Cool It! Quickly Take Your Oven from Lead-Free to Leaded

Jeffrey Baxter
Tektronix, Inc.
Beaverton, Oregon

Abstract
Mixed leaded and lead-free processing requires that reflow ovens change temperature. Cooling a modern oven can take a long time, even longer than an older oven because modern ovens are more insulated. We recently acquired new ovens and needed a method to cool them quickly. We analyzed two methods, a method of letting the oven cool without intervention, and a method of running aluminum heat sinks through the oven. Other methods, such as opening the oven or injecting liquid nitrogen, are also considered, but no analysis was performed on these methods.

Introduction
Heat transfer occurs when two bodies of dissimilar temperature are in proximity with each other. The second law of thermodynamics dictates that thermal energy is transferred to the cooler body. Heat transfer can only occur through conduction, convection or radiation. Heat transfer to a substance that experiences a phase change can be modeled as a convection problem. Heat transfer can also be accomplished by altering the physical makeup of a body. For example, the average temperature of a body can be increased by adding mass of a higher temperature to the original mass. This is called mass transfer. All of these methods of heat transfer have been routinely employed for soldering. For example, conduction and mass transfer are the heating methods used when wave soldering. Infrared soldering equipment emits radiation to heat a solder joint and most modern reflow ovens use convection to heat solder joints.

In convection reflow soldering, circuit boards are heated through gaseous convection, using air or nitrogen as the heat transfer medium. The heat transfer associated with the radiation emitted by the internal surfaces of a reflow oven is assumed to be negligible compared to the convection heat transfer. None the less, the internal surfaces of the oven do emit radiation because of their elevated temperature. The internal surfaces also store thermal energy, just as the gas inside the oven does. To cool the oven this thermal energy must be removed from both the hot oven surfaces, and the gas inside the oven.

The three methods of heat transfer have been used successfully to create solder joints. There is another heat transfer problem that plagues modern high-mix low-volume manufactures who manufacture using lead and lead-free solders. Manufacturing is not advisable in a reflow oven that is cooling or heating. This temperature variation is required when switching from a lead-free solder to a leaded solder. This is valuable manufacturing time lost waiting for heat transfer to occur. Modern reflow ovens can heat very quickly because of their high-power heaters. Most modern reflow ovens insulate the reflow environment from the ambient better than older ovens, making them more efficient and more challenging to cool. This increase in insulation results in less heat transfer to the ambient air through convection because the outside surfaces of the oven are cooler. This equates to longer cooling times.

This paper will explore various methods of cooling a reflow oven and propose several for further investigation.

Analysis
For this analysis two very different control volumes were drawn. The first control volume extended to just outside the oven. This included all the air in the reflow oven, its hot internal surfaces and the insulation around those surfaces. This control volume has energy input equal to the electrical current times the voltage, and it has energy output equal to the convection losses to the ambient environment. This control volume is denoted in Figure 1 with a heavy dashed line.

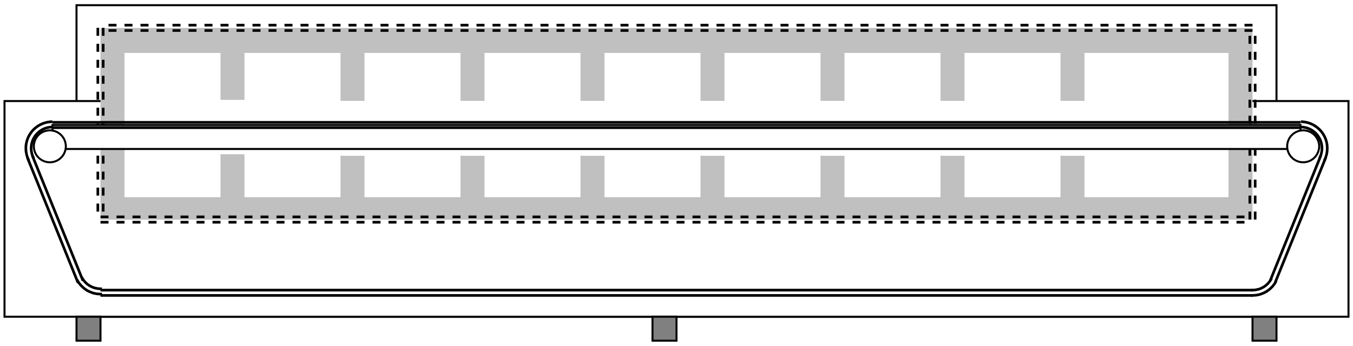


Figure 1- Large control volume

The second control volume was actually a set of control volumes, one for each heating zone in the oven. Each zone had its own energy input from an electrical source, convection transfer through the insulation, convection transfer to neighboring zones and mass transfer from neighboring zones. These zones are depicted in Figure 2 with a heavy dashed line.

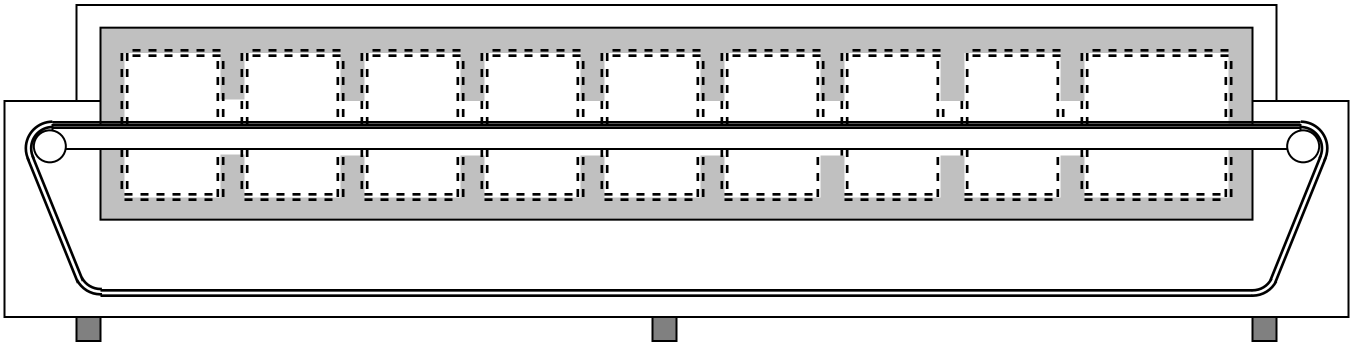


Figure 2- Individual heating zone control volumes

Cooling a reflow oven is a term that we used to mean that all the zones were individually cooled at least to their low-temperature set points. If all of the zones of a reflow oven are cooled except one, the oven cannot manufacture product. All of the zones must be cooled to their low-temperature set points.

The first control volume was much simpler to analyze and gave values that neglect the heat transfer from zone to zone. We assumed that this would be sufficient for this analysis because our oven literature indicated that the zones are relatively well insulated from each other.

With the model set up we began taking measurements to determine the magnitude of the problem. This was accomplished by measuring the power that it took to heat the oven from leaded to lead-free. This heating from leaded to lead-free constitutes a heating cycle, and the opposite process is called a cooling cycle. We attached an electrical current probe to the input power of our oven and measured the current during a usual heating cycle. The energy required to heat the oven is the integral of the power consumption during a heating cycle. The plot of the current draw during a heating cycle is illustrated in Figure 3. The equation used to calculate the input heat energy was Equation 1.

$$Energy_{in,total} = \int_{BeginHeatCycle}^{EndHeatCyde} (Voltage_{RMS-3ph} * Current_{RMS} * 1.73)dt$$

Equation 1- Energy Equation

The 1.73 in Equation 1 is a multiplier for three phase power. Our oven used about 11,800 kilojoules to heat up. This is the minimum amount of energy that would have to be removed from the oven to cool it back to its starting temperatures. 11,800 kilojoules represents the transient energy input to get the oven to its new operating condition. Once the transient current spike had past, the quiescent current draw was 17 amps at 480V three phase. This means that the oven uses 14.1 kilowatts of power to maintain those temperatures. This power was lost as heat flux through the insulation.

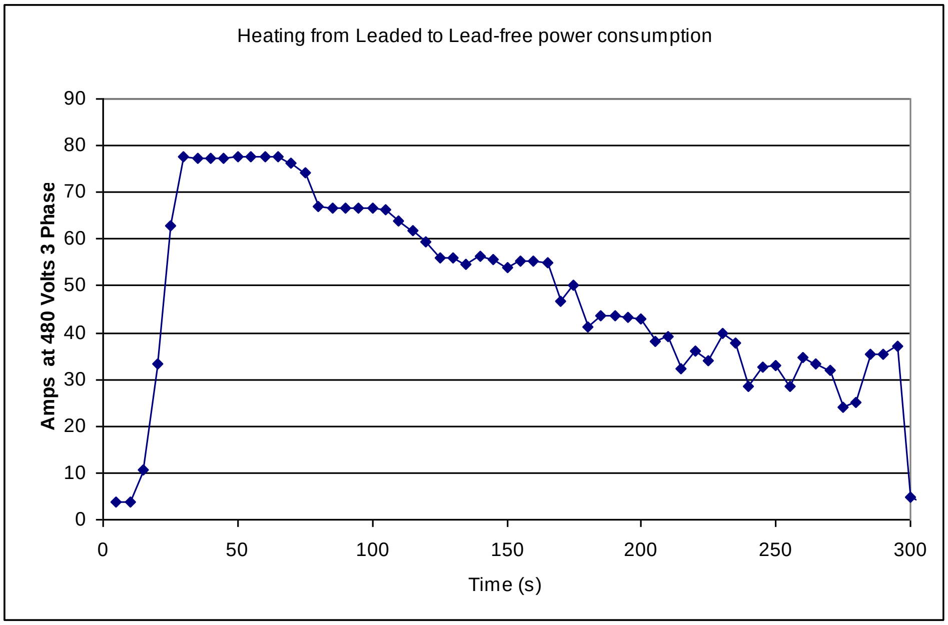


Figure 3 - RMS current during heating

With these numbers in hand we estimated the amount of energy that had to be removed from the oven. For example, if a cooling cycle were to take 10 minutes there would be 11,800 kilojoules to remove from the oven, 847 kilojoules would be lost to natural convection each minute during the 10 minutes of the cooling cycle, resulting in 3,300 kilojoules of heat left in the oven still to be removed. Ten minutes of natural convection losses would not be enough to return the oven to the energy state that it was in before it was heated with 11,800 kilojoules of energy. In order to remove the heat as quickly as possible we considered using other methods of heat transfer.

Conduction

To remove the heat by conduction we would have to bring some cooler part of the oven in contact with the hot parts of the oven. For example, if there were large cold metal bars outside of the oven that we could put inside the oven in contact with the hot surfaces on the inside of the oven, heat transfer would occur. This method was ruled out because transporting such bars would be cumbersome and potentially dangerous. They would also not cool the air in the oven directly, but would cool the metal surfaces in the oven that would in turn cool the air in the oven.

Radiation

The radiation given off by the hot surfaces of the oven is small compared to the energy stored in them. It would take a long time to transfer the heat out of the oven by radiation alone. It would also be technically difficult to construct something that can absorb radiation with out also exhibiting convection heat transfer.

Natural Convection

The natural convection method had two distinct advantages. First, it required no operator intervention. Second, it did not expose the oven to the large temperature fluctuations characteristic of other cooling methods. It had one major disadvantage – it was slow. In this case it was important to use the individual heating zone control volume analysis instead of the large control volume analysis. Using the large control volume analysis predicted that it would only take 14 minutes to cool the oven. Remember that this neglects mass and convection transfer between zones. Using the more accurate model, the individual heating zone control volume analysis, reminded us that as the oven was slowly losing heat through convection it was also coming to thermal equilibrium. 11,800 kilojoules of thermal energy could be removed in 14 minutes, but not from the right zones. For example, the hottest zones had greater heat convection heat transfer, and lost heat more rapidly than the cool zones. At the end of the 14 minute natural convection cooling cycle the hot zones were below their set points and the cool zones were still above their set points. It took 52 minutes to sufficiently cool all the zones. This method was not satisfactory.

Phase-Change Convection

In phase-change convection a material is exposed to heat and allowed to experience a phase change. When a material changes phases it often absorbs a large amount of heat without changing temperature. For example, heat could be transferred to liquid nitrogen that is introduced into the oven. It would then be allowed to vaporize, absorbing heat. This method would be particularly expensive because of the mechanics of piping and controlling liquid nitrogen, but has the potential to cool an oven extremely quickly. Similarly, a liquid other than nitrogen, like water, could be introduced. This too would be allowed to vaporize, absorbing heat. This option would be detrimental to the quality of the manufactured product because it would create a high-humidity environment. Also, the life of the oven would be reduced due to the steam environment. Neither of these convection methods was financially justifiable.

Mass transfer and convection

Opening the oven to allow heat and mass transfer has several disadvantages, and one advantage. This method exposes operators to a burn risk, a toxic fume inhalation risk, a risk of breathing oxygen deficient air (if nitrogen processing is used), and a risk of bodily harm as the oven closes. Routine opening and closing of the oven may expose the oven to more mechanical exercise than it was designed to handle. Opening the oven also does not cool it uniformly. Our oven opens like a clam-shell; one side of the oven is hinged, and the other opens. The part of the oven furthest from the ambient air will have the least convection, and will stay the hottest. This will introduce a temperature gradient across the width of the oven. The main advantage of opening the oven is that it is fast. Opening the oven can dissipate a lot of heat.

Because of the safety and wear concerns, this method for cooling the oven was not financially justifiable.

Storing heat energy in aluminum heat sinks was the next alternative. The head sinks would be introduced into the oven cold, and retrieved hot, at the exit of the oven. We wanted to maximize the heat transfer to the heat sinks, with the minimum weight, cost, and processing time. The constraints we decided upon were that each heat sink (more than one would be used to cool the oven) could not weigh more than 4.5 kilograms or cost more than 100 dollars.

The first design was lined with fins that would have been machined into a block of aluminum. The fins were optimized for machining time and material cost. The design is illustrated in Figure 4. It was a 412 mm square heat sink with fins on both sides and featured easy-grip handles. It was designed with a 6.35 mm gap between fins. The heat sink was designed assuming machining would begin with a 25.4 mm thick heat sink.

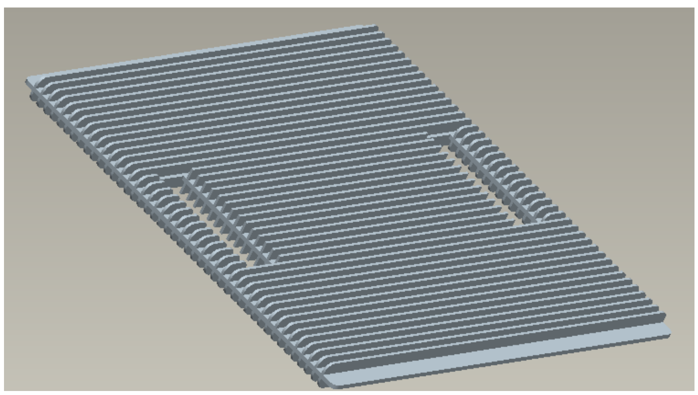


Figure 4- First version of the heat sink

Calculating the overall efficiency of the fin array was accomplished using some simple heat transfer equations. The overall effectiveness of the fin array is the primary factor that determines the effectiveness of using this method to cool the reflow oven. The overall effectiveness of a fin array is defined in Equation 2. In Equation 2 'h' is the convection coefficient, 'A_{unfin}' is the area of the base of the fin array that is not covered by fins, 'A_{fin}' is the area of the fin sides and tips, 'A_{nofin}' is the area of the base, 'η_{fin}' is the fin efficiency, 'T_b' is the temperature of the base of the fin array, and 'T_∞' is the ambient air temperature.

$$\varepsilon_{fin,overall} = \frac{\dot{Q}_{Total,\,fin}}{\dot{Q}_{Total,nofin}} = \frac{h(A_{unfin} + \eta_{fin} A_{fin})(T_b - T_\infty)}{hA_{nofin}(T_b - T_\infty)}$$

Equation 2 - Overall fin efficiency

Since the air temperature of the reflow oven varied as the heat sinks ran through the oven it was necessary to use an incremental approximation method to calculate the temperature of the fin array. This model uses an approach similar to a Riemann sum approximation of an integral. A heating cycle was divided up into very small time increments. The base temperature was calculated using the base temperature from the previous time step and measured the air temperature for that time step. The initial conditions were set as a starting point for the simulations.

To calculate the amount of heat transfer during each time step we used Equation 3. In Equation 3 'n' is the number of fins on the fin array. By knowing the properties of aluminum and the mass of the fin array, and assuming the heat sink was heated uniformly, we calculated the temperature rise associated with each time step's heat transfer.

$$\dot{Q}_{Total,fin} = h(A_{unfin} + n\eta_{fin}A_{fin})(T_b - T_\infty)$$

Equation 3- Total heat transfer rate for a finned surface

The air flow rate from the convection fans inside our oven is relatively constant. This means that the convection coefficient h was approximately constant inside the oven. Outside the oven it is a different constant. We measured the value of the convection coefficient as 65 W/°c m^2 inside the oven and 10 W/°c m^2 outside the oven. We measured this by heating a known geometry of aluminum inside the oven and repeating this outside the oven to determine the heat transfer coefficient.

Using the numerical methods described above we were able to approximate the integral shown in Equation 4 to determine the total energy that would be transferred to the heat sink from the oven. For this initial design the heat transfer for each heat sink was 352 kilojoules. A chart of the temperature profile during a heat sink heating cycle for this design is shown in Figure 5.

$$Q_{Total} = \int_{t,BeginHeating}^{t,EndHeating} Q$$

Equation 4 - Total energy transfer

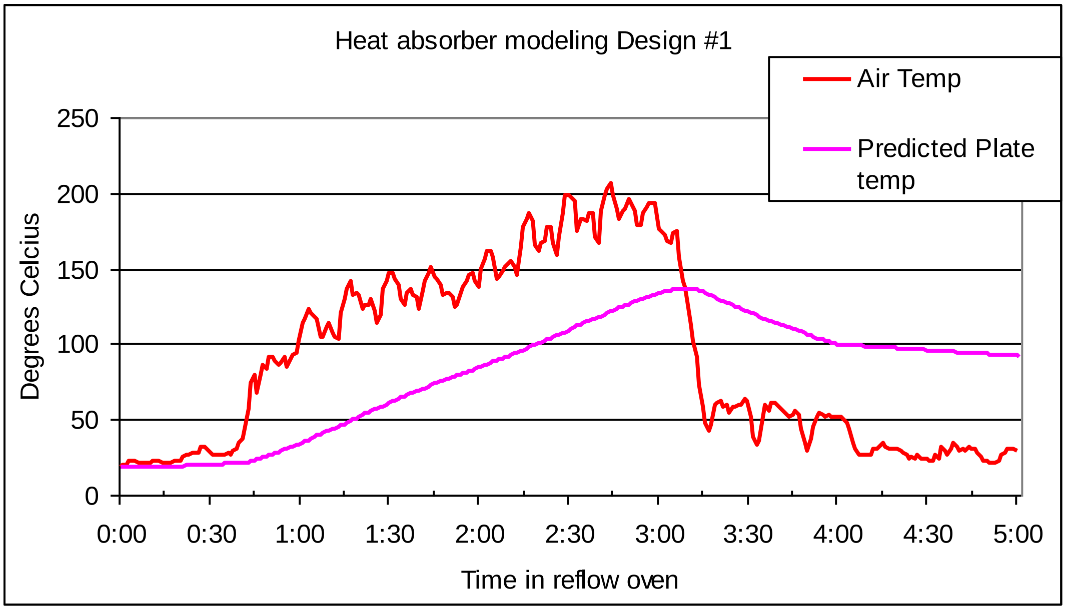


Figure 5- Design #1 temperature profile

With that information in hand, we calculated the required number of cooling heat sinks to go from lead-free to leaded. We assumed that there was a continuous loss of 14.1 kilowatts during the 10 minute heat removal process. This left 3,300 kilojoules to be removed, which would require more than 10 heat sinks.

Despite the efforts to reduce the manufacturing cost of this design it was still prohibitively expensive to machine 10 heat sinks. The next version added an easy method for mounting the heat sink to a CNC milling machine to reduce the machining costs. This is illustrated in Figure 6.

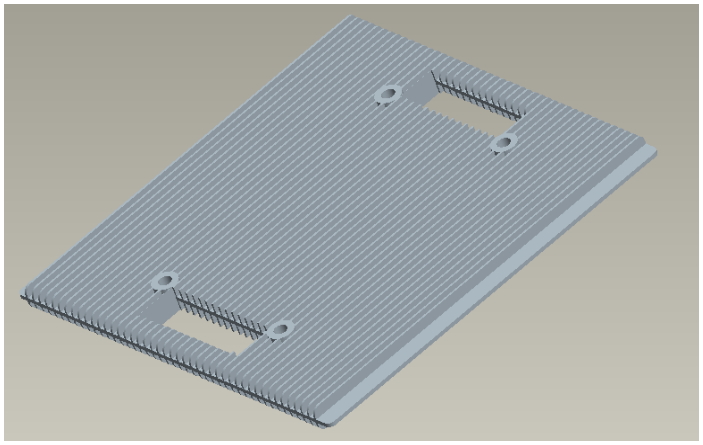


Figure 6- Version 2 of the heat sink

Upon further review, this design was still more than $100 to manufacture and not very thermally efficient.

The third aluminum heat sink design was heavily influenced by the availability of large extruded aluminum heat sink material. This design is illustrated in Figure 7.

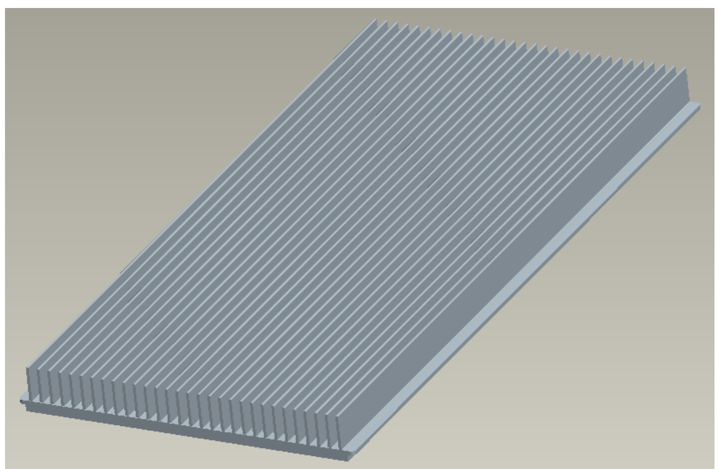


Figure 7- Version 3 of the heat sink.

This extruded heat sink heat sink was not only much cheaper, but proved to be much more thermally efficient. This was due to the shape of the fins. The thin fins (only 1.9 mm thick) allowed more of the mass of the aluminum to be placed in the base of the head sink. Since this fin array was so much more efficient fins were only required on one side of the heat sink. This design absorbed 540 kilojoules of energy, a 52% improvement over the previous designs. With this design only 7 heat sinks would be required to remove the remaining 3,300 kilojoules of heat. The heat sinks were so cheap that we could afford to order 10 of them.

This particular design also got a dull black anodized finish to improve radiation heat transfer and add to the corrosion protection and beauty of the heat sinks.

Figure 8 shows the predicted temperature rise in the version 3 heat sink. This is approximately the same temperature profile as the pervious version of the heat sink. This is commendable because the third version of the heat sink had 1.4 kilograms more aluminum in it. Being able to heat more aluminum to the same temperature for less money than any of the previous designs made this our design of choice.

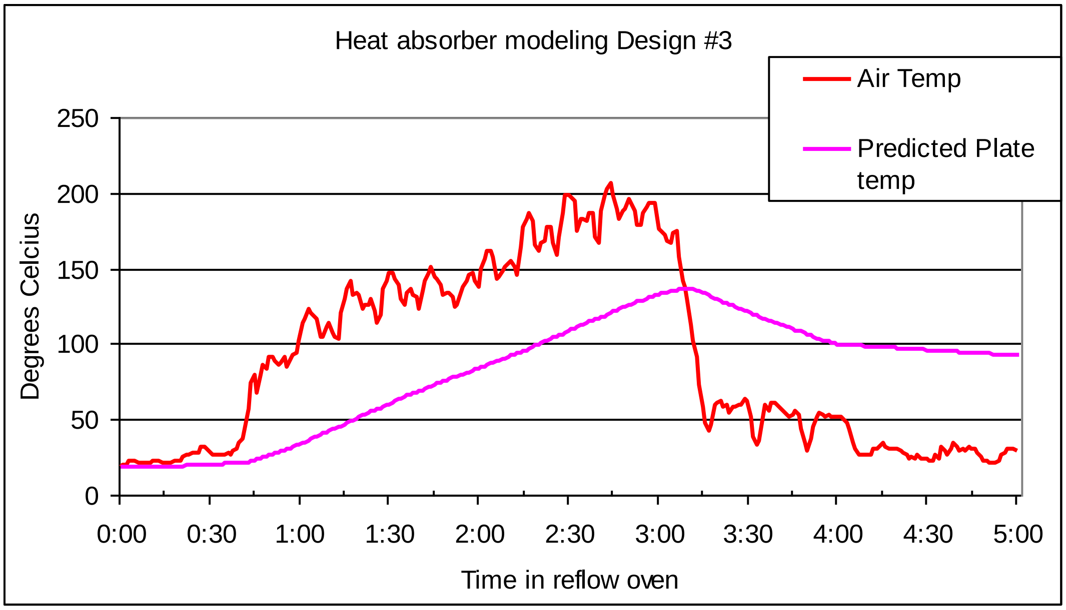


Figure 8- Design #3 temperature profile

Design Validation

After manufacturing these heat sinks we wanted to validate our assumptions and verify that each heat sink would indeed absorb 540 kilo joules of heat during a pass through the oven. We attached thermocouples to a heat sink of the third design and ran it through the reflow oven and logged the temperature data. We measured three thermocouples on the heat sink and averaged them to attain the heat sink temperature. Figure 9 shows the predicted and the measured heat sink temperatures.

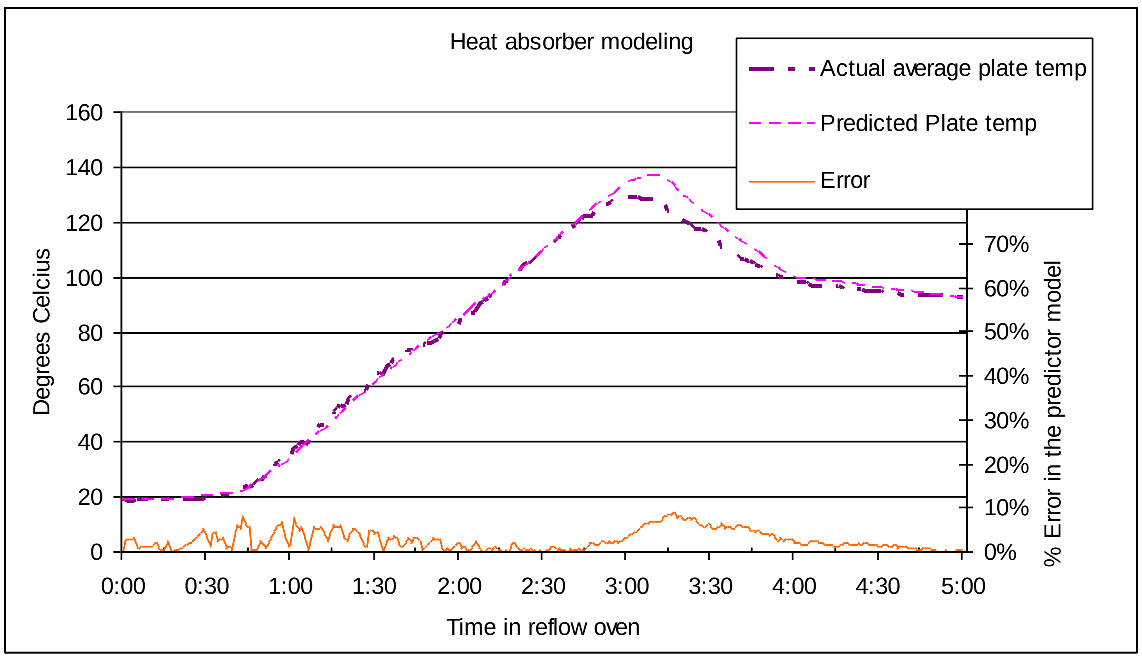


Figure 9- Validation of the predicted model

The model proved to be accurate enough to make good predictions of the temperature of the cooling heat sink. The predictor model was used for further investigations into other options, like pre-chilling the heat sinks before use. The model showed that this would not prove cost effective.

When using this design to cool the oven it exhibited a similar behavior as the natural convection method did. The cooler zones were not sufficiently cooled after passing 7 of these heat sinks through the oven. We successfully extracted 11,800 from the oven as a whole, but the cool zones were not cooled enough to be below their new set points. To fully understand this phenomenon, further analysis using the individual heating zone control volumes method should be performed. We successfully cooled the oven by simply running three more heat sinks, for a total of 10, through the oven.

Conclusion

To choose the best method to remove heat from a reflow oven, we considered many options. In our case the best option was to manufacture aluminum heat sinks to run through the oven. Our oven took 11,800 kilojoules of heat extraction to cool from lead-free temperatures to leaded temperatures. 8,460 kilojoules were lost to natural convection during the cooling process; the remaining 3,340 kilojoules of heat were removed through aluminum heat sinks. The final heat sink design could extract 540 kilojoules per heat sink. This only required 7 heat sinks to cool the oven.

The design of the heat sink made a significant impact to its efficiency. Some designs would have been more than $100 each to create and would have required more than 10 copies of the design to cool the oven.

A validation of the model was run by measuring the actual temperatures the heat sinks experienced in the oven. This showed low error between the model and the measurements during the heating of the heat sinks. The model proved useful for further decision making.

Cool it.

Take your oven quickly from lead-free to leaded

2008 – Jeff Baxter

Tektronix®

Outline

- Our oven story
- Modeling the oven
  - Lumped model
  - Individual control volumes
- The options
  - Conduction
  - Radiation
  - Convection
    - Opening the oven
    - Letting it sit
    - Passing heat sinks through it
- Model testing and validation
- Conclusions

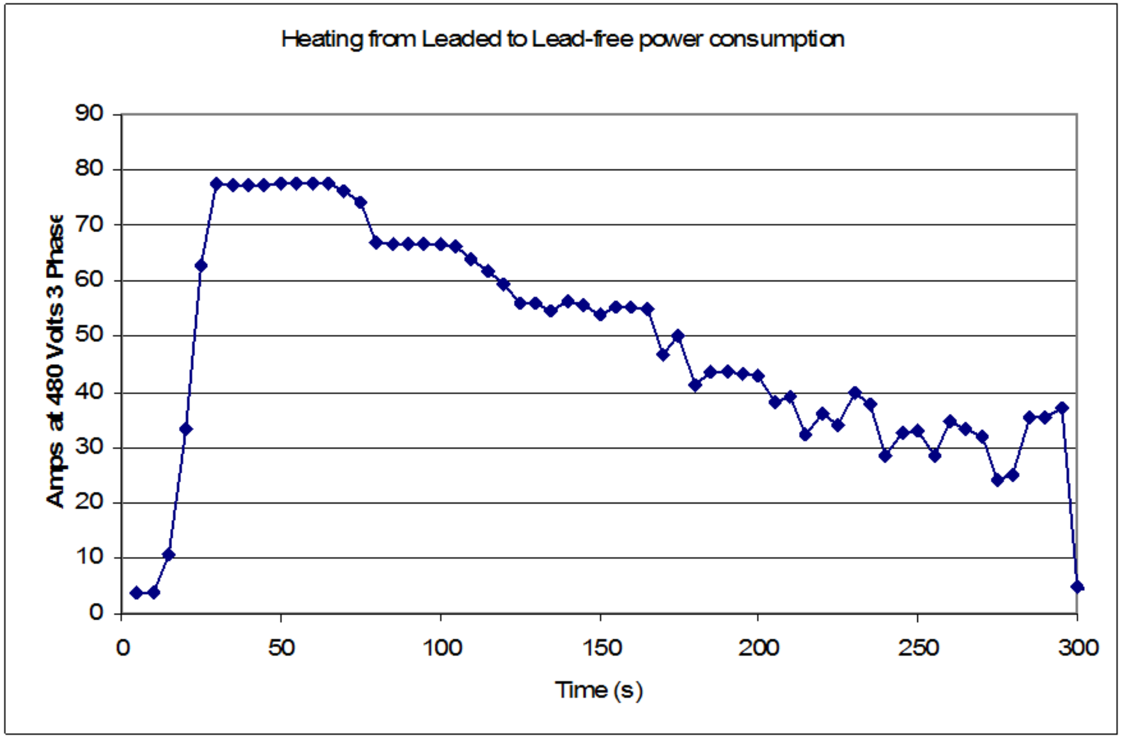
Our oven story

- Changeover times
  - Leaded to Lead-free took 15 minutes (N2 purge time)
  - Lead-free to leaded took more than 40 minutes
  - Goal is to changeover both directions in less than 15 minutes
- Capacity = Net Available Time / Time per Piece
- Capacity = Net Available Time / (Manual Time + Automatic Time) + (Changeover Time / Pieces per changeover)

Our oven story

- Problem: Faster changeover
  - New ovens
  - Mixed leaded and lead-free manufacturing

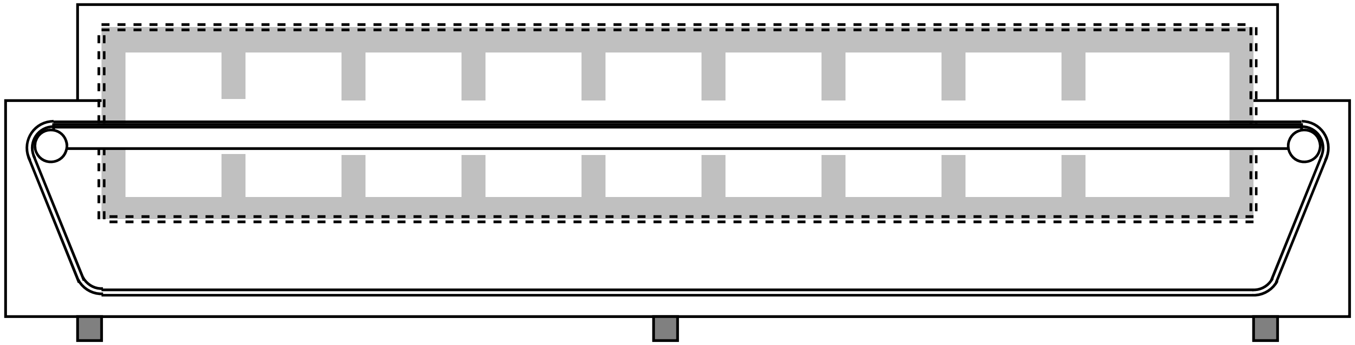
Our oven story



$$Energy_{in,total} = \int_{BeginHeatCycle}^{EndHeatCyde} (Voltage_{RMS-3ph} * Current_{RMS} * 1.73)dt$$ =11,800 Kilojoules

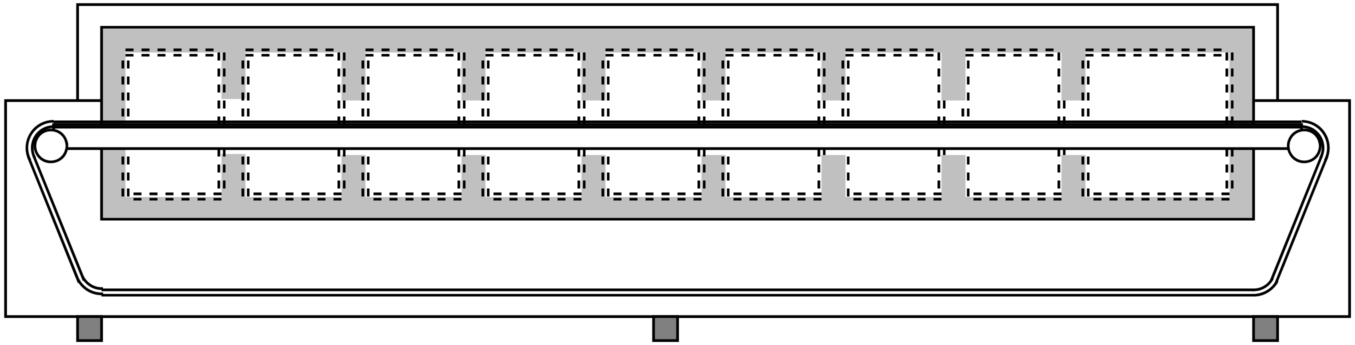
Modeling the oven

- Two models
  - Lumped model
    - Assumes no mass transfer, equal thermal properties throughout



Modeling the oven

- Two models
  - Lumped model
  - Individual control volumes
    - Accounts for mass transfer and the imbalance in thermal properties
    - Very challenging to calculate



Possible solutions to model

- Natural Convection
- Forced Convection
- Phase-Change Convection
- Other options
  - Radiation
  - Conduction
  - Opening the oven

Possible solutions to model

- Natural Convection
  - Requires almost an hour to cool from lead-free
  - Easy
  - Safe
- Forced Convection
- Phase-Change Convection

Possible solutions to model

- Natural Convection
- Forced Convection
  - Heating a plate of aluminum
  - Accelerated cooling times because of added heat extraction
  - Requires more worker intervention
- Phase-Change Convection

Possible solutions to model

- Natural Convection
- Forced Convection
- Phase-Change Convection
  - Liquefied N_2
  - Dry Ice

Modeling the oven

- Our oven story
- Modeling the oven
- The options
- Model testing and validation
- Conclusions

– Natural Convection
– Forced Convection
– Phase-Change Convection

– Predict the heat transfer using fin equations

$$\varepsilon_{fin,overall} = \frac{\dot{Q}_{Total,\,fin}}{\dot{Q}_{Total,nofin}} = \frac{h(A_{unfin} + \eta_{fin} A_{fin})(T_b - T_\infty)}{hA_{nofin}(T_b - T_\infty)}$$

$$\dot{Q}_{Total,fin} = h(A_{unfin} + n\eta_{fin} A_{fin})(T_b - T_\infty)$$

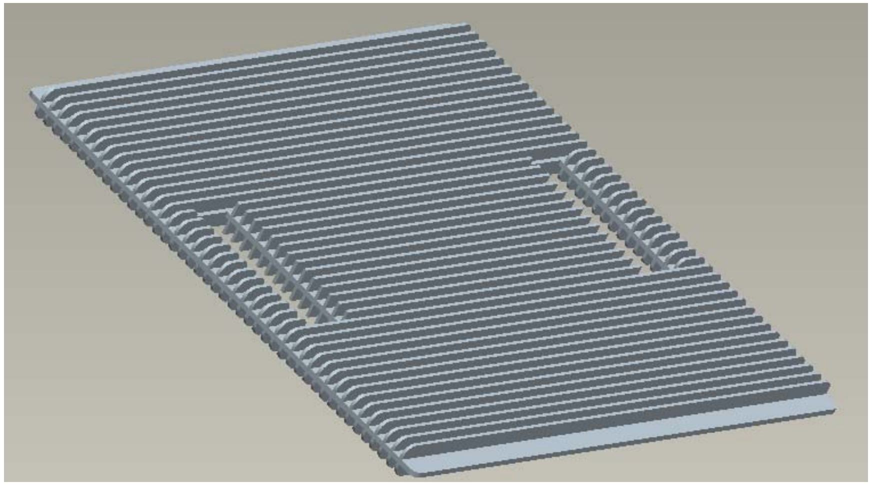
– Integrate the heat transfer with a piece-wise approximation

$$Q_{Total} = \int_{t,BeginHeating}^{t,EndHeating} Q$$

Modeling the oven

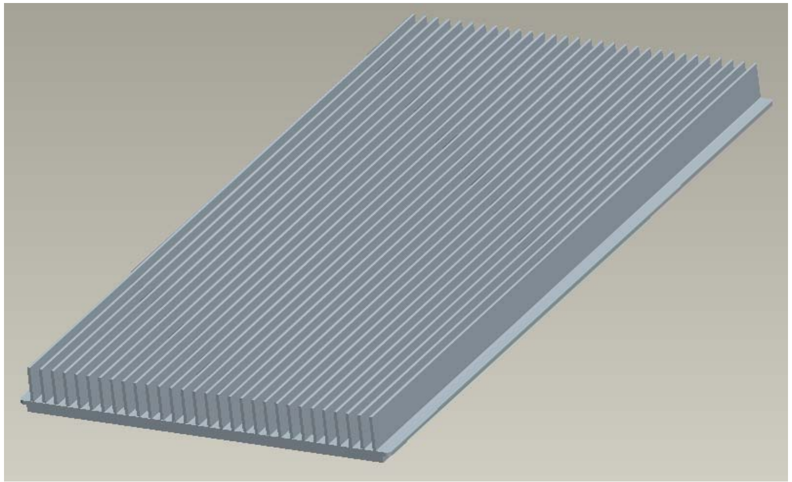
- Forced Convection
  - Reduce the changeover time to reduce the between-zone heat transfer
  - Store energy in metal plates

- Custom machined
  - 3.1 Kg (7 pounds)



- ~$200 each

- Off the shelf
  - 4.5 Kg (10 lbs)



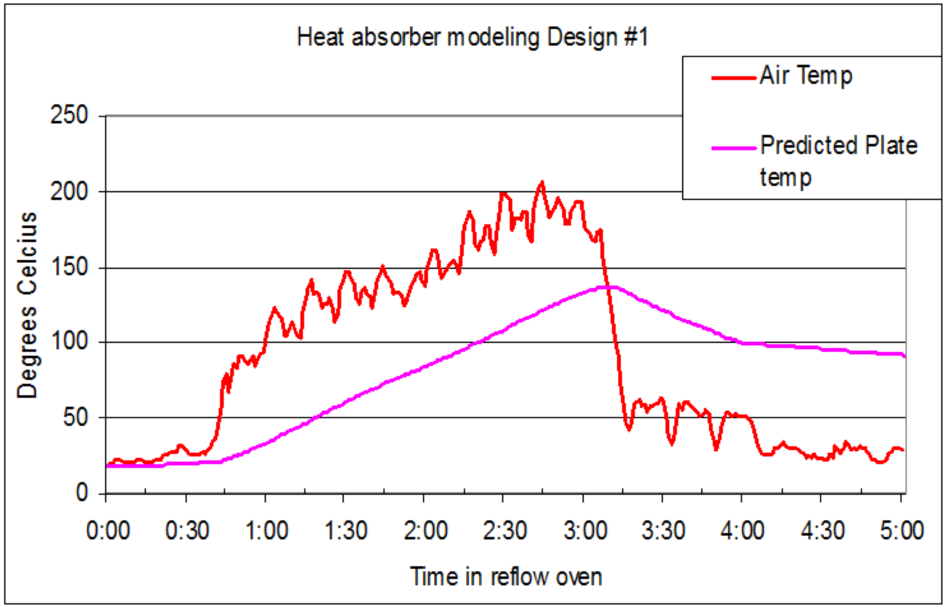
- ~$50 each

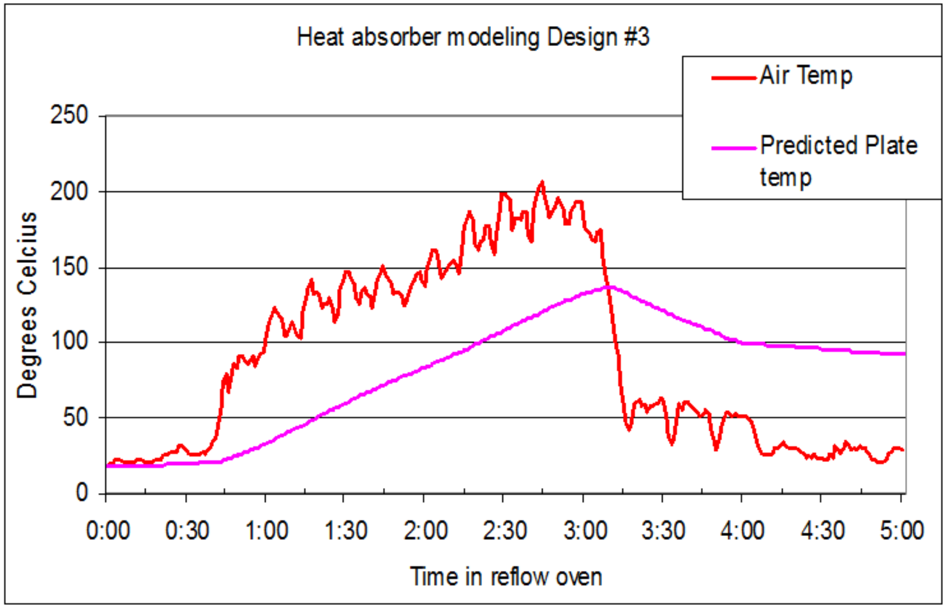
Modeling the oven

– Forced Convection
  – Reduce the changeover time to reduce the between-zone heat transfer
  – Store energy in metal plates

– Custom machined
  – 3.1 Kg (7 pounds)

– Off the shelf
  – 4.5 Kg (10 lbs)

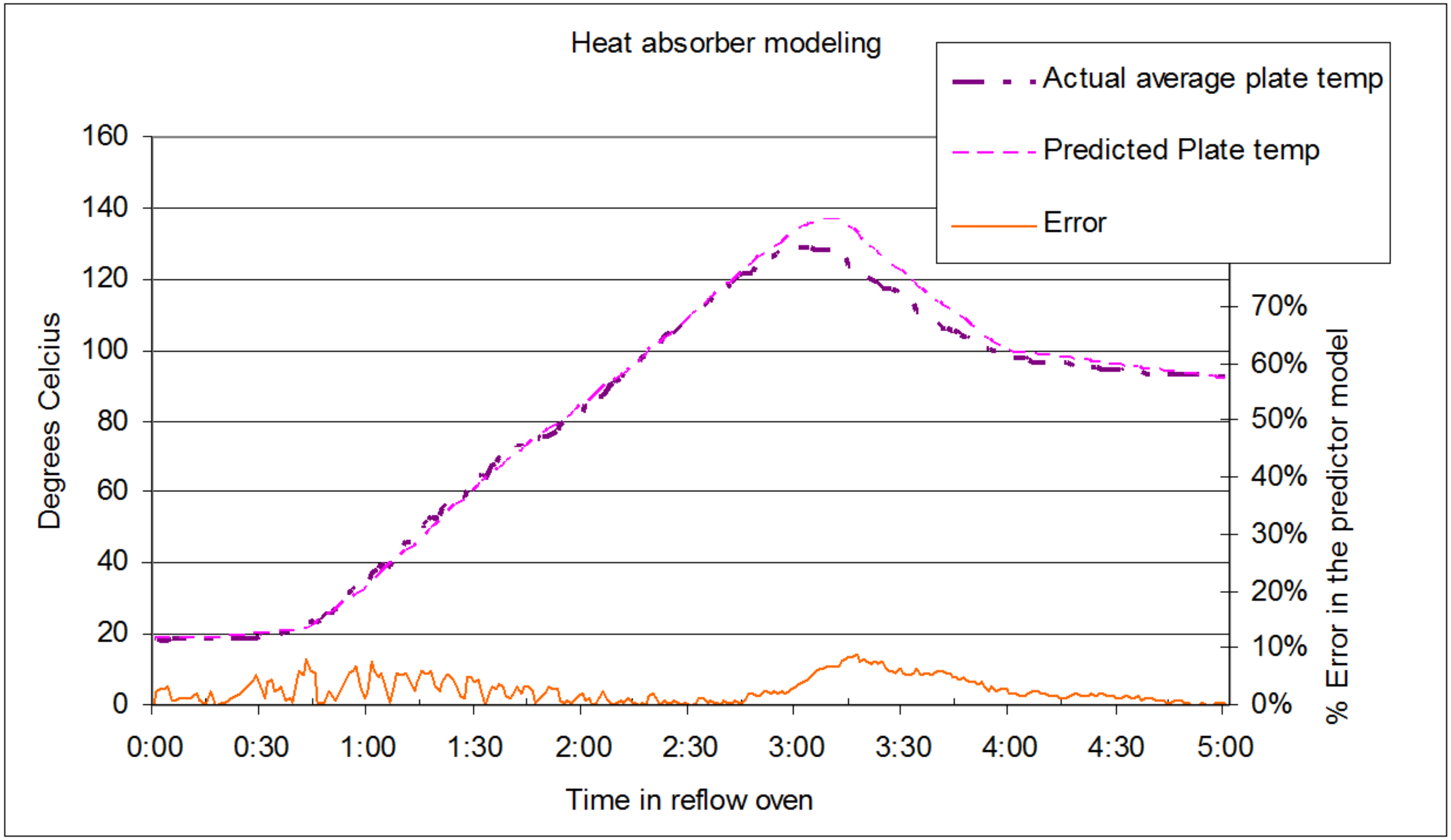




Much More Efficient

Modeling the oven

- Forced Convection
  - Validate the model
    - Pre-chilling the plates would not be cost effective



Conclusions

- Daily use
  - Zones 1 and 2 are not cooled enough
  - Zones 8 and 9 are over-cooled

Conclusions

- Forced convection cooling is possible
- Cooling efficiency depends greatly on the fin design
- Using off-the shelf materials is recommended for reduced cost
- Modeling the oven as a lumped model is accurate enough for approximation
- Development of the individual control volume model would yield a model with more predictive power

Questions?