

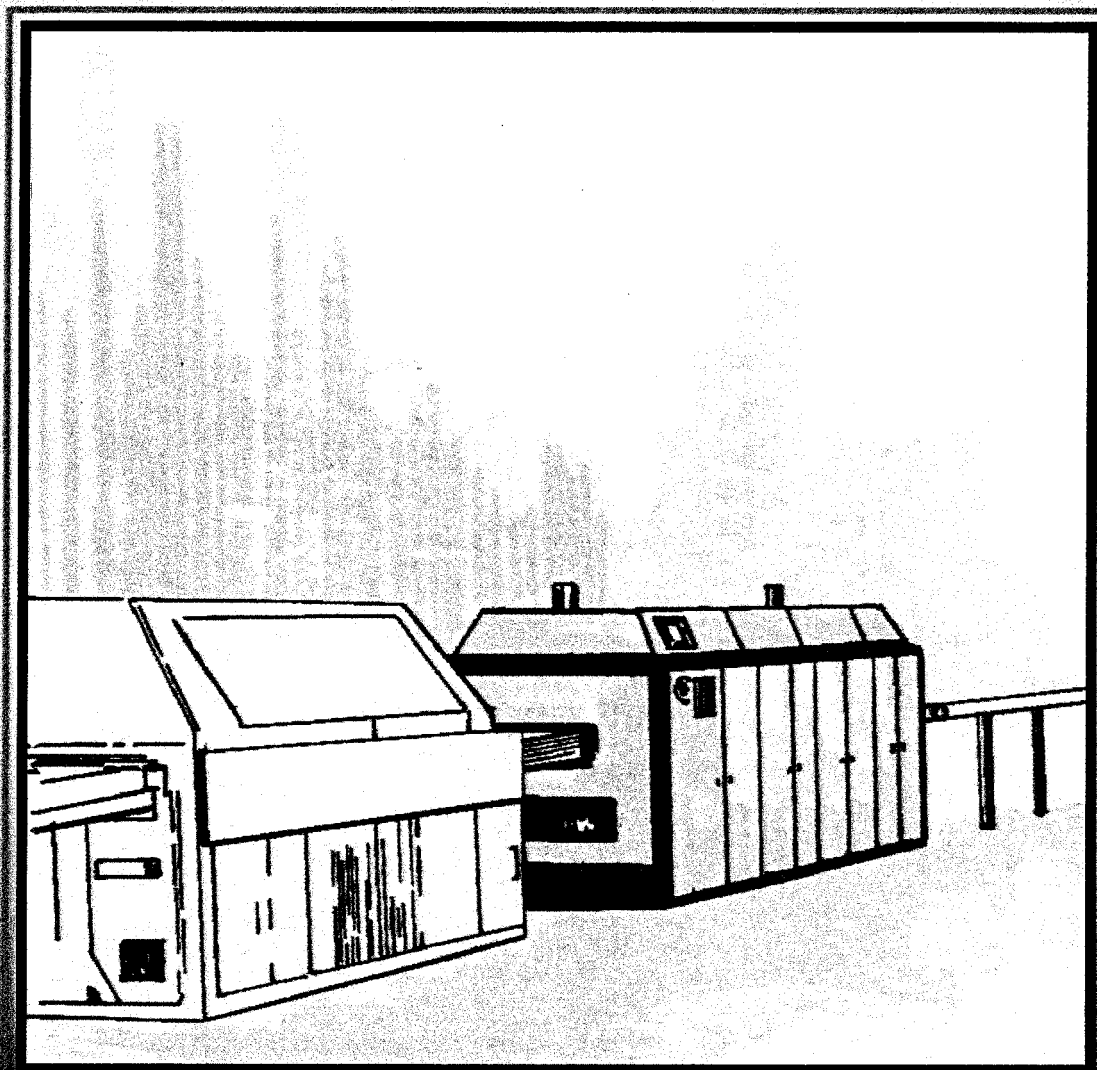
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# Reflow Technology Handbook

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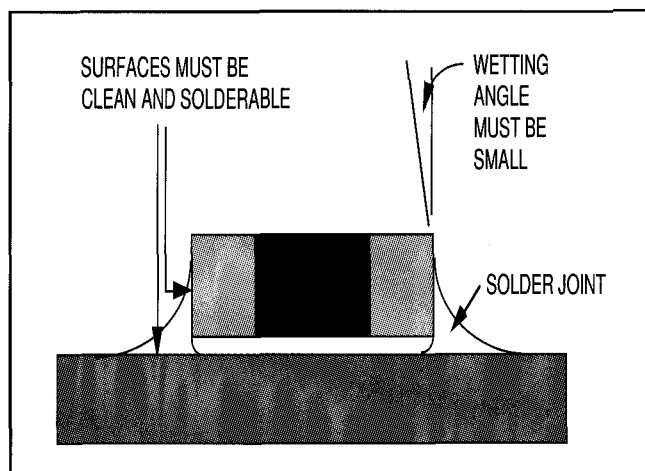


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## HOW DO YOU ACHIEVE HIGH QUALITY SOLDER JOINTS?

The process of producing high quality solder joints is similar to the process of learning how to ride a bicycle. If you do not understand the fundamentals, it is virtually impossible. However, once you understand and implement the basics, the results will follow. The goal of all SMT process engineers is to repeatedly produce high quality solder joints that have fine grain structure and excellent wetting characteristics, as shown in the figure below:



### CONTROL VARIABLES

In order to produce high quality solder joints, all process variables must be in control. The five general process variables <sup>(1)</sup> that need to be in control include the materials, machines, manpower, methods, and the environment. If the process variables are not in control, there is a very good chance that soldering defects will exist. Let's take a closer look at each.

### MATERIALS

The materials must meet functional specifications so that the product will perform to specification. Of equal importance is the solderability of the assembly. The solder paste/flux system must be compatible with the base materials of the parts to be soldered. The solder paste and parts should be as fresh as possible to enhance solderability.

### MACHINES

The machines used in the process must be able to perform to their specifications. The machines should operate within the range for which they are designed. Pushing a machine beyond its operating limits will ultimately cause a problem. The machines must be reliable and serviceable.

### MANPOWER

The manpower must be properly trained. All machines in the line require knowledgeable operators and maintenance personnel. A machine is only as good as the person operating it.

### METHODS

The methods and procedures must be defined and strictly adhered to. Inventory procedures should be implemented to ensure that components and boards do not stay on the shelf too long. Problems should be fully documented including all data that pertains to it.

### ENVIRONMENT

Finally, the processing environment must be controlled. This includes both the environment inside and outside of the machines. For example, if the humidity in the soldering area is too high, this can cause the solder paste to absorb moisture, which may cause problems during reflow. If the temperature in the room is not controlled, the thermal profile in the reflow oven may be affected, which again may cause a defect.

The purpose of this text is to address one aspect of high quality SMT soldering, the reflow process.

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*Producing high quality solder joints requires that five general process variables need to be in control; the materials, machines, manpower, methods, and the environment.*

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## WHAT IS THE IMPORTANCE OF THE PROFILE?

In order to fully understand Surface Mount Technology (SMT) reflow, one needs to have an understanding of what is being accomplished. One can take too simplistic a viewpoint in that all you need to do is to heat solder to a temperature greater than its melting point. One can also take too complicated a viewpoint in believing that a certain wavelength of infrared (IR) is required, or that a certain percentage of convection is required. Perhaps the most astute comment made on surface mount reflow was by an individual whom had just completed an evaluation of vapor phase, panel IR, and lamp IR equipment nearly five years ago. After coming up with virtually identical soldering defect results on all three types of soldering equipment, the following comment was made: "If you could hit the correct reflow profile using buckets of hot water, you would accomplish high quality, low defect solder joints." Although the above comment was made in jest (hot water is not quite hot enough to reflow solder), there is considerable truth to what was said.

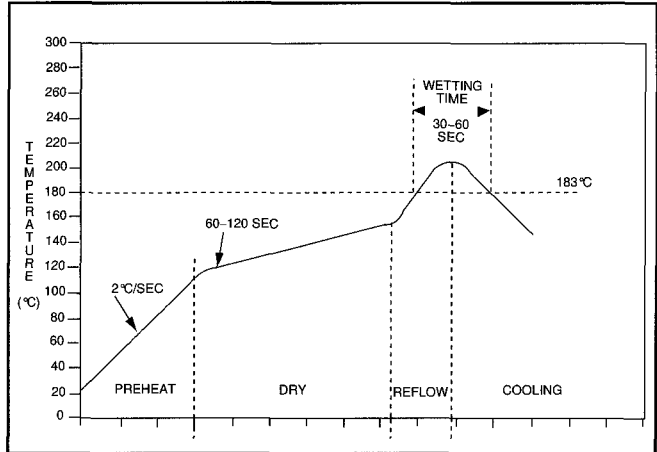
### REFLOW PROFILE REQUIREMENT

High quality, low defect soldering requires identifying the optimum temperature profile for reflowing the solder paste, and repeating over and over. Every solder joint on every board, needs to be heated similarly if the desired soldering results are to be accomplished. It **does not matter** how you apply the heat to the solder joint. What **does matter** is that the heat is applied to the solder joint in a controlled manner. The heating and cooling rise rates must be compatible with the solder paste and components. The amount of time that the assembly is exposed to certain temperatures must be defined and maintained. In other words, the solder reflow profile must first be defined and then maintained.

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*High quality, low defect soldering requires identifying the optimum temperature profile for reflowing the solder paste, and repeating it over and over.*

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### TYPICAL PROFILE

A typical profile consists of a preheat, dryout, and reflow section (zone) where different heating rates are used. In the preheat section, the goal is to fully preheat the SMT assembly to temperatures generally between 100°C to 150°C. The most critical parameter in the preheat section is to minimize the rate of rise to less than 2°C/second. The main concern is minimizing thermal shock on the components of the assembly. Multilayer ceramic chip capacitors can be vulnerable to cracking if heated too fast. Solder paste can spatter also, if heated too fast. The second heating section, referred to as the dryout, soak, or preflow zone, is used primarily to ensure that the solder paste is fully dried before hitting reflow temperatures. This zone also acts as a flux activation zone for some solder pastes. Solder reflow is accomplished in the reflow zone, where the solder paste is elevated to a temperature greater than the melting point of the solder. For 63/37 Eutectic solder, the melting temperature is 183°C. This temperature must be exceeded by approximately 20°C to ensure quality reflow. The amount of time the solder joint is above the melting point is referred to as the "wetting time". The wetting time is normally 30 to 60 seconds for most pastes. If the wetting time is excessive, intermetallics may occur in the joint, which result in brittle solder joints. In summary, define the profile, and hit it.

## HOW MANY HEATING ZONES ARE REQUIRED?

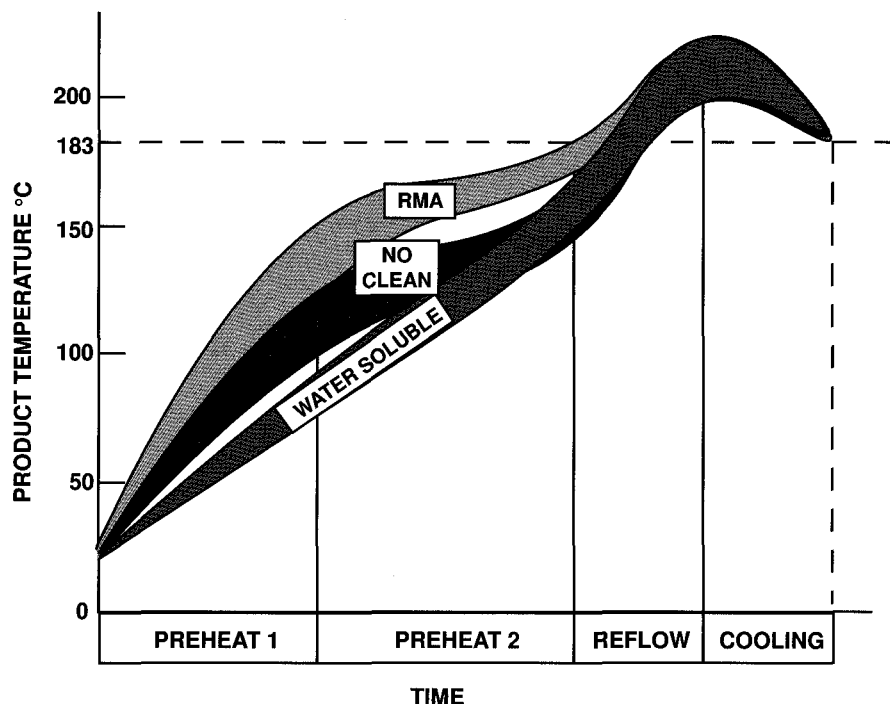
This question frequently arrives and can be a source of confusion. One theory is that if ten zones are good, then twenty zones are better. While in theory this may be true, in practicality it may not be true. While it improves the flexibility of oven, it also adds to the complexity and makes oven set-up more difficult.

Let's review this question from the standpoint of how many zones are really needed. Reflowing solder paste typically requires two or three different heating rates to accomplish the process. In the figure below, there are three "typical" profile bands for RMA, water soluble, and no-clean solder pastes. These profiles are rather generic, and one should consult with their solder paste vendor to determine the desired profile. All of the pastes in the figure could be successfully reflowed using three zones.

A second issue is the question of independent top and bottom heat control. A common conception in SMT

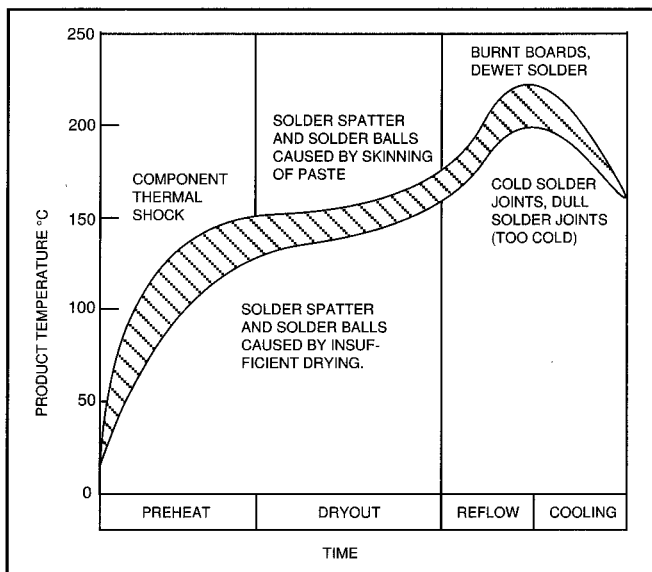
reflow is that if you can control your top and bottom heaters separately, then double sided reflow can be accomplished (without reflowing side A twice). This will not work with most SMT reflow processes, as most products are too thermally thin. Independent top/bottom heating control does help in machines with dual conveyors that are located at different heights in the chamber. Product warpage may also be minimized through proper control. The bottom line is that most machines have this feature, but most often the top and bottom heaters will be set at the same value.

Edge heating zones become significant when edge conveyors are used. Edge conveyors act as heat sinks on the edge of the product. Two zones of edge heat (one front, one back) will assist in compensating for edge conveyors. If mesh conveyors are used, these zones are unnecessary unless the product width is quite wide.



## WHAT IS THE PROFILE PROCESS BAND?

In reality the profile is not a line, but rather a band or process window.<sup>(2)</sup> The size of the band is defined by the range of temperature deviation that can occur during reflow and yield high quality results. This is indicated by the crosshatched area shown in the figure. In the example, the profile band size is indicated as 25°C. The actual size of the band will vary depending upon solder paste, component type, and circuit board material.



### REFLOW SOLDERING DEFECTS

If the product temperature profile is not maintained within the band, a defect will occur. Chip capacitors may crack if the rise rate in the preheat zone is excessive. Solder spatter and solder balls may occur if drying is excessive or insufficient. If drying is excessive, the solder paste may skin over and not allow any of the volatiles to escape. As the temperature of the solder joint continues to heat, the vapor pressure increases until the solder joint virtually explodes as the gases escape rapidly. The result is solder spatter and solder balls. If the preheat is insufficient, solder spatter and balls may occur in the reflow zone when higher heating rates occur. It is critical that the paste is dried at low controlled heating rates. In the reflow zone, insufficient heat will result in non-reflowed or partially reflowed solder joints. The

joints will have a dull, rough surface finish in this case. Excessive heating in the reflow zone may result in burnt boards, damaged components, or possibly solder dewetting. In a dewet solder joint, the solder is reflowed but it is pulled away from the pad or the component lead.

### DEFINE THE BAND

The profile band needs to be defined for the given SMT assembly. To define this band, one should be aware of not only the solder paste requirements, but also any specific requirements of components or the circuit board material. The process band width is defined as the total deviation in temperature that can occur and yield reliable results.

### OVEN PERFORMANCE

From a process standpoint, the reflow oven must be able to produce consistent results within the reflow profile band. The user should be aware of all variables that influence the band. These variables may be defined as product related and oven related. By far the most critical product related non-uniformity is that created by large mass differences on the product. Since it is easier to heat an area that has no components as compared with an area with large components, temperature differentials will exist on the product. Machine related non-uniformities such as repeatability under product load and edge-to-center and front-to-back product heating uniformities must also be considered. To achieve high quality, low defect soldering results, the sum of all the non-uniformities must fall within the defined reflow profile band.

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*In reality the profile is not a line, but rather a range of temperatures all solder joints must be exposed.*

*The total temperature deviation from component thermal mismatch, oven loading, and oven uniformity must be within the band.*

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## WHAT ARE THE CAUSES OF NON-UNIFORM HEATING?

In order to fully comprehend the capability to heat within the defined process band, one needs to better understand the causes of heating non-uniformities. The three main causes of non-uniform heating in the SMT reflow process include mass differential on the product, conveyor and heater edge effects, and product loading.

### MASS DIFFERENTIAL

The amount of temperature rise of a product as it travels through a heating zone depends upon a number of variables. The temperature rise of an object subjected to heat is determined by the following equation:

$$\Delta T = Q \times A \times t / (M \times C_p)$$

#### WHERE:

$\Delta T$  = Product Temperature Rise ( $^{\circ}\text{C}$ )

$Q$  = Heat Absorbed ( $\text{w}/\text{cm}^2$ )

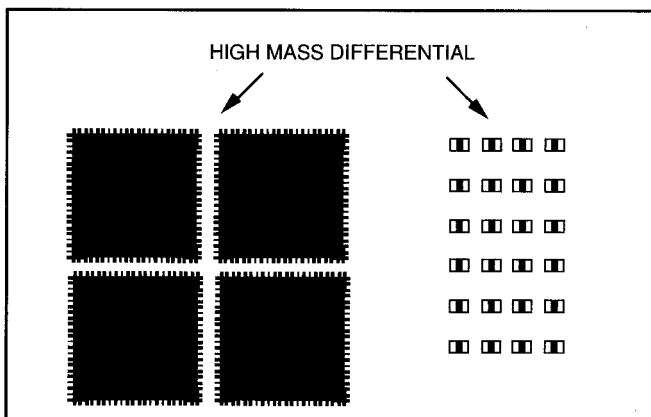
$A$  = Exposed Area ( $\text{cm}^2$ )

$t$  = Heating Dwell Time (seconds)

$M$  = Mass of Object (kg)

$C_p$  = Specific Heat ( $\text{w-sec}/\text{kg-}^{\circ}\text{C}$ )

The mass ( $M$ ) times the specific heat ( $C_p$ ) is often referred to as thermal mass. Greater thermal mass requires more heat to achieve a given temperature rise. In the figure shown below, the area populated with the PLCC's has considerably more thermal mass per unit area than the area with the discrete components. This area will be more difficult to heat. The non-uniformity caused by thermal mass differential may be measured by thermocoupling a lead on the largest and smallest device, and running a profile.

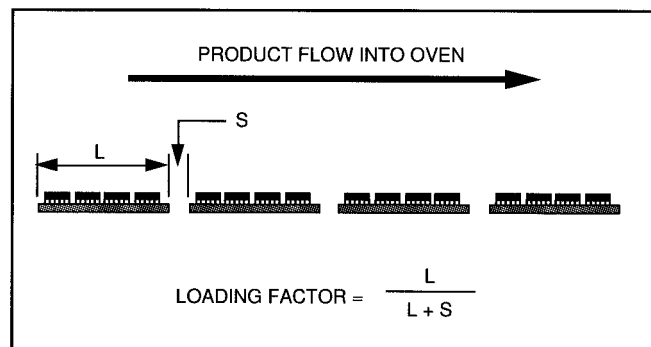


### OVEN UNIFORMITY

A second main cause of non-uniform product heating is the oven heating pattern. This can be caused by edge effects on the heaters (less heat at the end) or by heat sinking of the conveyor system. The edge effect may be caused by insufficient airflow around the edges of the machine, or by non-uniformities that are inherent in the heaters. The heat sinking of the conveyor is really a mass effect, similar to the one described above. The oven uniformity may be measured by thermocoupling a bare board over a matrix of points, and running a profile. The matrix should include points on the board edges (front, back, left, and right), and the center of the board.

### OVEN REPEATABILITY

Repeatability refers to the oven's capability to repeat a given profile. Repeatability is affected by machine loading. The figure below shows a typical product loading condition. The "Loading Factor" is defined in the figure.



The higher the value of the loading factor, the more difficult it is for any oven to give repeatable results. Ovens will generally specify a maximum loading factor (ranging from 0.5 to 0.9). The loading factor becomes an important consideration when sizing an oven. The non-uniformity caused by repeatability can be measured by running a profile on a test board, then load the oven down. Periodically, run the test board within the oven load and compare with the unloaded profile.

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*The three main causes of non-uniform heating in the SMT reflow process include mass differential on the product, conveyor and heater edge effects, and product loading.*

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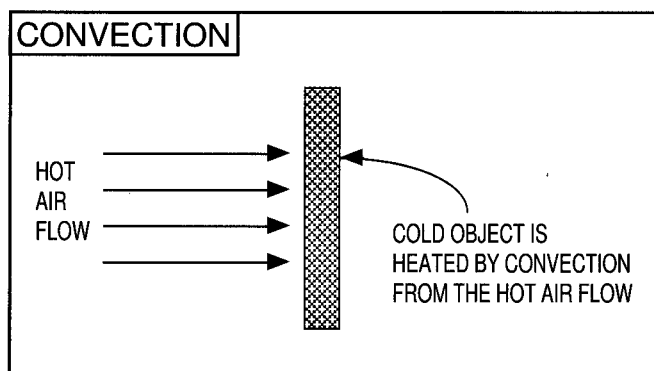


## WHAT ARE THE MODES OF HEATING?

There are three different heating modes involved with most SMT reflow processes; convection, conduction, and infrared radiation (IR). All three of these heating modes occur naturally in our daily lives. Perhaps the easiest way to understand each of these heating modes is through example.

### CONVECTION

Convection heat transfer occurs when a fluid (such as air, nitrogen, or water) passes over a solid (such as an SMT assembly). A cool breeze on a hot sunny day provides convective cooling. Hot air from a hair dryer provides convective heating. Convection heating or cooling requires contact of the flow with the solid part. Only the layer of the flow that is in contact with the part is actually transferring heat.



### CONDUCTION

Conduction heat transfer occurs when two solid masses of different temperature are in contact with each other. A good example is when a pan is placed on an electric burner. Most of the heat is transferred to the pan by the contact between the pan and the burner. Conduction also occurs within the same mass if a temperature differential exists within the mass.

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*Referring to a system as 100% convection or 100% IR is incorrect. A system may be dominated by convection or IR, but the other heat transfer is always present in significant quantities.*

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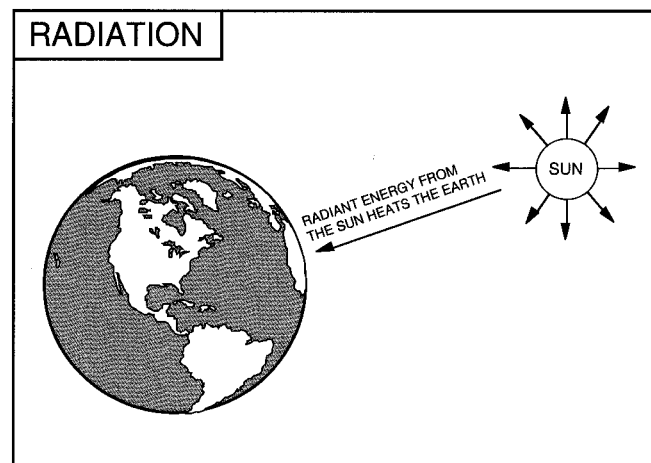
### CONDUCTION



HEAT FLOWS FROM HOT TO COLD TO HELP EQUALIZE TEMPERATURES

### RADIATION

Infrared Radiation (IR) occurs when two bodies of different temperature are in sight of each other. The best example of IR is the heating of the earth by the sun. IR is a non-contact heat transfer.



In SMT reflow applications (with the exception of vapor phase), convection, conduction, and IR all play a role in the heating process. Referring to a system as 100% convection or 100% IR is incorrect. A system may be dominated by convection or IR, but the other heat transfer is always present. IR dominant systems usually range in the convection/IR ratio of 60/40 to 40/60. Convection dominant systems have ratios in the range of 70/30 to 80/20. Conduction heat transfer occurs more within the product during the heating process. Heat is transferred through the product to help minimize hot or cold spots.

## HOW DOES INFRARED HEATING WORK?

Infrared (IR) heat transfer occurs when two objects at different temperatures are in sight of each other. The heat is transferred by electromagnetic waves of 0.78–1000 micron wavelengths. All objects emit some level of infrared. The quantity of infrared energy emitted and the wavelength of the emission are both dependent upon the absolute temperature of the object. As the source temperature increases, the heat transfer output increases exponentially to the fourth power. Increasing the source temperature results in shorter wavelengths. Decreasing the source temperature results in longer wavelengths. In SMT reflow the amount of heat transfer is important, so as not to exceed the 2°C/sec rate. When operating at these low heating rates all types of radiant emitters (lamps, panels, tubes) operate in the medium to long wavelength ranges.

### INFRARED HEATING EQUATION

In order to understand what parameters are important in infrared heating, one can consider the general equation for heat transfer between the heat source and the object being heated. Again, the purpose is not to memorize the equation, but rather to point out the significance of what is involved. The general equation for heat transfer is as follows:

$$Q = V \times E_s \times A_t \times K \times (T_s^4 - T_t^4)$$

#### WHERE:

$Q$  = Infrared heat transfer (w/cm<sup>2</sup>)

$V$  = Geometric view factor (0–1)

$E_s$  = Emissivity factor of the source (0–1)

$A_t$  = Absorptivity factor of the target (0–1)

$K$  = Stefan-Boltzmann Constant  
( $5.67 \times 10^{-12}$  w/cm<sup>2</sup>/°K<sup>4</sup>)

$T_s$  = Source temperature (°K)

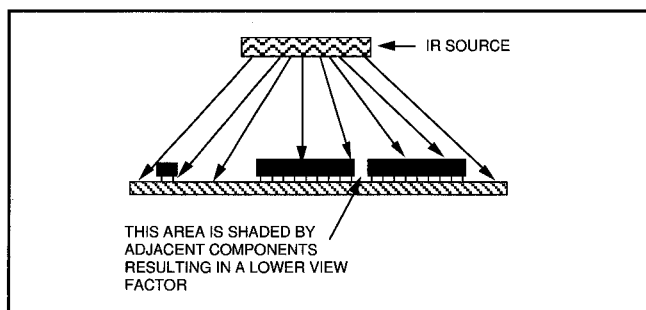
$T_t$  = Target temperature (°K)

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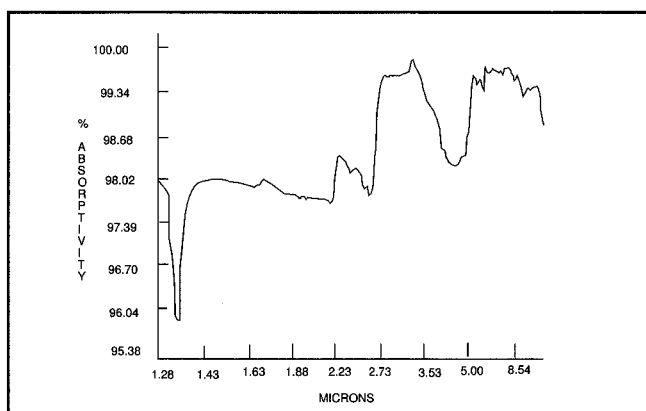
*Absorption characteristics of solder paste and circuit board material makes IR an efficient means of heating.*

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The geometric view factor “V” is the fraction of energy that leaves the source that hits the target. In SMT reflow, the oven chamber designs yield very high view factors in the range of 0.90 to 0.95. An important aspect of the view factor comes in product design. If two very large components are in close proximity to each other, the view factor to a solder joint between them is decreased, which makes it more difficult. Refer to figure.



The source emissivity and the target absorptivity factors are in the range on 0.90 to 0.95 for most SMT applications. Solder paste is an excellent absorber of infrared energy. Shiny gold components may be difficult to heat as they tend to be reflective. Most often, however, the board material, solder paste, and the components all absorb quite well. The figure below shows the spectral absorptivity for an RMA solder paste.<sup>(3)</sup>



Control of infrared is generally done by controlling the source temperature. Providing that the overall source emission can be regulated, IR can provide high levels of repeatability.

## HOW DOES CONVECTION HEATING WORK?

Convection heat transfer occurs when a fluid at a given temperature contacts a solid mass at a different temperature. If the fluid is hotter than the mass, the mass will be heated. If the fluid is cooler than the mass, the mass will be cooled. Perhaps the easiest way to understand convection is to look at the convection equation and note what is important and what is not important.

### CONVECTION EQUATION

The following is the general equation for convection heating or cooling:

$$Q = H \times \Delta T$$

#### WHERE:

Q = Heat absorbed per unit area ( $\text{w}/\text{cm}^2$ )

H = Convective film coefficient  
( $\text{W}/\text{cm}^2\text{-}^\circ\text{C}$ )

$\Delta T$  = Temperature difference between  
fluid and object ( $^\circ\text{C}$ )

The amount of heat transfer “Q” can be modified by either changing the convective coefficient “H” or the temperature difference “ $\Delta T$ ”. Increasing the source temperature will increase the temperature difference, and thus the amount of heat transfer “Q” will increase proportionally.

The convective coefficient “H” can have a significant impact on the heat transfer “Q”. The value of “H” is related to a number of variables, including velocity of the flow and angle of attack of the flow.

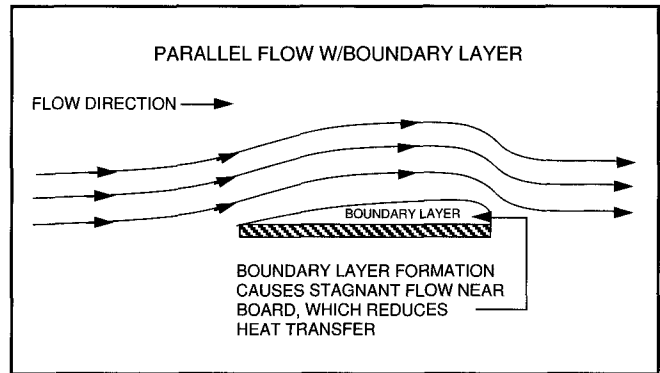
Increasing the flow velocity will increase the value of “H”. For example, when one is outside in the wind, a low velocity cool breeze on a warm day will feel quite nice. However, a strong wind on that same day may feel

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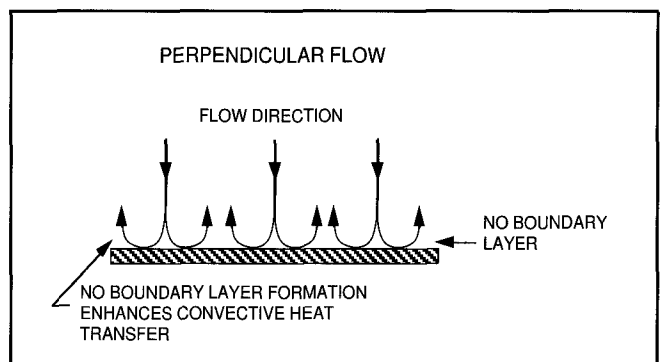
*Perpendicular flow convection breaks up surface thermal boundary layers, which enhances heat transfer.*

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very cold. That is because the higher velocity wind has a higher convective coefficient, and thus removes heat more effectively from your skin. In SMT reflow applications, increasing the velocity of the flow also improves the amount of convection heat transfer. There are practical limits to this, as too high of velocity may cause components to shift around. The flow direction also has a significant impact on “Q”. Parallel flow convection is shown below:



Note that in the parallel flow diagram, there is an area referred to as the “boundary layer”. In the boundary layer, there is no flow motion, which causes convective heat transfer to be very low. It is beneficial to break up the boundary layer to allow the flow to transfer heat freely to the object. The diagram shown below shows perpendicular flow convection:



In the diagram showing perpendicular flow, note that there is no boundary layer. This is the reason that perpendicular flow yields better convective heating or cooling results.

## WHAT ARE THE BENEFITS OF IR? ... CONVECTION?

In SMT reflow applications, there is no such thing as *pure convection* or *pure IR*. The only way to achieve a 100% convection system would be to have gas flowing over the product with no chamber walls. Of course this is not practical. To have a 100% IR system, the chamber would need to be operated in a vacuum. Again, this is not the case. However, some systems are more dominated by convection, while others utilize IR as the primary heat source. For the sake of simplicity this text will refer to a convection dominated machine as a convection machine, and an IR dominated machine as an IR machine.

### CONVECTION

Both convection and IR have their unique advantages and limitations. In convective systems, typically the temperature of the flow is close to the desired temperature of the product in a given zone. This has the advantage in that the product temperature will never exceed the gas flow temperature. This is useful when heating a product that has a large difference in the mass of the components and distribution. In this case, the larger components will continue to heat, while the smaller components will not overheat. Convection heat transfer is not thermally efficient. Air (or nitrogen) has a very low heat capacity, which means that high volumes of flow may be required to transfer the heat. One way to improve efficiency and reduce the amount of process gas required

is through the use of recirculation. In a recirculation loop, the process gas from a zone is evacuated, then reheated and re-input into the heating chamber. The limitation to recirculating is that high nitrogen purity levels are not typically attainable. There is also a concern that if the gas is recirculated excessively, it may affect soldering quality, as the atmosphere surrounding the product becomes contaminated with process by-products. Convection increases the chance of solder wicking, as typically the lead is heated faster than the circuit board.

### IR

IR systems have the distinct advantage of high heating efficiencies and low process gas flows required to reflow solder. IR systems are normally very repeatable, and have the capability to transfer high quantities of heat as needed. This becomes quite useful when reflowing very dense SMT assemblies or very heavy boards. The limitation with IR is that a high temperature differential between the source and the product is required to transfer the heat. Products with high component mass differential do not heat uniformly. They must be run quite slowly to accomplish reflow. IR systems are successful at reflowing products with component sizes up to and including 84 pin PLCC's. Large connectors and pin grid arrays are quite difficult to reflow on an IR dominated system.

CONVECTION		IR	
+	Less sensitive to shading	+	Control source temperature only
	Heats more uniformly		High efficiency (60–70%)
	$\Delta T$ (Source-target) is small		Easy to control rate of rise
—	Low thermal mass of air requires high flow rates to transfer heat	—	More sensitive to shading
	Inefficient (20 to 30%)		Less uniform high mass differences
	Will heat leads first, increasing chance of solder wicking.		$\Delta T$ (Source-target) is large

## WHAT ARE THE BENEFITS OF A NITROGEN ATMOSPHERE?

Reflow soldering in a nitrogen atmosphere is becoming a significant process consideration. The issue is really not the ability to reflow in nitrogen, but rather the ability to reflow in the absence of oxygen. Heating solder in the presence of oxygen will create oxides, which are generally non-solderable surfaces. In past days of reflow soldering, the solder paste consisted of aggressive enough fluxes to remove oxides during the reflow process. The future trend is moving away from strong fluxes in the paste. The future trends include two major process changes that are driving the need for reflow in nitrogen atmospheres; fine pitch soldering and no-clean fluxes.

### FINE PITCH REFLOW SOLDERING

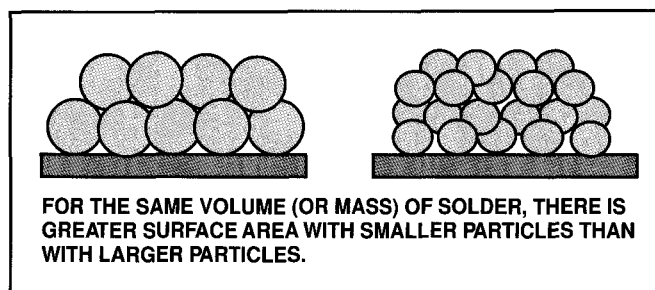
Fine pitch soldering presents many challenges. In order to obtain satisfactory paste print definition, the particle sizes of tin and lead are becoming smaller. As the particles become smaller, the ratio of surface area to volume of the particles increases. This can be shown by:

$$\text{RATIO} = (\pi \times D^2) / (1/6 \times \pi \times D^3)$$

$$\text{RATIO} = 6 / D$$

**WHERE:**

D = Particle Diameter



Thus, as particles sizes decrease, the ratio increases. With more available surface area in the solder paste, there is a greater tendency towards oxidation. Keep in mind that oxidation is a function of the metals involved, the temperatures of the metal, the exposed surface area, and the amount of oxygen present. The only variable that one can control is the amount of oxygen present. This can only be done through proper oven design.

### NO-CLEAN SOLDERING

The second technology change that is driving the need towards nitrogen atmospheres is the greater usage of no-clean pastes. The rapid trend away from solvent cleaning is creating this and other needs. No-clean soldering requires a tight control of the process. All of the components and boards must be highly solderable. The reflow process must not add any significant oxidation to the process. The fluxes used are very weak, and do not have aggressive oxide cleaning action. In addition, there is no cleaning that would remove any solder balls from the product. These solder balls eventually can create short circuits on the product if they are not removed. Reflowing in a high purity nitrogen environment reduces the possibility of creating solder balls.

A good question to ask is "How pure a nitrogen environment is required?" A recent study<sup>(4)</sup> by Colin Lea of the National Physics Laboratory in the United Kingdom was conducted to determine the affect of nitrogen purity on the process. The conclusions drawn in the study are listed below:

DESCRIPTION	PURITY LEVEL
Significant reduction in board discoloration	10,000 ppm
Ease of cleaning flux residues (RMA)	500 ppm
Reduction in solder balling (RMA)	200 ppm
Reflow of low-residue solder paste	< 100 ppm

The paper presents a number of excellent graphs that show the affect of nitrogen purity on parameters including flux spread, wetting force, wetting time, solder balls, cleaning, residue, board discoloration, and micro-structure. It is recommended reading if your process may require the use of nitrogen. You must determine the nitrogen requirements for your process. The benefits of using nitrogen definitely exist, however you must determine if the additional cost of nitrogen is worthwhile for your process.

## SECTION II – EQUIPMENT SELECTION

### WHAT ARE THE STEPS IN THE SELECTION PROCESS?

When selecting reflow equipment, it is important to take into consideration all aspects that may affect the process and production. Try to avoid becoming too focussed on one issue, such as populated uniformity, as it may not lead you to the optimum decision. The recommended steps in the selection process are described in the following paragraphs.

#### DEFINE PROCESS BAND WIDTH

The first step is to define the acceptable process profile band width for your SMT assemblies. Try to be as accurate as possible when defining the band. If the band is too restrictive, some aspect of production will be negatively affected. If the band is too loose, a defect will show up in the process. The band width should be defined as a range of temperatures (°C) that the entire profile must fall within. Refer to page 4 for a more detailed description.

#### DEFINE HEATING NON-UNIFORMITIES

The next step is to define causes of heating non-uniformities that may occur in the process. These non-uniformities are caused by mass differential, oven uniformity, and oven repeatability under production loading conditions. A set of tests must be conducted with the desired product on the oven in question. The sum of the non-uniformities (°C) must be less than the profile band width defined in the first step. Refer to page 5 for a more detailed description.

#### SIZE THE OVEN PROPERLY

The oven must be sized to handle the production rate of the pick-and-place equipment. The calculation is shown below:

$$\text{LINE SPEED (MINIMUM)} = \frac{\text{BOARDS PER MINUTE X LENGTH PER BOARD}}{\text{LOAD FACTOR}}$$

Operating at a conveyor speed greater than the calculated speed ensures that no product jams will occur on the onload area of the reflow oven.

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*Try to avoid becoming too focussed on one issue, such as populated uniformity, as it may not lead you to the optimum decision.*

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In order for the oven to be properly sized, the process speed defined below must be greater than the minimum calculated line speed. This will ensure that bottlenecks will not occur at the reflow oven. The process speed should be determined through testing or by the following equation:

$$\text{PROCESS SPEED} = \frac{\text{OVEN CHAMBER HEATED LENGTH}}{\text{PROCESS DWELL TIME}}$$

#### DEFINE PROCESS GAS

If a nitrogen atmosphere is required for solderability or no-clean processing (see page 10), one needs to consider the purity required and the gas consumption. Be careful how the purity is measured, such that it is not measured at the gas inlet.

#### REVIEW CONVEYOR DESIGN

The conveying mechanism is perhaps the most overlooked aspect of equipment selection. One needs to define whether a mesh conveyor or an edge type is required. Typically edge conveyors are used for in-line processing or if double-sided assembly is required. The most important issue with edge conveyors is the ability for the conveyor to remain straight to avoid dropping product.

#### RELIABILITY/SERVICEABILITY

Once a machine is placed into service, it is critical that it remains operational. Evaluate the product design from a structural as well as a functional standpoint. Is the oven designed to withstand the rigors of production? Review the product manuals, drawings, and spare parts lists. Find out where the nearest servicing center is located. Is training available? These are the questions that must be asked during the selection process.

#### INTERFACING REQUIREMENTS

Conveyor and control interfacing requirements may also be an important selection issue. Make sure that the edge conveyor fixed rail justification is the same as the pick-and-place equipment. Ask questions about networking machines to a host and product flow control schemes if needed.

## HOW CAN YOU EVALUATE COSTS?

The selection steps listed on the previous page should all be considered when comparing equipment. When multiple ovens pass the selection criteria listed, then a proper cost evaluation may be used to compare ovens. This is especially important when comparing ovens that utilize different heating technologies, as first cost and operating costs can be significantly different. This section describes various costs that may be included in the analysis.

### EQUIPMENT COST

Often, the initial cost of the equipment is the only cost considered when comparing equipment. It is certainly important, although it is only a part of the total cost picture. To make a fair comparison, all costs should be analyzed with a common basis, such as annual cost. As an example let's look at a machine that costs \$50,000 and has an expected life of 5 years, with an interest rate of 10%. Assume the value of the equipment is zero at the end of five years. The annualized cost of the equipment is equal to the initial cost times the Capital Recover Factor.<sup>(5)</sup> For an interest rate of 10% with a period of 5 years, the CRF value is equal to 0.2638. The annualized cost is then equal to:

$$\begin{aligned}\text{Annual Cost} &= \$50,000 \times 0.2638 \\ &= \$13,190\end{aligned}$$

### OPERATING COST

The operating cost needs to include the electrical power to operate the machine and also the cost of any process gases (such as nitrogen). If there are other pertinent operating costs, include them in this analysis.

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*When multiple ovens pass the selection criteria listed, then a proper cost evaluation may be used to compare ovens.*

*The importance of factoring in operating costs should be noted.*

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### MAINTENANCE AND SPARE PARTS COSTS

The maintenance and spare parts costs should be included in the analysis. This may be the most difficult to predict, but it should be included.

### SUMMARY

An example of an annual cost analysis is shown in the table below, comparing a convection (hot gas) machine to an IR machine. The values used are not specific to any vendor's equipment or products, merely typical values from the market. The total annual estimated costs reveal the importance of including the operational costs in the analysis.

DESCRIPTION	HOT GAS	IR
GAS USAGE	1800 CFH	1200 CFH
POWER USAGE	20 KW	12 KW
HOURS/YEAR	2080 HRS	2080 HRS
INITIAL COST	\$50,000	\$60,000
GAS COST PER 1000 CFH	\$5.00	\$5.00
POWER COST PER KW-HR	\$0.10	\$0.10
CRF (FROM ABOVE)	0.2638	0.2638
<b>COST SUMMARY</b>		
EQUIPMENT	\$13,190	\$15,828
GAS COST	\$18,720	\$12,480
POWER COST	\$ 4,160	\$ 2,496
MAINTENANCE	\$ 1,000	\$1,000
<b>TOTAL</b>	<b>\$37,070</b>	<b>\$31,804</b>

## SELECTION CRITERIA CHART

PROCESS VARIABLE	VENDOR A	VENDOR B	VENDOR C
PROCESS BAND WIDTH REQUIRED (°C)			
HEATING NON-UNIFORMITIES			
MASS DIFFERENTIAL (°C)			
OVEN UNIFORMITY (°C)			
REPEATABILITY (°C)			
TOTAL (°C)			
LINE SPEED REQUIRED			
MAXIMUM LOADING FACTOR			
PROCESS SPEED			
PROCESS GAS TYPE			
DRYOUT ZONE PURITY (PPM)			
REFLOW ZONE PURITY (PPM)			
PROCESS GAS FLOW			
POWER REQUIRED UNDER PRODUCTION LOAD (KW)			
CONVEYOR TYPE			
CONVEYOR STRAIGHTNESS (IF EDGE)			
CONVEYOR DIRECTION/ RAIL JUSTIFICATION			
GENERAL MACHINE QUALITY RATING (1–10)			
MANUALS AND DOCUMENTATION RATING (1–10)			
SERVICING LOCATION			
COMPUTER INTERFACE AVAILABLE			
ANNUAL COST TO OPERATE			



## CONVECTION OVEN THERMAL CONTROL

Convection oven thermal control requires tight control of two variables; temperature and flow. In order to maintain constant heat flux to the product, it is critical that both these variables are controlled. Research, Inc.'s *MICRI-FLO XG* forced convection reflow system will be used as an example. The temperature and flow control are defined specific to this system.

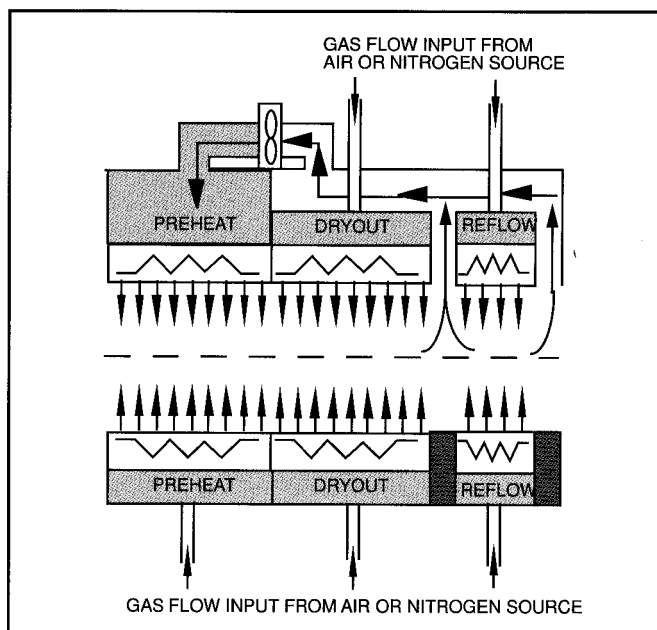
## CONVECTION OVEN DESCRIPTION

Temperature control of the system must consider both the gas and the surrounding wall temperature. Remember, even in a convection dominant heating system, the walls radiate IR energy worth about 20%–30% of the total heat flux of the system. The figure below shows the heater cavity flow diagram for the *MICRI-FLO XG*. The reflow and dryout zones each receive input gas (air or nitrogen) through a series of flow meters. This controlled flow enters a diffusion plenum behind the heating plenum to distribute the flow. The flow then enters a second plenum, where the gas is preheated by a series of heaters. The heaters consist of a wound nickel-chromium wire encased in a stainless steel jacket. The

heaters are bent in a “U” shape such that easy removal can occur from one side of the machine. The gas then enters the process chamber through an array of holes. The product is heated from a combination of the hot gas and the hot chamber surroundings. A control thermocouple is mounted in each zone to maintain cavity repeatability. A PID (Proportional – Integral – Derivative) control loop is used to maintain the cavity at constant conditions.

The flow is removed from the reflow area by two exhaust ducts located on each side of the reflow zone. This flow is pulled from the zones using a high temperature, low flow recirculating blower. The flow is pushed by the blower through the preheater plenum arrangement. The temperature control is accomplished in the same way as the dryout and reflow zone.

The flow that heats the product (in all zones) is forced through the walls in an array of holes to break up the boundary layers on the product. The perpendicular flow arrangement shown on page 8 is used to optimize heat transfer.




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*Convection oven thermal control requires tight control of two variables; temperature and flow. In order to maintain constant heat flux to the product, it is critical that both these variables are controlled.*

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## CONVECTION OVEN WITH NITROGEN ATMOSPHERE

Convection ovens are a greater challenge to inert for several reasons. First, the amount of flow that would be required to transfer 80% of the energy by convection is extremely high, and cost prohibitive. In order to minimize this, recirculation ducts are added, which result in the degradation of the purity of the source flow entering a given zone. Higher velocities and turbulent flow are also required, which can result in a greater opportunity for oxygen to enter the system. Third, the pressure in the heater cavity is positive in some areas, and negative in others. Balancing this flow becomes a difficult task. The job of inerting a convection oven is not impossible. However, it should be noted that purity levels and flow rates are less optimum than with an IR based machine.

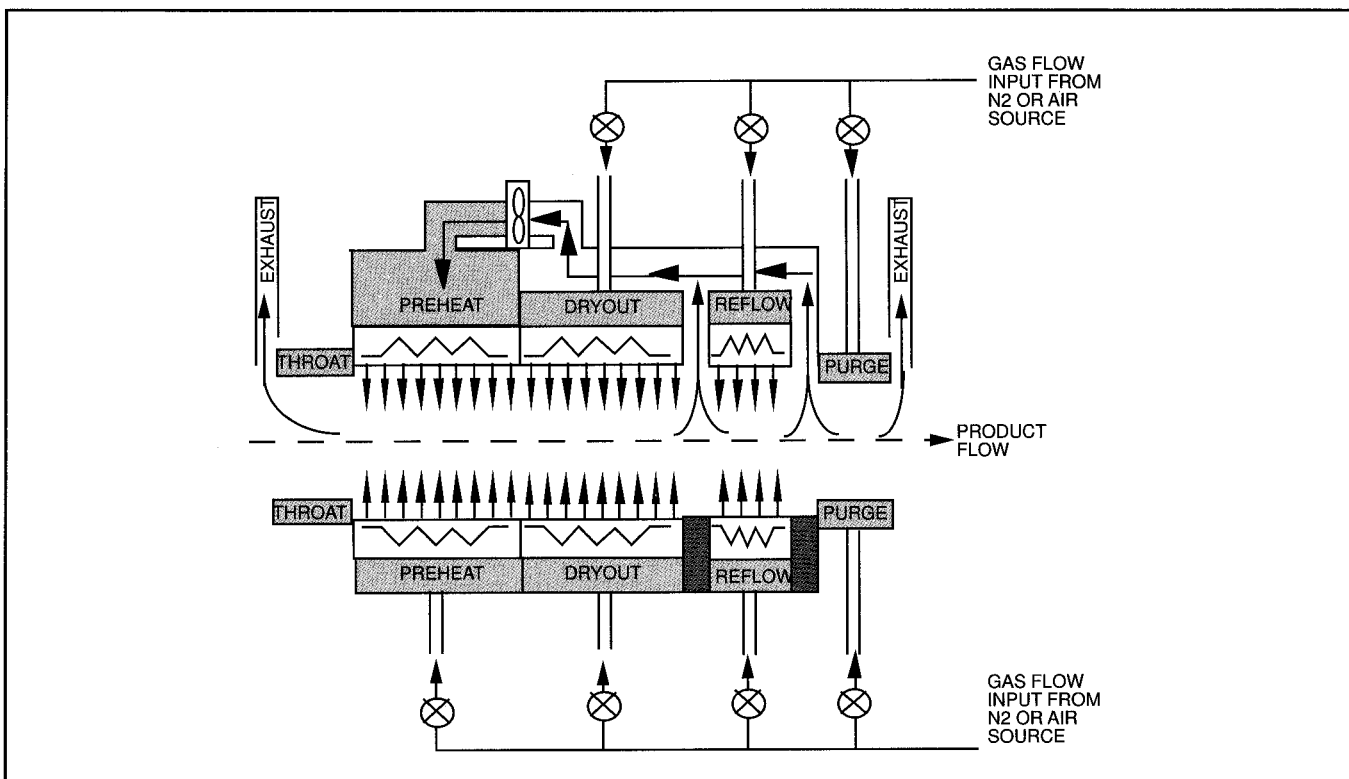
### CHAMBER DESCRIPTION

Many of the same principles apply for inerting when comparing a convection oven to an IR oven. The *MICRI-FLO XG* convection oven shown below utilizes a very similar scheme to the 4470XN IR oven. The gas is brought into each zone very uniformly using the propri-

etary gas plenum distribution system. The pressure in the entry and exit purge sections are maintained at sufficient levels to minimize oxygen infiltration. Flow meter controlled venturi exhausts are used to balance the flow in the system and to remove process volatiles.

In order to maintain the best purity levels in the zones where the product temperature is greater than 150°C, pure nitrogen is delivered to the reflow and dryout zone. This is a key point, as this ensures that the product experiences a nearly pure environment at its most critical stages (dryout and reflow). The recirculated gas from these zones is reheated and used in the preheat zone. Here, purity is not as critical, so the use of recirculated gas is not detrimental to the process.

Purity levels in the dryout and reflow zone can be maintained at 35 PPM over incoming purity levels at flow rates of 1800 cubic feet per hour (51 cubic meters per hour).



## IR/CONVECTION OVEN CLOSED LOOP CONTROL

One of the key oven performance issues is the ability to repeat a product temperature profile. Repeatability is influenced most by product loading. Heavy or non-variable loading can result in the oven incorrectly compensating, resulting in a loss of repeatability. High levels of repeatability can be achieved only if all the components of heat transfer are maintained constant.

### LAMP DEFINITION

The closed loop heat flux control method used in a Research, Inc. lamp based oven will be used as an example of one type of control. The primary heat source in this system is the tungsten filament (T3) lamp. The T3 lamp consists of a tungsten filament encased in a sealed quartz envelope. The envelope is filled with an inert gas to keep the filament from oxidizing and failing. The lamps are rated for 5000 hours when operated at 100% capacity. In SMT applications, the lamp power never exceeds 20% capacity, resulting in lamp life in excess of 20,000 hours. At typical operating setpoints of 5–15%, the heat transfer to the product is controlled such that heating rates are under 2°C/second, and the IR emission is in the medium to long wavelength range.

The greatest advantage that T3 lamps have is their rapid response capability. Within 1 to 2 seconds after a voltage change occurs, the lamp is at its new temperature equilibrium. This rapid response is ideal for closed loop control, as energy can be replaced in the heating chamber instantly after its removal.

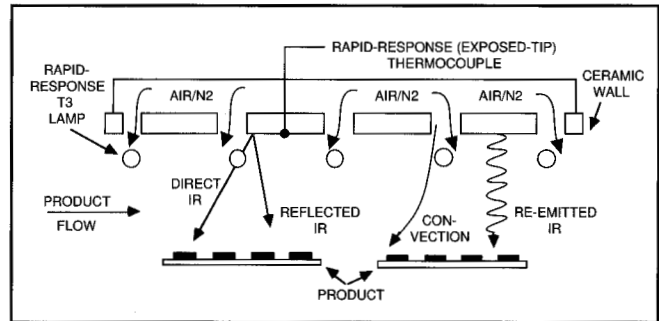
### CONTROL DEFINITION

In order for the product profile to be repeatable, the total heat flux to the product must be held constant. The total heat flux to the product is the sum of IR from the lamp and wall plus the convective component. Refer to the figure.

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*Within 1 to 2 seconds after a voltage change occurs, the lamp is at its new temperature equilibrium. This rapid response is ideal for closed loop control, as energy can be replaced in the heating chamber instantly after its removal.*

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Accurate control is not achieved by maintaining only one of the components constant, but rather the sum of all the thermal energies involved. The lamp IR component is regulated by the SCR power controlled system. The wall and convective components are collectively monitored by the bulk chamber temperature measured with a thermocouple probe. There are two reference setpoints; percent voltage for the lamp, and the bulk chamber temperature. The bulk chamber setpoint drives the equation. If the chamber is at the correct temperature, then the lamp setpoints will be at their setpoints. If the chamber is too hot, then the lamps will decrease in intensity. If the chamber is too cool, the lamps will operate at a level greater than their setpoint. The lamp power is modified only enough to compensate for the bulk chamber heat transfer deviation. In doing so, the total heat flux to the product is maintained. The correct compensation will occur providing the bulk chamber temperature is within  $\pm 25^{\circ}\text{C}$ . Product temperature repeatability of  $\pm 2.5^{\circ}\text{C}$  will occur if the bulk chamber is within this defined band.

The ability to operate within this wide band has two significant advantages. The first is that the oven may be loaded down to levels up to 80% load. The second is that profile changeover times are reduced significantly. Loading may begin when all oven temperatures are within  $\pm 25^{\circ}\text{C}$  of setpoint. This requires far less time to achieve the "ready" state than if the "ready" process window was  $\pm 3^{\circ}\text{C}$ , which is often the case in reflow oven operation. Warm-up times of less than 15 minutes occur. Profile changeover times are 3 to 5 minutes for profile increases of under  $40^{\circ}\text{C}$ , and under 10 minutes for profile decreases of under  $40^{\circ}\text{C}$ . Even in the worst case of going from a reflow profile to an adhesive cure profile, the changeover time is under 15 minutes.

## IR/CONVECTION OVEN WITH NITROGEN ATMOSPHERE

Infrared ovens do not require high quantities of flow to accomplish reflow. The predominant heat transfer occurs with IR, which does not require any flow to transfer the heat. The flow in the oven is used to provide some of the benefits of convection, which includes improving populated board uniformity and volatile removal. The amount of flow in the oven is more related to the quantity required to accomplish a high purity nitrogen environment, which is considerably less than in the case of a convection oven.

### NITROGEN OVEN DESCRIPTION

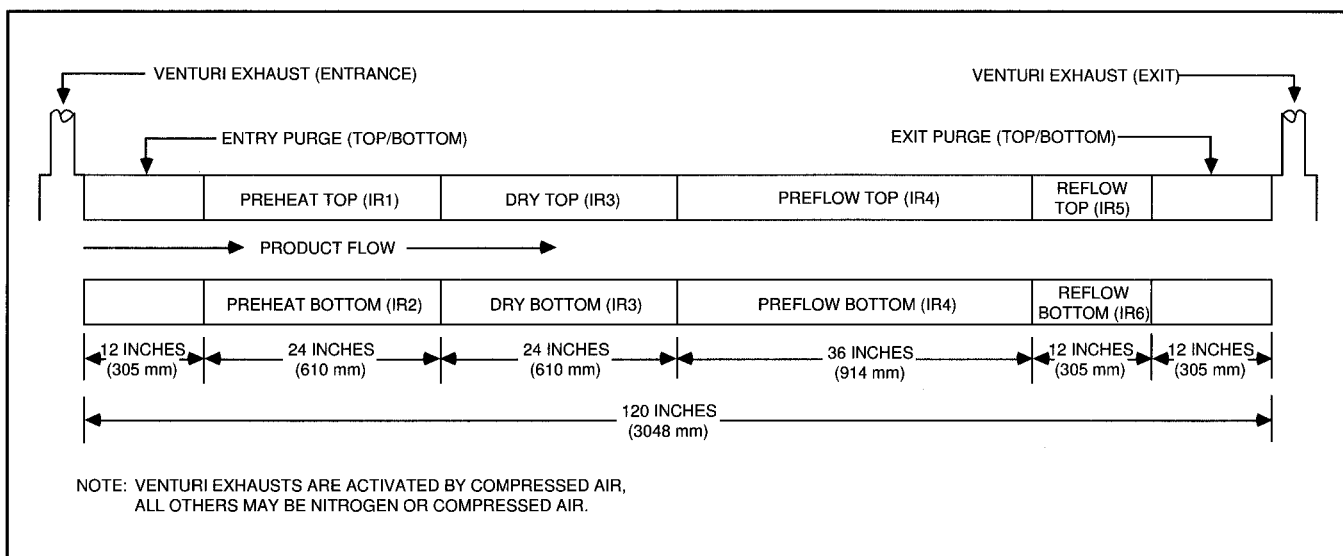
The 4470XN from Research, Inc. is an example of an IR dominant oven that provides a high purity nitrogen environment at low flow levels. The system uses a proprietary gas flow distribution method through the chamber walls to uniformly blanket the chamber with the process nitrogen. A slight positive pressure inside the chamber helps minimize external room effects and helps keep oxygen out of the chamber. Entry and exit purge sections are present to provide a nitrogen curtain at the chamber entrance and exit, which also assists in keeping oxygen out of the chamber. Flow meter controlled venturi exhausts are used to balance the flow in the system and to remove process volatiles.

The gas system is non-recirculatory, in that the gas is used once and then expended. This has the advantage that process contaminants are not recirculated which helps maintain high nitrogen purity levels. The heat chamber is accessible by unfastening six clamps and elevating the top heater vertically through the use of a crank mechanism. Purity levels of 20 PPM (over incoming purity level) are attainable in all heating zones. Flow rates are in the 1200 to 1600 cubic feet per hour (34 to 45 cubic meters per hour) range. Machines in the field are experiencing total purity levels of 10–15 PPM (including incoming) at flow rates of 1300 cubic feet per hour (37 cubic meters per hour). These purity levels are measured with the machine fully loaded with product.

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*The amount of flow in the oven is more related to the quantity required to accomplish a high purity nitrogen environment, which is considerably less than in the case of a convection oven.*

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## EDGE CONVEYOR

Proper design of the edge conveying system is critical, as typically only 0.17 inches (4 mm) is in contact with the bottom side edges of the product. If the conveyor has lateral warpage of greater than this amount, the product will fall into the oven. Thus, edge conveyor straightness is a key issue in SMT processing.

As the conveyor rails heat during the machine warm-up period, they will grow and tend to warp. The patented system from Research, Inc. shown below tensions the rails, which pulls the rail assembly straight. The lever (outlined in dark) is attached to the rail. The bottom side of the lever is attached to an adjustable spring mechanism that runs from end to end in the machine. Approximately 1500 lbs (681 kg) of tensioning force is applied to each

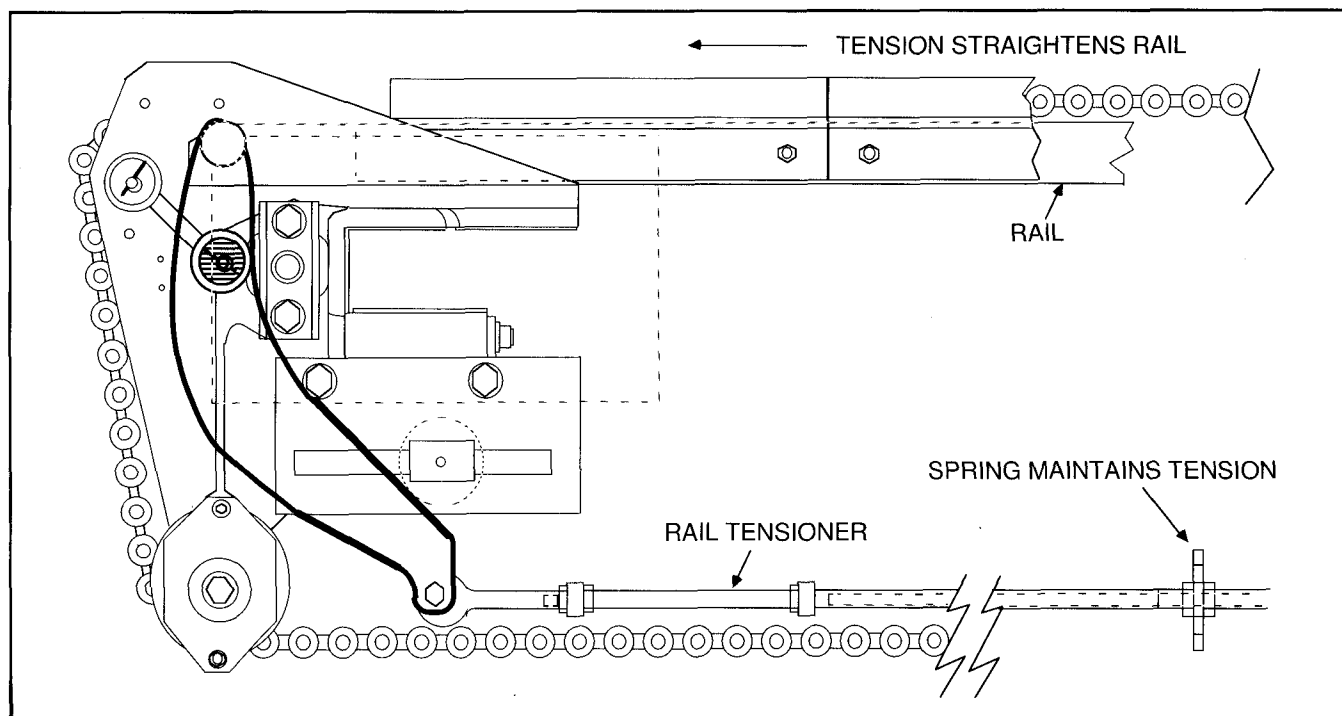
rail to maintain straightness. The machine frame is made of welded structural tubing in order to maintain its structural integrity.

The use of the tensioning system allows the mass of the rails to be maintained at a reasonably low value, which minimizes the thermal affect of the rail on the product.

---

*As the conveyor rails heat during the machine warm-up period, they will grow and tend to warp. The patented system from Research, Inc. shown below tensions the rails, which pulls the rail assembly straight.*

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## REFERENCES

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2. "Radiation Plus Convection: The Total Solution", Norman R. Cox, Research Inc., U.S.A., NEPCON West 1990.
3. "Optimization of Solder Reflow with IR", Norman R. Cox, Research, Inc., U.S.A., ISHM 1985.
4. "Inert IR Reflow: The Significance of Oxygen Concentration in the Atmosphere", Colin Lea, National Physics Laboratory, Teddington, U.K., Surface Mount International, 1991.
5. Managerial and Engineering Economy, George A. Taylor, D. Van Nostrand Company, © 1975 by Litton Educational Publishing, Inc., page 31.

## PRODUCT MATRIX

FEATURE	4440	4470MP	4470XP	4470HP	4470XN	4470HN	4480XG
<b>PROCESS AREA</b> STD LENGTH IN OPT LENGTH IN	36 N/A	36 N/A	96 120	114 138	96 N/A	148 N/A	96 N/A
STD LENGTH MM OPT LENGTH MM	914	914	2438 3048	2895 3505	2438	3759	2438
<b>PROCESS SPEED</b> STD LENGTH IN/MIN OPT LENGTH IN/MIN	9-12	9-12	24-32 30-40	30-40 36-48	24-32	36-50	24-32
STD LENGTH CM/MIN OPT LENGTH CM/MIN	20-30	20-30	60-80 76-102	70-100 90-120	60-80	90-130	60-80
<b>HEATER TECHNOLOGY</b> FORCED CONVECTION IR/CONVECTION	X	X	X	X	X	X	X
<b>PROCESS GAS</b> AIR HIGH PURITY N <sub>2</sub>	X	X	X	X	X X	X X	X X
<b>CONVEYOR TYPE</b> EDGE MESH DUAL (EDGE/MESH)	N/A STD N/A	STD N/A N/A	STD OPT OPT	STD N/A N/A	STD OPT OPT	STD N/A N/A	STD OPT OPT
<b>CONTROLLER</b> MICROPROCESSOR HOST INTERFACE	X X	X X	X X	X X	X X	X X	X X
<b>DIMENSIONS</b> LENGTH IN WIDTH IN	90 50	90 47	168 45	222 45	168 45	222 45	168 45
LENGTH MM WIDTH MM	2286 1258	2286 1194	4274 1143	5639 1143	4274 1143	5639 1143	4274 1143
<b>VOLTAGES</b> 200V, 3PHASE, 50 HZ 208V, 3PHASE, 60 HZ 380V, 3PHASE, 50 HZ 415V, 3PHASE, 50 HZ 480V, 3PHASE, 60 HZ (AVAILABLE ON ALL MODELS)							

\* Add 36 inches (914 mm) to overall machine length for Dual Conveyor Extension Option.





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