# Reflow Oven Evaluation Using The ECD OvenRIDER


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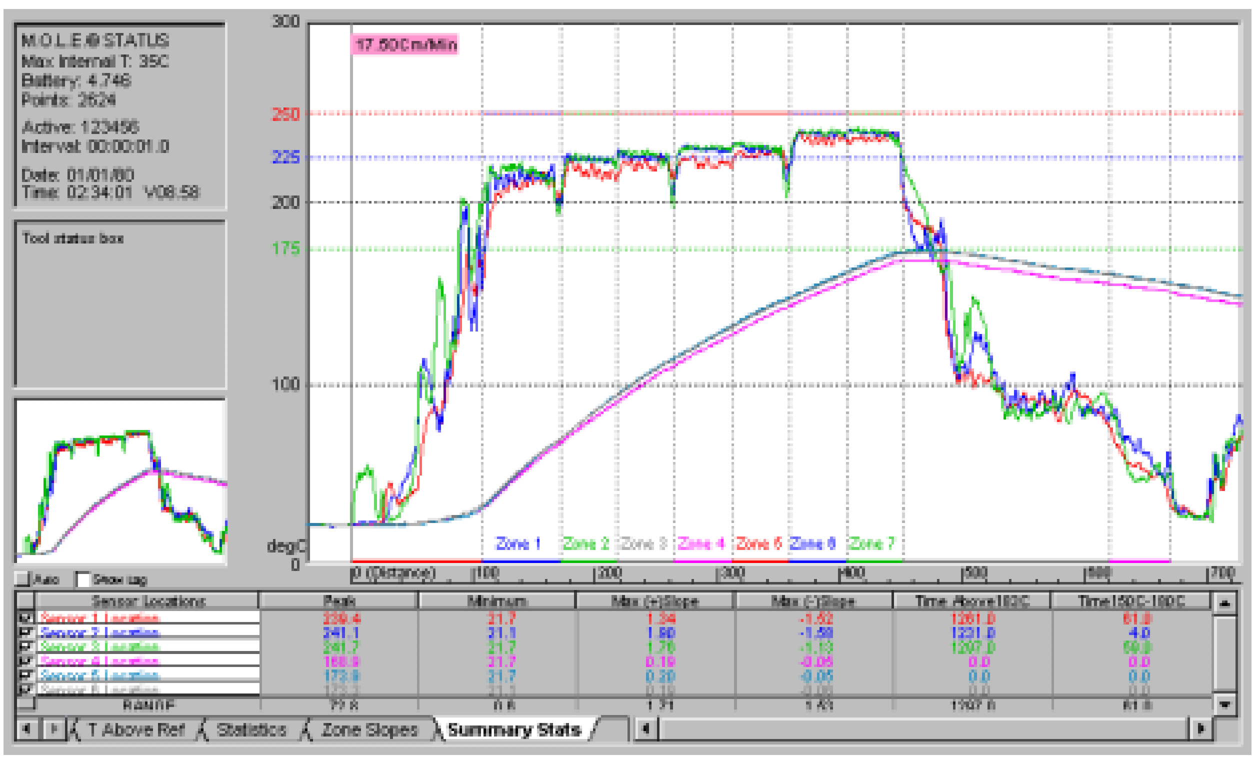

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## Introduction

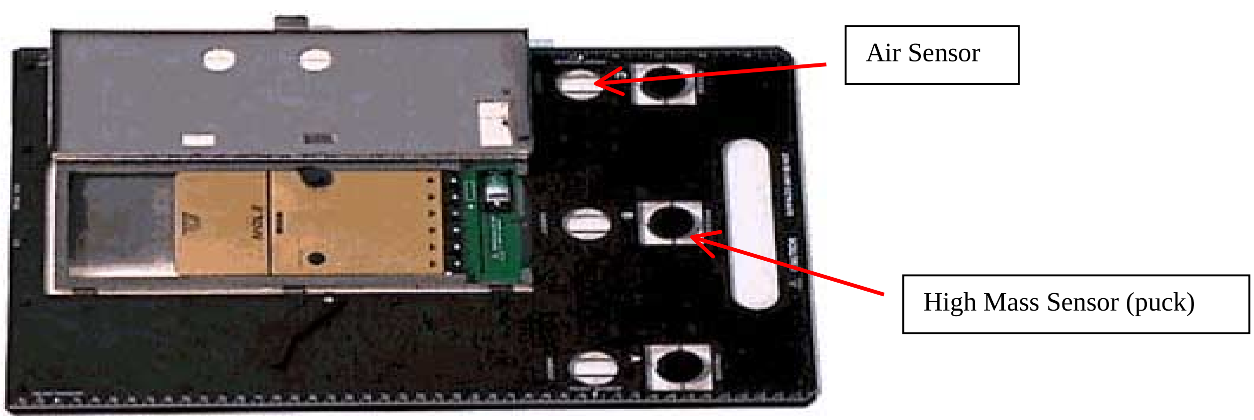
Characterization of the thermal performance of modern convection reflow ovens is important in ascertaining the process window for a particular product or application. This is especially true for lead free processes. Using typical manufacturing materials such as FR4 can be problematic in that the product changes thermal characteristics after a relatively short number of thermal excursions. Other potential test vehicles such as a stainless steel or aluminum plate are more robust and able to withstand repeated thermal cycles, however, introduce significantly different thermal conductivities that masks potential weaknesses in oven design. Trying to match these physical properties within a single test vehicle is necessary in order to characterize the various oven parameters. Such materials exist in composites with highly insulating properties similar to typical FR4 material as well as a high tolerance to numerous thermal excursions. This paper investigates the performance of three different ovens by measuring the uniformity of gas temperature and the heat transfer characteristics using a commercially available test vehicle specifically designed for this purpose. Using this test vehicle, it is possible to characterize specific physical properties of a given oven design. The results indicate dramatic differences in oven performance, specifically, the uniformity across the width and length of the tunnel as well as the heat transfer capacity. Using this test vehicle, it is possible to characterize specific physical properties of the oven. Oven design significantly impacts the steady state operation of the individual zones as well as the entire heated length. The uniformity or lack thereof in the measured air temperature along the length of the tunnel and across the width of the tunnel will have an impact on the ability to consistently and uniformly heat the product to be run. The difference in temperature as measured between the air and the high mass sensors demonstrates the efficiency of the oven to transfer heat, or heat transfer value. A higher heat transfer value allows for tighter control over the reflow process. This proportionality is related to the heat transfer coefficient, however, is not the exact heat transfer coefficient for any particular oven. Several tools exist to characterize the heat transfer coefficient as well as defining the portion of heating associated with infrared energy.

## Experimental

*Materials*

The test vehicle is the 12" ECD OvenRIDER as shown in Figure 1. It is comprised of a proprietary composite material able to withstand exposure to a temperature of 300°C in the short term and 200°C in the long term. Six symmetrically located thermocouples are located at the leading edge to examine temperature changes within the oven. Accuracy of the temperature measurement is 1.1°C or 0.4%. The high mass sensors (pucks) are made of 6061 aluminum stock rod and weigh 17.713g. The thermocouples are located across the OvenRIDER at distances of 1.25", 6.0", 10.75" starting from the left side. The Sensors A, B, and C correspond to oven locations right, middle, and left. The recording device is the ECD mole that records data at a rate of 0.1 points per second. The software used in this experiment is the OvenRIDER SPC ver. 4.05.

Figure 1. The ECD OvenRIDER.



*Experiment*

Time and temperature specifications define the thermal profile. By fixing the variables of time and temperature, the resulting data represents the heat transfer capability that is inherent in the technology of any particular convection oven. Simply stated, if the OvenRIDER is to be influenced by the same temperature for the same amount of time, the only deviation in peak temperature as measured by the pucks from the gas temperature is attributable to the heat transfer capacity of the oven. It is then possible to directly relate even predict, the results on actual electronic assemblies in terms of ΔT at peak by characterizing the heat transfer capacity of any particular oven.

For this experiment, the heating cycle was fixed by appropriately adjusting the conveyor speed for the oven length. The conveyor speed was fixed so that the OvenRIDER is in the heated portion of the tunnel for two minutes regardless of the number of zones and sizes. This allows for the comparison of the resulting data at the end of the last heating zone. The temperature in all zones was set to the same temperature to determine the accuracy and deviation in air temperature from zone to zone. For the purposes of this test all zones are set to 250°C.

**Discussion**

This paper investigates the oven parameters previously mentioned by analyzing and comparing the results of the ECD OvenRIDER for three different ovens. The following discussion provides a methodology for evaluating and ranking oven performance.

*Analysis of Test Results*

Air Sensors

With all of the zone setpoints at 250°C, it is expected that the OvenRIDER air sensors would demonstrate a consistent temperature in every zone, as well as, across the width in any given zone. However, the test vehicle behaves similar to an actual product observing a gas environment in the middle of the tunnel as opposed to where the oven hardware measures the temperature for setpoint purposes. As a result, the observed temperatures from the air sensors are lower than the setpoints of 250°C. This offset differs in various ovens due to changes in oven design, heat transfer value, control thermocouple location, etc. The observed pattern in gas temperature over the length of the oven is the fingerprint for a given oven. The even distribution of the three sensors across the OvenRIDER also allows for the measurement of the temperature consistency and uniformity across the individual zones and throughout the tunnel. Figure 2 illustrates the gas temperature profile of one oven from the three air sensors. Figure 3 superimposes the gas temperature profile of the center air sensor for the three ovens investigated in this study.

Figure 2. Gas Temperature As Measured by the Three Air Sensors Across the OvenRIDER.

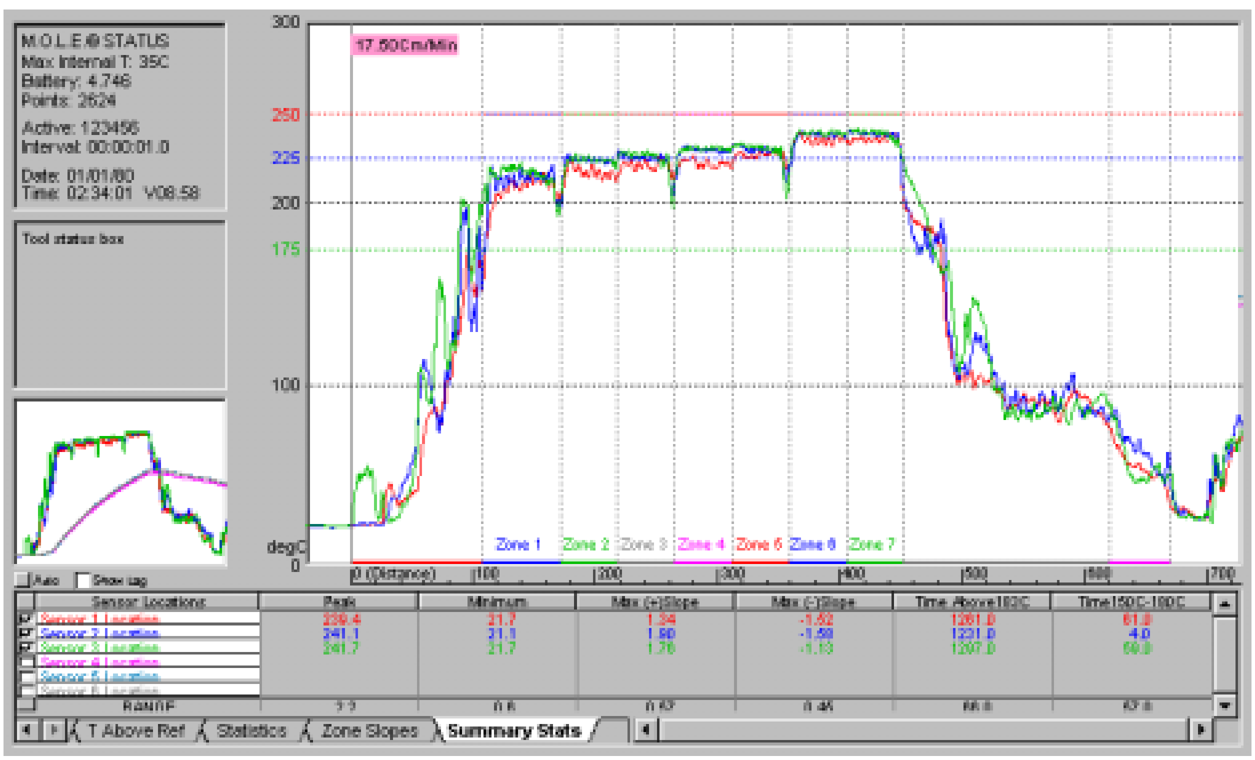
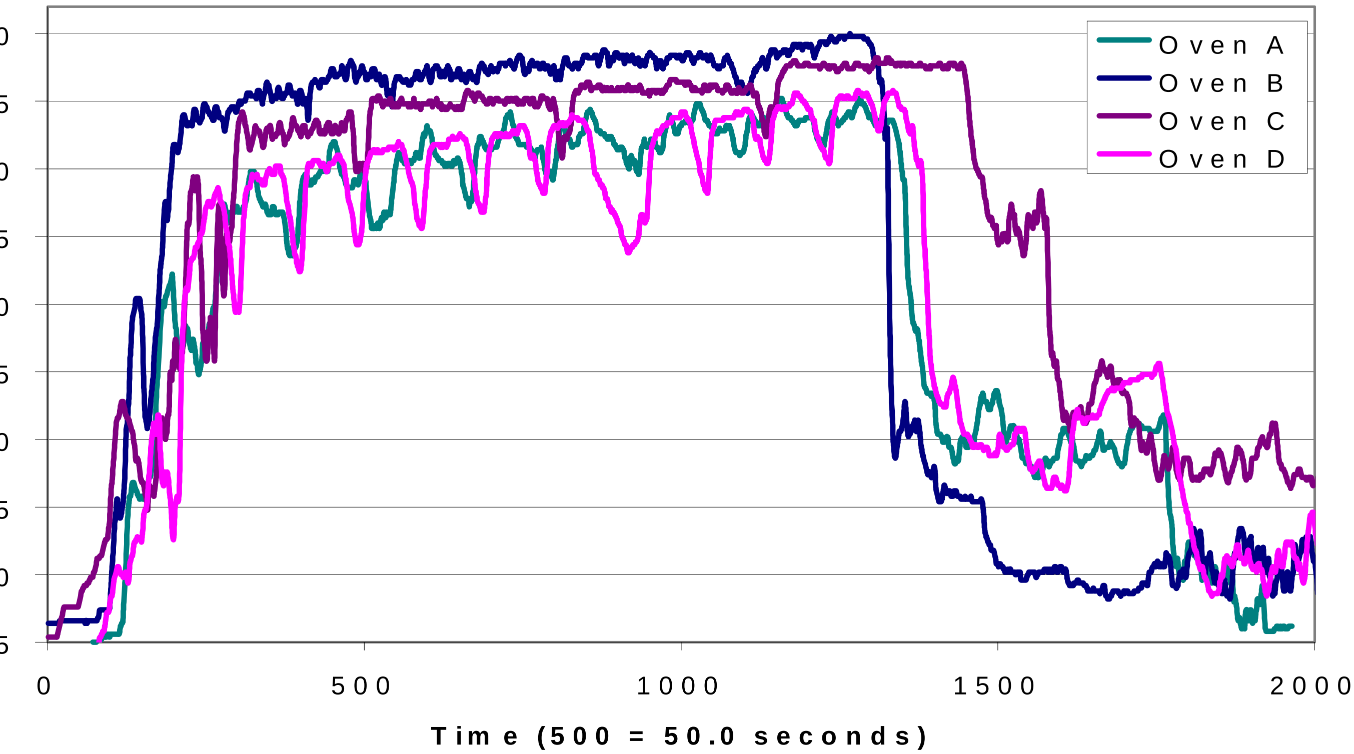


Figure 3. Gas Temperature Measurement from the Center Air Thermocouple




Due to the sensitivity of the air thermocouples the following graph displays the <u>average</u> air temperature per zone. These values are reported as calculated from the OvenRIDER software. The calculations are the result of averaging 70% of the points corresponding to the defined zone, the first 15% and last 15% are not included in this calculation. This is calculated individually per air sensor. Figure 4 graphs the average gas temperature from the center air thermocouple versus the corresponding heating zone.

It is apparent that although the temperature setpoints are at a consistent temperature there is some substantial differences in the actual temperature that the OvenRIDER measures in different zones as well as across any individual zone. A trend is observed in that there is always a relatively lower temperature towards the entrance of the tunnel. This is attributed to various factors including conveyor impact, test vehicle loading, and proximity to ambient temperature and air environment, heat transfer coefficient, convection levels with associated turbulence.

Figure 4. Average Gas Temperature Per Zone as Reported in the Ovenrider Spreadsheet

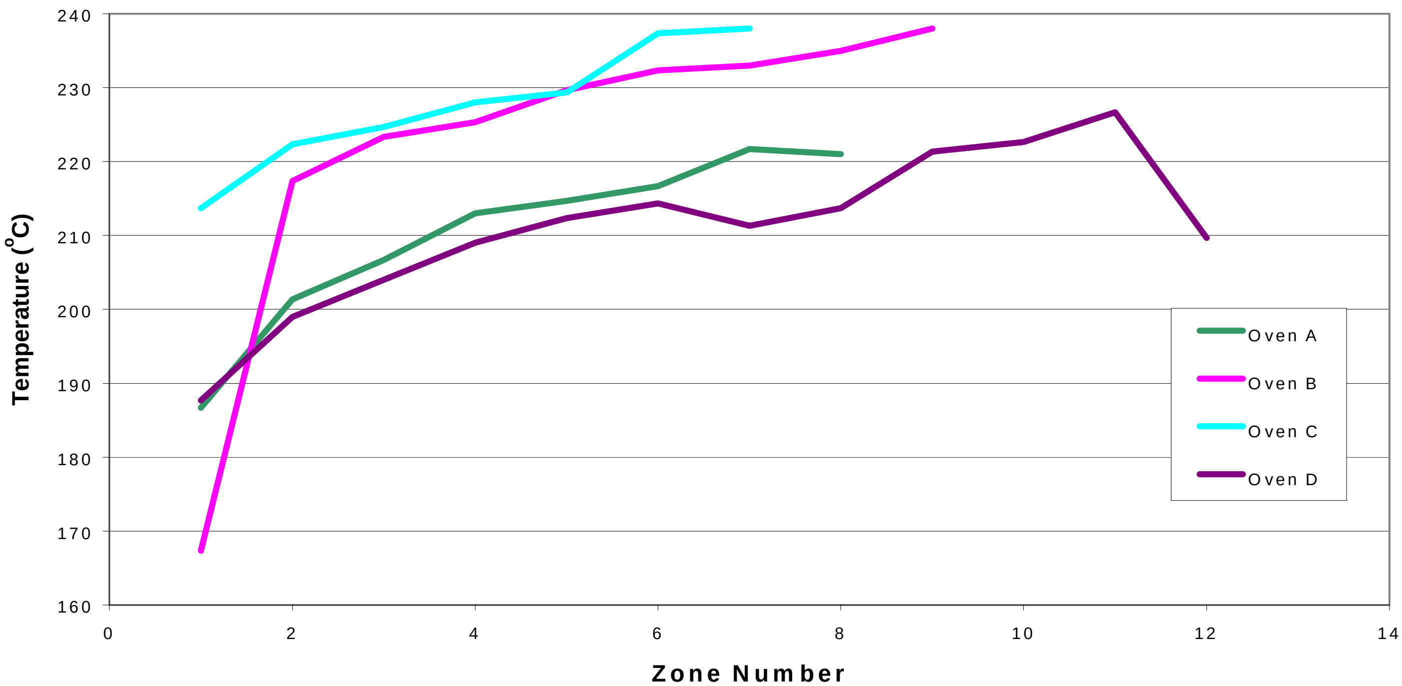



Table 1 identifies the change in the gas temperature averaged over the length of the heated tunnel as reported by the three air sensors.  Based on this range it is possible to characterize the heating uniformity across the width of the oven.  An oven with good uniformity shows the smallest range in the average temperature.  The result of good uniformity on an actual product is the equal transfer of heat over the entire board.  Thus the cross board gradient is not influenced by the oven itself.

Table 1. Average Air Temperatures Over the Oven Length as Reported by the Three Air Sensors.

| | AIR SENSOR | | | Range | Deviation from 250°C |
|---|---|---|---|---|---|
| | A | B | C | | |
| OVEN A | 210.8°C | 208.3°C | 211.6°C | 3.3°C | 41.8°C |
| OVEN B | 224.3°C | 226.5°C | 217.4°C | 9.1°C | 32.6°C |
| OVEN C | 224.3°C | 228.6°C | 230.0°C | 5.7°C | 25.7°C |
| OVEN D | 215.4°C | 207.8°C | 211.8°C | 7.6°C | 42.2°C |

Examining the variation in average air temperature measured in each zone is an indication of the repeatability to be expected from zone to zone as well as from oven to oven. These results are shown in Table2.

Table 2. Range of Average Air Temperature Along the Length of Tunnel.

| | AIR TEMPERATURE | | DEVIATION From Max to Min |
|---|---|---|---|
| | MINIMUM | MAXIMUM | |
| OVEN A | 185°C | 224°C | 39°C |
| OVEN B | 166°C | 248°C | 82°C |
| OVEN C | 209°C | 239°C | 30°C |
| OVEN D | 180°C | 228°C | 48°C |

High Mass Sensors (Pucks)

The next step in analyzing the OvenRIDER data is identifying the trends related to the high mass sensors or pucks. For these three sensors only the peak temperature observed is necessary to characterize the physical properties of the oven. This is due to the fact that the puck peak temperature is a direct result of the time exposed to the varying gas temperature. Since the time is fixed and the gas behavior is characterized by the air sensors, the puck peak temperature yields the information on the oven uniformity along the width as well as the proportionality to the heat transfer coefficient. Additionally, as with the gas temperature uniformity, the difference in peak temperature between the three pucks is important. The trend observed with the range in peak puck temperature mirrors that of the average gas temperature. This is shown in Table 3. In ovens that exhibit a high variation across the air thermocouples there is a resulting high variation on the puck peak temperature. This observation yields further evidence for previous arguments surrounding induced cross board gradients due to oven design and technology.

Table 3. The Peak Puck Temperature As Measured Across the Width of the Last Heated Zone.

| | AIR SENSOR | | | RANGE | PUCK SENSOR | | | RANGE |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | | A | B | C | |
| OVEN A | 210.8 | 208.3 | 211.6 | 3.3 | 155 | 157.2 | 157.2 | 2.2 |
| OVEN B | 224.3 | 226.5 | 217.4 | 9.1 | 182.8 | 191.1 | 181.7 | 9.3 |
| OVEN C | 224.3 | 228.6 | 230.0 | 5.7 | 168.9 | 173.9 | 173.3 | 5.0 |
| OVEN D | 215.4 | 207.8 | 21108 | 7.6 | 161.1 | 157.8 | 158.3 | 3.3 |

Another series of data that should be analyzed is the heat transfer value associated with the pucks. Assuming that the heat transfer is uniform across the width of the tunnel, a higher heat transfer will allow for lower setpoints, faster line speeds, faster ramp rates, and lower $\Delta T$. For this analysis the following equations are used to calculate the heat transfer value.

Convective heat flux, the rate of energy transferred per unit area, to or from an object is represented by Newton's law of cooling Eq. (1):

$$q'' = h \left( T_\infty - T_s \right) \qquad \text{Eq. (1)}$$

Where: h = Convection heat transfer coefficient,

$T_\infty$ = Temperature of the fluid,

Ts = Surface temperature of the object.

Incorporating the surface area of the object, the heat transfer rate is obtained in Eq. (2):

$$q = h A \left( T_\infty - T_s \right) \qquad \text{Eq. (2)}$$

The heat transfer rate can be determined experimentally by measuring the temperature gain for a known object and applying the equation Eq (3):

$$q = \frac{m(T_2 - T_1)\,Cp}{(t_2 - t_1)} \qquad \text{Eq. (3)}$$

Where: m = Mass of the object,

Cp = Specific heat of the material,

(T2 – T1) = Change in temperature of the object

(t2 – t1) = The elapsed time.

Solving for the two equations results in Eq (4):

$$h = \frac{m(T_2 - T_1)\,Cp}{(t_2 - t_1)\,A\,(T_\infty - T_s)} \qquad \text{Eq (4)}$$

which delivers the convection heat transfer coefficient. It is evident from this equation that the use of a consistent vehicle, such as the OvenRIDER, will make the mass, specific heat and surface area terms constants. If the test is performed over a fixed time interval, the (t2 – t1) term will also be a constant. When this is the case, the heat transfer coefficient will be proportional to the change in temperature of the object divided by the difference between the fluid temperature and the object temperature Eq. (5):

$$h \propto \frac{(Ts2 - Ts1)}{(T\infty - Ts)} \qquad \text{Eq. (5)}$$

In this case, we are assuming that since the object is small and made of a highly conductive material, temperature gradients within the object are negligible and temperature at the surface is equal to temperature of the object.

Based on equations 1 – 5, the following heat transfer values are proportional to the difference in measured values measured between the air temperature and puck sensors of the OvenRIDER.

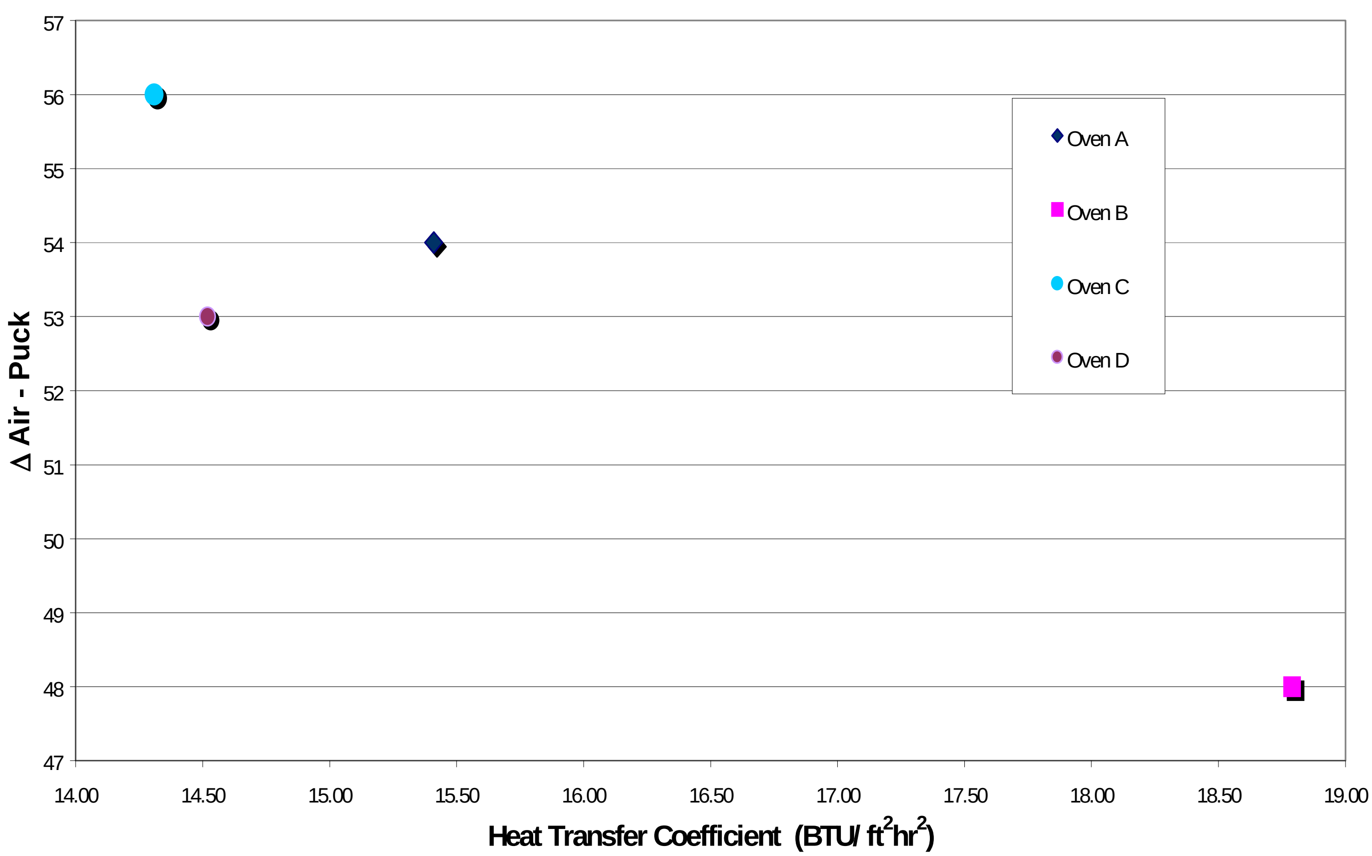
Table 4. Comparison of the Average Air and Average Puck Temperatures for the Three Ovens.

| | Average Air Temperature | Average Peak Puck Temperature | Range | Heat Transfer Coefficient (BTU/ $ft^2hr^2$) |
|---|---|---|---|---|
| OVEN A | 210°C | 156°C | 54°C | 15.41 |
| OVEN B | 233°C | 185°C | 48°C | 18.79 |
| OVEN C | 228°C | 172°C | 56°C | 14.31 |
| OVEN D | 212°C | 159°C | 53°C | 14.52 |

As the difference in measured values increases the coefficient of heat transfer decreases.

Graphing the above numbers shows the relationship of the calculated coefficient of heat transfer to the difference in measured values of the ending average air temperature and average peak puck temperature. The relationship exhibits exponential behavior as shown in Figure 5. Some variation to these results may be realized as a result of the deviation in average as well as peak temperature across the tunnel width. Average temperatures were used in this analysis for comparison purposes. Additional deviations are realized by oven design due to pre-heating occurring prior to the test vehicle entering the tunnel. This uncontrolled area of the oven is not factored into the calculations but effort is taken to minimize the impact.

Figure 5. The Impact of Heat Transfer on OvenRIDER Temperature Measurements. The Difference in the Gas Temperature Versus the Puck Temperature as a Function of Heat Transfer.



*Summary*

The four ovens are ranked in the following categories based on the ECD OvenRIDER results as shown in Table 5. The ranking within each category is assigned as follows:

1 = First based on results

2 = Second based on results

3 = Third based on results

4 = Fourth based on results

The oven that has the lowest average over the five categories is the oven that performed best in the overall OvenRIDER evaluation.

Table 5. Oven Performance Comparison

| | Oven A | Oven B | Oven C | Oven D |
|---|---|---|---|---|
| Gas Consistency across tunnel | 1 | 4 | 2 | 3 |
| Gas Consistency along tunnel | 2 | 4 | 1 | 3 |
| Gas Accuracy | 3 | 2 | 1 | 4 |
| ΔT Puck | 1 | 4 | 3 | 2 |
| Temp. Difference Air-Puck | 3 | 1 | 4 | 2 |
| AVERAGE | 2.0 | 3.0 | 2.2 | 2.8 |

Air temperature consistency and accuracy:

- Oven A demonstrated the tightest consistency across the tunnel with a range of 3.3°C at average peak air temperature. - Reference Table 1
- Oven C demonstrated the tightest consistency along the tunnel with a range of 30°C from zone to zone. – Reference Table 2

- Oven C demonstrated a higher accuracy with respect to setpoint 250°C, with the measured air temperature only 26°C lower than setpoint temperature. - Reference Table 1

Puck uniformity:

- Oven A demonstrated the tightest delta across the high mass pucks, although the puck achieved the lowest peak temperature. Reference table 3

Heat transfer:

- Oven B demonstrated the lowest measured difference between the air temp and the puck temperature and the highest calculated heat transfer efficiency. - Reference table 4

## CONCLUSIONS

As exemplified in this study, the ECD OvenRIDER provides a test vehicle and methodology for evaluating a specific oven or comparing several ovens based on several physical oven aspects. Each oven incorporates certain technologies and designs that enable it to execute certain functions that are measurable by utilizing various physical methods. In this evaluation of four ovens, Oven A had the overall best performance as tested by the ECD OvenRIDER.