewed as a paramount issue. Figure 9 illustrates the potential path lead from solder joints in electronics assemblies could easily take to enter drinking water. Despite rising concern, legislation banning the use of tin-lead solder would not take effect until 2006 in Europe as part of the Restriction of Hazardous Substances Directive, ROHS. In Japan market pressures moved many manufacturers away from tin-lead solder. In response to the European legislation and increased market pressures, much of the world would move to lead-free solders within the same time frame. Replacing tin-lead solder proved to be difficult, but many members of the electronics industry predicted this transition and began research into new alloys[12], [15], [14].

However, replacing tin-lead solder would be no easy task. As Seeling described in 1995 any plausible alternative to tin-lead solder would need to possess eight distinct characteristics

[14]:

- “1. The selected element will have no negative environmental impact now or in the future.
2. Sufficient quantities of base materials must be available now and in the future.
3. Melting temperatures similar to 63/37 tin/lead, preferably below 200°C.
4. Equal or similar thermal and electrical conductivity.
5. Adequate joint strength and thermal fatigue resistance.
6. Easy repairability.
7. Low cost.
8. Compatibility with existing processes.”

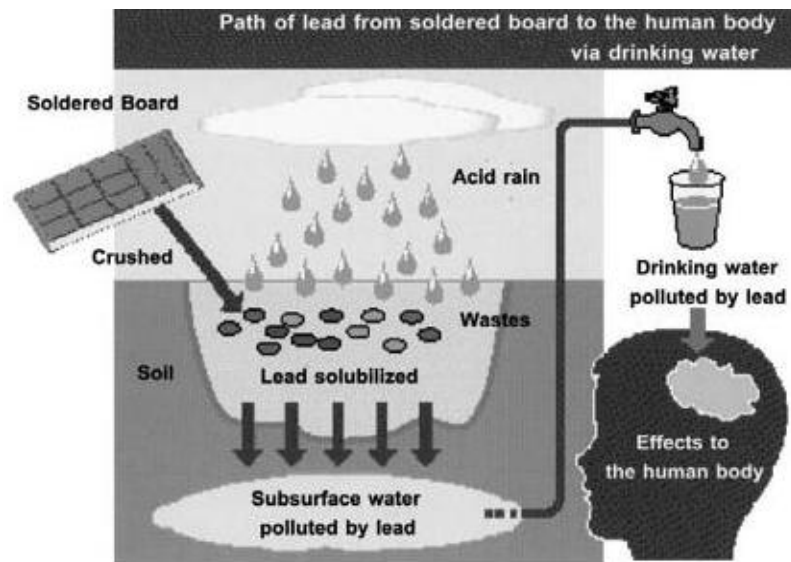


Figure 9 - Path of SnPb Solder Electronics to Nervous System - Puttlitz

The search for a suitable replacement to tin-lead solder was arduous and many new alloys were proposed. In 2000 Abteu and Selveduray studied approximately 70 newly proposed lead-free solder alloy combinations; eventually concluding that “Sn rich compositions are the most likely candidates” [15]. Today much more research has been carried out and we have a better understanding of lead-free solder alloys. Alloys which have been popularly considered as replacements for tin-lead solder include: tin-silver, tin-copper, tin-bismuth, tin-zinc, tin-silver-copper, and tin-silver bismuth [12]. Other elements such as Indium and aluminum have also been added to solder alloys in order to achieve specific properties [12]. Though each of these specific alloys has interesting properties, this work has dealt with the popular tin-silver-copper alloy. This popular solder is also known as SnAgCu or SAC.

SAC has been a very popular alloy for manufacturers moving away from lead based solders. The SAC alloy comes in many different combinations of the three base metals. Two popular mixtures are SAC105 and SAC305, these are 98.5Sn/1.0Ag/0.5Cu and 96.5Sn/3.0Ag/0.5Cu respectively. Studies have found SAC105 to present somewhat better mechanical reliability than SAC305 [16], [17]. Henshall et al. conducted a few fairly extensive experiments comparing the manufacturability and reliability of the different SAC alloys [18]. The SAC105 solder alloy has a slightly higher melting point (227°C) in comparison to SAC305 (217°C). Thus, a few tradeoffs exist between the various SAC alloys. This work has dealt with the SAC305 alloy, which has been a widespread choice for manufacturers moving to comply with the lead-free standards. Though SAC305 has been very popular, it is by no means a direct drop in replacement. The most frustrating difference between the SAC alloy and tin-lead solder is its much higher melting point. Sn63Pb37 solder has a eutectic melting point of 183°C. In contrast, SAC305 becomes liquidus more than 30°C north of that temperature. Figure 10 is a good illustration of this shrinking process window. Equipment and methodology changes have

## ***LEAD-FREE SOLDER PROCESS WINDOW***

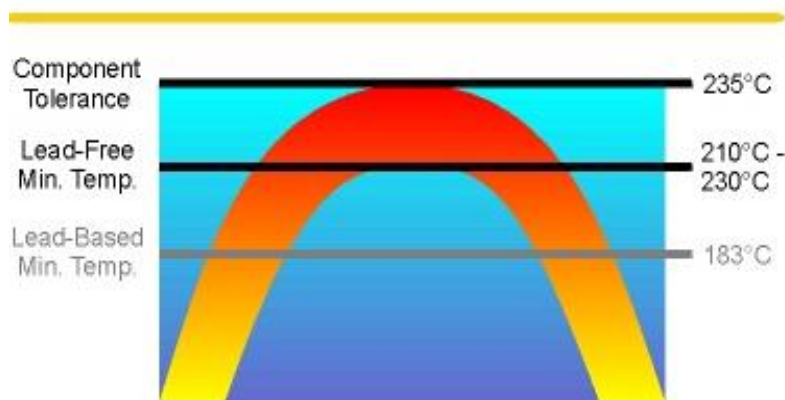


Figure 10 - Lead-Free vs Lead-Based Processing Windows - KIC.com

been necessary to continue the production of high quality electronic assemblies in a lead-free world which requires higher process temperatures. These higher temperature requirements have had a direct impact on the reflow profile companies must use to process their assemblies [12].

The most critical variable of reflow soldering is the heating profile, also called the reflow profile or thermal profile. This thermal profile almost completely dictates the outcome of the reflow soldering process and in turn the quality of the final product. The higher melting point of the popular lead-free solders has caused a direct shift in the shape of the typical reflow profile. This shift has necessitated the advent of more robust reflow ovens and new processing techniques. The reflow profile is often seen as a graphic of temperature plotted against time as in Figure 11. Ed Briggs of Indium Corporation, a solder paste manufacturer, sets out a good framework for understanding the reflow profile[19]. He breaks it down into 4 distinct phases: Preheat, Pre-reflow/Soak, Reflow, and Cooling.

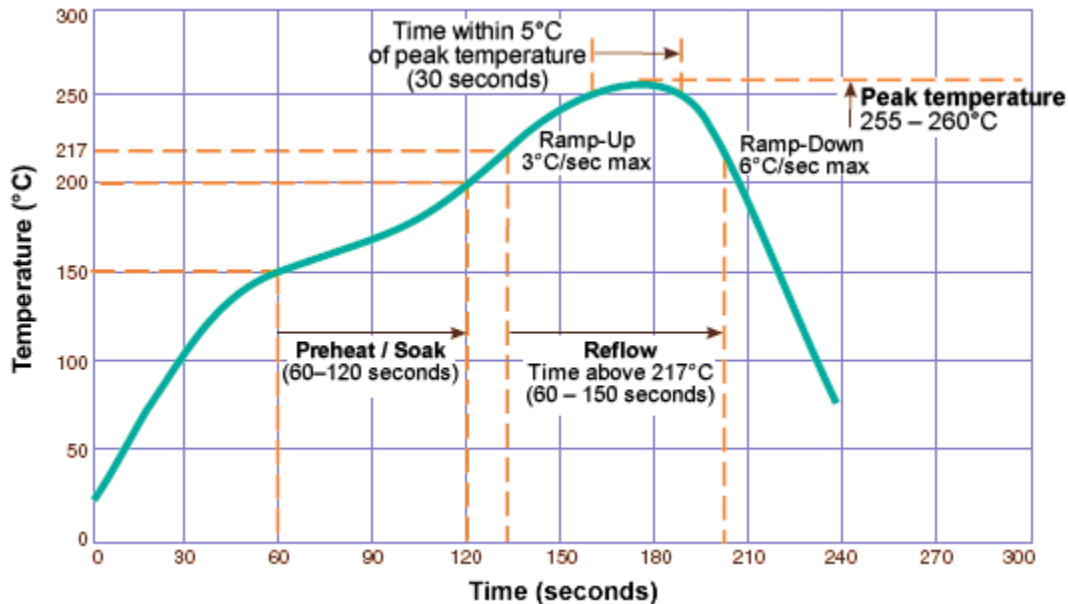


Figure 11 - Reflow Profile - Token.com



### 2.1.2.2 Preheat Phase

Preheat is the first stage of the reflow process. During this reflow phase, the entire board assembly climbs towards a target soak or dwell temperature. The main goal of the preheat phase is to get the entire assembly safely and consistently to a soak or pre-reflow temperature. Preheat is also an opportunity for volatile solvents in the solder paste to outgas. For paste solvents to be properly expelled and the assembly to safely reach pre-reflow temperatures the PCB must be heated in a consistent, linear manner. An important metric for the first phase of the reflow process is the temperature slope rate or rise vs time. This is often measured in degrees Celsius per second, C/s. Many variables factor into a manufacturer's target slope rate. These include: target processing time, solder paste volatility, and component considerations. It is important to account for all these process variables, but in most cases sensitive component considerations are paramount [20].

“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” [21]. However, if thermally sensitive components are not in use and maximizing throughput is of great concern, aggressive slope rates may be tailored to improve processing time. For this reason, many manufacturers push these slope rates up to the maximum common allowable rate of 3.0°C/Second. Conversely, if a solder paste containing particularly strong solvents is being used, heating the assembly too fast can easily create an out of control process. As the volatile solvents outgas they may splatter solder off the pads and onto the board. Solder-balling is the main concern of violent outgassing during the preheat phase. Once a board has been ramped up to temperature in the preheat phase it is time to enter the soak or pre-reflow phase [22].

### 2.1.2.3 Soak of Pre-Reflow Phase

The inclusion of a pre-reflow soak can help to eliminate multiple types of defects. The soaking period is often when flux activation in the solder paste occurs. Although the soak phase often holds merit, some process engineers choose not to include a soak. Instead they rely on a ramp to spike profile. Figure 13 shows a useful comparison of a ramp to spike, RTS, profile and a ramp soak spike, RSS, profile. Though the figure is useful for comparison, most profiles fall somewhere on a spectrum between the two shown below. This spectrum runs from the true ramp to spike profile to the extended soak profile. In a true ramp to spike profile the temperature slope never levels off staying constant from preheat through reflow. Ramp to spike type profiles are useful when flux may be activated too soon during soak causing poor wetting, especially with water soluble paste and difficult to solder components. Ramp to spike profiles can also produce shinier solder joints and can be more economical as the oven uses less energy [23]. Extended soak profiles have a prolonged soaking phase in which the temperature rises very slowly or even remains constant. This drawn-out soaking of the assembly can last for over 50% of the total time in oven. However, such an extended time of stagnant temperatures is often unnecessary to realize the benefits of a soak profile [24].

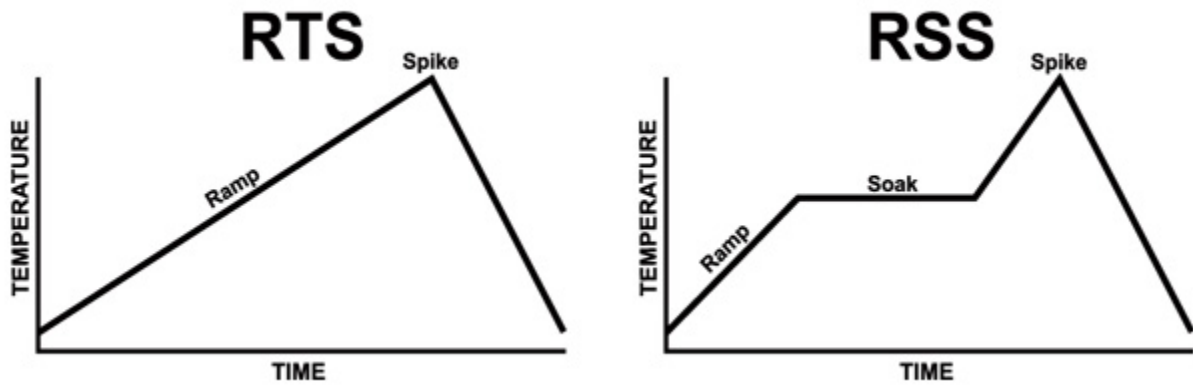


Figure 13 - Soak vs Ramp to Spike Profiles - profilingguru.com

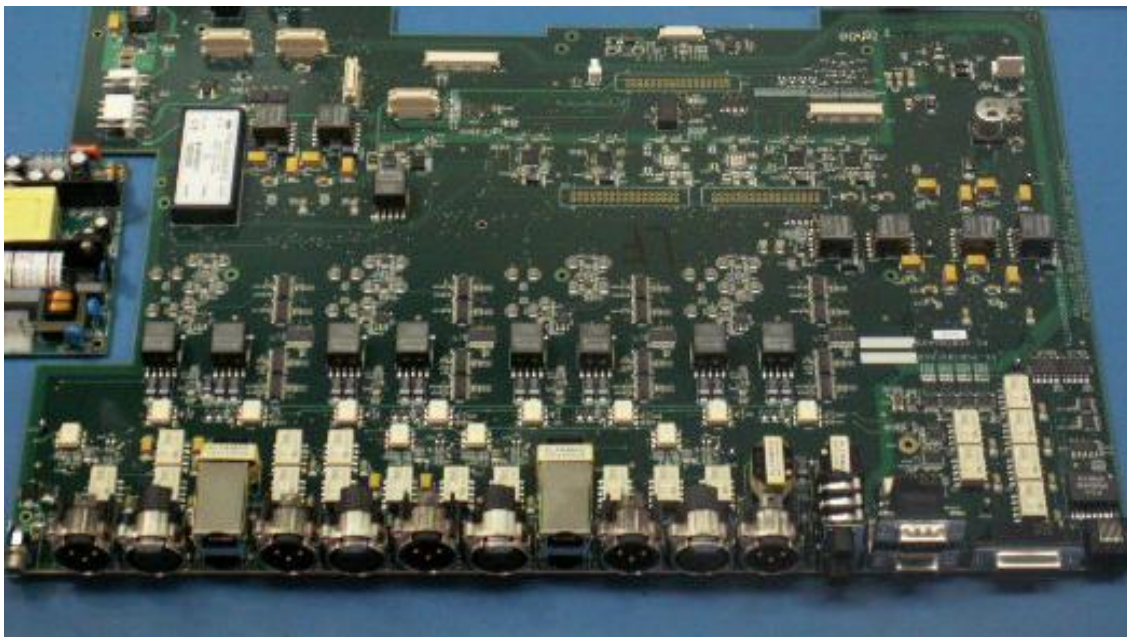


Figure 12 – Four Channel Base Station Audio Board - CoachComm

Soak profiles have become very popular as a means of minimizing the negative effects of complex board designs. When reflow soldering boards with a complex array of components, there can be a tendency for the board to heat unevenly. This often results from the use of some large and small components which leads to a wide variability in thermal mass across the board. Figure 12 shows a good example of such an assembly; note the lack of components at the top of the board, but high volume of large components at the bottom. It is critical to achieve an even

temperature across the board before the reflow spike to ensure no defects. If the small components on the board are much hotter than the large components they may crack during reflow. On the same PCB the cooler large components may be subject to cold solder joints. The inclusion of a soak period allows the entire board to reach a level of thermal equilibrium before reflow. During the soak the small component temperatures may climb very slowly or remain constant while the larger component's temperatures rise more quickly. Eventually the entire assembly reaches a balanced temperature just prior to reflow. This helps to minimize the temperature difference during the reflow portion of the profile. Figure 14 shows a good example of a soak profile, the different color lines represent thermocouple attachments on different parts of the board. As the image shows, the board was heating somewhat unevenly, but the soak period allowed all the various parts of the board to come together in temperature. This minimized the overall temperature differential during the reflow spike. Once the board has soaked, or reached the target pre-reflow temperature in the case of a ramp-to-spike profile, it is time to reflow the solder.

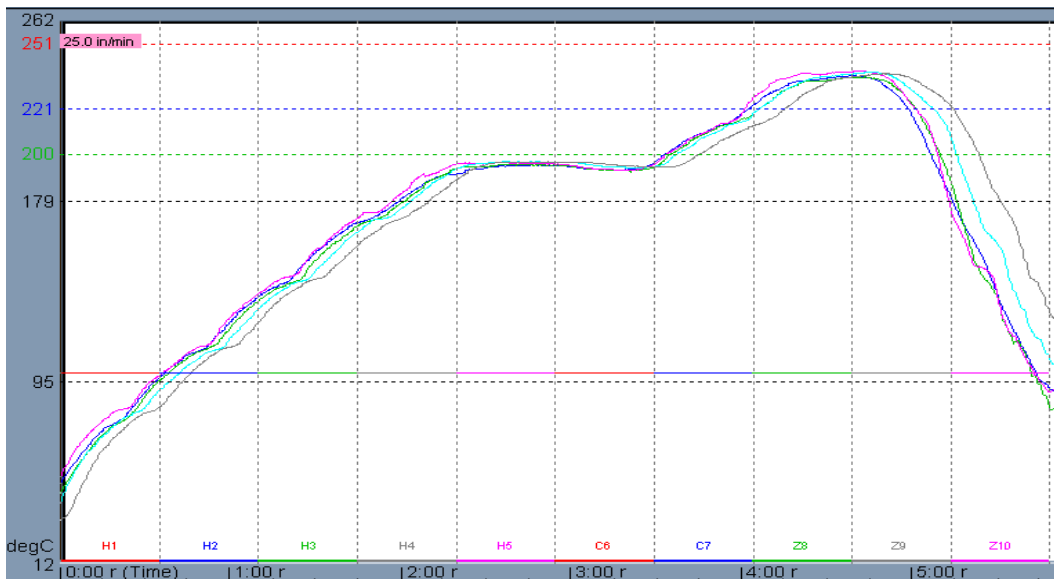


Figure 14 - CoachComm Transceiver Board Bottom Thermal Profile

#### 2.1.2.4 Reflow Phase

During the reflow phase the solder alloy becomes liquidus creating the electrical/mechanical connection between the components and PCB. The two defining metrics of the reflow phase are peak temperature and time above liquidus, TAL. These two measures are fairly self-explanatory, TAL is the amount of time the assembly spends above the melting point of the solder alloy and peak temperature is the maximum temperature reached by any one point on the assembly. The peak temperature must be considered carefully. High peak temperatures can often lead to very shiny joints. This is sometimes aesthetically tempting, but does not signify a quality joint. The temperature peak must be high enough for the entire assembly to wet and form quality solder joints. However, too high of a peak temperature can cause defects on heat sensitive components. Process engineers must be especially careful when profiling with high liquidus temperature lead-free solders. With such solders, the process window between melting point of the solder and failure point of sensitive components becomes very tight. Setting the correct peak temperature is important, but TAL should also be carefully considered. During the reflow phase the formation of intermetallic begins. The assembly must remain above the melting point of the solder for long enough to form quality solder joints at all locations on the PCB. Longer than 30 seconds is generally enough time for this to occur. However, too long of a TAL (in most cases greater than 90 seconds) can cause excessive formation of intermetallic which can eventually weaken the final joint. Excessive TAL can also result in charring of the joints or other types of thermal damage. Aside from the joints, many components are susceptible to cracking or other heat related failure if the TAL is too long. Thus, the formation of correct intermetallic during the reflow phase is important. However the cooling phase also plays a large part in the final grain structure of the joint [25].

#### 2.1.2.5 Cooling Phase

The cool down phase of the thermal profile determines the grain structure of the final joint. The more quickly the assembly is cooled, the finer the grain structure. A fine grain structure is desirable for mechanical reliability. Qi et al. explored the relationship between thermal fatigue and cooling rate in the SAC alloys, finding that a moderate cooling rate of 3.8°C/second out performed cooling rates of 1.6°C/second and 6.8°C/second [24][25]. Yang et al similarly investigated the relationship between cooling rate and mechanical fatigue, finding faster cooling rates to be preferable [26]. These findings are in line with the recommendations set forth by various solder paste manufacturers. Indium recommends a cooling rate between 2-6°C/second for all of its SAC alloys, with the target rate being 4°C/second [27]. The cooling phase is much less process dependent than the other reflow profile phases. The cooling rate may often be restricted by environmental factors or oven limitations. In general the recommendation can be made to have the fastest cooling rate possible up to around 4°C/second.

#### 2.1.2.6 Reflow Ovens

Though many environmental and production concerns weigh heavily into the reflow profile, the reflow oven itself is in many cases the key contributing factor. Often times the reflow oven is much more of a limited factor for the reflow profile than a facilitating tool. Reflow ovens come in many functional styles. Infrared, convection, and vapor phase are the three major types of ovens which have seen use in the electronics industry. Some convection ovens also employ the use of alternative atmosphere gases, a popular choice is nitrogen. This

work has dealt with a conventional forced convection reflow oven, see Figure 16 [2], [1], [5]. The operation of the reflow oven is relatively simple.

After a board has completed component placement it enters the reflow oven. Convection ovens have a set of metal chains which run parallel down the center of the oven, these act as conveyors for the board. Internally the oven will contain a number of independently controlled heating stages, referred to as heating zones. In a convection oven air will be circulated rapidly, this is achieved through the use of fans or compressed air flow in most cases. As a board enters the oven it is exposed to the circulating air at a given zone temperature setting. As it advances through the oven, the PCB's temperature will rise in a controlled manner as it hits each differing temperature zone in series. Through careful setting of both the chain speed and zone temperature settings, process engineers dial each board into the predetermined thermal profile. Figure 15 shows a reflow profile through a 10 zone oven, the dashed vertical lines separate the heating zones and the red numbers along the x axis are the zone temperature settings. As the image shows the actual board temperature follows the defined zone setting temperature gradient. Process engineers specifically set the temperature in each zone to ensure adherence to a defined reflow profile. Having an oven with more heating zones allows further fine tuning of the reflow profile and in turn greater process control. However, SMT production line style ovens are available with as few as 3 heating zones. In most cases, an oven with less than 5 zones will show poor process capability for tin-lead solder. To properly reflow lead-free solder at least 7 zones are recommended by most process engineers [2], [20], [1]. For complex reflow operations ovens with greater than 15 zones are available [28].

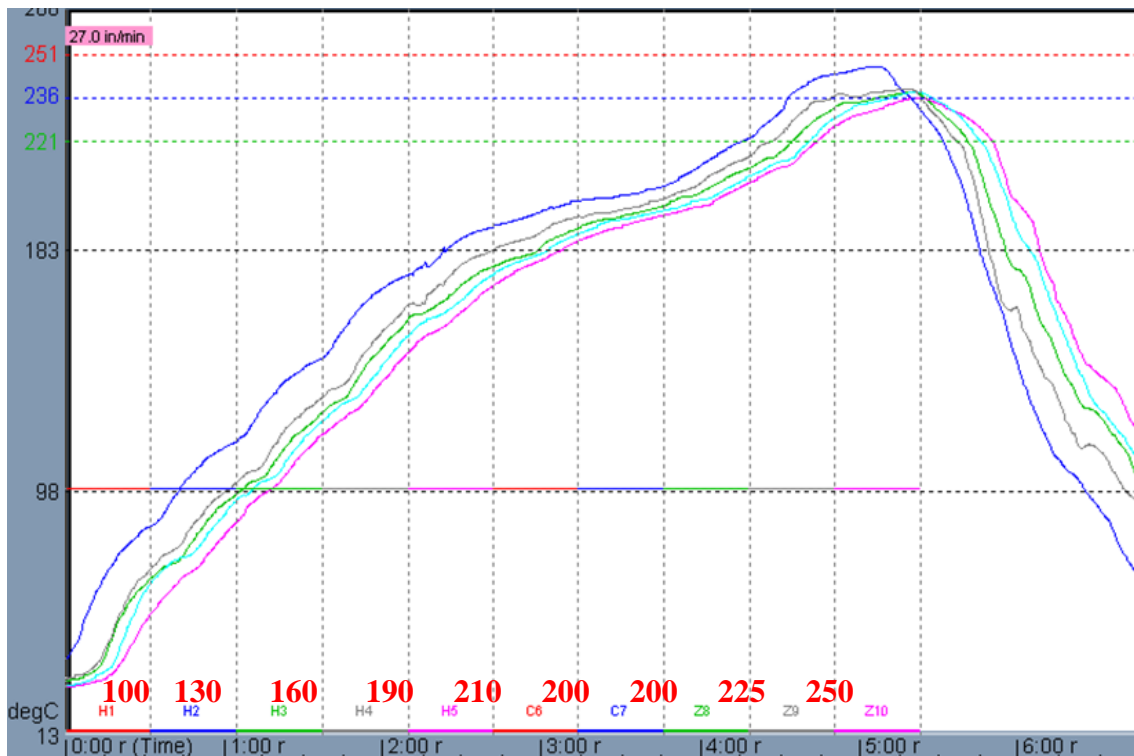


Figure 15 - Reflow Profile With Oven Zone Settings - CoachComm



Figure 16 - Convection Reflow Oven - Conceptronics.com



## 2.2 Single Minute Exchange of Die

Single Minute Exchange of Die (“SMED”) is a setup reduction technique principally developed by Shigeo Shingo. Shingo developed the SMED techniques while working to improve efficiency at various manufacturing facilities around Japan in the 1950s and 60s. In the ensuing years, while working at Toyota, he polished the system and eventually it was fully adopted. SMED was largely held as a trade secret until former Toyota president Taiichi Ohno wrote an article on the technique in 1976. As the car company gained momentum so did the SMED ideology. Some years later, Shingo [29] would write the seminal book on the subject, *A revolution in manufacturing: the SMED system*. Today SMED is considered one of the basic tools of Lean Manufacturing and has many applications across the gamut of manufacturing. This is largely due to Shingo’s book and the successive texts which have simplified the ideas of SMED and set forth a simple framework for its application across industries.

The main principle of SMED is to reduce setup times through the use of simple, widely

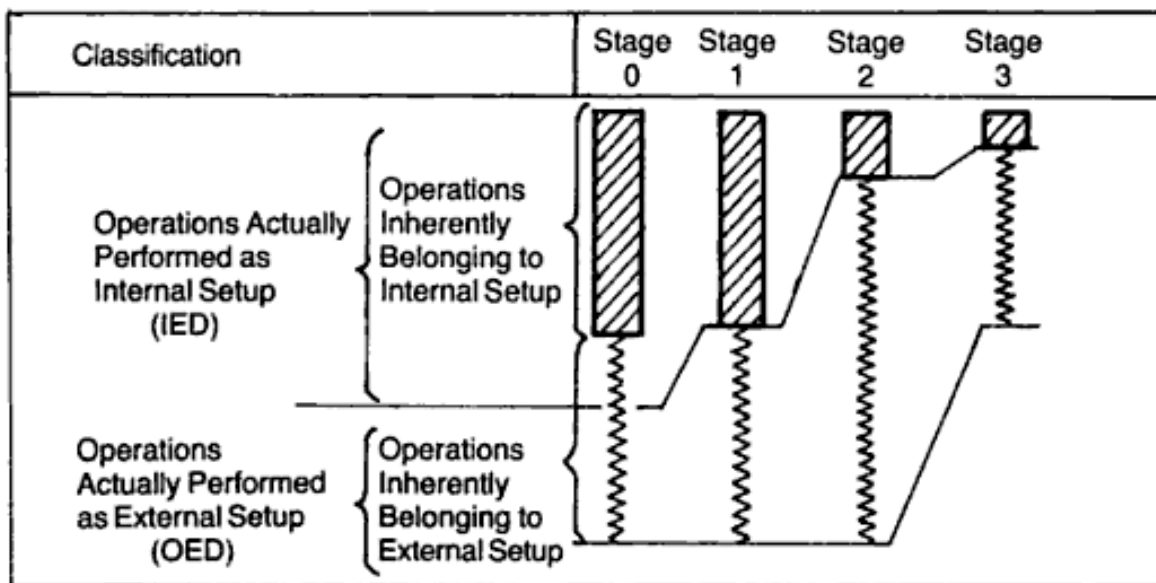


Figure 17 - SMED Stages and Shift of IED to OED - Shingo 1985

applicable tools. In *A revolution in manufacturing: the SMED system*, Shingo heavily emphasizes the divergence of SMED from the traditional setup time reduction techniques of large-lot production and skilled technicians. Early on in his text Shingo defines the aspects internal, IED, and external setup, OED. Internal setup can only be performed while the machine is in an inoperable state. A good example of internal setup is changing the blade on a cutting machine. External setup is all setup operations which could be performed while the machine is operating. The transportation of dies to and from a machine would be included in external setup. IED setup tasks have an adverse effect on per unit production time, while OED setup tasks have no effect on this same metric. As a result, the distinction of IED from OED is very important in the framework of SMED. Shingo proposes a three stage framework for the implementation of SMED.

The first stage is the separation of internal setup and external setup. Next a practitioner would convert as much of the IED as possible to OED. Third, all aspects of the Setup Operation would be streamlined. Figure 17 shows the expected shifts in setup times through the 3 main stages of SMED. Stage 1 of Shingo's process has no direct effect on reducing the setup times, but rather serves to distinguish between types of setup task to aid in time reduction during the second phase. Distinguishing between types of setup tasks may not always be completely lucid. Though some task which may currently be performed during downtime could easily and readily be accomplished during a production run, other changeover tasks are not as easily seen as OED. However, the inherent advantage of an external setup task means that during stages 1 and 2 of the SMED process special care should be taken in identifying task which are currently IED, but which could be made OED through the purchase of equipment, use of jigs, or exploits in machine operation practices. In general when working on a system which has never been

improved from a SMED perspective, we would hope to gain the greatest overall setup time savings through the conversion of some internal setup procedures into external. However, the third stage of Shingo's process definitely adds its own merit. The use of custom tools, more skilled laborers, and long-term training effects can all help lower the remaining IED setup task.

### 2.3 SMED and Increasing Throughput in SMT Electronics Manufacturing

Since the early 1990's various techniques have been applied to reduce product changeover time of surface mount electronics assembly. Electronics manufacturers, machine vendors, process engineers, and scholars have all worked towards reducing setup times in situations of high product mix. There are numerous distinct optimization problems which may be faced when working to streamline setup of a SMT electronics line. In cases of high product mix the largest hurdle is often finding the quickest setup strategy for the automated component placement machines [30]. As noted earlier, component placement machines represent not only the chief impediment to reduced setup times, but are also the production bottleneck in many operations [1]. As a result, serious effort has aimed to improve almost every aspect of placement machine operation. The main burden of component placement setup is the changeover of component feeders. Loading and changing over a part feeder can take between 1-5 minutes[6], [31], [32], [32], [33]. Changing feeder slots for a component can take between 15 seconds and 1 minute. This can become highly problematic when over 150 parts may need to be changed over during line downtime. Reducing the number of setups is often a very important task, but per panel production times also matter.

Increasing SMT line throughput is not an easy task and in many cases a solution must be tailor-fit to the specific situation. In a high mix operation product changeovers could be key to increasing efficiency. However, in low mix situations part location on the machines may be the most important piece of the puzzle. The speed at which component placement machines operate and the time it takes to for product changeover are heavily intertwined. Another important consideration is the operating style of the particular placement machine being studied. In some cases multiple component placement machines of different types are operating on the same production line. Often there is no one improvement strategy which is appropriate for all of the machines. The literature on increasing component placement efficiency reflects the difficult and entangled nature of the problem. On a very basic level the complexity of increasing throughput during the placement stage of SMT production can be understood as a simple equation.

$$\begin{aligned} \textit{Total Production Time} &= \textit{setup time} * \textit{required setups} \\ &+ \textit{time per panel} * \textit{panels produced} \end{aligned}$$

Equation 1

We must assume that due to production scheduling constraints, the required number of setups and number of panels produced cannot be changed through any optimization attempts. Equation 1 is wildly different depending on the volume and product mix a particular manufacturer produces. Though this relationship seems simple, setup times and per panel processing times are highly correlated. Often faster per panel processing times come with the costs of greater setup time or more setup instances. Certainly there are numerous other factors which can play a role in overall throughput. However, this basic equation is sufficient for understanding the implications of the basic SMT setup strategies which are popular today.

### 2.3.1 Popular Setup Strategies

When working to increase the efficiency of component placement machines, one of the first steps is to decide on the most appropriate setup strategy for the particular production line being improved. The vast landscape of setup ideas for increasing throughput in SMT electronics manufacturing reflects the many different manufacturing environments which exist in the industry. In high volume situations it is common to make minimizing the per panel processing time the goal. This is a result of the lack of product setups required, if the number of setups required is substantially low it is fruitful to only be concerned with per panel times. If setups required equals zero in equation 1, setup time becomes a non-issue. To achieve the fastest per panel times, components must be assigned to the most optimal feeder slots on each machine. The most high volume parts should generally be closest to the location of the board during placement; this positioning will minimize the total distance travelled by the placement head, and machine cycle time, in gantry style machines. Strategies which seek to minimize the per panel processing time often include high setup costs. In a high volume, low mix environment product changeover is usually not an issue. As a result low and medium volume manufacturers often choose a very different goal.

Recently, some SMT manufacturers have moved towards leaner manufacturing environments, smaller size batches, and increased product variability. As a result, new setup strategies have been proposed to reduce the costs associated with high mix production [6]. These new setup methods run the gamut from the purely per panel oriented mass production strategies to the least setup possible strategies of very small batch manufacturers. As the number of panels being produced falls and the number of setup instances increases, equation 1 shows that setup time reduction would now be the likely goal. In order to reduce setup times producers may use

shared feeder configurations, product families, or other similar strategies. However, in most cases it is impossible to achieve the fastest possible per panel processing times while using these strategies. For example, setup time between two products may be minimized with a common feeder setup. However, if the same part is the most used on one product and least used on the other, then both their per panel times cannot be optimal with a shared feeder slot configuration. Resultantly, there is a vast amount of literature on setup strategies. Leon and Peters classified strategies present in the popular literature into four setup categories: unique, group, minimum, and partial [34]. Salonen proposed an additional hybrid setup strategy [6]. In addition some research has explored the ‘hot swap’ setup strategy which will be the core of this work.

#### 2.3.1.1 Unique Setup

The unique setup strategy seeks to achieve the lowest possible per panel production time. This goal is accomplished by finding the best combination of feeder slots and the best order of component placements for a given panel. This strategy is best employed when dealing with a SMT line which produces one or very few products. If the number of setup instances required over a period of time is substantial, the unique setup strategy can be a very poor setup choice. If multiple placement machines are being used, it is also most applicable on the bottleneck machine after line balancing has been performed. Ball and Magazine modeled such a component placement problem as a variant of the traveling salesman problem [35]. Subsequently many authors have formulated and studied the problem as a traveling salesman problem or transportation network problem [1-7]. Today most commercial SMT line software comes with optimization packages which will automatically line balance PCB assemblies. Such software can also seek out near optimal feeder configurations [11]. If the SMT line being studied

produces any significant number of varied products, the group setup strategy could be a better choice.

#### 2.3.1.2 Group Setup

The group setup strategy exploits component similarities across products to reduce the setup time between products in a given group to zero. Components occupy the same feeder slots throughout the group run and only change when production is shifted to another product group. While in the same group, any order of boards may be run with no risk of an additional setup instances. Feeder setup changes are only required when moving from one product group to another. A side effect of the group setup strategy is that products will not be produced near their optimal per panel production time. This makes the grouping method more useful for high mix, low volume situations. It is very efficient if batch sizes are small or if a one piece flow is desired. An enormous amount of research has been performed on group setup strategies [29], [36], [37], [38], [39], [40], [41], [42], [43]. Yilmaz et al. describes the progression of group setup strategies [47]. Early on many authors used component similarity between PCBs as the main metric of choosing groups [44]. Later researchers used linear and Integer programming models to define product groups [33], [43]. Other mathematical formulations have also been proposed, some even taking into account more practical matters such as feeder differences and other specific machine considerations [42]. For the most comprehensive review of group setup related literature see Yilmaz et al. [47] and Crama et al. [41]. Though setups do not occur often with the group setup strategy, one major downside is that when a group changes occurs the setup can be extensive. As such, the total setup time over the course of the entire board run may still be large. The minimum setup strategy ensures total setup time is sufficiently low.

### 2.3.1.3 Minimum setup

The minimum setup strategy seeks to find the board run order requiring the lowest total amount of feeder changes. This should in theory minimize the total setup time for the entire board run. The group strategy may have fewer setup instances, but the minimum setup strategy should have the least total setup time. The idea is to find the board run order which demands the fewest feeder changes and then to change only the necessary parts between boards. In a true minimum setup situation there are no part changes targeted at reducing per panel placement time. Application of the minimum setup strategy normally results in the most similar boards being built in sequence. The minimum setup strategy is fairly well researched [48], [49]. Gunther et al. used various heuristics to seek out the minimum setup for a sequence of PCBs [48]. His model included many more real world constraints than most previous models including: feeders taking up multiple machine slots, variable job arrivals, and two sided assemblies with precedence. This gave proof of concept for the use of minimum setup strategy in industry. Though the minimum setup strategy is useful in situations of very high product mix with some knowledge of future production schedule, the partial setup strategy can greatly reduce per panel production times weighing those savings against the costs of added setup.

### 2.3.1.4 Partial Setup

The partial setup strategy falls somewhere between the unique and the minimum setup strategies. Partial setup seeks to find the minimum possible total setup, but also considers realignment of feeders to reduce the per panel time on high volume boards. Leon and Peters



compared many popular setup strategies and concluded that “the partial-setup strategy adapts to a variety of production conditions” [34], [9]. They point out that the success of the partial setup strategy is due to its ability to find situations in which the added setup costs will be outweighed by the benefits of per panel time reductions. In this way the partial setup strategy is truly adaptable to fit most production situations. The partial setup strategy has been further explored by Peters and Subramian; their model of the partial setup strategy used the minimum setup solution as an input [50]. Resultantly the partial strategy always outperformed the minimum. Though the partial setup technique has performed well it falls short in modeling some facets of the real world production problem. A hybrid setup strategy has been proposed by Salonen to address this issue [6].

#### 2.3.1.5 Hybrid Setup

The hybrid setup strategy seeks to take the best parts of the minimum and group setup strategies. The minimum and group strategies both work well in particular situations. However, their main objectives are divergent. The minimum setup strategy seeks to minimize total setup time, while the group works to minimize setup instances. Salonen states that “in a real world production environment of the PCB assembly it is often needed to consider both problems at the same time, especially in high mix environments” [6]. This need arises from some real world considerations which are often left out of optimization models. The changeover between two PCB assemblies will never be zero as other process parameters must be changed over in order for the placement to occur. In practice there will always be a 15-25 minute setup time requirement between board groups, called ‘setup occasions’. This is in contrast to the 1-5 minutes required for each individual ‘component setup’. The hybrid setup strategy seeks to optimize a weighted

sum of component setups and the setup occasions [6]. In this way the hybrid setup is able to receive some of the benefits of both the minimum and group setup strategies.

#### 2.3.1.6 Hot Swap Setup

The hot swap setup strategy has been somewhat less reviewed in the literature than the other aforementioned strategies. However, for my project it plays a very important role. Trovinger and Bohn researched single minute exchange of die philosophies for electronics in 2005 [30]. In this paper they describe the use of feeder ‘hot swapping’ and its benefits. Hot swapping is only possible on line with particular machine configurations which allow the removal and insertion of component feeders while production is running. Fully hot swapping a product also requires the two products being transitioned have a combined total of unique parts which is less than the number of feeder slots available on the machine. The changeover strategy allows loading of the second product into unused feeder slots while the first is running. Once this has been completed the only remaining internal setup task on the placement machines is to change the machine program files. Trovinger and Bohn reported great success in using hot swapping to reduce the amount of required internal setup [30].

## Chapter 3: Installation of New Reflow Oven

### 3.1 Previous Oven Setup

When this work began at CoachComm the company was using a Vitronics Soltec XPM-520 reflow oven. The oven had been on their production line since they began assembling their own electronics in Early 2002. The Vitronics Soltec XPM-520 has 5 heating zones and 2 cooling zones. At the time of purchase, this oven was well suited to CoachComm's production environment. The most important factor which ensured this oven's success was the use of tin-lead solder in all of CoachComm's assemblies. CoachComm uses the Indium NC-SMQ 92J tin-lead solder paste. This is a standard 63% Tin and 37% Lead solder paste. The Eutectic melting point of this tin-lead alloy is 183°C. Figure 18 shows the recommended profile for this solder alloy. This manufacturer suggested profile shows a slow ramp up to near liquidus followed by a quick spike of at least 25°C above the melting point of the solder. The Vitronics Soltec XPM-520 5 zone oven was very capable of reproducing such a profile. During its first few years of service, the Vitronics Soltec oven built a very low percentage of defective PCB assemblies. (An

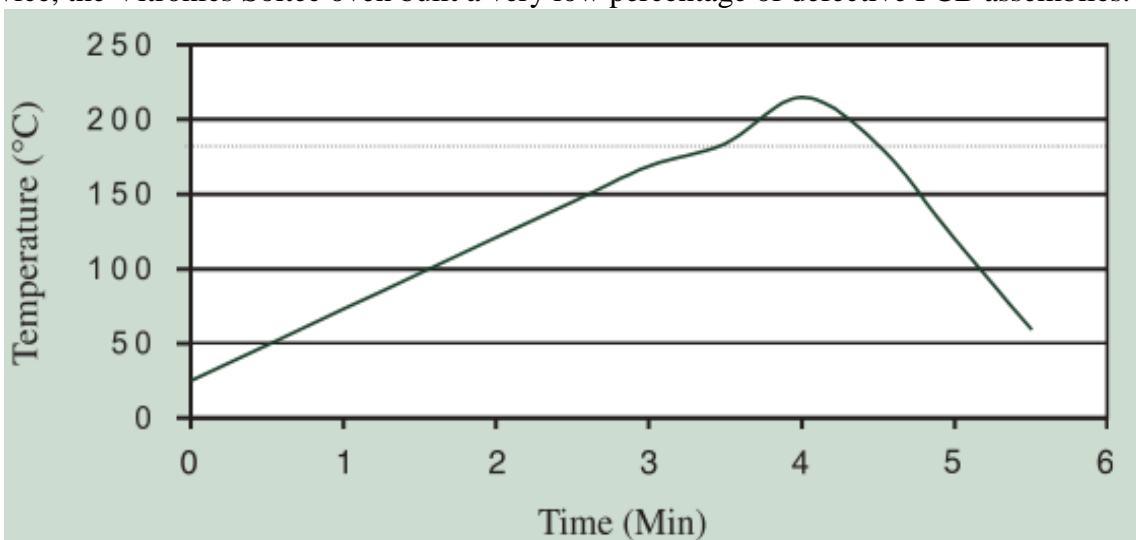


Figure 18 - NC SMQ 92j Recommended Profile - Indium Corporation

actual measure of defective units from this period is unavailable. However, the baseline study data below shows the defective rate of tin-lead boards over the past 10 months.) As CoachComm moved away from the NC-SMQ 92j solder paste and to a lead-free alternative they witnessed a dramatic increase in the number of defective boards being produced.

In 2007 CoachComm began producing ROHS compliant assemblies. The most important part of the move to ROHS compliance meant switching over to a lead-free solder alloy. Indium 8.9 is CoachComm's lead free solder paste. Indium 8.9 comes in a few different alloy combinations, but CoachComm's variant of the paste is a standard SAC305. This means the solder paste consists of 96.5% Tin, 3% Silver, and 0.5% Copper. The melting point of this particular solder alloy is 217°C. At the recommended profile in Figure 19 shows, this lead-free solder paste requires a much tighter and hotter processing window in comparison to the tin-lead

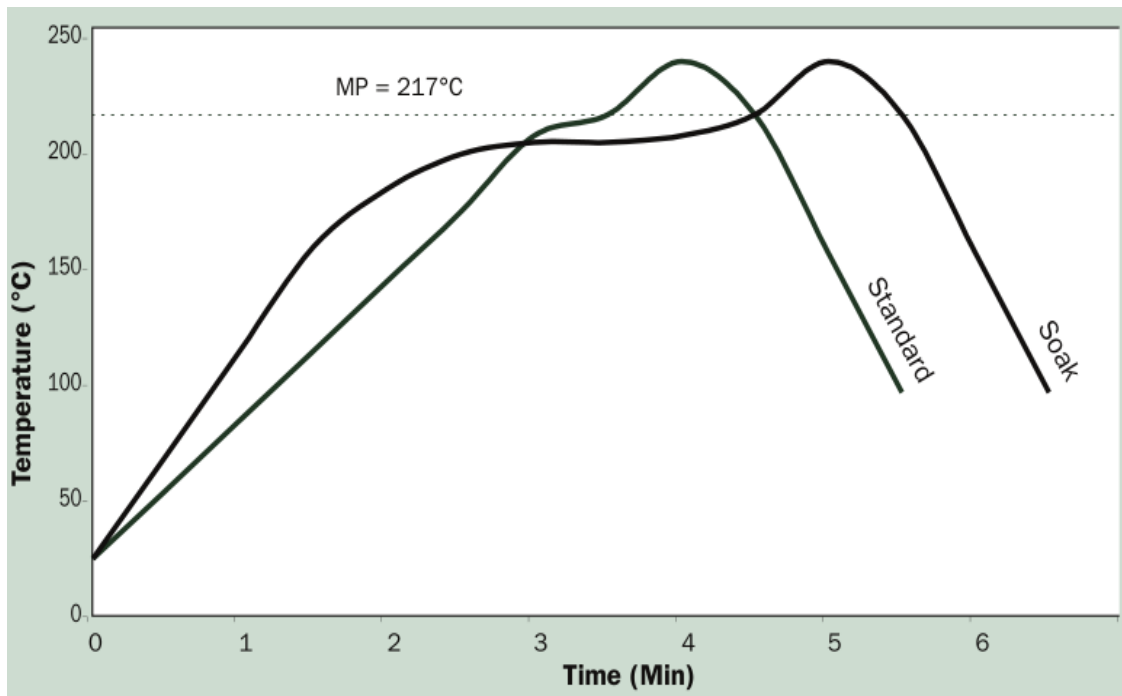


Figure 19 - Indium 8.9 Recommended Profile - Indium

paste. With this solder paste, it is advisable to peak the reflow profile between 15-30 degrees above its melting point. This leaves a process window of between 217-247°C in which we could expect to get a decent solder joint. At the low side we may not see good wetting and at the high side we may be pushing the limit for some components' heat tolerance. Comparing this to the extremes of the process parameters for the tin-lead paste, 183-228°C, it is easy to see the challenge a move to lead-free assemblies presented to CoachComm's reflow process. The issues associated with transitioning to lead-free solder for some products were magnified by the sales volume of these lead-free products.

Over the past few years lead-free products have come to make up a large percentage of CoachComm's overall production mix. This has served to amplify the effects of the poor performing oven. Lead-free products make up around two thirds of CoachComm's product mix and around 70% of their total production volume. As lead-free products have come to represent a greater percentage of the company's total production, the number of soldering related defects has increased as well. CoachComm has brought in various consultants and process engineers over the past few years in attempts to increase the reflow process yield. However, even after extensive work the defect rate has remained relatively high. The 5 zone Vitronics Soltec oven has shown very poor capability in meeting the demands of lead-free reflow soldering.

### 3.2 Performance Metrics and Measurement Systems

The performance of the Vitronics Soltec XPM-520 reflow oven will be evaluated based on two simple metrics. First, the percentage of reflow related defects produced by the oven. Second, the adherence of the produced reflow profile to solder paste and any other relevant

specifications. The defect percentage metric is fairly straightforward, but it is fairly difficult to actually measure the amount of defects being produced. CoachComm currently inspects boards at numerous points throughout its production process. Figure 20 is a flow chart which shows the production process for one of the company's products. The blue boxes represent inspection points throughout the process. The second blue box in the series is the post reflow visual inspection station. At this point in the production process a technician visually inspects each assembly as it exits the oven. There was no salient defect collection system in place when I came to work at CoachComm. The defects caught at the post reflow inspection station were marked with stickers and sent to the rework station. They were then sometimes later tallied into categories on an offline spreadsheet which included many types of defects. Some of which were related to wave soldering and other processes no longer in use at the facility. Overall this system was inefficient and it was nearly impossible to tell which defects were related to the reflow process.

At this point the choice was made to implement a more formal and up to date defect tracking system at this station as it was catching the majority of the reflow soldering related defects. Over 90% of the total defects found on the floor were found at this inspection station; this inspection point also creates over 90% of the jobs performed at the soldering rework station. These numbers are based on observational statistics taken over a few days watching the various processes. The conclusions of this study were validated by the production supervisor and technicians. To implement a more formal system, I created a spreadsheet with defect categories matching closely to those in IPC standard 610. The post reflow inspectors completed their job in much the same way as before, only now they would log the defects based on these more finite, predefined categories. This system is by no means perfect and I suspect there is still some

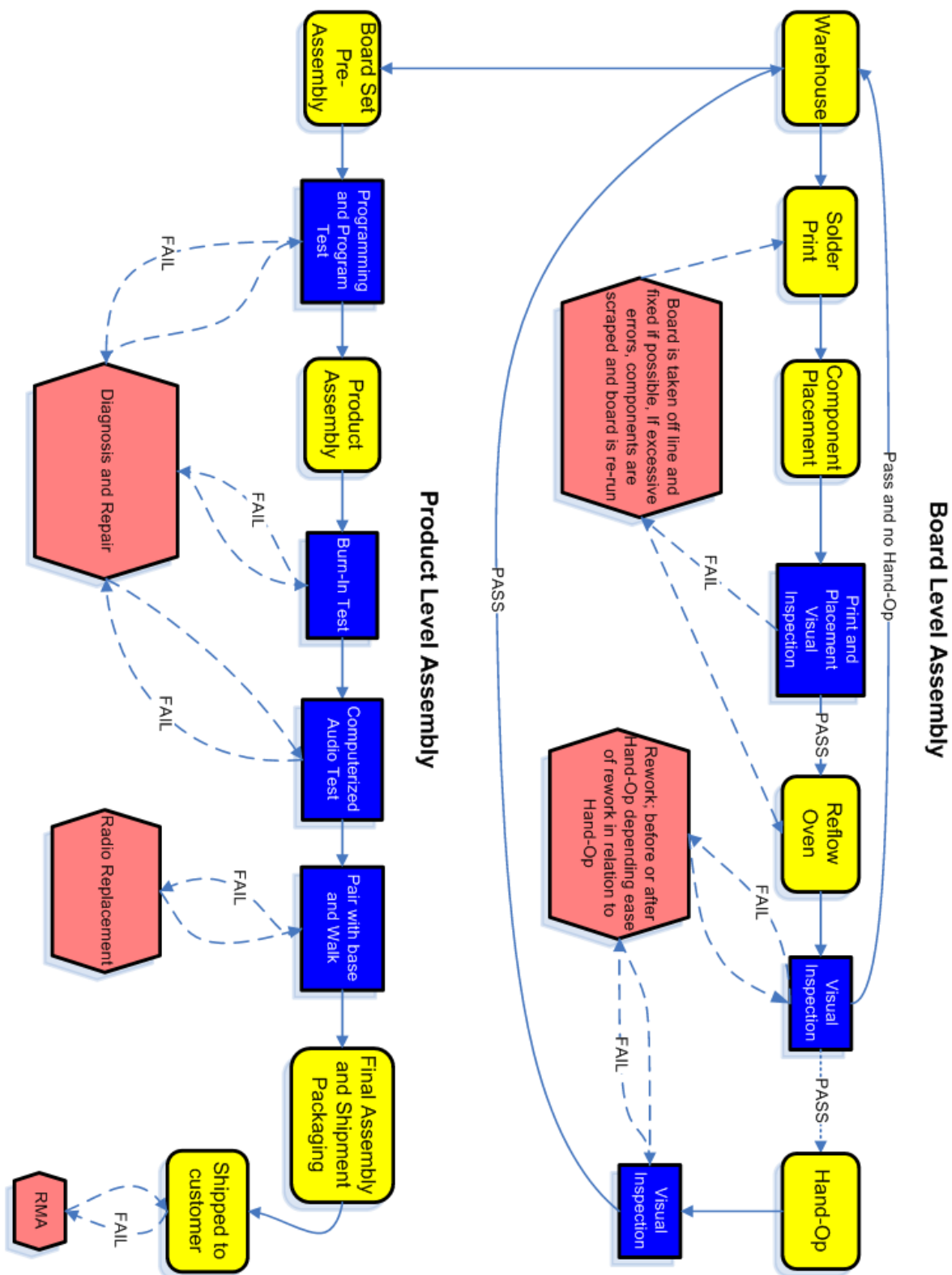


Figure 20 – CoachComm Belt Pack Production Process

amount of error present in the collection of post reflow defect data. However, in this instance it was very important for me to implement a system which would be used and accepted by the line operators and supervisor. Given these constraints, this was a good defect tracking structure. The second reflow oven performance metric, adherence to specified reflow profile, serves as verification for the defect percentage data.

The adherence of the observed to the desired heating profile is a very good measure of overall oven performance. There are a few critical characteristics of thermal profiles which can be compared and evaluated to determine this adherence. These metrics were discussed in further detail during my review of the reflow process. Each metric defined here seeks to quantify a phase of the reflow process. Figure 21 is a mapping of these previously discussed metrics to the phases of the reflow process they measure. Each of these metrics was measured using industry standard reflow profiling practices. Further discussion of these practices can be found in O’Leary and Limberg 2009 [20]. The thermal profiler used was an ECD SuperMOLE Gold.

<b>Reflow Phase</b>	<b>Metric</b>
Preheat	Slope Rate
Pre-reflow/Soak	Soak or Preheat Temperature, Soak Time
Reflow	Peak temperature, Time Above Liquidus
Cooling	Cooling Rate

**Figure 21 – Metrics for Reflow Profile**

This thermal profiler has points for the attachment of up to 6 K-type thermocouples. The SuperMOLE Gold is capable of accurately measuring temperatures to within 1°C and can sample at intervals as fast as 0.1 seconds. ECD provides SuperMOLE Gold SPC software for interfacing with the profiler. This software generates useful graphics of the thermal profiles and



allows the user to measure all important metrics of the given thermal plot. Thermocouple attachment was also performed in an industry standard manner.

High temperature Kapton tape was used to secure the thermocouples on the PCB and component leads. Thermocouples were attached to various different points of the board depending upon what areas were assumed to be most difficult to solder. In most cases care was taken to put thermocouples on the areas with the lowest and highest thermal mass respectively. This was important as ensuring that all areas of the board were heated evenly was of great concern. Some particularly heat sensitive components were drilled into so that internal thermocouples could accurately confirm the temperature of the package. In all cases a lead thermocouple was placed roughly an inch in front of the board in the open air. This would act as a trigger for the profiler and ensure its proper function.

Accuracy of the profiler was verified using a few test runs. All zones of the oven were set to 60, 100, 150, 200, and 250 degrees Celsius respectively. The profiler was then run through the oven and the output graph was observed to ensure proper calibration. Oven temperatures were verified on the Vitronics Soltec using both the oven's internal thermocouples and handheld thermometer. The new oven was verified using both its internal thermocouples and a secondary set of thermocouples installed in the oven which were part of an external process monitoring system. After all these verifications, we were confident that both the ovens settings and the profiler were accurate. At this point we could begin taking data and performed a baseline study.

### 3.3 Baseline System Performance

Initially the performance of the Vitronics Soltec reflow oven was quite poor. Over the past 10 months data collected at the post reflow visual inspection station shows that of the 8,562 boards produced 2,919 had at least one defect. This is a 34 percent defective rate. However, not all of these defects were soldering related (in fact a large percentage of the defects were actually related to the printing process). If only the reflow related defects are counted, there were 1,442 defects; so just less than half of the total defects were related to the reflow process. Of all the boards produced over the past 10 months just under 17 percent showed soldering related defects. These defects included tombstoned parts, solder bridging, cold solder joints, cracked components, and some other miscellaneous soldering related defects. At this point, it is fruitful to look at the ability of the original oven to produce tin-lead assemblies. This analysis is important as it can help to solidify the argument that the ovens poor performance may be due to its inability to faithfully reach the higher lead-free soldering temperatures.

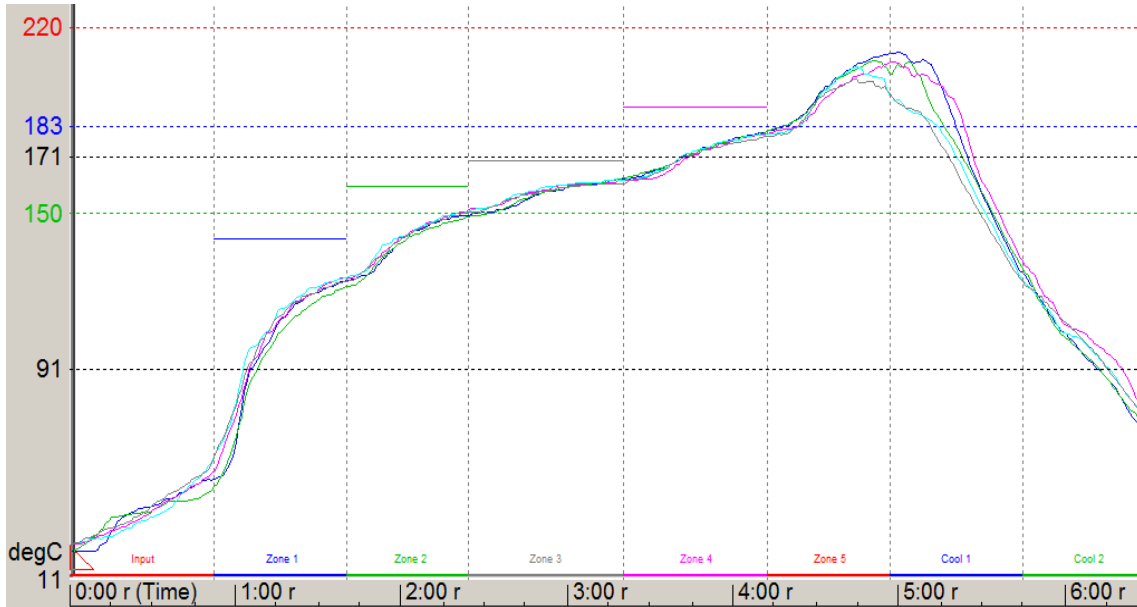
	Assembly Type		
	Tin-Lead	Lead-Free	Total
Total PCBs Produced	2,676	5,886	8,562
Total Recorded Defects	421	2,498	2,919
Soldering Related Defects	91	1,351	1,442

Figure 22 - Vitronics Soltec Defects Table

Among defects in tin-lead assemblies, soldering related defects accounted for only 91 of the 421 total defects or 21.6 percent. This is compared to 1,351 of 2,498 or 54 percent of defects in lead-free assemblies. A proportions test proves that these two assembly types are statistically different at the 5 percent level; returning a p-value of less than 0.000. See Appendix A for complete proportions tests. Total defects as a percent of boards produced was significantly

lower for tin-lead assemblies than for lead-free assemblies, 42 percent for lead-free assemblies and 16 percent for tin-lead assemblies. This is likely due to the greater number of board revisions which have been performed on the tin-lead assemblies. Resultantly, looking at soldering defects as a percentage of total defects is a more apt analysis than looking at soldering defects as a percentage of total boards produced. However, a similar proportions test is significant in comparing soldering defects as a percent of total boards produced. This analysis illustrates the initial theory that the oven is underperforming on lead-free assemblies. To further solidify this notion and gain a root cause understanding, it is productive to look at the reflow profiles the original oven is producing for various tin-lead and lead-free circuit boards.

The Vitronics Soltec oven utilized two distinct profiles for its tin-lead and lead-free assemblies. Looking at these profiles and the oven's physical capabilities gives valuable insight into its inability to produce quality lead-free assemblies. Figure 23 and Figure 24 show representative tin-lead and lead free profiles, respectively. More thermal profiles for the Vitronics Soltec oven can be found in Appendix B. As the tin-lead profile figure shows, this oven is perfectly capable of a creating a relatively controlled profile for tin-lead PCB assemblies. The only real disadvantage of this profile is that the maximum slope rate experienced by this assembly was  $3.79^{\circ}\text{C}/\text{second}$ . This initial slope rate would ideally be lower, the solder specification suggests no greater than  $2^{\circ}\text{C}/\text{second}$ . However, by the time the assembly hits 90 degrees Celsius the slope rate has slowed significantly and is well within spec. This quick initial slope is necessary in such a short, 5 zone, oven. Without some portion of quick heating, the assembly would never reach liquidus. The tin-lead profile also shows a nice slow linear slope up during the soak phase. Finally a quick spike gets the assembly up above the liquidus point of the solder where it remains for right around a minute at all points measured on the board. Overall



**Figure 23 - Vitronics Soltec Tin Lead Profile – Belt Pack Daughter Board CoachComm**

this profile seems very well in control, all points of the board heat up fairly evenly, and the profile matched the solder specification well (with the exception of the steep initial ramp). On the other hand, reaching lead-free temperatures is very taxing on this oven and during this type of production the oven's shortcomings begin to show.

As Figure 24 shows the Vitronics Soltec oven is being pushed to its limit in attempts at producing assemblies utilizing the SAC305 alloy. The oven requires the same undesirably steep initial slope for a much greater time window when reflow soldering lead-free assemblies. In this case the board experiences a maximum heating slope of  $4.26^{\circ}\text{C}/\text{second}$ , retaining a very steep slope until the assembly reaches over  $150^{\circ}\text{C}$ . After the initial preheat phase, the slope rate remains relatively high, at some points greater than  $2^{\circ}\text{C}/\text{second}$ , even during the pre-reflow/soak phase. The reflow spike in this profile is not nearly as steep as the tin-lead profile and the board remains above liquidus for an extended period of time. All measured locations on the board remained above the solder melting point for more than a minute and a half, the solder specification maximum. Throughout the thermal profile for the lead-free assembly there is a

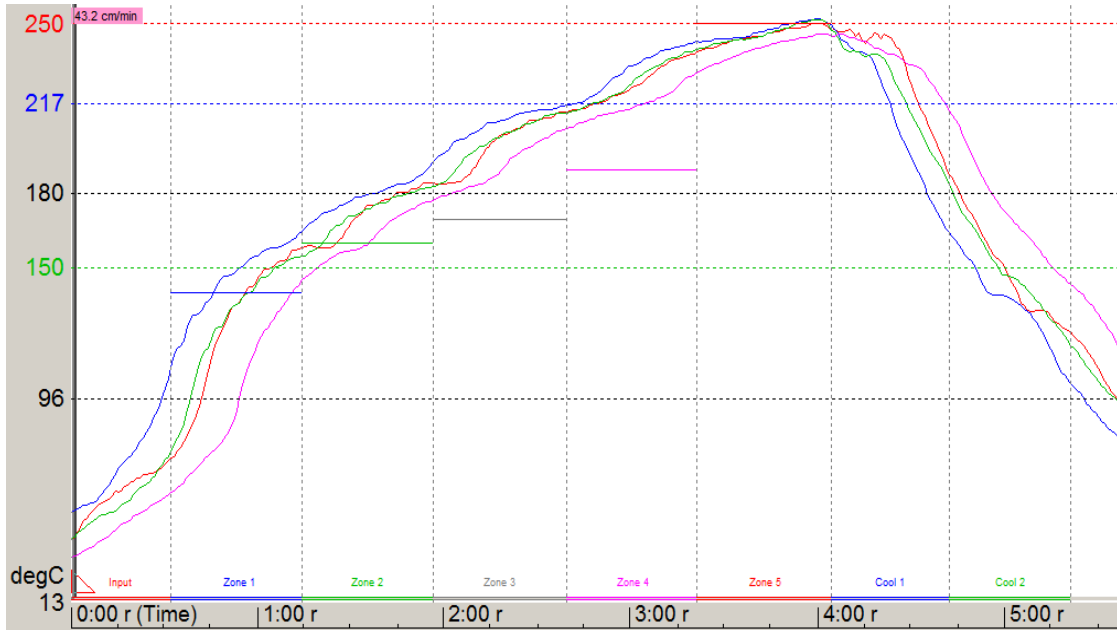


Figure 24 - Vitronics Soltec SnPb Profile – Tempest BP Audio Board CoachComm

disconcerting temperature differential between the different areas of the board. At some points the temperature differential reaches 15°C. Overall this thermal profile exemplifies the oven being pushed to its limit.

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
140°C	160°C	170°C	190°C	250°C

Figure 25 - Belt Pack processor Oven Zone Settings - CoachComm

With only 5 heating zones, the Vitronics Soltec’s chains must be run at a slow speed, 17 inches per minute, and the temperature of the first zone set very high. This creates the steep initial spike. The specific zone settings for this profile are seen in Figure 25. To reach the higher lead-free soldering temperature, a fairly sharp incline remains necessary for zones 2 through 4. This same slope remains into the fifth oven zone. The temperature may not be set high enough to truly spike the temperature up quickly into the reflow zone, as this would push the overall assembly temperature much too high at such a slow chain speed. Even at such a steep inclines, the oven’s first four zones were necessary the ramp the temperature up to a pre-reflow

level, this left only the final zone to spike the temperature. The true limitations of the oven can easily be seen in the lead-free profile. This poor thermal profile has been a major part of the apparent soldering issues in lead-free assemblies and necessitated the installation of a new reflow oven. A reflow oven with more controllable heating zones would provide a more controlled heating profile for lead-free assemblies and in turn improve the process yield.

### 3.4 New Oven Setup and Target Lead-Free Profile

The new oven recently installed at CoachComm was a Conceptronics HVA-155. This oven contains 10 individually controllable heating zones, which offers much more flexibility in thermal profiling. Reaching lead-free temperatures consistently is much less of an issue with the new oven. In comparison to the Vitronics Soltec oven, the new oven also has a much more reliable and predictable convection system. The Conceptronics Oven uses a high speed fan to create convective airflow in each heating zone. The previous oven simply used compressed air, and was not capable of consistently even heat distribution. At the onset of this new oven installation there were a few key characteristics which were desired in the new thermal profile. Namely a slower initial ramp, more of a real soak profile, a shorter time above liquidus, and lower maximum temperature.

These goals were determined by looking at pitfalls of the previous oven profiles, CoachComm's production mix, board complexity, production environment, taking into account component concerns. One major issue of note looking at the profiles from the Vitronics Soltec oven was the steep initial preheat ramp rate. The Conceptronics oven would be a great tool to eliminate this volatile process parameter. With 10 heating zones, the initial heating zones were

set to much lower temperatures and the assembly still reached lead-free reflow temperatures towards to end of the profile. In many cases, the third heating zone in the Conceptronics oven would be set at the level of the first zone in the old oven. This helped create a profile with a greatly reduced initial ramp. After the new slow ramp up, it was important to include a longer and more stable soak in the new profile. The desire for a longer soak was largely a product of CoachComm's high production mix and very complex assemblies.

CoachComm's high production mix required a very robust profile which would be compatible with all of the company's diverse products. Rather than working to create the most energy or time efficient profile; it was desirable to set a target profile which would be useful for an array of products and not be susceptible to process variations. Such a profile was also necessitated by the complexity of many assemblies the company produces. A good example of these complex assemblies is the four channel base station audio board seen in Figure 12. The low volume nature of CoachComm's production line made the task of creating a robust profile easier. As a result of the reflow oven's continuously running conveyor, the only way this process could be a bottleneck was if the rest of the production line had drop rates lower than the time it took the oven to intake a board (plus a bit of clearance space between boards). All of CoachComm's products experienced placement times of more than 40 seconds, with over 90 percent of the company's products taking greater than 2 minutes at one or more upstream station. Therefore, we could set a very slow chain speed when necessary and utilize a long soak profile. The long soak will also allow sensitive components which may have absorbed some level of moisture from the humid, warehouse production environment to dry out prior to the reflow phase. This dry out period will ensure components do not crack during the reflow phase. After this important, extended soak the reflow portion of the profile will also be brought into spec.

The solder specification for CoachComm’s lead-free solder paste suggest 30 seconds to one and a half minutes above liquidus and a maximum temperature of no more than 251° Celsius. Due to component concerns a maximum temperature slightly lower than this specification would be ideal. Installation of the Conceptronics oven will allow the company to meet those specifications much more closely. Again this is a product of the greater number of controllable heating zones in the Conceptronics oven. The overall desired new heating profile is mapped in Figure 26. Here you can see all the facets of the heating profile which have been mentioned in the previous paragraph. Overall this new target profile will be much more robust to process variations and would put much less stress sensitive components. Figure 27 shows a good comparison of the greater flexibility allowed by the additional heating zones. It is important to note the much cooler initial settings and long soak just below the reflow temperature. More thermal profile settings for the new oven are available in Appendix D.

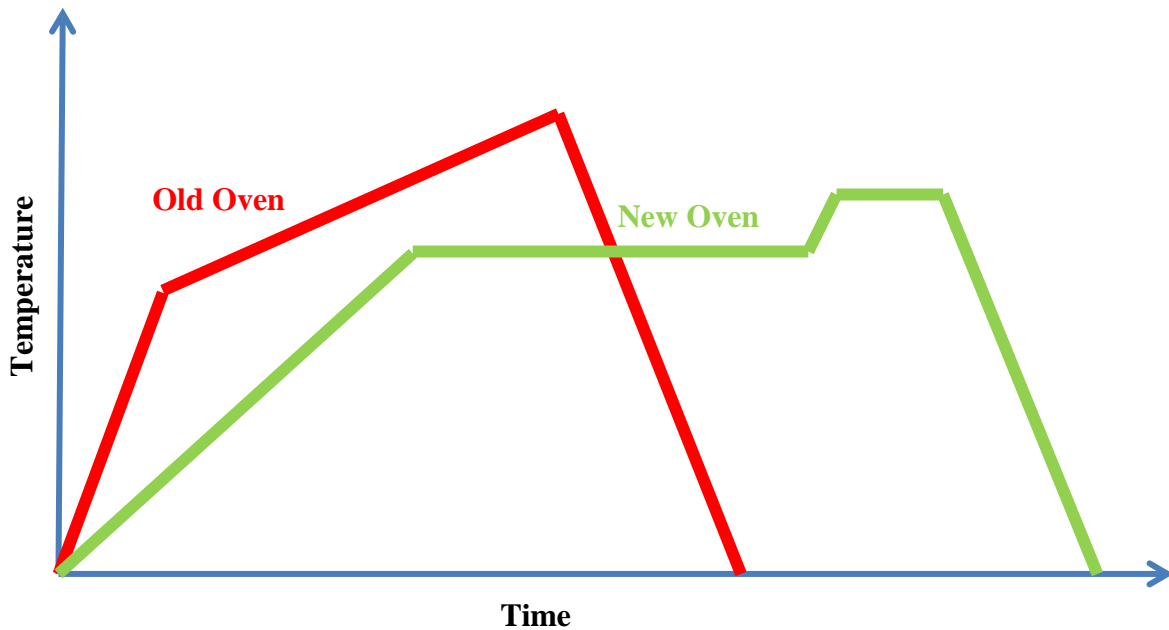


Figure 26 –New Target Profile vs Old Profile

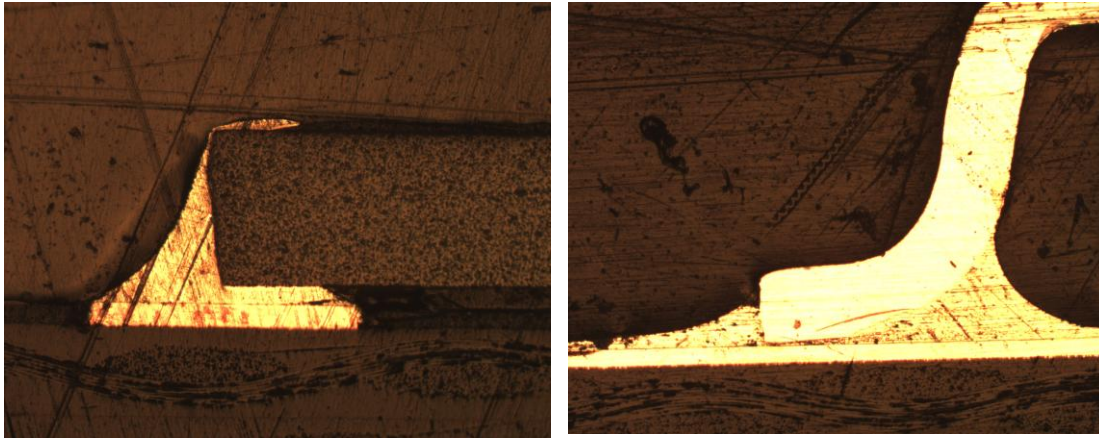


Vitronics Soltec Oven				
Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
140°C	160°C	170°C	190°C	250°C

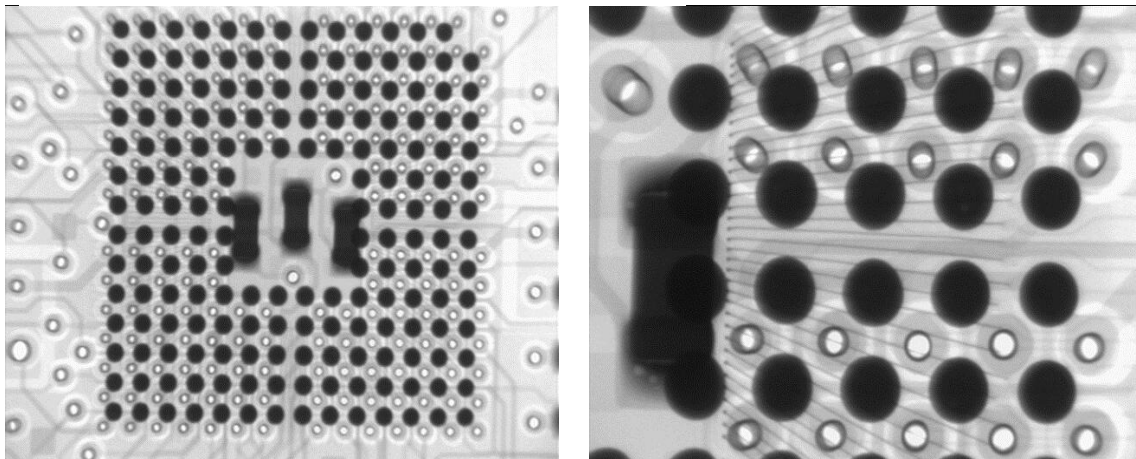
Conceptronics Oven									
Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10
100°C	130°C	160°C	190°C	220°C	200°C	200°C	230°C	250°C	250°C

### 3.5 Results

After installing and thermally profiling all of CoachComm's products on the Conceptronics oven, the results were very encouraging. To verify that quality solder joints were being produced, with this very different profile, solder joint cross sections from multiple boards were produced. Figure 28 shows two cross sections which were taken from boards produced in the new oven, more cross sections can be seen in appendix F. As you can see the solder seems to be attracted to both the component lead and the pad on the PCB. The joint exhibits good wicking of the solder and in the case of the small passive component on the left, solder has even crept unto the top pad of the device. Along with the cross section analysis, X-rays were taken to inspect the joint quality underneath packages which could not be visually inspected externally.



**Figure 29 – Joint Cross Sections CoachComm Belt Pack Processor Board**



**Figure 28 – BGA X-ray CoachComm Belt Pack Processor Board**

Around 400 boards with grid array packages have been run through the oven up to this point and have functioned correctly, so there was little worry about serious defects under those components. Nonetheless, X-ray was completed on a selection of BGA components to prove that good wetting was occurring. Figure 29 shows two screen captures of the x-ray analysis (more x-ray images in Appendix E). Bridging underneath these packages had been an issue when CoachComm initially started producing lead-free assemblies. The x-ray analysis showed no signs of bridging and the solder joints underneath these grid array packages appear to be of good quality. This result was in line with our expectations and further proved the merit of the Conceptronics oven installation.

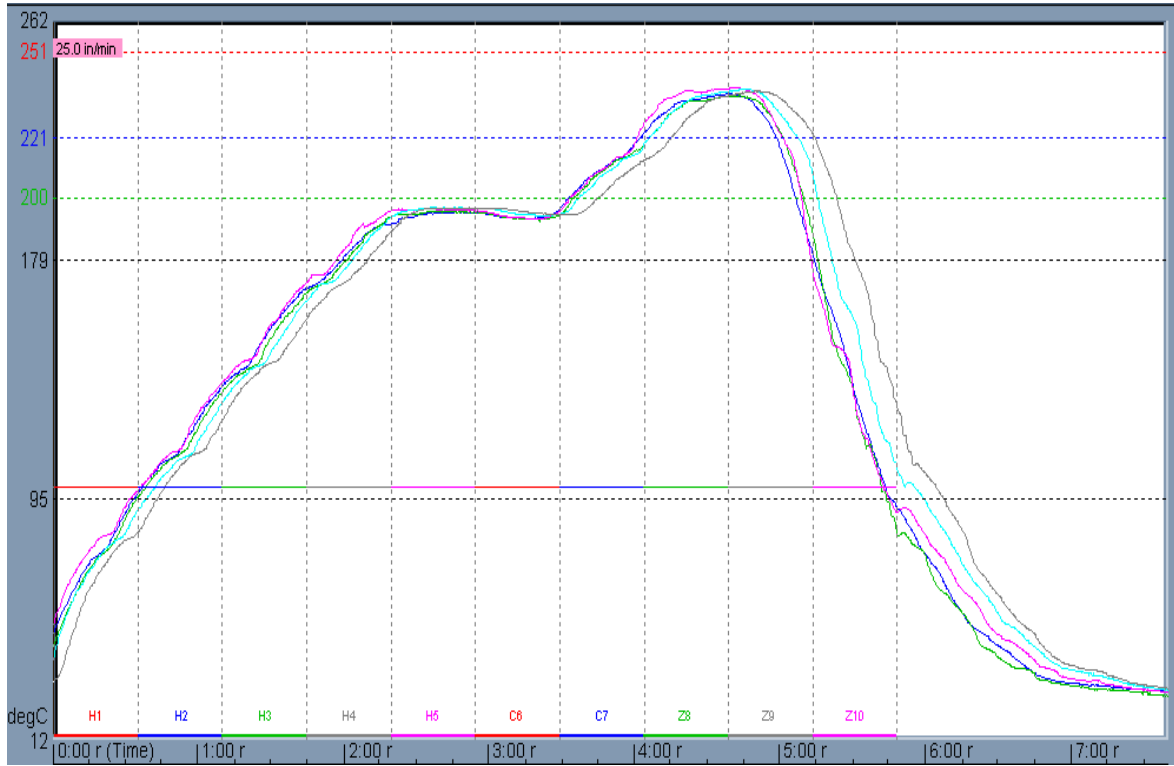


Figure 310 – CoachComm Transceiver Bottom Conceptronics HVA-155

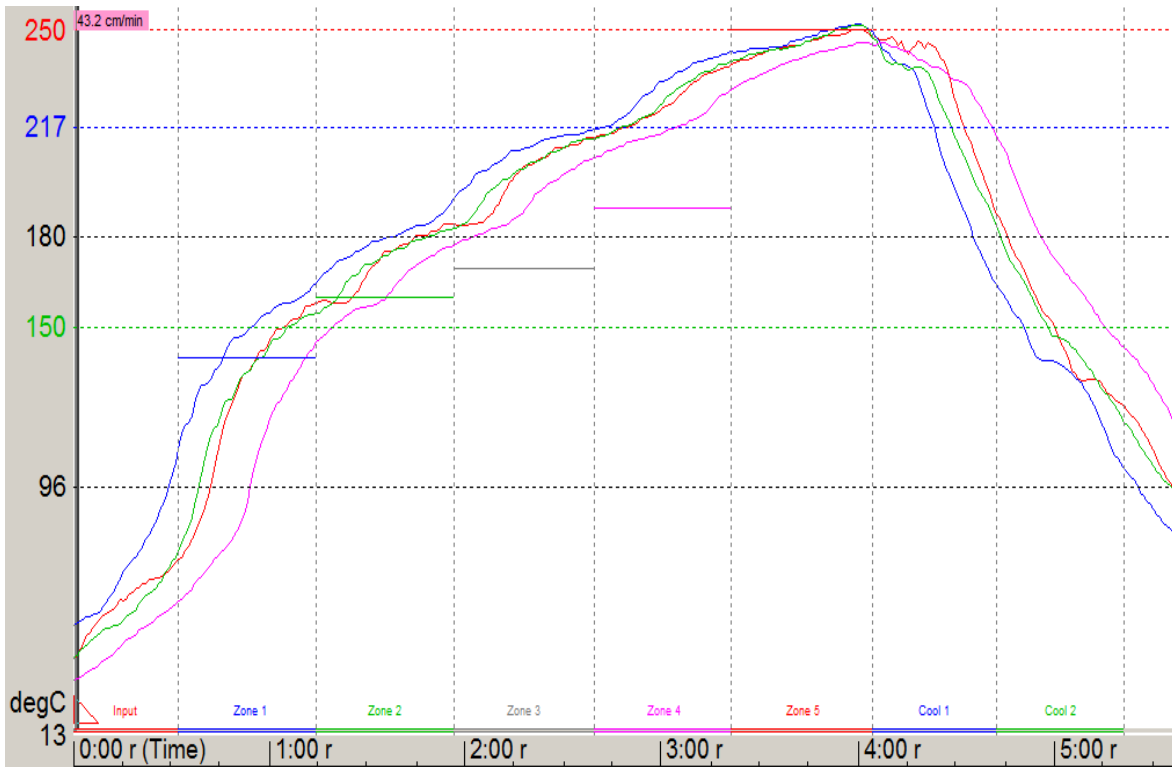


Figure 31 - Vitronics Soltec SAC Profile – Tempest BP Audio Board CoachComm

To further assess the improvement of this new oven installation we can compare the Conceptronics oven to the Vitronics Soltec in terms of thermal profile performance and soldering defect rate. Figures Figure 3 and 24 (reproduced from baseline study) show the thermal profile of the same assembly as produced in the new and old ovens respectively. More thermal profiles for the new oven can be found in Appendix C; profiles for the old oven are in Appendix B. With this new oven we were able to hit our target profile for each assembly. Thus, the assemblies are being reflow soldered within the solder and component specifications. As these profiles show the Conceptronics oven was able to tie the temperature across the board together in a much more even manner. The new profile also shows a much better initial slope with the maximum rate being 2.4°C/second, recall from the baseline study on this same board the Vitronics Soltec oven required a slope of 4.26°C/second. The time above liquidus is also much more reasonable in the new oven with the maximum location remaining above 221°C for just over a minute. Considering the number of heat sensitive components being used at CoachComm the drop in maximum temperature from over 250°C to just 238°C is a large improvement as well. Overall the profile is much more in control and at this point is 100% within the solder specification. This improved profile has led to much improved first past yield for the reflow soldering process.

As the baseline study illustrated there was a significant amount of rework being performed as a result of poor reflow soldering. After setting up the oven for each product to match the target profile a sample of 5 production PCBs was reflowed for each product. For some products this equated to 10 total boards as there were two boards per panel. This was a total sample run of 90 boards. During this sample run only one soldering related defect was found. After a root-cause analysis was performed, this was deemed to be due to the offline transport required to move the board to the new reflow oven temporary staging area. The oven has now

been moved into production and at the time of writing over 400 production panels had been run with no soldering related defects. However, these 400 are not a representative sample as they are made up of only 5 of the company's products which have been produced in the time since the equipment move. The aforementioned 90 boards were a representative sample and that test run included all boards CoachComm produces.

### 3.6 Discussion and Future Work

After looking at these results we can be confident that a very positive change has been made on CoachComm's SMT production line. The company should expect quality to improve and rework to decrease significantly. These benefits will no doubt extend onto the company's balance sheet. The hours billed by the rework and repair departments should decrease by a reasonable amount. However, there are still significant issues on the SMT line. Not enough data has been logged at this point, but it can reasonably be assumed that the defect rate will remain much higher than industry standard. Even if the soldering related defects are reduced to zero, there are still serious print and placement related issues to be addressed in the future. If these issues can be resolved and the process yield improved to a sensible level, further economic benefits may be realized. Post reflow inspection at CoachComm requires the time of roughly one and a half full time workers. Currently every component on every PCB is inspected at the end of the SMT line. As process yield continues to increase it would be logical to relax these inspection standards. Perhaps only inspecting 5-10% of the board's critical components, which would lead to a significant labor reduction. Though the print and placement processes must be improved to some degree to reach this goal, the new reflow oven installation would be the first step.

Ensuring the long term stability of the reflow process will be a constant battle. The Conceptronics HVA-155 oven installed at CoachComm is equipped with a sophisticated process monitoring system. However, this system requires a substantial initial setup for each product it monitors. It also requires a fair amount of operator input at the beginning of a production run. Regardless, this monitoring system could be very beneficial in safeguarding the control of the reflow process. Another important issue which should be addressed in the near future is the company's hardware designs. The manufacturability of many of the company's assemblies is poor at best. Significant time and quality improvements would be realized through circuit board redesigns. If the thermal mass of the PCB assemblies was more evenly distributed this could also lead to some savings in energy costs.

Reducing the energy usage of the oven would be a great future project, but at this point it would be hard to achieve as a very robust profile is necessary to ensure quality. Eliminating some of the soak portion of the profile and reducing the set points of some of the oven's zones would make a dent in the energy costs associated with running the oven. Currently, the long soak is necessary as there is such wide variation in thermal mass across the most of CoachComm's boards. Lastly, a new defect detection and collection method would be a great improvement. Within the confines of this project, the method put forth to record defects by type in a spreadsheet at the post reflow inspection station sufficed. However, in the future a more salient defect tracking method which aggregates defects found at any inspection point on the production floor would be a great improvement.

## Chapter 4: SMT Product Changeover Time Reduction

### 4.1 Current Product Changeover Method

Formal setup time reduction techniques have never previously been applied at CoachComm. Currently nearly all of the required changeover steps take place during SMT line downtime. The majority of time spent during this downtime cycle is used to load the components necessary for the next board onto the pick and place machines. CoachComm currently utilizes two Universal Instruments Corporation component placement machines. The models are both gantry type machines with one having a 30 spindle high speed rotary type head and the other having a 7 inline spindles. These are machines are called the HSP and GSM respectively. The current product changeover standard operating procedure is to load feeders with parts reels of all the required components. Next an operator removes all the feeders from the machines which are occupying slots necessary for the next product. Once all the slots are free, the components for the new assembly are loaded onto the machines. Lastly, the machine program file for the new product is loaded and the parts are verified as being in the correct slot by two operators. The total downtime due to this changeover is highly dependent on the boards being transitioned.

Formal scheduling is a very important part of most changeover SMT electronics strategies. However, at CoachComm scheduling is largely based on stock on hand, customer demand, and engineering needs. At project onset there was no consistent monthly board run order. There are certain PCB combinations which are required to produce products; many products require 2 PCBs. So in most cases these boards are run in close succession so that

product may be assembled. CoachComm produces two distinct product variants broadcast and football. The broadcast units make up a large part of the company's sales for much of the year, while the football units are very seasonal. Broadcast units are sold through a distributor who gives sales figures for 30, 60, and 90 days. CoachComm then ships the units once a month to this distributor. This unique scenario makes a heavily schedule oriented setup strategy ideal.

Scheduling setup strategies in general exploit component commonalities to reduce the total amount of feeder changeovers or setup instances. In general scheduling optimization is a mathematically hard problem. In CoachComm's situation, there are many practical considerations which make this type of setup optimization very difficult. Most formulations of the optimization are similar to the traveling salesman problem with precedence. In CoachComm's situation the precedence runs deep. There are often unused parts loaded onto the machines which have been untouched through 4 or even 5 product changeovers. Adding further difficulty to the scheduling problem is CoachComm's current use of permanent feeders. There are some components which are used on 80-100% of the company's assemblies. These feeders remain loaded in their slots throughout the product run. The permanent feeders are a choice which the company wishes not to change. This consideration makes the problem much more difficult if the setup strategy being employed focuses on board throughput optimization.

Regardless of the setup strategy employed at CoachComm, single board production times will continue to be a concern. The company currently uses some feeders which take up more than one machine slot, but which only hold one component. In addition, the manufacture of some boards requires waffle trays which take up 4 or more slots. One of the most difficult considerations is that all of CoachComm's assemblies are two sided and there is a build order constraint which must be followed. The company also uses two different placement machines



and in most cases the parts are not interchangeable between these machines. These considerations would make the throughput piece of the optimization much more difficult. The management and supervisors also wished the new changeover method to be somewhat similar to the current operation. This was one of the largest hurdles being faced in this setup reduction task.

#### 4.2 Changeover Time Study and Baseline Analysis

The current process as described above is very inefficient. From Shingo's perspective of internal and external setup tasks, almost all of the product changeover tasks are being performed as internal. The time it takes the operators to load a parts reel onto a feeder is currently an important facet of the product changeover. After a time study analysis, I found the loading of component reel feeders to take on average 3.56 minutes with standard deviation 1.34 (n=35). This is in line with times proposed in the literature [34], [32], [6]. During product changeovers operators currently load anywhere from 2 to 75 reels onto feeders. However, loading the reels onto feeders is only part of the larger product setup task. Taking further data on the complete product changeover, we found the average downtime during changeover to be 110 minutes with a standard deviation of 49 minutes (n=140). This data was taken from the time the last board of the ending product exited the oven to the time the first board of the next product run entered the oven. The large standard deviation can be attributed to the varied number of setup tasks required between different board types. Moving between one set of boards may only require changing 2 components, another changeover could require the change of over 100 components. However, the average number here is valid when looking at the data from a larger

perspective. During a normal month the company will run a representative sample of their boards. Thusly, changeover time per month or per year is a fairly stable metric. In the long run, it is very unlikely there would be a significant period of time with only short or long changeovers. There is a definite floor to the data as well, with the lowest changeover time being 4 instances 19 minutes.

Even if there are very few feeder changeovers to be performed during a product change, there will still be some amount of downtime spent changing over the line. This is why the floor effect can be seen on the product changeover times. Per the current operating procedure this time is necessary to verify product setups on placement machines, change the solder print screen, placement machine program files, the oven profile, and all conveyor widths. Some of this time could possibly be made external as well, but obviously the bulk of the time spent during product changeovers is related to component feeder operations. This is highly reflective of the literature on product changeover optimization. CoachComm's current setup operation represents a great opportunity to employ some of the scheduling and product changeover strategies present in the literature.

## 4.3 New Changeover Strategy

### 4.3.1 Background

The new product changeover strategy employed at CoachComm is somewhat along the lines of the minimum setup strategy which has been studied extensively in the literature. The company is particularly well suited to this type of setup strategy as it is a high mix, relatively low volume production environment. Though much of the initial changeover time reduction work is

based on the minimum setup strategy, there are some other important considerations and embellishments to the strategy which were made to ensure functionality on CoachComm's production floor. The new setup strategy needed to utilize the current system of permanent feeders. A feasible schedule order for the company would have to consider board combinations necessary for final assembly. Moreover, both the scheduling process and changeover operation needed to be easily understood by the floor supervisor and operators. Another important consideration is that the pick and place machines at CoachComm have a hot swap capability which could be exploited to speed up the product changeover. However, this capability carries the potential consequence of machine damage which must be considered as well. At the projects conclusion the hot swap exploit would be the most beneficial piece of the new changeover strategy.

At the onset of this project, we explored some commercial options for speeding up product changeovers. There are many products on the market which seek to lower the time costs associated with placement machine setup. Feeder carts and back changeover system are two very popular products target at solving this issue. As part of this research the machine's capabilities and compatible products were investigated. When looking into the machine abilities it was discovered that these particular machines were equipped with a 'hot swap' ability. Hot swapping offered the option to load multiple feeders of the same high volume component during a product run. The machine would then pick from one feeder until it was completely exhausted. When this occurred the other feeder would be used for that particular component. At this point, the first feeder could be replenished. When the second feeder was then emptied of components, the machine could go back to the first. The hot swap machine feature was intended to eliminate the downtime associated with part exhaustion during a long product run. However, hot swapping

also represented a way to make loading and unloading feeders an external setup tasks. Utilizing the hot swap feature would allow setup of the next product during run time of the previous. This was the real merit for the purposes of reducing product changeover.

After extensive talks with Universal Instruments, the machine's vendor, it was concluded that the hot swap feature could be used to perform product changeovers during production. However, it was first necessary to make some machine software modifications to realize the great potential benefit of this hot swap system. The hot swap operation was only intended for part replenishment. As such it was only allowed on redundant feeders for the current product being run. With help of the machine vendor's technical support team we were able to make a few high level safety bypasses to enable the hot swapping operation for all feeder slots. This represented the first step towards moving much of the product changeover to external task. However, it did nothing to cull the fears some members of the production crew had about using the hot swap system. In the past CoachComm had used the hot swap ability on a few assemblies for particularly high volume parts. It had worked well, but operator error during one feeder change caused serious machine damage. An operator had inadvertently removed a feeder which was being picked from and this had broken one of the placement spindles, it could have potentially damage the entire placement head. This was costly to repair and CoachComm had not utilized the hot swap ability since this accident. Adding some machine safety to the hot swap operation would be key to its acceptance. After looking further into the scheduling problem a safe solution became salient.

The hot swap ability looked very promising in the framework of CoachComm's current product mix and production setup. Most of the company's assemblies, 11 of the 15 being studied, required less than 35 feeder slots per machine. The pick and place machines each had

70 feeder slots. This meant that any of those 11 assemblies could potentially be built in succession with all feeder changeover tasks performed as hot swap. The placement machines both contained 35 feeder slots per side. By utilizing the two sides of the machine independently a level of machine safety could be assured. For example if product 1 is being run and all of its parts are located on side 1 of the machine, then the placement head will never be on side 2 of the machine. During this product run a second product can be loaded onto side 2 of the machine and there is no danger of machine damage (so long as the operator remains on the correct side of the machine). This hot swap idea would become the basis of the new changeover strategy. The setup strategy would be hot swapping coupled with a product run order formulated under the rules of the minimum setup strategy, but with some weight for board families.

#### 4.3.2 Implementation

The minimum setup strategy was first employed to seek out the product run order which

		Change to this board							
		50037 Bot	50037 Top	50039-R Bot	50039-R Top	50038 Bot	50038 Top	50029-CC Bot	50029-CC Top
From this board	50037 Bot	*	18	46	16	27	21	70	92
	50037 Top	*	*	54	21	25	20	74	92
	50039-R Bot	38	20	*	14	25	22	48	87
	50039-R Top	42	21	*	*	27	22	74	89
	50038 Bot	45	17	51	19	*	20	72	87
	50038 Top	45	18	54	20	*	*	75	93
	50029-CC Bot	40	18	26	18	24	21	*	78
	50029-CC Top	43	17	46	14	20	20	*	*
	50058-G Bot	40	18	26	18	24	21	0	75
	50058-G Top	43	17	46	14	20	20	59	3
	50030-K Bot	40	19	52	19	26	22	75	90
	50030-K Top	35	18	48	17	24	15	74	85
	50060-D Bot	40	19	52	19	26	22	75	90
	50060-D Top	36	18	48	17	24	21	74	85

Figure 32 – Necessary Feeder Changes Between Products

would minimize the number of total required feeder changes during the product run. Even though feeder changes could now be external task, it was still desirable to reduce this number as much as possible. This product changeover work was performed only on the boards which CoachComm produces every month, further discussion of implementing this on less run boards can be found in the future work section. The formal mathematical formulation of the minimum setup strategy was not implemented, as this would be too difficult for the company to reproduce in the future and it did not take into account the need to complete certain board sets in close proximity for assembly. An excel spreadsheet was created which contained a grid of all possible setup changeovers and their feeder change costs. This spreadsheet ignored parts which were currently a part of the permanent feeder configuration. Figure 32 shows an excerpt of this spreadsheet. The spreadsheet is easily modified to support new products. Simply pasting in the bill of materials and editing a few cells adds the changeover costs for a new board to the grid. I ran an excel solver for the traveling salesmen problem with precedence at this point to get a few near optimal solutions. A meeting of scheduling planners and production personnel was held and we looked over some possible production scenarios. A feasible production schedule was chosen and work began on moving feeder slot assignments to enable hot swapping.

A simple heuristic was used to assign feeders to slots in the new machine programs. This rule set was born from the following list of concerns and ideas. These are ranked from most important to least:

1. Only perform feeder changes when necessary.
2. Ensure machine safety by hot swapping feeder as far as possible from those being used for production of current product.
3. Hot swap as many parts as possible.

4. Highest volume parts remain close to center of machines to minimize per panel production times.

The feeder location assignment rules are as follows:

1. If a feeder is still loaded from a previous board its slot remains the same. All feeders which are on the machine as carry over are checked off the bill of materials.
2. A) If this is the first product in the schedule or the last product was run primarily on side 2, then assign parts to side 1 until slots are exhausted. B) If last product was run primarily on side 1, then assign parts to side 2 until all slots are exhausted.
3. The highest volume part is assigned to the most central feeder slot. If there are carryover parts present which are being used during the hot swap a minimum of 5 (or the most possible in the case of very large products) empty slots is kept between those parts in use and the part being assigned. If multiple parts rank as highest in volume, the most central component in the original machine program is assigned first.
4. Repeat step 3 as needed for the all parts on the bill of materials.

The first rule is best case scenario and obviously used as we want to minimize the number of total feeder changes. The third rule ensures as much machine safety as possible and puts the highest volume parts in the center of the machine which should help minimize placement head travel and per panel production time. With the use of this simple rule set and a spreadsheet, feeder slot assignments for the entire production schedule can be set in very little time. Figure 33 shows an example of the spreadsheet used for the feeder slot assignments. A simple addition

which added feeder types for each component on the

Feeder Slot	50038 Bot	50038 Top	50037 Bot	50037 Top	50039-R Bc	50039-R To	50029-CC B	50058-G Bc	50058-G To
2	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00001216	CARRY OVER	501-3110-1332	501-3110-1332	00000431
3	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00001234	CARRY OVER	00000727	00000727	00001234
4	CARRY OVER	CARRY OVER	00000299	00000299	00001238	CARRY OVER	00001238	00001238	421-1336-4710
5	CARRY OVER	CARRY OVER	421-2212-4760	421-2212-4760	00000405	CARRY OVER	00000406	00000406	501-3110-4993
6	CARRY OVER	CARRY OVER	421-2122-1060	CARRY OVER	00001239	CARRY OVER	00000748	00000748	00000437
7	CARRY OVER	CARRY OVER	00000636	00000636	CARRY OVER	CARRY OVER	421-1326-3320	421-1326-3320	00001530
9	CARRY OVER	CARRY OVER	421-1322-2240	CARRY OVER	00000776	CARRY OVER	00000776	00000776	00000267
10	00000671	00000671	CARRY OVER	CARRY OVER	00000722	CARRY OVER	00000734	00000734	00000734
11	CARRY OVER	CARRY OVER	00001451	CARRY OVER	00001451	00001451	CARRY OVER	CARRY OVER	00000404
15	00000475	CARRY OVER	00001316	CARRY OVER	00001316	00001316	00001316	00001316	00001469
16	00000725	CARRY OVER	00000737	CARRY OVER	00000327	CARRY OVER	501-3110-4752	501-3110-4752	00000407
17	00000402	CARRY OVER	501-5154-10R0	CARRY OVER	00000657	CARRY OVER	00000551	00000551	00000703
18	00000406	CARRY OVER	00000397	CARRY OVER	00000687	CARRY OVER	00000132	00000132	00001437
19	00000127	CARRY OVER	421-1324-6830	CARRY OVER	00000117	CARRY OVER	00000724	00000724	00000724
20	501-3110-5493	CARRY OVER	501-3110-3743	CARRY OVER	00000402	CARRY OVER	00000402	00000402	00001438
22	501-3110-6193	CARRY OVER	00001240	CARRY OVER	00001240	CARRY OVER	00001240	00001240	501-3110-5621
24	421-1322-3340	CARRY OVER	421-1322-3340	CARRY OVER	421-1322-3340	CARRY OVER	421-1322-3340	421-1322-3340	00000427
26	00000198	CARRY OVER	00000271	CARRY OVER	00001406	CARRY OVER	461-0400-0007	461-0400-0007	461-0400-0007
27	501-8650-1040	CARRY OVER	421-1336-3300	CARRY OVER	00001337	CARRY OVER	00000433	00000433	00000716
28	00001517	00001517	CARRY OVER	CARRY OVER	421-1324-6830	CARRY OVER	00000281	00000281	00000203
30	CARRY OVER	CARRY OVER	421-1356-1000	CARRY OVER	421-1356-1000	421-1356-1000	CARRY OVER	CARRY OVER	00000425
31	CARRY OVER	CARRY OVER	00001239	CARRY OVER	00000439	CARRY OVER	501-3110-2493	501-3110-2493	501-3110-2493
32	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00000658	CARRY OVER	00000658	00000658	00000130
35	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00000300	CARRY OVER	421-1726-1050	421-1726-1050	421-1726-1050
38	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00001336	CARRY OVER	501-3110-3010	501-3110-3010	501-3110-3010
40	CARRY OVER	CARRY OVER	CARRY OVER	CARRY OVER	00001309	CARRY OVER	00000747	00000747	00000747
41	CARRY OVER	CARRY OVER	CARRY OVER	00000203	CARRY OVER	00001589	CARRY OVER	CARRY OVER	CARRY OVER
42	CARRY OVER	CARRY OVER	CARRY OVER	501-3110-2493	501-3110-2493	CARRY OVER	00001428	00001428	00001428
43	CARRY OVER	00001314	CARRY OVER	00000671	00001334	CARRY OVER	00001334	00001334	CARRY OVER
45	CARRY OVER	00000387	CARRY OVER	CARRY OVER	00001335	CARRY OVER	00001335	00001335	CARRY OVER
46	CARRY OVER	00000852	CARRY OVER	CARRY OVER	421-1326-3320	00001533	501-3110-6041	501-3110-6041	CARRY OVER
47	CARRY OVER	501-3110-3010	501-3110-3010	CARRY OVER	00000267	00000267	00001336	00001336	CARRY OVER
49	CARRY OVER	00000853	00000853	CARRY OVER	00001469	00001469	501-3110-7502	501-3110-7502	CARRY OVER
52	CARRY OVER	00000488	CARRY OVER	CARRY OVER	00001338	CARRY OVER	00000439	00000439	CARRY OVER

Figure 33 - Feeder Assignment Worksheet

GSM machine allows easier configuration with feeders requiring more than one slot. This embellishment also highlighted feeders taking up two slots. Once the feeder assignments were completed, the machine program files were edited and the new changeover system was ready for use. It's important to note that all assemblies cannot currently be fully hot swapped as the company does not have enough feeders for all of the scenarios. Some feeders must be removed from the machines during downtime, the parts reel removed from the feeder and new part loaded. Finding the number of new feeders required for the hot swap to operate seamlessly would require a good bit of analysis. CoachComm wishes to implement and test this system for a while before deciding on the purchase more feeders. Simply keeping a necessary feeder log for the first month of hot swapping could yield a list of needed feeders and the number of instances they are necessary.



#### 4.4 Results

The results of this new changeover technique were very encouraging and there were no real detrimental effects to production. Two major fears coming into the application of this project were that the new production run order would leave assembly waiting for full board sets and that we would see increases in per panel production times as a result of the feeder slot assignment changes. The final schedule we implemented put no gap between boards in a set more than 2 PCBs apart. In real world terms, there would never be boards on the floor waiting more than 2 days without their partner boards for assembly. If this ever became an issue, the production supervisor could easily look at the changeover costs grid and weigh out the costs of changing the schedule. In the end this fear was alleviated and CoachComm has been running the adjusted production schedule for over six months with no issues. This has greatly reduced the number of feeder changes required, exact numbers are discussed further below. Aside from this assembly concern the company was concerned per panel times might increase as we moved feeder slot assignments.

This thought had some merit due not just to the slot changes, but also because we would now be utilizing only one side of the machines for many of the products. The machines were now loaded all the way out to the edge, when previously both sides of the machine would have simply had feeders clustered in the middle. However, the placement machines offline software contains software for optimizing feeder locations. This same software will give very accurate predictions of per panel production times. After all the boards were reprogrammed for the hot swap, they were simulated for times in this software. Luckily, the per panel times remained the same or were slightly faster for all except two products. Each of these were low volume, less

than 50 units per month and their per panel times only increased by 2 seconds. The savings allowed by the hot swap significantly outweigh these costs. These savings were quantified through a number of trial runs which have been completed.

To date six test runs of the new changeover system have been completed. Four of these runs were on products which could currently be completely hot swapped. The other 2 runs were products for which CoachComm does not have enough feeders to completely hot swap. The average downtime during setup of the completely hot swappable products was 22 minutes with a standard deviation of just 2.16 minutes. Average for the other two products was 45 minutes, though these times would come down significantly if enough feeders were purchased to facilitate a complete hot swap. These results compare very well to the 110 minute average seen before the new changeover strategy was employed. The process variation is also much lower especially in the case of complete hot swap, 2.16 minutes compared to 49 minutes. The hot swap system itself was not the only piece of this new strategy which made an impact.

The results of the relaxed minimum setup strategy are also very positive. The new production schedule took the total number of required feeder slot changes down from 538 in the original schedule to just 367 in the modified schedule. This is slightly more than a 30% reduction in the total number of feeders which must be changed. If we assume these took the average changeover time found in the original time study, 3.56 minutes, this would be total operator time savings of 10 hours per month. However, the most impressive improvement of all is the true potential of the hot swap system if enough feeders were purchased to allow all products to be hot swapped. The original number of 538 changeovers, all of which were occurring during machine downtime, would now be reduced to only 71 downtime feeder changes. This could potentially reduce monthly downtime due to feeder changes by more than

13 production hours. Total downtime feeder change savings would be 27 hours, but CoachComm currently employs two operators to perform these changeovers. Aside from the production time savings there were some other unexpected benefits. This new system was revered by the line operators as it took much of the downtime stress away from their jobs. The line operators were no longer scrambling to find parts or being instructed by their supervisor to get the line “up-and-running” again.

#### 4.5 Discussion and future work

The results of hot swap and modified minimum setup strategies were very encouraging. However, there are still quite a few additions which could be added to the system. Hot swapping of component feeders allows complete next product setup while the previous product is being run. This has been proven to significantly shorten the downtime associated with product changeovers. In this work we have created a finite schedule which allows the hot swap to function. The use of this schedule allows minimization of the overall number of feeder changes. Even though most feeder changes now occur during production and do not add to the downtime between products, it is still fruitful to minimize the work for operators. Lowering the number of changeovers required frees up the workers to perform other tasks and ensures all feeders will be hot swapped before a short production run has ended. One potential valuable addition would be the creation of mirrored profiles for each side of the machine for the boards requiring 35 components or less. If each product had programs for side 1 and 2 of the machine, then any two boards in that group could be run successively with a feeder hot swap. If the current product was

running on side 1 we could simply load the side 2 profile for the next desired product. This embellishment of the hot swap system would allow very lean production scheduling.

Another potential area for future work would be a cost to benefit analysis of purchasing additional feeders. As mentioned earlier, CoachComm currently does not own enough feeders to completely hot swap all of its products. However, the savings of purchasing a given number of certain feeder types could be quantified out. It would just be necessary to find the number of instances when that feeder would be used to hot swap during a production run. Then the time savings from those additional hot swaps could be calculated and a dollar amount assigned. Time savings could also be gained by working to externalize some of the other setup task associated with product changeover. In this work I have dealt with placement machine changeover. Pick and place machine changeover represents the largest proportion of the total changeover task. However, there are still savings to be found by exploring better ways to change over the oven profile, solder print stencil, and conveyor widths. For example, the conveyor widths could easily be changed right behind the final board as it was running through the SMT line. Multiple products could even be in the line at the same time if the changeover was started as the final board from one assembly exited each machine.

Aside from this future work it would be very interesting to actually program one of the minimum setup strategy heuristics to evaluate the success of my approach. My approach for scheduling did not take into account the compounding precedence of the real problem. This was not a huge issue as the scheduling piece of this setup strategy was much less beneficial than the hot swap. However, it would still be useful and interesting to look at the performance of my off the cuff implementation against a more formal method. One of the formal setup strategies could

even be modified to fit CoachComm's situation adding in some constraints to bound how far apart the product family boards are allowed to be in the schedule.

Overall this hot swap implementation was successful and viewed positively by all parties involved. The large reduction in changeover time shows that the hot swap will solve the bulk of CoachComm's setup downtime problem. The majority of the downtime has now been eliminated and any further improvement will be much more difficult. Nonetheless, there are a lot of areas of the setup process which could stand to see improvement. Greater gains in overall production throughput would probably be realized now by looking at other areas of the issue. In particular, line balancing some of the company's products could prove very lucrative in saving time. No doubt there is still a good amount of work to be done in bringing CoachComm's SMT line up to a high level of efficiency. Still, this project has been a great first step and will serve as the foundation for many future improvements.

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## Appendix A – proportions tests

Proportions test output for tin-lead vs lead-free on Vitronics Soltec oven; soldering defects as percentage of total defects.

### Test and CI for Two Proportions

Sample	X	N	Sample p
1	1351	2498	0.540833
2	91	421	0.216152

Difference = p (1) - p (2)  
Estimate for difference: 0.324681  
95% CI for difference: (0.280773, 0.368588)  
Test for difference = 0 (vs not = 0): Z = 14.49 P-Value = 0.000  
Fisher's exact test: P-Value = 0.000

Proportions test output for tin-lead vs lead-free on Vitronics Soltec oven; soldering defects as percentage of total units produced.

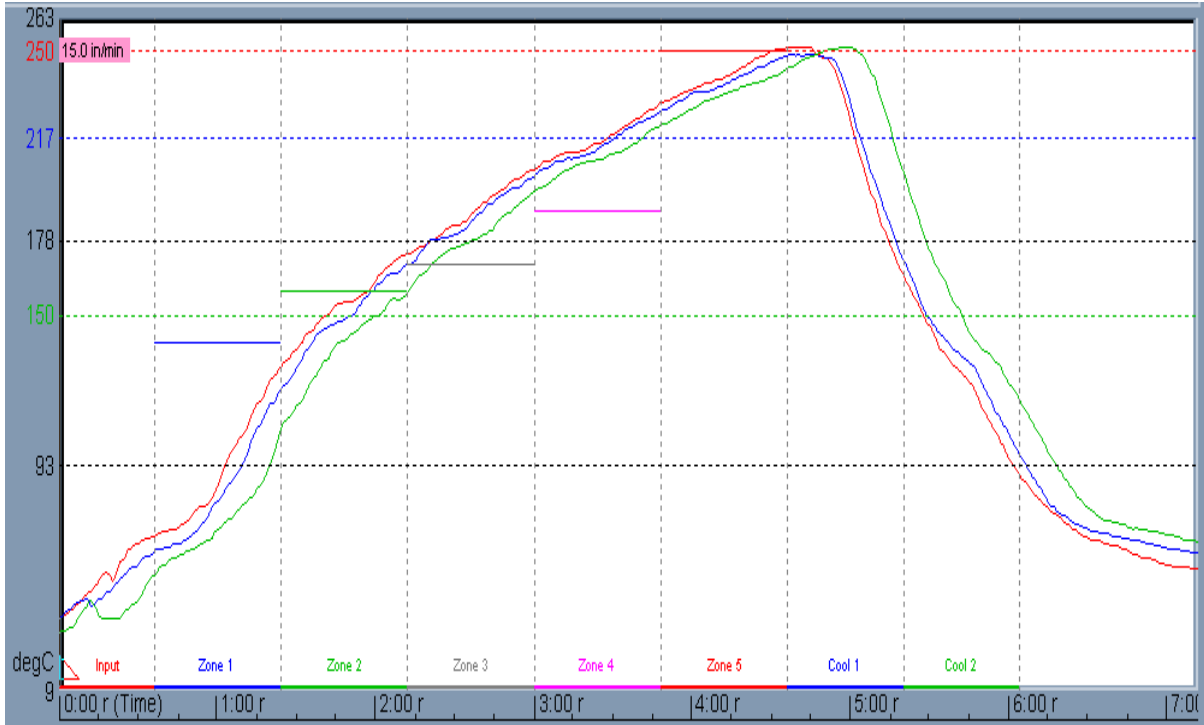
### Test and CI for Two Proportions

Sample	X	N	Sample p
1	91	2676	0.034006
2	1351	5886	0.229528

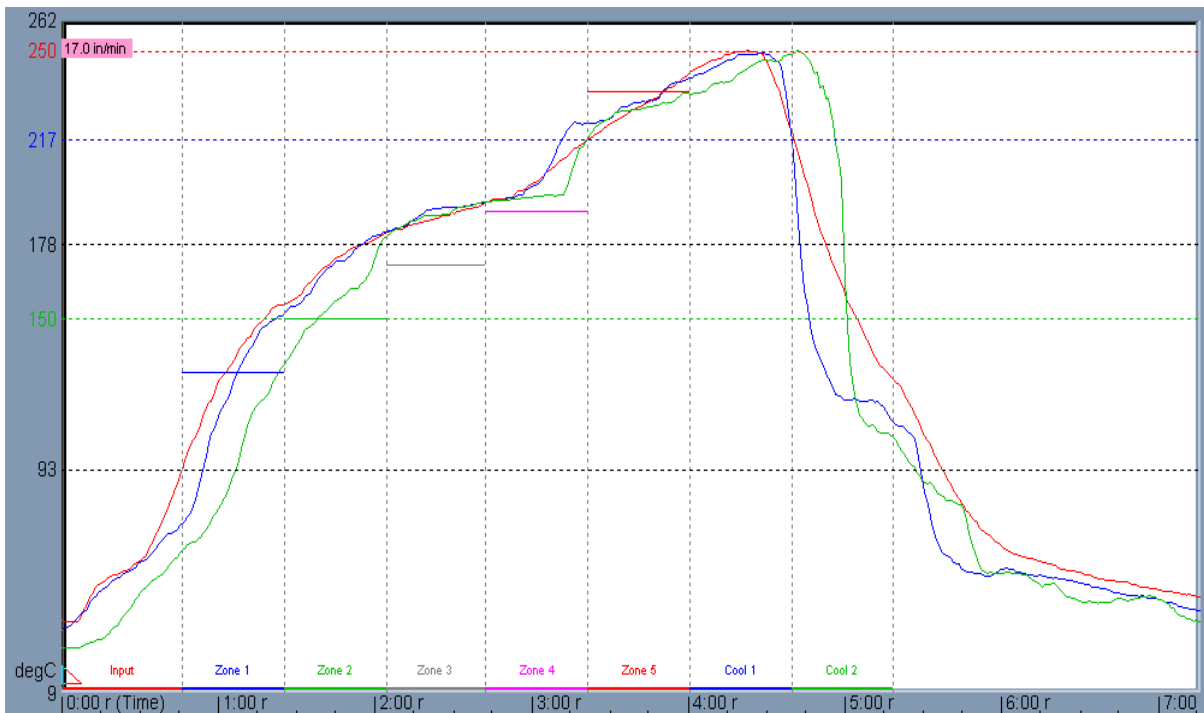
Difference = p (1) - p (2)  
Estimate for difference: -0.195522  
95% CI for difference: (-0.208272, -0.182771)  
Test for difference = 0 (vs not = 0): Z = -30.06 P-Value = 0.000  
Fisher's exact test: P-Value = 0.000

## Appendix B – Vitronics soltec xpm-520 oven profiles

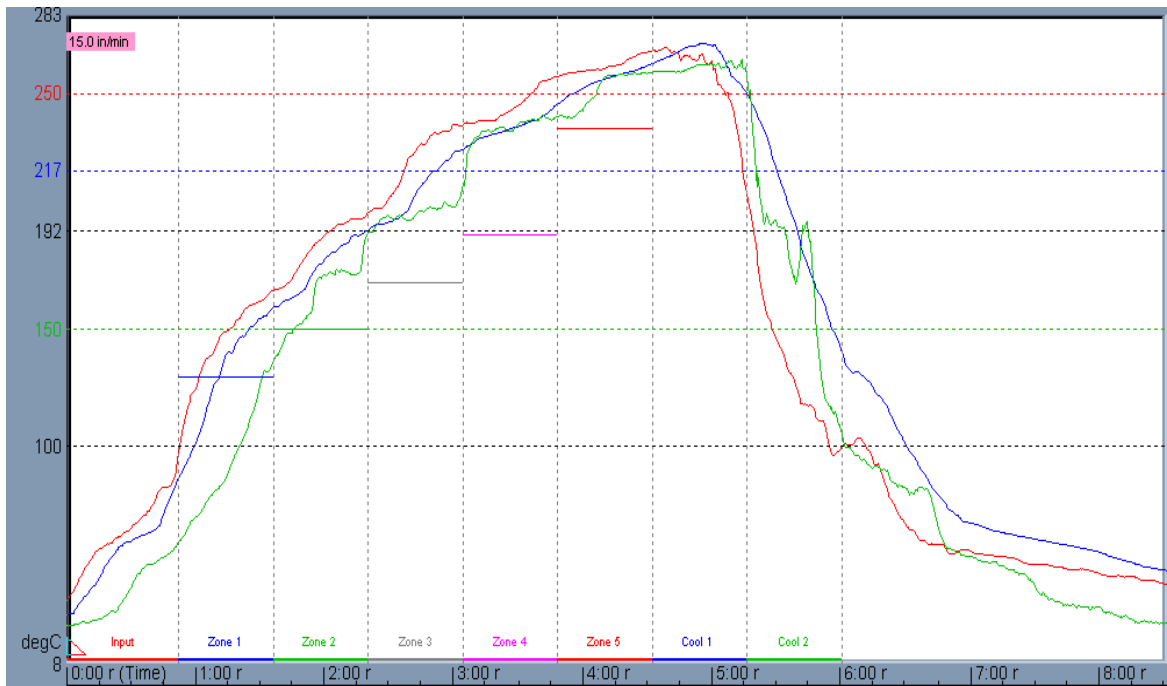
### Transceiver Bottom



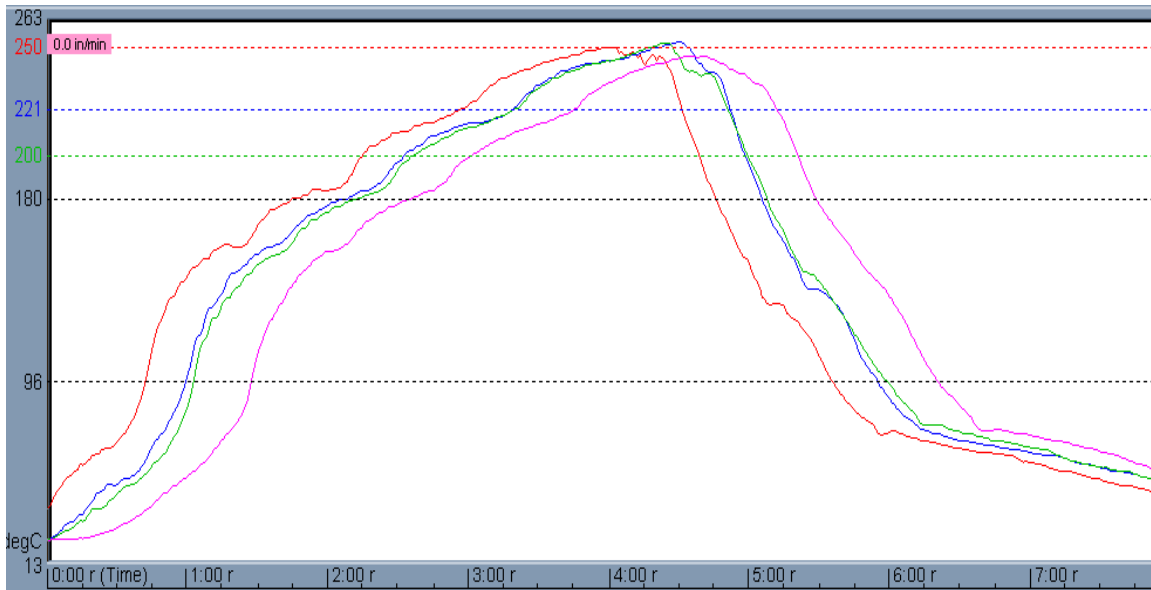
### Belt Pack Audio Top



### Transceiver Top

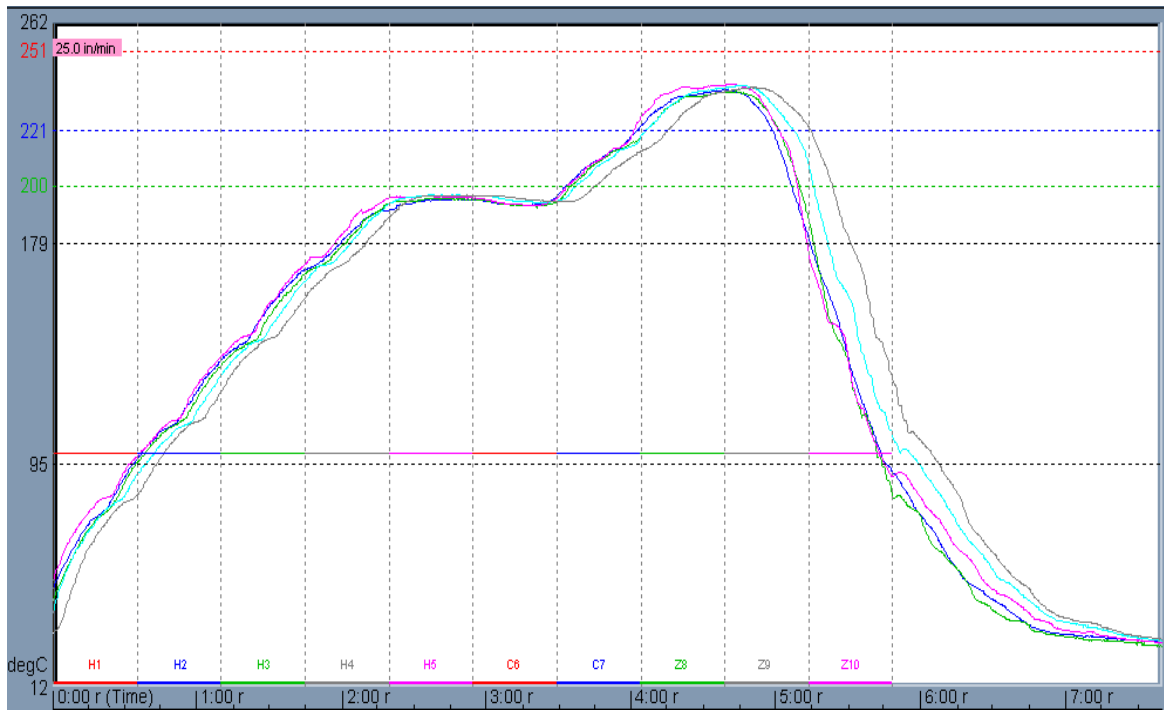


### Belt Pack Processor Bottom

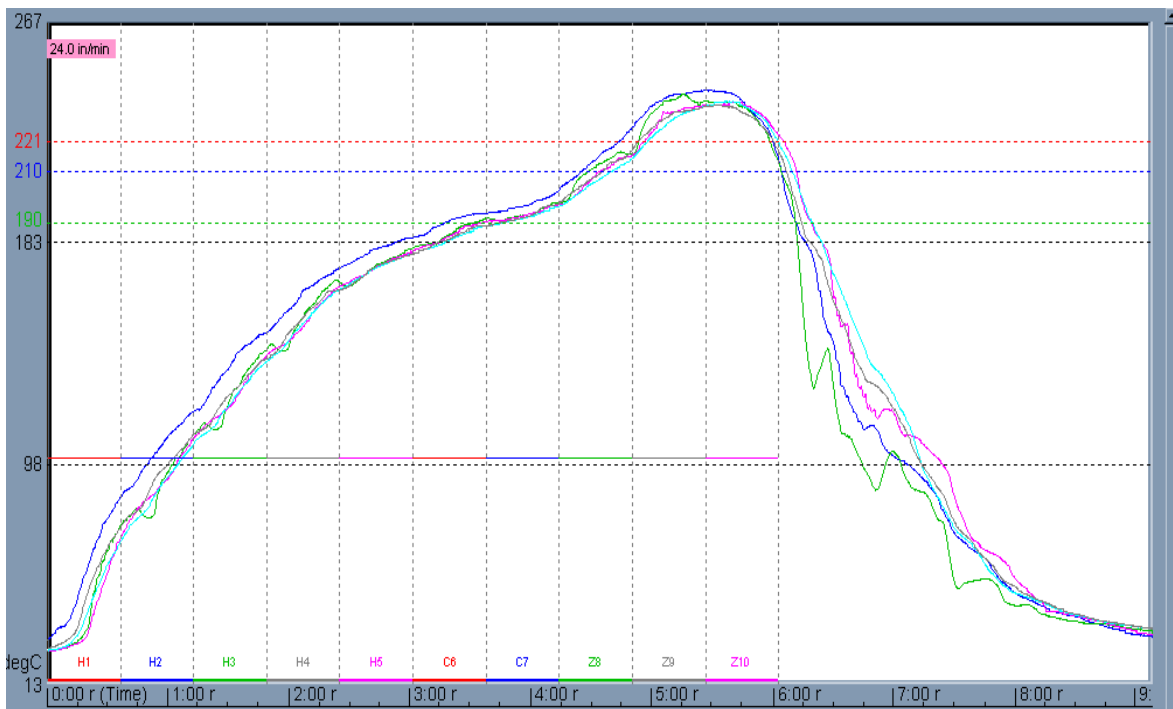


## Appendix C – Conceptronics HVA-155 oven profiles

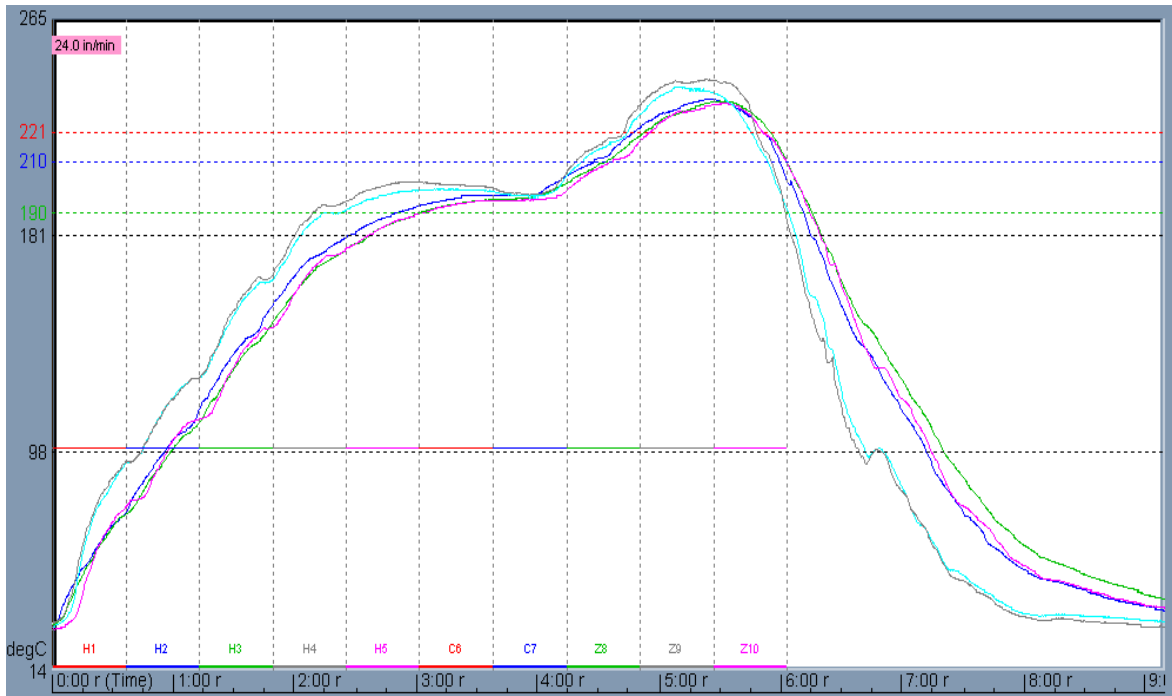
### Transceiver Bottom



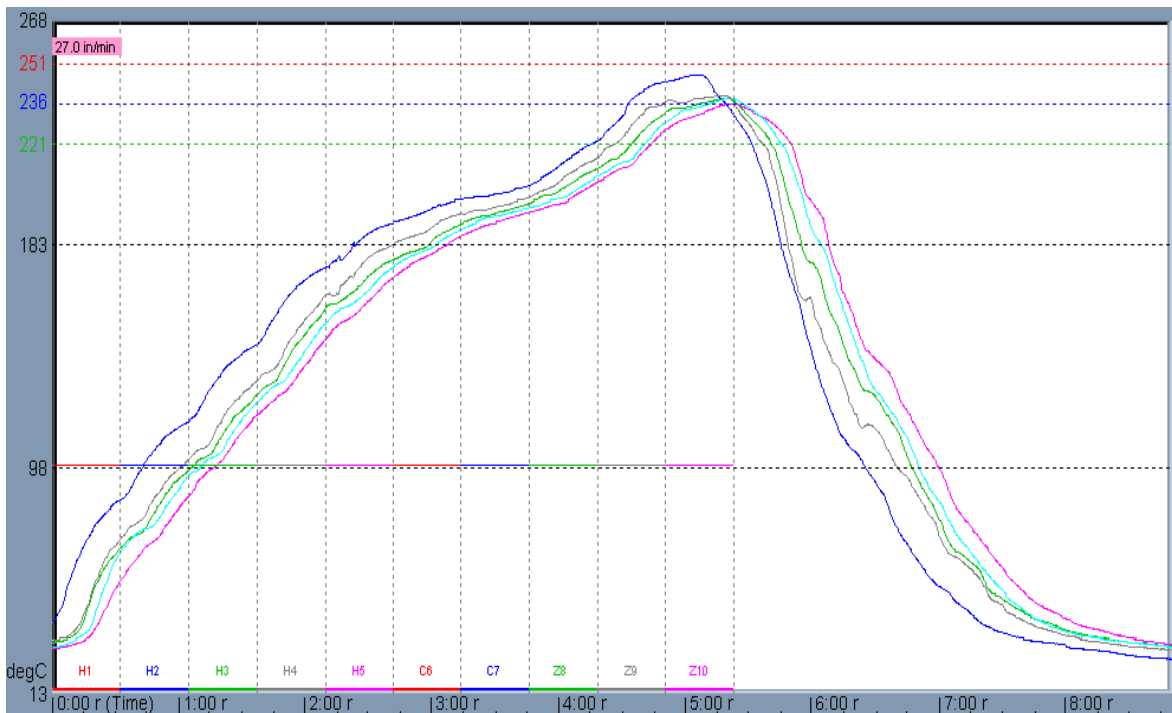
### Belt Pack Audio Board Bottom



### Transceiver Top



### Belt Pack Processor Bottom

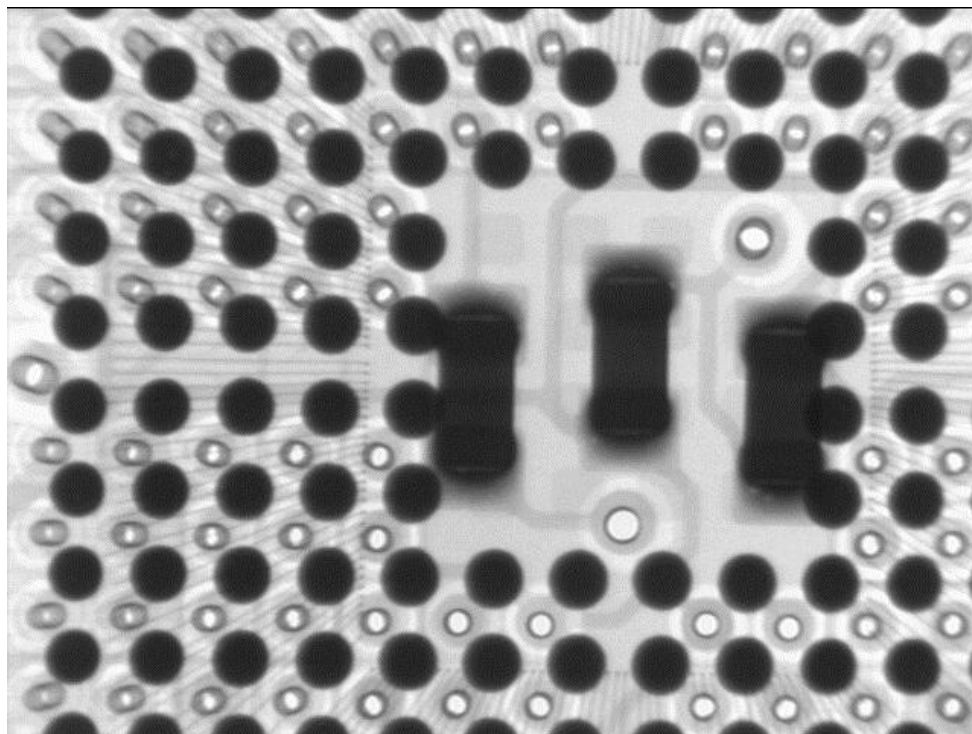


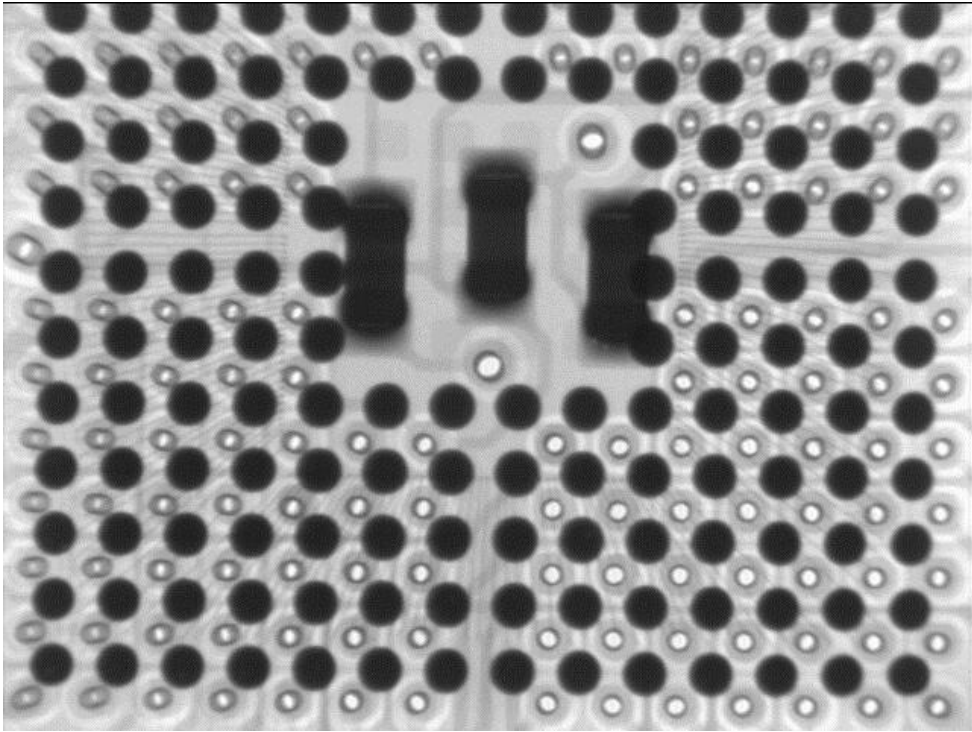
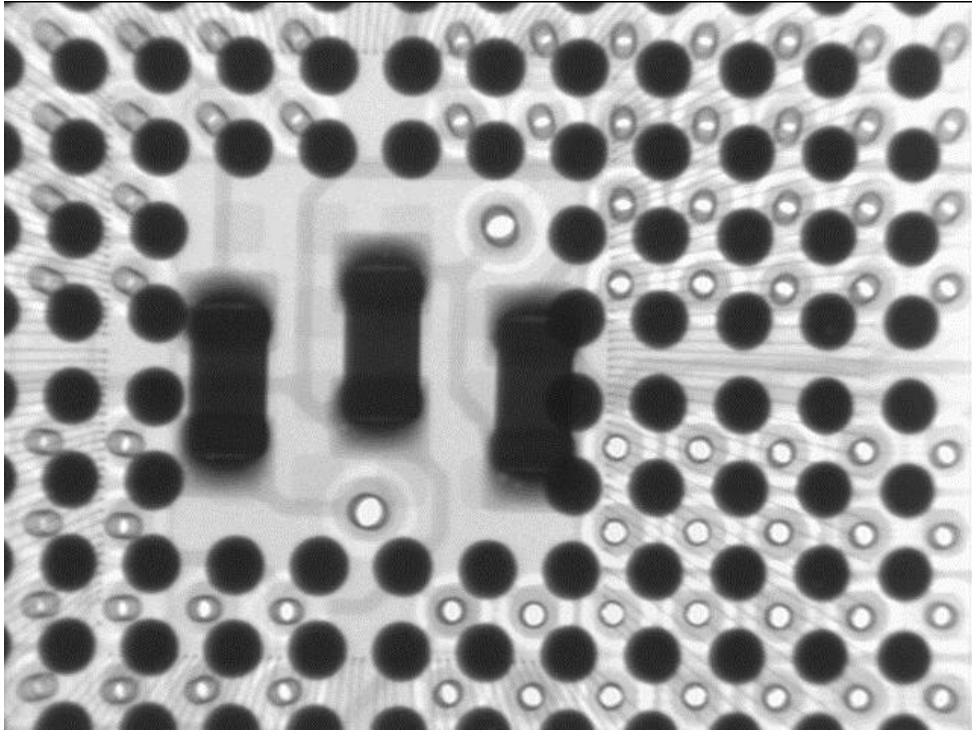
Appendix D – Conceptronics HVA-155 oven Zone Settings

<b>Board</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>chain speed</b>
50029 2	130	150	170	190	210	195	190	210	250	250	24in/min
50029 1	130	150	170	190	190	190	190	210	240	240	24in/min
50038 2	120	145	185	210	210	200	200	230	250	250	24in/min
50039 2	115	140	170	190	200	200	200	225	250	250	24in/min
50039 1	115	140	170	190	210	200	200	225	245	245	24in/min
pc-ppcbbpm 2	100	125	150	190	185	165	165	190	245	245	27in/min
pc-ppcbtbsf 1	130	160	190	175	175	175	175	185	250	250	24in/min
50037 2	100	130	160	190	215	205	205	225	250	250	24in/min
50037 1	100	130	160	190	210	200	200	225	250	250	24in/min
50038 1	100	130	160	190	220	200	200	230	250	250	24in/min
50030 2	100	130	160	190	210	200	200	230	250	250	24in/min
50030 1	90	120	150	180	200	200	200	230	250	245	24in/min

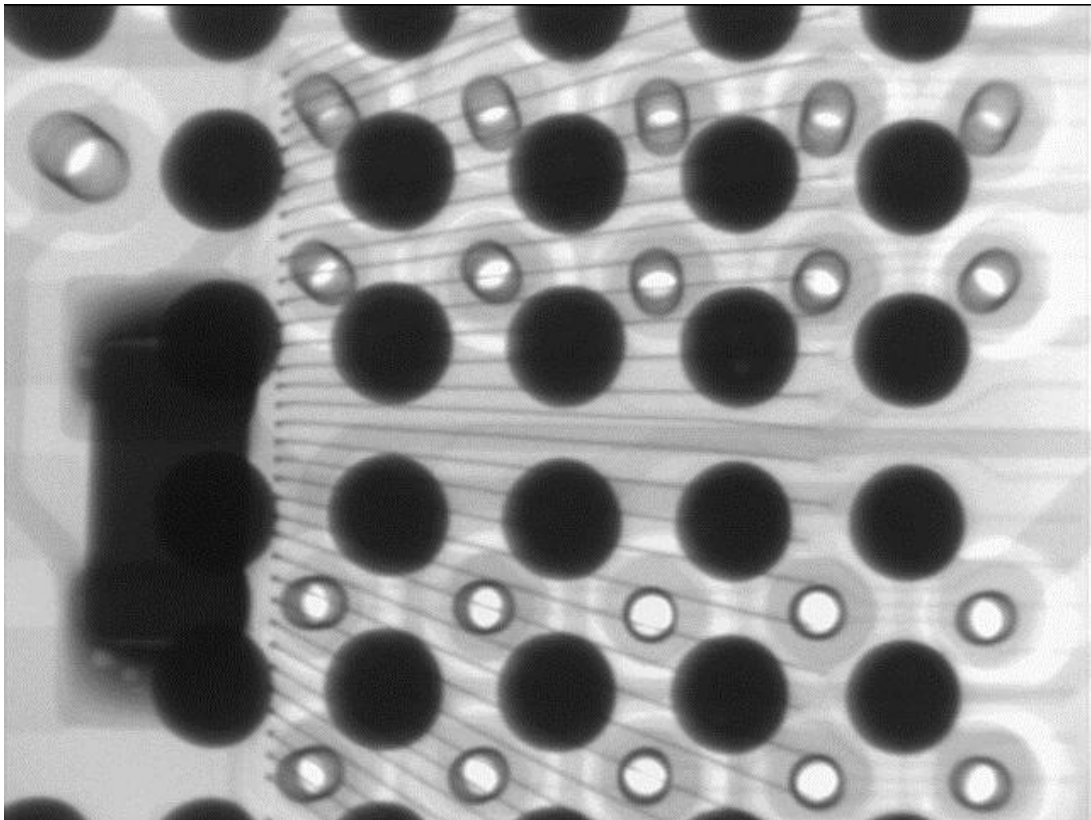
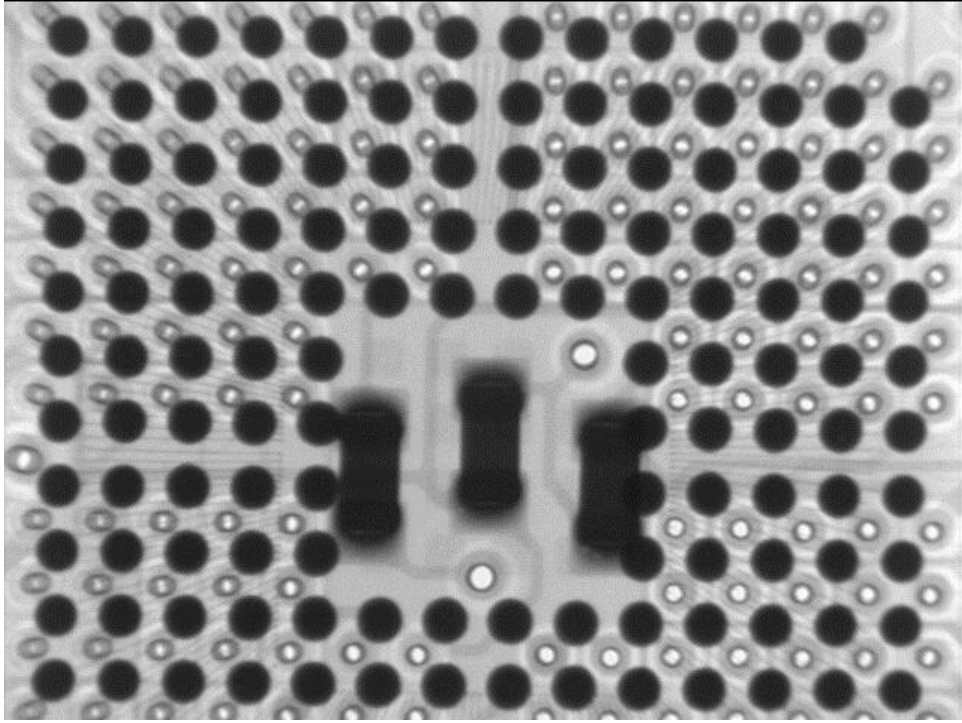
## Appendix E – X-ray analysis of BGA packages

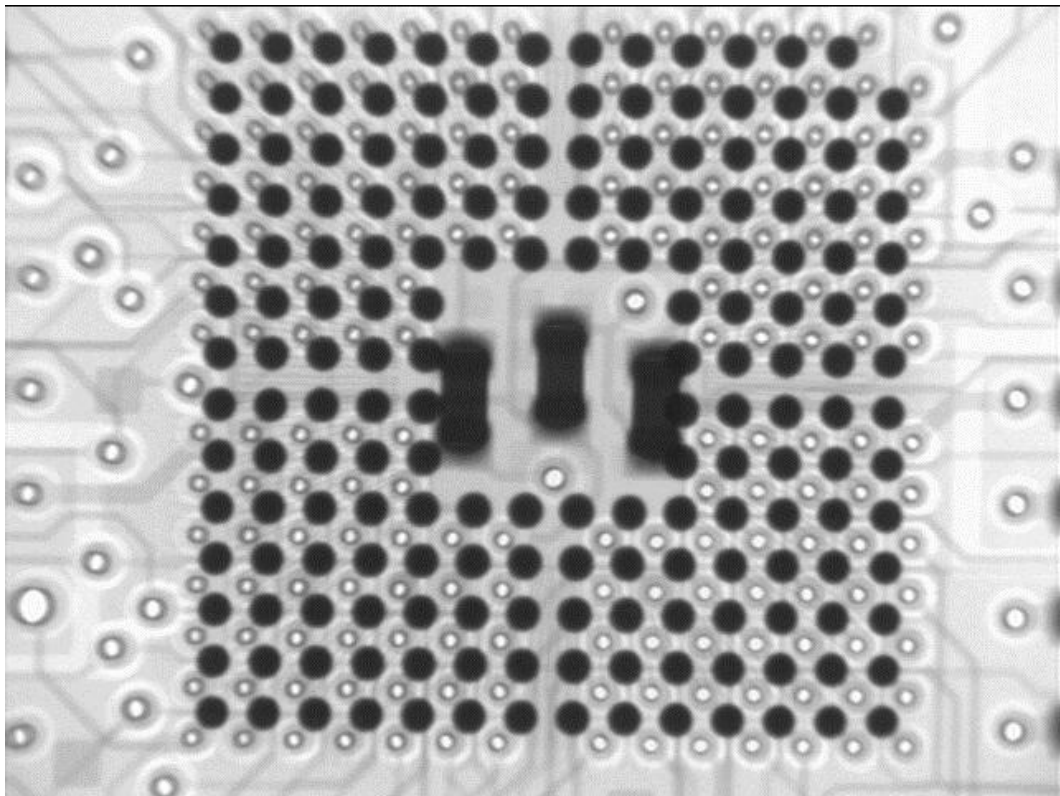
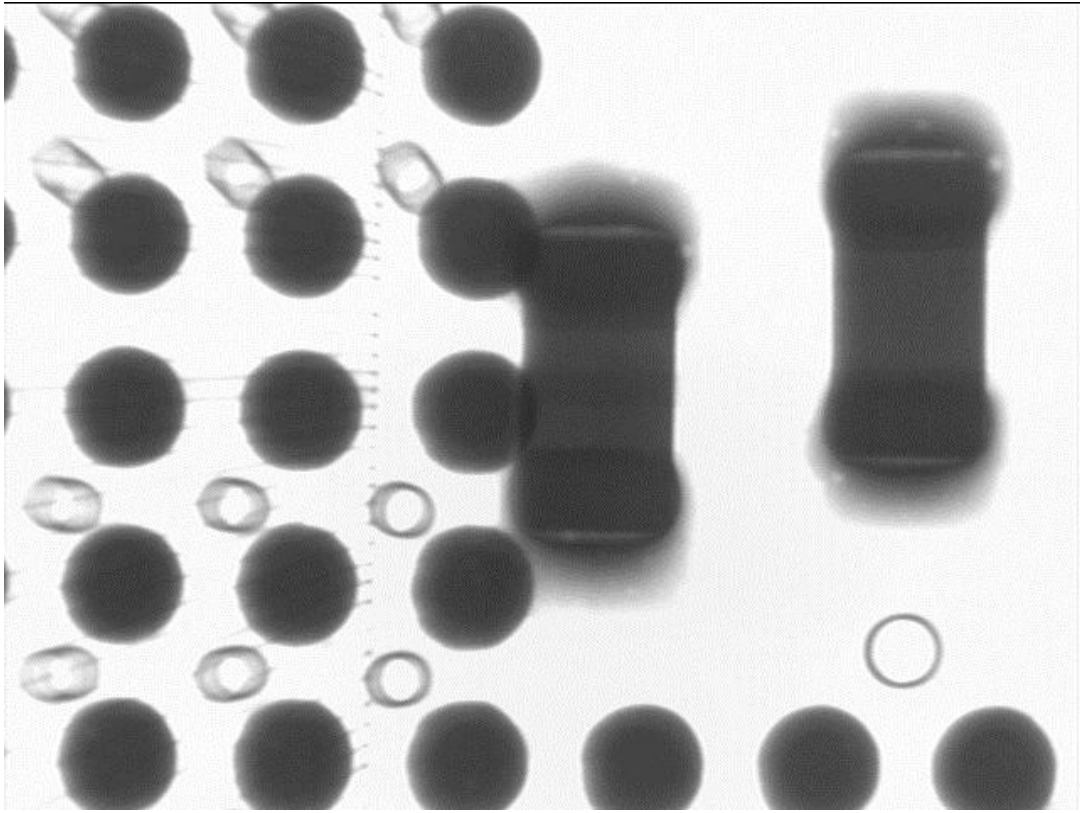
These are all of CoachComm Tempest Wireless Belt Pack Processor Boards.

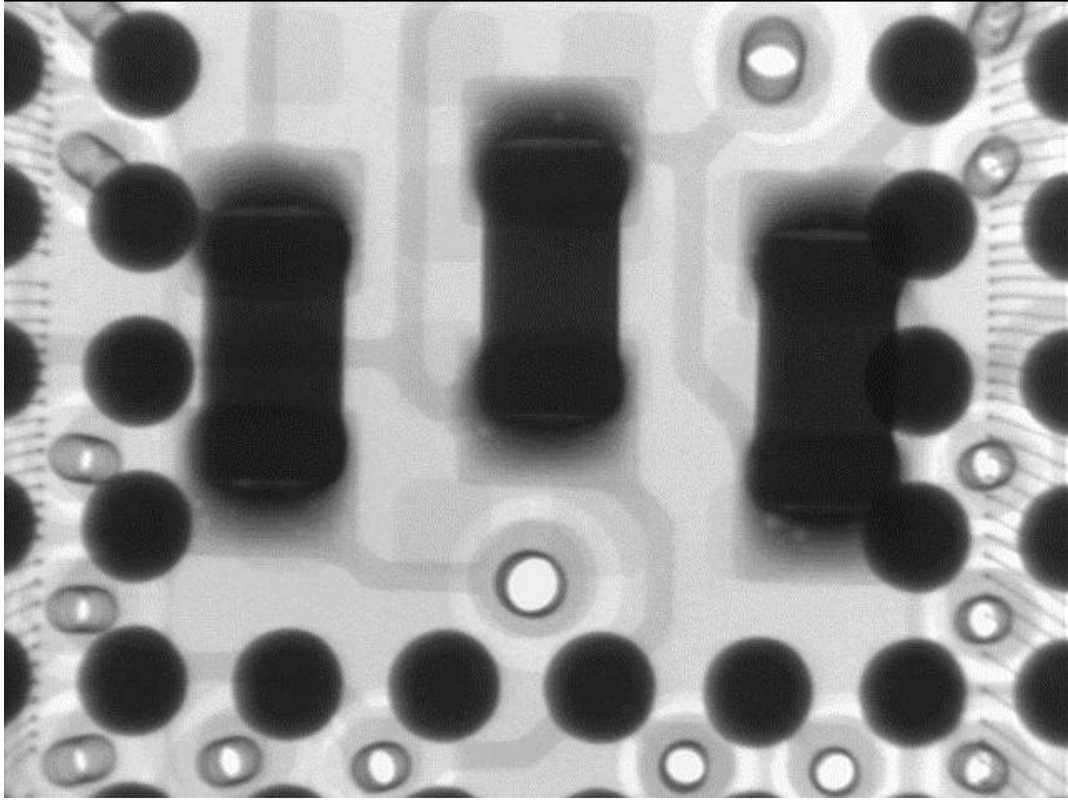








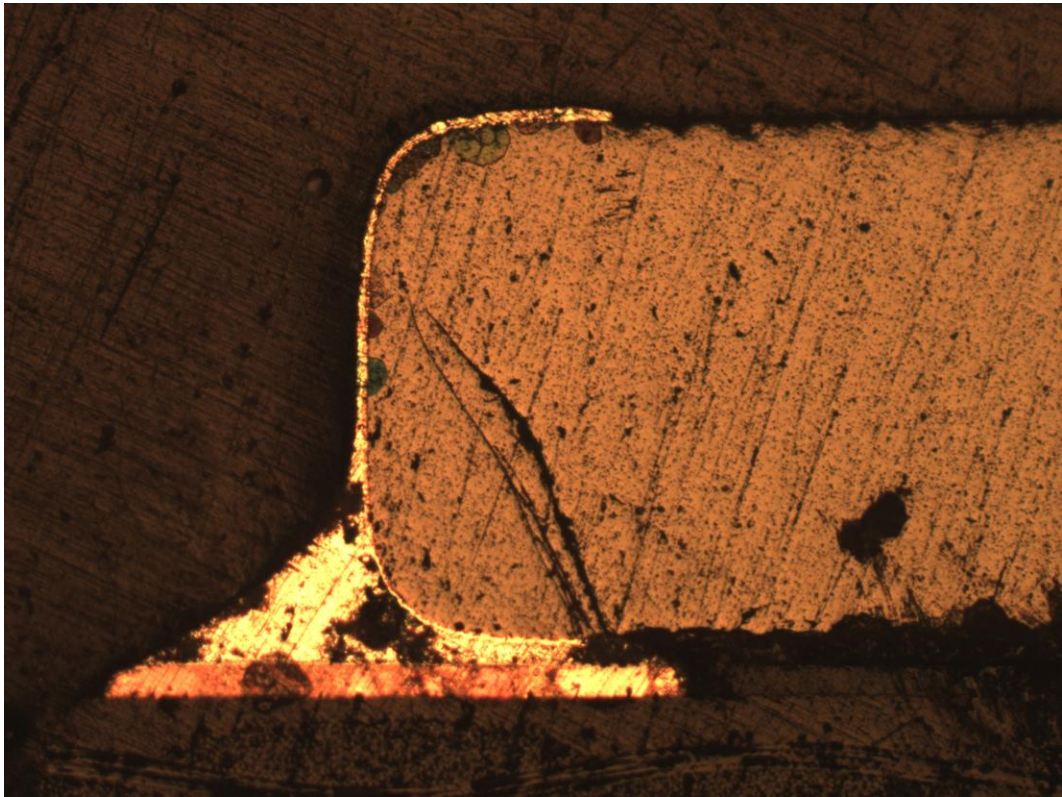
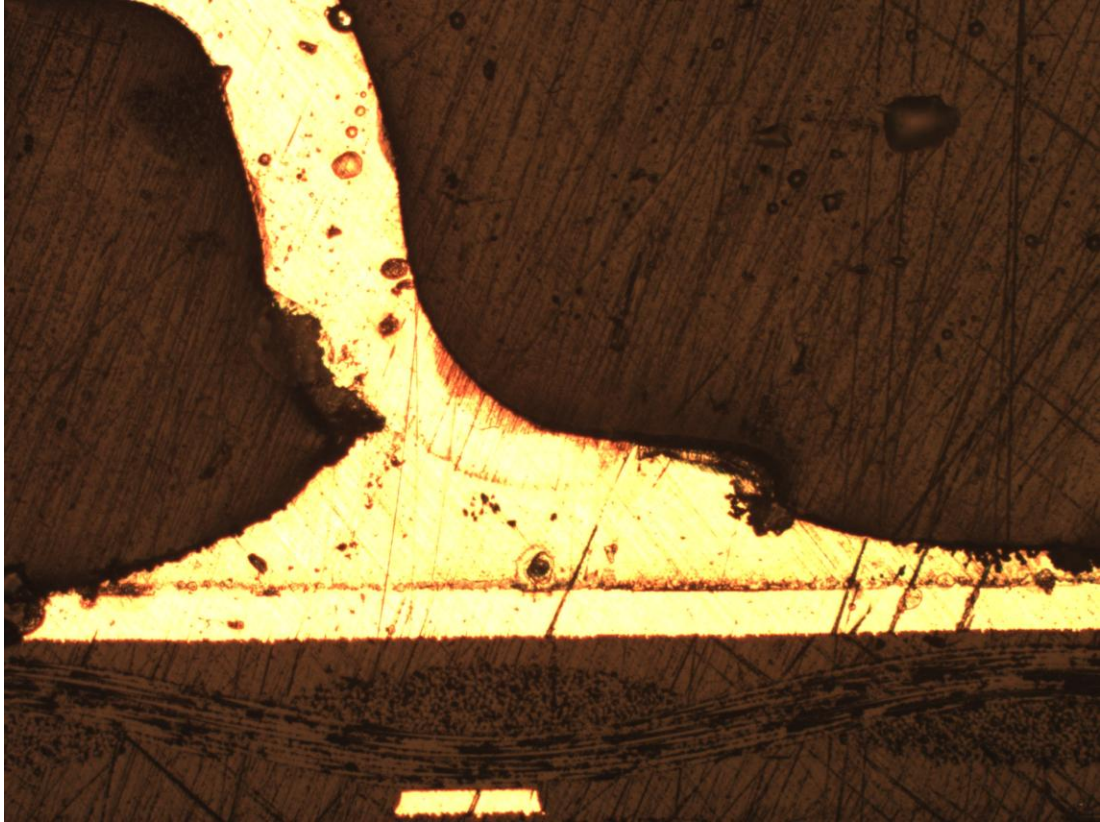


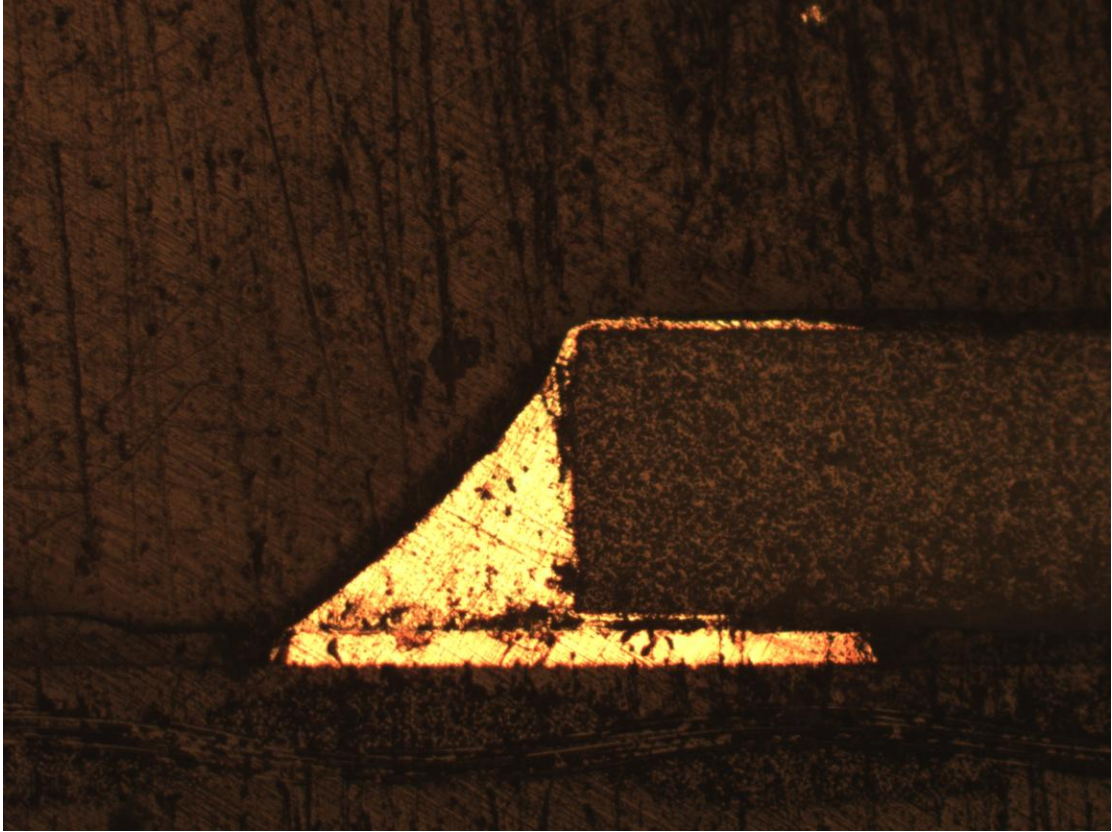


## Appendix F – Old Oven Joint Cross Sections

All joint cross sections below were taken from a CoachComm belt pack processor board.







## Appendix G – New Oven Cross Sections

All joint cross sections below were taken from a CoachComm belt pack processor board.

