April 2017

Design of Small-Scale Furnace for Fire Resistance Testing of Building Construction Materials

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Design of Small-Scale Furnace for Fire Resistance Testing of Building Construction Materials

A Major Qualifying Project Report
Submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science.

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Submitted: April 27, 2017

Professor Nicholas A. Dembsey, Advisor
Abstract

Fire resistance testing is a critical tool that contributes to meeting the fire and life safety objectives prescribed by model building codes. For many types of building construction, these prescriptive codes employ structural fire engineering to promote the strategic placement of fire rated walls, partitions, and floor or roof assemblies. The ratings of these assemblies are determined by fire resistant test procedures, including ASTM E119, *Fire Tests of Building Construction and Materials*. Specific ratings are measured by an assembly’s time to failure under a standardized fire exposure. Full-scale E119 furnace testing is expensive and not well suited to assembly optimization. The goal of this project was to build a small-scale furnace apparatus capable of performing economical fire resistance tests. Analyses supporting the design, manufacture and operation of a small-scale furnace test apparatus were conducted to establish correspondence between the small-scale furnace and the full-scale E119 furnace.
Acknowledgements

Throughout the process of the design and development of this project, there were a set of individuals that contributed to our progress and positively influenced our efforts. The following individuals played a critical role throughout the completion of this project, and without them, we would not have achieved the many accomplishments we were able to reach with their facilitation:

Professor Dembsey
Raymond Ranellone
Statia Canning
Professor Albano
Professor Savilonis
Professor Guceri
Professor El-Korchi
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1.0 Introduction
Passive fire protection is a component of critical importance in the design and construction of buildings. This method of protection promotes building fire containment within a limited area for a certain period of time, while maintaining the structural integrity of the building. In the event of a fire, the subdivision of compartments prevents the rapid spread of fire, thus allowing occupants to exit the building more safely. Passive fire protection is accomplished by implementing fire-resistant walls and floor or ceiling assemblies in the building design. Fire-resistant ratings of different assemblies are designated through prescriptive building codes and standards.

In the United States, the International Building Code\(^1\) and the National Fire Protection Association\(^2\) designate fire-resistant ratings of different assemblies based on the construction, occupancy, and room type. These standards require most construction types to have walls, partitions, and floor or roof assemblies with a specified fire resistance rating. The ASTM E119, *Fire Tests Of Building Construction and Materials*, test procedure is used to determine whether the performance of assemblies meets the fire resistance rating requirements specified in the prescriptive building codes. The ASTM E119 standard defines the performance of an assembly as “the period of resistance to standard exposure before the first critical point in behavior is observed.” Ultimately, the end point criteria analyzed in fire resistance tests are the heat transmission through the specimen and the time to failure\(^3\). These metrics evaluate the structural integrity of the assemblies noted above during the event of a fire. In most cases, fire resistant testing is carried out using a furnace test apparatus capable of replicating the standard fire exposure designated by the ASTM E119 time-temperature curve\(^4\).

ASTM E119 specifies the test to be carried out using a 9 ft by 9 ft test apparatus. Depending on the type of assembly being tested, these large scale furnaces are either vertical or horizontal apparatuses. Many laboratories, however, have utilized small-scale apparatuses as a more economical alternative and precursor to the large-scale test procedure specified in ASTM E119\(^5\). For this reason, the Fire Protection Engineering Department at Worcester Polytechnic Institute has arranged for the design and construction of a furnace capable of screening 4 ft by 4 ft vertical assemblies. The intent of this apparatus is to test such specimens following the standardized test procedure outlined in ASTM E119. Furthermore, the ongoing trend of performance based structural fire engineering has made alternative fire resistance test procedures desirable\(^6\). This report outlines the analysis, design, and assembly procedure for the production of a small-scale furnace apparatus.

1.1 Furnace Design
The furnace would consist of three main components that would work in conjunction with each other to test vertical assemblies; the burner, the specimen mount, and the furnace apparatus. The Solidworks models and technical drawings for each part can be seen in Appendix E.

1.1.1 Design of the Furnace Frame
The furnace frame consists of a number of integrated parts and serves to create a high temperature environment to meet the requirements of standardized and performance based fire exposures. The furnace apparatus consists of two major components; a steel frame, and supplemental insulation. The steel frame is constructed from hollow structural steel and steel sheet. Thermal insulation lines the inside of the furnace frame to retain heat and create an inner cavity which will contain the high temperature thermal environment. The structural analysis and insulation research were performed to determine material selection. Specifications of the furnace frame and cavity are provided in proceeding Sections 2.0 and 3.0 of this report. The procedure...
taken in constructing the furnace frame is outlined in Appendix A.2. Overall, the furnace was designed to supplement the various needs projected by the multiple analyses conducted throughout the course of this project. Size, shape, and functionality were all determined based on results that communicated the overall needs of the test apparatus, and construction capabilities determined by available resources.

1.1.2 Design of the Specimen Mount
The specimen mount is designed to secure a 4 ft by 4 ft vertical wall specimen to the open face of the furnace frame. The design was intended to provide a structurally strong, rigid, and mobile fixture, which could fit to the furnace frame to easily achieve and maintain the desired atmospheric conditions throughout testing. Furthermore, the mount was designed to achieve a degree of flexibility so that multiple construction materials could be easily implemented, tested, and removed. Construction details for the specimen mount can be seen in Appendix A.3 and Solidworks models and technical drawings can be seen in Appendix E.2.

1.1.3 Design of an Automatic Premixed Burner System
Control of the forced air and gas burner system is of critical importance when performing a fire test of building materials. Standardized tests such as ASTM E119, and ANSI/UL 262 require temperatures within the furnace to conform to the specified time-temperature curve. This requires a premixed system which can automatically control the fire exposure of the test specimen. A premixed system contains a variable speed blower delivering forced air to the burner, and a gas line (typically natural gas or propane) delivering fuel for the system. Two processes are necessary for automatic control of premixed burners. First off, the system must maintain a near stoichiometric fuel to air mixture for efficient burning. The specific component required to sustain a near stoichiometric mixture is known as the regulator valve. This valve is installed on the gas line, and controls fuel pressure through an air impulse line. Air pressure pushes down on a diaphragm and opens (or closes) a valve plunger to regulate the gas pressure accordingly. The second part of the control process involves a programmable unit which has the capability of reading thermocouple measurements within the apparatus. This unit delivers a signal to the variable speed blower which adjusts the volumetric air flow based on the measured temperature. As the airflow is adjusted, the system in turn adjusts the fuel input, thus making both processes relative. On top of this, necessary piping, gas and air mixers, and limiting valves are required to complete the premixed system.

Another important part of the design criteria was the heat output of the system. The premixed burners and components needed to be sized appropriately in order to produce a heat output that could satisfy both standardized and performance based fire resistant tests. A heat balance analysis was conducted to approximate the losses through the interior furnace walls, as well as enthalpy losses expected through the vent. The results of the analysis (Appendix B) indicated that a 200 kW system would be sufficient to meet the desired application.

As seen in the figure below, a manifold was designed with multiple burners to uniformly distribute the temperature within the furnace. For specific details on the system components and assembly procedure, refer to Appendix E.3.
2.0 Structural Analysis

A structural analysis was organized and conducted to identify the capabilities and limits of the furnace design, and supplemental fixtures. The analysis was set up to be both conservative, as the values applied projected the worst case scenario, and flexible in order to coordinate with design transformations and changes throughout the course of the project. The system was generated in compliance with Allowable Stress Design (ASD) standards for steel, established by the Manual of Steel Construction. These standards served as an evaluation tool to identify the ultimate needs of the design, and acceptable dimensions of construction materials. Details associated with the ASD limits pertaining to the governing equations of the analysis are provided in Appendix A.1.

2.1 Furnace Frame

The analysis designated for the furnace frame investigates the conditions of the fixture under static loads, dynamic loads, and loads due to the thermal expansion of the steel. As beam and column size was a varying component throughout the design process, the structural calculations performed contributed to the final dimension selection and final design of the frame. Furnace frame specifications and dimensions are provided in Appendix A.

2.1.1 Static Analysis

To evaluate the structural integrity of the furnace frame, the first priority was to justify that the design could withstand its own static, dead load. Figure 1 depicts how load distribution was interpreted. The total weight of the furnace, including all steel, insulation, and instrumentation was projected to be 915 lbf (415 kg). Each member was calculated as a simply supported beam (pinned-end conditions) to identify the maximum possible deflection, shear stress, and bending stress of each column and beam. Diagrams associated with these components of the analysis are represented in Figure 2.

When calculating the strength of connections, the beams were assumed to have fixed-end conditions to maximize the potential moment that could occur at each connection. Connections
were confirmed to be able to withstand these maximum moments based on their calculated bending capacity\textsuperscript{11}. Calculations for each of these concepts are provided in Appendix A.3. The values provided in Table 1 represent significant results pertaining to dead loads subjected to the furnace.

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
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<tr>
<td>Maximum Dead Load (lbf)</td>
<td>915</td>
<td>Simply Supported &amp; Fixed</td>
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<tr>
<td>Top Beams</td>
<td>L=5’ Max Deflection (in)</td>
<td>0.13</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress (psi)</td>
<td>472</td>
<td>27600</td>
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<td>Max Shear Stress (psi)</td>
<td>64</td>
<td></td>
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<td></td>
<td>L=3’ Max Deflection (in)</td>
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<td>Max Shear Stress (psi)</td>
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<td>Bottom Beams</td>
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<td></td>
<td>Max Bending Stress (psi)</td>
<td>10742</td>
<td>27600</td>
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<td>Max Shear Stress (psi)</td>
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<td></td>
<td>L=3’ Max Deflection (in)</td>
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<td></td>
<td>Max Bending Stress (psi)</td>
<td>3552</td>
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<tr>
<td></td>
<td>Max Shear Stress (psi)</td>
<td>518</td>
<td>27600</td>
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<td>Columns</td>
<td>L=5’ Load Applied (lbf)</td>
<td>66</td>
<td>23242</td>
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<td>Brackets</td>
<td>5’x5” Max Moment (in”/lbf)</td>
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<td>1515</td>
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<td>5’x3’, t= 1/8” Max Deflection (in)</td>
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<td></td>
<td>Max Bending Stress (psi)</td>
<td>1585</td>
<td>22800</td>
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<tr>
<td></td>
<td>Max Shear Stress (psi)</td>
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<td></td>
<td>5’x3’, t= 1/4” Max Deflection (in)</td>
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<td>0.083</td>
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<tr>
<td></td>
<td>Max Bending Stress (psi)</td>
<td>4781</td>
<td>22800</td>
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2.1.2 Dynamic Analysis
In order to safely store and run the test apparatus, each component of the design would have to be easily maneuvered around the fire laboratory. A dynamic analysis exploring the effect of live loads subjected to the furnace was performed to assess the durability of the structure in motion, and identify the most suitable location for pushing.
The forces required to achieve and maintain motion of the furnace were interpreted as the force applied to overcome both the static and rolling friction between the casters and concrete floor of the lab. Figure 3 represents the interpretation applied throughout identifying required loads for motion, and resembles the relevant forces acting on each caster. The equations, sample calculations, and results justifying the respective forces are provided in Appendix A.4.

Further analysis was conducted to justify that the design could withstand the required live loads to move the furnace. It was determined that the furnace design would have to incorporate a form of structural bracing, following analysis that expressed column buckling under live loads without bracing members. Horizontal steel tube implemented directly in the center of each face were selected as bracing members of the design, as represented in Figure 4. The bracing aids each column in buckling, deflection, and shear. Each bracing tube was analyzed to assure the loads would not cause buckling of the brace through bending stress or deflection. These calculations can be found in Appendix A.4.

2.1.3 Thermal Analysis
A Thermal Analysis measuring temperature spread among the furnace throughout time was conducted. Results demonstrated the potential of the structural steel to reach a temperature of 80°C. A thermal analysis examining the thermal expansion and resultant forces was conducted to evaluate the effect this temperature has on the structural steel of the furnace design.

Since the design of the furnace consists of a series of connected steel beams and columns, this analysis focused on the interaction among each structural component subject to the maximum temperature. The linear expansion of the hollow structural steel (HSS) members is depicted in Figure 5. Equations, sample calculations, and results representing the interpreted forms of thermal expansion are provided in Appendix A.5.

Due to the displacement caused by thermal expansion, structural members within the design impose and are subjected to resultant axial forces. These forces were interpreted to distribute from the members to the connection hardware. Screw strength was examined through a single shear analysis, as provided in Appendix A.5, to evaluate whether the connections would be able to sustain the imposed stresses and forces. Figure 6 depicts the applied analysis and represents a screw connecting two pieces of expanding steel, of thickness \( t \).
2.2 Specimen Mount

2.2.1 Static Analysis
This analysis was performed assuming the dead load of a 1600 lb. concrete specimen, which would be one of the heavier materials the specimen mount would have to support. The dead load of the specimen mount that was analyzed is provided in Table 2.

<table>
<thead>
<tr>
<th>Maximum Dead Load (lbf)</th>
<th>Beam/ Column Interpretation</th>
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<tr>
<td>1800</td>
<td>Simply Supported</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Beam</td>
<td>Max Deflection</td>
<td>0.065</td>
<td>0.25</td>
</tr>
<tr>
<td>Bottom Beams 3.5&quot;x3.5&quot; L=3&quot;</td>
<td>Max Deflection (in)</td>
<td>0.019</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress (psi)</td>
<td>7188</td>
<td>35928</td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress (psi)</td>
<td>1954</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 represents the load distribution throughout the mount. The weight from the specimen is distributed upon across an I beam. The weight of the I beam and wall specimen is then divided as point loads into two rectangular tubes on either end of the mount. This load imposed on each tube was then interpreted to distribute the load into two casters. The static structural analysis of the specimen mount I-beam, steel tubes, and casters can be found in Appendix A.6. Key results are provided in Table 2.

2.2.2 Dynamic Analysis
A dynamic analysis was completed to justify the structural integrity of the specimen mount while being maneuvered around the lab. Key results pertaining to this analysis can be found in Table 2. This analysis was completed with the assumption of a 4 inch thick concrete specimen with an approximate weight of 1,600 lbs. A cantilever beam condition of the angle iron which supports the specimen mount was interpreted in Figure 4. This angle iron will be taking on the live load of the pushing force while being moved. Calculations for the cantilever beam can be found in Appendix A.6, which proved bracing to be necessary to ensure the angle iron does not deflect more than
the allowable deflection. After adding bracing to the specimen mount, a separate analysis was completed to determine the location one should push on the mount without exceeding the bending capacity of connections. The calculations for the specimen mount bracing can be found in Appendix A.7.

2.3 Burner Mount

An analysis was performed to ensure that the burner frame design will maintain stability. Details regarding this analysis can be found in Appendix A.8. The analysis applied is consistent with the static analysis of the furnace frame. Diagrams pertaining to the major components of the analysis are represented in Figure 2. Key results and values are provided in Table 3.

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beams, L=3'</td>
<td>Max Load to Shear (lbf)</td>
<td>150</td>
<td>499</td>
</tr>
<tr>
<td></td>
<td>Max Load to Max Deflection(lbf)</td>
<td>150</td>
<td>464</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Load to Max Deflection(lbf)</td>
<td>150</td>
<td>297</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>167</td>
</tr>
<tr>
<td>columns, L=5'</td>
<td>Column Load (lbf)</td>
<td>200</td>
<td>4023</td>
</tr>
</tbody>
</table>

3.0 Insulation Selection

3.1 Material Selection

While in operation, the testing furnace will reach up to 1000$^\circ$ C and research was conducted to reduce the temperature of the outside steel during operation. A small-scale fire resistance study conducted by the University of Southampton$^{17}$ provided initial insight on microporous board and ceramic blanket insulation that was used in a 0.5 m by 0.5m by 0.5 m furnace. Following material research and coordination with respective manufacturers, a mix of microporous boards and ceramic fiber blankets were selected to achieve the aforementioned criteria and meet the needs of the furnace design. The layer that will be exposed to the operating temperature of 1000$^\circ$ C will be 25mm (1 inch) of Cerachem blanket, followed by 150mm (6 inches) of Cerablanket, 12mm (½ inch) of WDS Ultra microporous material, and a 25 mm (1 inch) air gap, a representation can be seen in the Figure 9. The blankets have the same thermal properties, however the Cerachem has a higher continuous use temperature limit, which makes it more durable when exposed to the direct heat of the burners. The Cerachem is also more expensive compared to the Cerablanket, thus only one layer was used. The microporous material will store most of the heat from the furnace, as it has a very low thermal conductivity combined with a very high density.
3.2 Material Analysis

Various modes of analysis were conducted to understand the heat flow and the resultant temperatures between each insulation layer. The manufacturer provided a simulation program that estimates the temperature change as well as the heat losses and storage among the various layers of insulation. A full explanation and the results from the Morgan simulation can be seen in Appendix C.1. After reviewing the results from the simulation, steady-state hand calculations were performed to further justify the insulation selection and modify it slightly to fit the presence of the air gap. The steady-state calculations performed included the heat loss by means of conduction through each layer of insulation, the storage of heat within the layers, and a temperature profile. When completed, all results were compared to the results from the Morgan simulation, the heat balance analysis used in determining the output for the burner, and the Solidworks simulation. A full explanation and results from the steady-state calculations completed with and without an air gap can be found in Appendices C.3 and C.2, respectively. Figure 10 below shows the temperature profile comparison between the various methods of analyses using three layers of insulation (without the air gap present). The green lines on the graph indicate the length of each insulation layer. The first line is the length of the Cerachem blanket (25 mm), the second is the length of the Cerablanket (150 mm), and the final line is the length of the WDS Ultra microporous material (12 mm).
The temperature profiles from all four methods of analysis were compared and can be seen above in Figure 10, and legend on the bottom indicates which profile corresponds with each method. Two of the profiles have final temperatures around 75°C, with the Solidworks profile being much lower and the heat balance analysis being higher. The Morgan simulation and steady-state hand calculations yield very similar temperature profiles and is further explained in Appendix C.4. Since these profiles are very similar, it confirmed the validity of the steady-state analysis conducted. The heat balance analysis has more of a curved profile and has similar initial temperatures and ending temperatures, although it only accounts for 175 mm (7 inches) of ceramic blanket and does not have the large drop in temperature between the blankets and the microporous material that is present in the other two profiles. The Solidworks model shows a temperature profile at temperatures much lower than the other three methods, possibly due to a setting in the program. With the exception of the heat balance analysis, all the profiles were completed using three layers of insulation (the Cerachem, Cerablanket, and WDS Ultra) and assumed to be at a steady-state after 3600 seconds. All of these methods of analysis aided in determining if the outside sheet metal encasing the furnace would be safe to touch according to OSHA standards. Next, the heat losses and storage were calculated and compared between all four methods.

<table>
<thead>
<tr>
<th></th>
<th>Morgan Simulation</th>
<th>Steady State Analysis</th>
<th>Heat Balance Analysis</th>
<th>Solidworks Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Heat Losses and Storage</strong></td>
<td>21.6 kW</td>
<td>50.8 kW</td>
<td>50 kW</td>
<td>87 kW</td>
</tr>
</tbody>
</table>
The Morgan Simulation had significantly lower values compared to the other three methods. This difference is because the Morgan simulation uses material performance from physical testing and the application of a semi-infinite wall rather than an enclosed geometry. It was unclear if the simulation included a time component and was assumed to have constant and uniform heat distribution. The simulation provided initial insight for expected results of the current insulation layout. The steady-state calculation and results are larger than those from the simulation and assumed the temperature to be a constant operating parameters. Calculations conducted were based on the same input parameters used in the Morgan simulation (length, thermal conductivity, specific heat, etc.) and can be seen in Appendix C.2. The heat balance analysis is a quasi-steady state method that used time steps and multiple iterations to determine the heat losses. This method examined the heat loss from the hot gases to the furnace walls as well as the enthalpy flow through the vent. Conceptually, the losses from gas to the furnace walls should be similar to the total energy flow through the furnace walls. Results from heat balance analysis showed agreement with the steady state hand calculations. It should be noted that the results from the heat balance analysis indicated in Table 4 do not account for the enthalpy flow out the vent. The Solidworks simulation accounted for the losses to the walls, the losses through the vents, just as the heat balance analysis did, and accounted for the various layers of insulation. The Solidworks simulation predicts a greater total heat loss and storage than determined by the steady state analysis and the heat balance analysis.

As with the temperature profile, it is possible that there was a setting in the program that caused this difference. The heat loss to the walls and the heat storage helped determine the burner output needed to maintain the appropriate temperature to follow the ASTM E119 curve and ensure accurate results.

4.0 Computational Fluid Dynamics Modeling

Two CFD models were constructed to simulate the operation of a standard fire test and obtain results for the application of interest. CFD models have the capability of solving many fluid flow problems and can output measurements including fluid temperature, velocity, wall temperature, net heat flux, and incident heat flux towards the specimen. Results assisted in verifying the thermal analyses conducted for this project and also provided insight on specific design criteria, such as burner and instrumentation orientation, and sizing of exhaust vents.

Solidworks Flow Simulation, an add-on CFD program developed by Dassault Systemes for their Solidworks program, can be used to test models under various conditions pertaining to fluids, gases, and heat transfer problems. The program enables the application of both external and internal fluid dynamics investigations. When calculating fluid flows Flow Simulation applies the Navier-Stokes Equations, which are located in Appendix D.1, for laminar and turbulent flows. The second model used was the Fire Dynamics Simulator (FDS) which was developed by National Institute of Standards and Technology. FDS is a powerful program that is used to model various fire scenarios ranging from small trash can fires in a typical room to industrial-scale fires.

4.1 Simulation Boundary Conditions

The boundary conditions used in the CFD models were similar to the intended apparatus design. Specifically, the furnace wall properties were representative of the selected insulation, and the specimen wall properties were that of a concrete wall. The inner dimensions of the furnace measured 3 ft by 4 ft by 4 ft. Additionally, a 6 in by 2 in vents was placed on the back wall facing the specimen. Vent sizing, placement, and opening time were varied to study the effect it would
have on the heat flow within the furnace. Refer to Appendix D.5 for further details of the Flow Simulation and FDS input file.

4.2 Device Measurement Selection and Location
Devices were strategically placed in the CFD models to examine the conditions within the test apparatus. The data collected also allowed for a ventilation study between multiple models. Measurements of interest included gas temperature, specimen wall temperature, mass flow at the burner and exhaust outlets, and velocity flows.

To further replicate the furnace apparatus design, nine 0.1 mm steel plates were implemented in the FDS model. The plates are perfectly insulated on the back side and given the material properties of a plate thermometer. When properly implemented in FDS, these devices can approximate the adiabatic surface temperature (AST) of the specimen as well as the net and incident heat flux towards the specimen.

4.3 Combustion Reaction
The simulations intended to predict the thermal conditions within the apparatus as it is being subjected to a standard fire exposure. Although Flow Simulation and FDS do not have the capabilities to model a premixed flame, they can simulate concentrations of gas species at specified temperatures. For this reason, two vents were created to inject the products of combustion for a propane and air mixture at a mass flux determined by experimental results (Appendix D.5). Vent sizing and placement were relative to the design of the premixed burner system.

In order to simulate a standardized fire resistant test, percentages of the adiabatic flame temperature (see Appendix D.5) for the complete combustion of propane were varied at time intervals relative to the E119 time-temperature curve. The table below shows the rise in gas temperature throughout the simulations.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Percentage of Adiabatic Flame Temperature</th>
<th>Simulation Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>50</td>
<td>0.15</td>
<td>300</td>
</tr>
<tr>
<td>100</td>
<td>0.25</td>
<td>500</td>
</tr>
<tr>
<td>150</td>
<td>0.35</td>
<td>700</td>
</tr>
<tr>
<td>200</td>
<td>0.45</td>
<td>900</td>
</tr>
<tr>
<td>250</td>
<td>0.50</td>
<td>1,000</td>
</tr>
<tr>
<td>600</td>
<td>0.55</td>
<td>1,100</td>
</tr>
<tr>
<td>900</td>
<td>0.57</td>
<td>1,140</td>
</tr>
<tr>
<td>1500</td>
<td>0.58</td>
<td>1,160</td>
</tr>
</tbody>
</table>

4.4 Simulation Results
In order to be consistent with the standardized test procedures, the simulations were run for 3600 seconds. Figure 11 compares the simulation temperature measurements to the ASTM E119 time-temperature curve. The average temperature of nine plate thermometer show exceptional convergence with the ASTM E119 time-temperature curve as they both approach 930 °C.
Although the Flow Simulation fluid temperature exceeds both curves, the gradient is not significant.

![Standardized Test Simulation](image)

*Figure 11: ASTM E119 Fire Resistance Test Simulation Using CFD Models*

Figure 12 displays the average incident heat flux measured at the nine plate thermometers. The intent of this method was to approximate the combined convective and radiative heat flux towards the specimen. The simulations indicate that the incident heat flux approaches 120 kW/m². The cut plot below displays the resulting temperature distribution within the furnace and across the concrete specimen.

![Incident Heat Flux on Specimen](image)

*Figure 12: Incident Heat Flux on Specimen*

Figure 13 below shows a cut plot displaying temperature taken in the middle of the furnace. The temperature distribution inside the furnace is uniform throughout the entire inside cavity of the furnace. Additionally, the outer walls of the furnace are at 25°C which is ambient temperature. A
surface plot of temperature of the concrete specimen can be found in Appendix D.3 for the side vent simulation along with a cut plot of temperature taken directly in the middle of the furnace.

![Figure 13: Temperature distribution in Solidworks Flow Simulation Model](image)

4.4.1 Verification of the Heat Balance Analysis

Temperature profiles of the concrete specimen were examined via points values placed in the concrete wall specimen concrete wall. The resulting temperature profiles of the concrete specimen for both simulations can be seen below in Figure 14 alongside the temperature profile that was calculated via the heat balance analysis. Overall, the difference between the temperature profiles from the Heat Balance Analysis and Solidworks is not immense. Both profiles show a similar descending trend in temperature going from the interior walls of the furnace to the outside walls that are only exposed to ambient conditions.

![Figure 14: Temperature Profile of Concrete Specimen (HBA & Flow Simulation) After 1 Hour](image)
Both FDS and Flow Simulation have the capability of outputting the total heat lost to the system. Table 6 below displays the heat losses from Sim FDS, Solidworks Flow Simulation, and the calculations of the heat balance analysis. Overall the calculated losses from the three analyses are relatively close to one another. Figure 15 below indicates the convective, radiative, and conductive heat losses in the standardized fire resistance test simulation. The results showed agreement with the estimated losses from the heat balance analysis (Appendix B).

<table>
<thead>
<tr>
<th>Heat Loss (kW)</th>
<th>Heat Balance Analysis</th>
<th>FDS</th>
<th>Flow Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>65</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Verification for Estimated Heat Loss

![Total Heat Loss](image)

Figure 15. Heat Loss by Each Mode of Heat Transfer

4.4.2 FDS Ventilation Study

Another important metric analyzed in this simulation was the temperature uniformity of the wall specimen. In standardized fire resistant tests, the wall should be exposed to a uniform heat flux so temperature measurements do not fluctuate throughout the surface area of the specimen. Some design criteria that can affect the heat distribution in furnaces are burner placement, vent size, vent placement, and the opening time of the vents. Several models were run where burner and vent placement were varied. Table 7 and Figure 16 indicate vent and burner design criteria that produced acceptable specimen temperature uniformity in one simulation. This information is significant to the burner system design and operating procedures relative to the surface area of the exhaust vent.
Figures 17 displays simulated temperature at nine plate thermometers. For the first 1000 seconds of the simulation, there is a maximum temperature gradient of approximately 100˚C. After this point, the measured temperatures begin to converge as the gradient decreases to 20˚C. Similarly, Figure 17 shows acceptable uniformity in heat distribution towards the specimen. Refer to Appendix D.5 for display of temperature profiles throughout the FDS simulation.

### Table 7: Table of Vent Opening

<table>
<thead>
<tr>
<th>Vent #</th>
<th>Time when opened during simulation (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>1,000</td>
</tr>
<tr>
<td>6</td>
<td>2,000</td>
</tr>
</tbody>
</table>

### 5.0 Instrumentation

#### 5.1 Temperature Instrumentation

In Ulf Wickstrom’s article, *Adiabatic Surface Temperature and the Plate Thermometer for*
Calculating Heat Transfer and Controlling Fire Resistance Furnaces\textsuperscript{21}, he argues that plate thermometers are capable of recording more accurate data than thermocouples because it measures a realistic ratio of convective to radiative heat transfer. Specifically, the thin metal plate creates a larger surface area to capture radiative heat measurements. The plate thermometer is also conditioned to have a low thermal inertia which allows the instrument to obtain accurate temperature measurements from the surroundings at a faster rate than a thermocouple would. When thermocouples and plate thermometers were used to control an exposed surface temperature of calibration elements as a comparison test, the plate thermometers performed more consistently when compared to the thermocouples.

According to ASTM E119 standards\textsuperscript{22}, no fewer than 9 thermocouples may be used for temperature recording and as such 9 plate thermometers will be placed 4 inches from the wall test specimen to gather the temperature of the wall test specimen throughout the test as well as a heat flux on the specimen. To mount the plate thermometers, 3 poles will be erected in the furnace, and 3 plate thermometers will be mounted on each pole, as can be seen in Figure 20. This mounting method was chosen ensure the plate thermometers stayed stationary during operation, eliminating any potential damage from plate thermometers deflecting into the specimen. The average of all 9 plate thermometers will be reported as the wall test specimen temperature and heat flux. The placement of the plate thermometers can be seen in the Figure 18 and 19. The plate thermometers will be a fixed to piping which will then be threaded into flanges into the bottom of the furnace. Stand construction details can be seen in Appendix F.1. The backside temperature will be read by 9 thermocouples in a similar array as the plate thermometers. These thermocouples will be covered by insulation to measure a more accurate back face temperature. The average from these 9 thermocouples will be read as the back face temperature.

![Figure 18: View from the Burner of PT Placement](image1)

![Figure 19: Isomeric View of PT Placement](image2)
Initially the furnace instrumentation will be used to record the temperature the specimen is exposed to, however the intent is to use the plate thermometers to control the burner output dependent on the accuracy of the plate thermometers in reading time-temperature data.

5.2 Plate Thermometer Testing and Analysis
In order to calibrate the plate thermometers to calculate a heat flux from a measured temperature, small scale tests were completed using a cone calorimeter. For initial plate thermometer testing, a plate thermometer was placed under a cone calorimeter and was connected to the computer with a LABVIEW Express Signals program. These tests were run using two plate thermometers, the construction details can be found in Appendix F.1. The cone calorimeter was set to a known heat flux of 80 kW/m², which resulted in a temperature of about 740°C. While the cone calorimeter was set to 740°C, the actual temperature of the cone calorimeter fluctuated between 660-700°C, this was based on the limitations of the cone calorimeter. The following equation, Equation 1, was used to calculate the cone temperature.

**Equation 1: Equation for Cone Temperature Given Desired Heat Flux**

\[ \text{Cone Temperature} = -0.05035y^2 + 10.92y + 189 \]

Each plate thermometer was heated under the cone for one hour per test, and the temperature was recorded using the LABVIEW Express Signals program created by the National Instruments Corporation. The temperatures recorded were used to calculate the incident heat flux on the plate using the following equation:

**Equation 2: Equation to Calculate Incident Heat Flux using Plate Thermometer Data**

\[ \dot{q}' = \rho c_p \delta \frac{dT}{dt} + h(T_s + T_g) + \varepsilon \sigma T_s^4 + \frac{(T_s - T_{\text{insulated}})}{\frac{1}{h_e} + \frac{L}{k}} \]

This equation calculates the incident heat flux using the radiative heat transfer and convective heat transfer to account for the net heat transfer between the furnace and the steel plate. Also, the heat lost from the steel plate to the insulation of the plate thermometer is accounted for through conductive heat transfer. Once the incident heat flux of the furnace is calculated, the temperature on the exposed face of the specimen can be computed. This temperature as well as the temperature reading from the thermocouples on the back face of the specimen can be used to determine the heat transmission through the specimen. A MATLAB script was created to calculate the heat flux on the plate. The results of furnace plate thermometers can be seen in Table 8 below, and the results of the initial test plate thermometers can be seen in Table 19 in Appendix F.2. These results demonstrate how heat flux can be calculated from a measured temperature, and they show a correlation between increasing temperature and increasing incident heat flux. The script and calculations can also be seen in Appendix F.2.
### Table 8: Measured Temperature and Calculated Heat Flux of Furnace Plate Thermometers

<table>
<thead>
<tr>
<th>Plate Thermometer</th>
<th>Measured Temperature [°C (K)]</th>
<th>Calculated Heat Flux [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>560 (833)</td>
<td>73</td>
</tr>
<tr>
<td>2</td>
<td>570 (843)</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>540 (813)</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>540 (813)</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>550 (823)</td>
<td>72</td>
</tr>
<tr>
<td>6</td>
<td>545 (818)</td>
<td>71</td>
</tr>
<tr>
<td>7</td>
<td>540 (813)</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>580 (853)</td>
<td>80</td>
</tr>
<tr>
<td>9</td>
<td>545 (818)</td>
<td>71</td>
</tr>
</tbody>
</table>

### 5.3 Pressure Instrumentation

To read pressure inside the furnace, to prevent overpressure leading to furnace damage and hazardous operating conditions pressure gauges will be added to the furnace. There will be two pressure gauges total, one located at the top of the furnace cavity and one located at the bottom furnace cavity to allow for a pressure differential across the cavity to be read. These pressure gauges would be positioned the same distance away from the specimen as the final plate thermometer distance for the same reasons. The pressure gauges should be tube sensors adhering to ISO 834 or EN 1363-1 standards, and should measure a positive furnace pressure of up to 20 Pascals. In addition the pressure gauges would allow us to see in real time from LABVIEW the change in pressure, allowing us to stop the test if there is a sudden pressure spike.
References


Appendix A: Structural Analysis

Appendix A.1 ASD

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Variables</th>
</tr>
</thead>
</table>
| $R_a \leq \frac{R_n}{\Omega}$ | $R_n$: Required Strength (Dead or Live; Force, Moment, Stress)  
$R_n$: Nominal Strength Specified  
$\Omega$: Safety Factor |

Factors of Safety  
(applied in order to limit the stresses for allowable stress values)

<table>
<thead>
<tr>
<th>Type</th>
<th>$\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending (Braced Member, $L_b &lt; L_p$)</td>
<td>1.67</td>
</tr>
<tr>
<td>Bending (Unbraced Member, $L_b &lt; L_p$ &amp; $L_b &lt; L_r$)</td>
<td>1.67</td>
</tr>
<tr>
<td>Shear (Beams)</td>
<td>1.67</td>
</tr>
<tr>
<td>Shear (Bolts)</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Appendix A.2: Construction Procedure

Appendix A.2.1: Construction Procedure-Furnace Frame

Furnace Frame

Procedure Specifications

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Process</th>
</tr>
</thead>
</table>
| 1         | Cut Steel Tube:  
1"x1"x1/8" (A 513)  
2"x2"x 1/4" (A500)  
Cut Angle Iron:  
1½"x1 ½" x 1/8" (A36)  
3"x2"x3/16" (A36)  
Note:  
Refer to Drawing for cut lengths. |
| 2         | Cut Steel Plate:  
11 gauge (0.12 in.) Hot Rolled Steel |
Note:
Refer to Drawings for cut lengths.

3 Hole Layout, Drill, and Tap: Steel Tube to Steel Sheet
Each member was assigned an Identification Number. The nomenclature generated for these ID’s was based on hole location upon each member. The table below provides the member ID, length, tube dimension, and the hole size drilled and tapped into each member.

3.A: 1” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>59”</td>
<td>1”x1”x1/8” (A 513)</td>
<td>7</td>
<td>1/4”-20</td>
</tr>
<tr>
<td>V2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS1</td>
<td>34”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB1</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB2</td>
<td></td>
<td></td>
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</tr>
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<td>SB1</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>TB1</td>
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</tr>
<tr>
<td>TB2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TFH</td>
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<td>1”x1”x1/8” (A 513)</td>
<td>7</td>
<td>1/4”-20</td>
</tr>
<tr>
<td>TBH</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BHB</td>
<td>58”</td>
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<td></td>
<td></td>
</tr>
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</table>

3B: 2” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>32”</td>
<td>2”x2”</td>
<td>7</td>
<td>1/4” -20</td>
</tr>
<tr>
<td>BS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BFH</td>
<td>60”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBH</td>
<td></td>
<td></td>
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</table>

3C: STEEL SHEET

<table>
<thead>
<tr>
<th>ID</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSH</td>
<td>5’x3’, t=1/8”</td>
<td>5/16”</td>
<td>Thru</td>
</tr>
<tr>
<td>BSH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSH</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>RSH</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BKSH</td>
<td>5’x5’, t=1/8”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

4 Hole Layout, Drill, and Tap: Steel Tube to L Bracket
Each bracket was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and hole size drilled and tapped into each member.

### 4A: L BRACKET TO 1” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>TS1, V1</td>
<td>5”x5”x7/8” t=1/8”</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>1.2</td>
<td>SB1, V1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>SB1, V1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>TFH, V1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>TS1, V2</td>
<td>5”x5”x7/8” t=1/8”</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>2.2</td>
<td>SB1, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>SB1, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>TBH, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>BHB, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>BHB, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>TS2, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>SB2, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>SB2, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>TBH, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>BHB, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>BHB, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>TS2, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>SB2, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>SB2, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>TFH, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.1</td>
<td>TBH, TB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.2</td>
<td>TFH, TB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.3</td>
<td>TBH, TB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.4</td>
<td>TFH, TB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.1</td>
<td>TBH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.2</td>
<td>TFH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.3</td>
<td>TBH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.4</td>
<td>TFH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4B: L-BRACKET TO 2” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>BFH, BS1</td>
<td>5”x5”x7/8” t=1/8”</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>1.2</td>
<td>BFH, BB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>BFH, BB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>BFH, BB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>BFH, BB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>BFH, BS2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>BBH, BS1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>BBH, BB1</td>
<td>5”x5”x7/8”</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>2.3</td>
<td>BBH, BB1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Note:
Refer to Drawing for a visual of each component assembled, respective hole placement and amount.

### 5: Hole Layout, Drill, and Tap: Steel Tube to T Bracket
Each bracket was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and the hole size drilled and tapped into each member.

#### 5A: T BRACKET TO 1” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>TFH, TB1</td>
<td>3”x3”x7/8” t=1/8”</td>
<td>29</td>
<td>8-32</td>
</tr>
<tr>
<td>1.2</td>
<td>TFH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>TBH, TB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>TBH, TB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>V1, SB1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>V4, SB2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 5B: T BRACKET TO 2” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>BBH, BB1</td>
<td>3”x3”x7/8” t=1/8”</td>
<td>29</td>
<td>8-32</td>
</tr>
<tr>
<td>3.2</td>
<td>BFH, BB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>BBH, BB2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>BBH, BB1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:
Refer to Drawing for a visual of each component assembled, respective hole placement and amount.

### 6: Hole Layout, Drill, and Tap: Steel Tube to T Bracket
Each bracket was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and hole size drilled and tapped into each member.

#### 6A: CORNER BRACKET TO 1” STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>TS1, TFH</td>
<td>4”x4”x7/8”</td>
<td>29</td>
<td>8-32</td>
</tr>
</tbody>
</table>
### 2.1 TS1, TBH
t=1/8"

### 3.1 TS2, TBH

### 4.1 TS2, TFH

#### 6B: CORNER BRACKET TO BOTTOM STEEL SHEET & 2" STEEL TUBE

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Components</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>BSH, BS1, V2</td>
<td>4&quot;x4&quot;x7/8&quot; t=1/8&quot;</td>
<td>29</td>
<td>8-32</td>
</tr>
<tr>
<td>1.3</td>
<td>BSH, BS1, V1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>BSH, BBH, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>BSH, BBH, V2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>BSH, BS2, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>BSH, BS2, V3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

#### 7: Hole Layout, Drill, and Tap: Steel Tube to Caster

Each caster was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and hole size drilled and tapped into each member.

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>BFH, BS1</td>
<td>4 1/8&quot;x 4 1/8&quot; x 1 1/4&quot; t= 1/8&quot;</td>
<td>18</td>
<td>5/16&quot;</td>
</tr>
<tr>
<td>1.2</td>
<td>BBH, BS1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>BBH, BS2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>BBH, BS2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

#### 8: Hole Layout, Drill, and Tap: Angle Iron to Steel Sheet and Steel Tube

In order to effectively implement a gasket to the furnace frame open face, angle iron was connected to each open edge. Each section of angle was assigned an Identification Number. The table below provides the Angle ID Number, coincident components, and hole size drilled and tapped into each member.

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Components</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>8: Angle Iron to Steel Sheet &amp; 1&quot;Tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID</td>
<td>Coincident Components</td>
<td>ID Dimension</td>
<td>Drill Size</td>
<td>Tap Size</td>
</tr>
<tr>
<td>----</td>
<td>-----------------------</td>
<td>--------------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>1.1</td>
<td>LSH, V1</td>
<td>3”x2”x3/16”</td>
<td>7</td>
<td>Thru</td>
</tr>
<tr>
<td>1.2</td>
<td>TSH, TFH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>LSH, V4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

**ID Legend**
- V: Columns
- TS: Top Side Beam
- TB: Top Brace
- SB: Side Brace
- TFH: Top Front Horizontal Beam
- TBH: Top Back Horizontal Beam
- BHB: Back Horizontal Brace
- BS: Bottom Side Beam
- BB: Bottom Brace
- BFH: Bottom Front Horizontal Beam
- BBH: Bottom Back Horizontal Beam
- TSH: Top Steel Sheet
- BSH: Bottom Steel Sheet
- BKSH: Back Steel Sheet
- LSH: Left Steel Sheet
- RSH: Right Steel Sheet

**Procedure Order**
1. Phase 1
2. Phase 2
3. Phase 3A
4. Phase 4A
5. Phase 5A
6. Phase 6A
7. Assembly 1: V1, V2, V3, V4, TS1, TS2, TB1, TB2, SB1, SB2, TFH, TBH, BHB
8. Phase 3B
9. Phase 4B
10. Phase 5B
11. Phase 6B
12. Phase 7A
13. Phase 4C
14. Assembly 2: BS1, BS2, BB1, BB2, BFH, BBH, BSH
15. Assembly 3: Assembly 1 & 2
16. Phase 3C
17. Phase 8
18. Assembly 4: Assembly 3, BKSH, BSH, LSH, RSH, TSH, Angle Iron
Appendix A.2.2: Construction Procedure Diagrams and Drawings - Furnace
Appendix A.2.3: Construction Procedure – Specimen Mount

Specimen Mount Design

Procedure Specifications

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Cut Steel Tube:</strong></td>
</tr>
<tr>
<td></td>
<td>1 ½” x 1 ½” x 1/8” (A 513)</td>
</tr>
<tr>
<td></td>
<td>3 ½” x 3 ½” x 3/16” (A500)</td>
</tr>
<tr>
<td></td>
<td><strong>Cut Angle Iron:</strong></td>
</tr>
<tr>
<td></td>
<td>2”x2”x 1/8” (A36)</td>
</tr>
<tr>
<td></td>
<td>3 ½” x 3 ½” x ¼” (A36)</td>
</tr>
<tr>
<td></td>
<td><strong>Cut I Beam:</strong></td>
</tr>
<tr>
<td></td>
<td>S 4*7.7 lb (A36)</td>
</tr>
<tr>
<td></td>
<td><strong>Cut U-Channel:</strong></td>
</tr>
<tr>
<td></td>
<td>4x5.4 lb (A36)</td>
</tr>
<tr>
<td></td>
<td><strong>Note:</strong></td>
</tr>
<tr>
<td></td>
<td>Refer to Drawing for cut lengths.</td>
</tr>
</tbody>
</table>

| 2         | **Cut Steel Plate:**                         |
|           | 11 gauge (0.12 in.) Hot Rolled Steel (1/4") A 36 |
|           | **Note:**                                    |
|           | Refer to Drawings for cut lengths.           |

| 3         | **Hole Layout, Drill, and Tap:** Miscellaneous Steel to Tube Steel and ½” Steel Plate |
|           | Each member was assigned an Identification Number. The nomenclature generated for these ID’s was based on hole location upon each member. The table below provides the member ID, length, tube dimension, and the hole size drilled and tapped into each member. |

<table>
<thead>
<tr>
<th>3.A: U-CHANNEL</th>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U1</td>
<td>68.5”</td>
<td>4” X 1.584” X .184” (A36)</td>
<td>N</td>
<td>Thru</td>
</tr>
<tr>
<td>Holes connecting to steel tube</td>
<td>F</td>
<td>5/16”-18</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3B: I-BEAM

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>68.5”</td>
<td>4.00”x0.193”x2.663” (A36)</td>
<td>N</td>
<td>Thru</td>
</tr>
<tr>
<td>Holes connecting to steel tube</td>
<td>F</td>
<td>5/16”-18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3C: ANGLE IRON

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>61.5”</td>
<td>2”x2”x1/8” (A36)</td>
<td>16</td>
<td>12-24</td>
</tr>
</tbody>
</table>

3D: 3.5” STEEL TUBE
### 3E: STEEL PLATE

<table>
<thead>
<tr>
<th>ID</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSH</td>
<td>60&quot;x10&quot;, t=1/4&quot; (A36)</td>
<td>N</td>
<td>Thru</td>
</tr>
<tr>
<td>TSH</td>
<td>60&quot;x10&quot;, t=0.12&quot; (11 Gauge)</td>
<td>N</td>
<td>Thru</td>
</tr>
</tbody>
</table>

**Note:**
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

### 4 Hole Layout, Drill, and Tap: Steel Tube to 8” L Bracket to Angle Iron

Each bracket was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and hole size drilled and tapped into each member.

#### 4A: 8” L BRACKETS

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>S1, A1</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>1.2</td>
<td>S2, A2</td>
<td>16</td>
<td>12-24</td>
</tr>
</tbody>
</table>

#### 4B: ANGLE IRON

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA1</td>
<td>60&quot;</td>
<td>3 ½” x 3 ½” x ¼” (A36)</td>
<td>16</td>
<td>12-24</td>
</tr>
<tr>
<td>VA2</td>
<td>60&quot;</td>
<td>3 ½” x 3 ½” x ¼” (A36)</td>
<td>16</td>
<td>12-24</td>
</tr>
</tbody>
</table>

4C: Bracing: Two steel tube bracing beams were inserted using 60 degree and 30 degree brackets. The steel tubes were cut at a 60 degree angle as well as a 30 degree angle. These were assembled using strut connections. The appropriate thread size for these connections were 9/16"-12.

**Note:**
Refer to Drawing for a visual of each component assembled, respective hole placement and amount.

### 5 Hole Layout, Drill, and Tap: U-Channel to Steel Sheet Frame

Each member was assigned an Identification Number. The nomenclature generated for these ID’s was based on hole location upon each member. The table below provides the member ID, length, and the hole size drilled and tapped into each member.

#### 5.A: U-CHANNEL

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>68.5&quot;</td>
<td>4” X 1.584” X .184” (A36)</td>
<td>F</td>
<td>5/16”-18</td>
</tr>
</tbody>
</table>

#### 5B: STEEL SHEET FRAME
### Hole Layout, Drill, and Tap: Steel Tube to Caster

Each caster was assigned an Identification Number. The nomenclature generated for these ID’s was based on bracket placement among members. The table below provides the bracket ID, coincident members, and hole size drilled and tapped into each member.

<table>
<thead>
<tr>
<th>ID</th>
<th>Coincident Members</th>
<th>ID Dimension</th>
<th>Drill Size</th>
<th>Tap Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>S1</td>
<td>4 ½”x 4”, t=1/4”</td>
<td>5/16”</td>
<td>3/8”-16</td>
</tr>
<tr>
<td>1.2</td>
<td>S1</td>
<td>Wheel Size: Dia=5”, Width= 1 ½”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>S2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>S2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

#### ID Legend
- U: U-Channel
- I: I-Beam
- S: Steel Tube Side
- AB: Angle Iron Bottom
- VA: Vertical Angle Iron
- FSH: Steel Sheet Frame

#### Procedure Order
1. Phase 1
2. Phase 2
3. Phase 3A
4. Phase 3B
5. Phase 3C
6. Phase 3D
7. Phase 3E
8. Phase 4A
9. Phase 4B
10. Phase 4C
11. Phase 5A
Appendix A.2.4: Construction Procedure Diagrams and Drawings – Specimen Mount

1) Steel Tube to Attach Steel Plates

2) Furnace Frame – Hole Layout

3) All holes for brackets were laid out as brackets were held in place with respective holes.

4) Vertical Steel Tubes → V1, V2, V3, V4 (Length = 59"

5) Top Horizontal → TFH & TBH (Length = 60"

6) Horizontal Brace → BHB (Length = 58"

7) Sides & Bracing → TS1, TS2, SB1, SB2, TB1, TB2 (Length = 34"

8) Indicate hole placement.
HOLE LAYOUT - SPECIMEN MOUNT

a) 3.5" x 3.5" STEEL TUBE -> S1, S2 (LENGTH: 36") (TOP VIEW)

-> CONNECT U-CHANNEL & I-BEAM

1.5" 16.75" 1.125"

-> FRONT FACE

b) 3.5" x 3.5" STEEL TUBE -> S1, S2 (TOP VIEW)

-> CONNECT VERTICAL ANGLE & ANGLED BEARING

4.75" 16.75" 1.5"

-> FRONT

1.5" 2.75"

1.5"

TOP VIEW

TOP VIEW

c) 3.6" x 3.5" STEEL TUBE -> S1, S2 (BOTTOM VIEW)

-> CONNECT CASTERS

4.75"

-> FRONT

TOP VIEW

* 5/16"-18 HOLE SIZE

-> THREADED IN STEEL TUBE

* 1/2"-13 HOLE SIZE

-> CONNECT 8" L-BRACKET

* 9/16"-12 HOLE SIZE

-> CONNECT ANGLED 30/60 BEARING

* 3/16"-16 HOLE SIZE

-> HOLES ALIGNED W/ CASTER PLATE HOLES
HOLE LAYOUT - SPECIMEN MOUNT

a) I-BEAM (TOP VIEW)
→ CONNECTS 1/4" PLATE TO I-BEAM
- FRONT FACE
- SIDE 1

b) U-CHANNEL (TOP VIEW)
→ CONNECTS 1/4" PLATE TO U-CHANNEL
- FRONT
- SIDE 1

C) U-CHANNEL (FRONT VIEW)
→ CONNECTS STEEL PLATE FRAME (0.12" THICK)
- SIDE 1

D) 1/4" STEEL PLATE (TOP VIEW)
→ CONNECTED TO U-CHANNEL & I-BEAM
- FRONT
- SIDE 1

*5/16"-18 HOLE SIZE
→ I-BEAM THREADED

*5/16"-18 HOLE SIZE
→ U-CHANNEL THREADED

*5/16"-18 HOLE SIZE
→ STEEL PLATE WAS THRU HOLE & COUNTERSUNK
### Appendix A.3: Furnace - Static

#### DEAD LOADS

<table>
<thead>
<tr>
<th>Framing Material</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Frame</td>
<td>Inner Cavity</td>
</tr>
<tr>
<td>3' x '5 x 5'</td>
<td>4' x 4' x 2'</td>
</tr>
<tr>
<td>Steel Sheets</td>
<td>Wall Type</td>
</tr>
<tr>
<td>425 lbs</td>
<td>Weight (lbs.)</td>
</tr>
<tr>
<td>Tube Steel</td>
<td>Back wall</td>
</tr>
<tr>
<td>140 lbs</td>
<td>131.6</td>
</tr>
<tr>
<td>Total Weight of Frame</td>
<td>Sidewalls</td>
</tr>
<tr>
<td>565 lbs</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Top/Bottom</td>
</tr>
<tr>
<td></td>
<td>93.7</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>350.3</td>
</tr>
</tbody>
</table>

**Total Weight**

| Furnace | 915 lbs |

**SIMPLY SUPPORTED BEAM/COLUMN CALCULATIONS FOR THE FURNACE FRAME**

<table>
<thead>
<tr>
<th>Top/Bottom</th>
<th>HSS Tube Equation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td></td>
<td>$I = (bd^3 - kh^3) ÷ 12$</td>
</tr>
<tr>
<td></td>
<td>Maximum Shear</td>
</tr>
<tr>
<td></td>
<td>$V = (wL) ÷ 2$</td>
</tr>
<tr>
<td></td>
<td>Maximum Moment</td>
</tr>
<tr>
<td></td>
<td>$M = (wL^2) ÷ 8$</td>
</tr>
<tr>
<td></td>
<td>Bending Stress</td>
</tr>
<tr>
<td></td>
<td>$\sigma = (MC) ÷ I$</td>
</tr>
<tr>
<td></td>
<td>Allowable Stress</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{max} = 0.6\sigma_y$</td>
</tr>
<tr>
<td></td>
<td>Deflection</td>
</tr>
<tr>
<td></td>
<td>$\Delta = (5wL^4) ÷ (384EI)$</td>
</tr>
<tr>
<td></td>
<td>Allowable Deflection</td>
</tr>
<tr>
<td></td>
<td>$\Delta_{max} = L ÷ 240$</td>
</tr>
<tr>
<td></td>
<td>Shear Stress</td>
</tr>
<tr>
<td></td>
<td>$\tau = VQ/It$</td>
</tr>
</tbody>
</table>
### Variables
- **Moment of Inertia**
  \[ I = \frac{(bd^3 - kh^3)}{12} \]
  \[ = \frac{(1\text{in} \times 1^3\text{in} - 0.88\text{in} \times 0.88^3\text{in})}{12} \]
  \[ = 0.0334 \text{in}^4 \]

- **Maximum Shear & Maximum Moment**
  \[ w: \text{Distributed Load (lbs./ft.)} \]
  \[ L: \text{Length (ft.)} \]

- **Bending Stress**
  \[ M: \text{Max Bending (ft \times lbs.)} \]

- **Allowable Stress**
  \[ \Omega: 1.67 \]

- **Deflection**
  \[ E: \text{Elastic Modulus of Steel (psi)} \]

- **Shear Stress**
  \[ V: \text{Max Shear (lbs)} \]

- **Second Moment of Area (in}^4\)**
  \[ Q: \text{tube thickness (in.)} \]

### Sample Calculation
- **Moment of Inertia**
  \[ I = \frac{(bd^3 - kh^3)}{12} \]
  \[ = \frac{(1\text{in} \times 1^3\text{in} - 0.88\text{in} \times 0.88^3\text{in})}{12} \]
  \[ = 0.0334 \text{in}^4 \]

- **Loads**
  - **Insulation:** \[ = (1/3) \times (133 \text{ lbs}) = 44.33 \text{ lbs} \]
  - **Top Plate:** \[ = (1/3) \times [(5 \text{ ft} \times 4 \text{ ft}) \times (5 \text{ lbs/ft}^2)] = 33.33 \text{ lbs} \]
  - **Self weight:** \[ = 4 \text{ ft} \times (1.44 \text{ lbs/ft}) = 5.76 \text{ lbs} \]
  - **Total:** \[ = 83.42 \text{ lbs} \]
  - **Distributed:** \[ w = (83.42 \text{ lbs} \div 4 \text{ ft}) = 20.86 \text{ lbs/ft} \]

- **Maximum Shear**
  \[ V = \frac{(wL)}{2} \]
  \[ = [(20.86 \text{ lbs/ft}) \times (4 \text{ ft})] \div 2 \]
  \[ = 41.71 \text{ lbs} \]

- **Maximum Moment**
  \[ M = \frac{(wl^2)}{8} \]
  \[ = (20.86 \text{ lbs/ft} \times 4^2 \text{ ft}) \div 8 \]
  \[ = 41.71 \text{ ft} \times \text{lbs} \]
Bending Stress
\[ \sigma = \frac{(MC)}{I} = \frac{M}{S} \]
\[ = \left[\frac{((41.71 \text{ ft lbs} \times (12\text{in/ft})) \times (0.5 \text{ in})}{0.0334 \text{ in}^4}\right] = 7502 \text{ psi} \]
Allowable Stress
\[ \sigma_{\text{max}} = 0.6\sigma_y \]
\[ = 0.6 \times 46000 \text{ psi} \]
\[ = 27600 \text{ psi} \quad \text{OK} \]

Deflection
\[ \Delta = \frac{(5wL^4)}{(384EI)} \]
\[ = \frac{((5 \times (20.86 \text{ lbs/ft} \times 12\text{in/ft})) \times (4 \text{ ft} \times 12\text{in/ft})^4)}{(384 \times 29 \text{ ksi} \times 0.0334 \text{ in}^4)} \]
\[ = 0.124 \text{ inches} \]
Allowable Deflection
\[ \Delta_{\text{max}} = L \div 240 \]
\[ = (4\text{ ft} \times 12\text{in/ft}) \div 240 \]
\[ = 0.20 \text{ inches} \quad \text{OK} \]

Shear Stress
\[ \tau = \frac{VQ}{It} \]
\[ \tau = \frac{(41.7 \times 0.070)}{(0.033 \times 0.12)} \]
\[ \tau = 363.8 \text{ psi} \]
\[ 363.8 \text{ psi} \leq 27600 \text{ psi} \quad \text{OK} \]

<table>
<thead>
<tr>
<th>Results</th>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Units</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Tubes: 1”x1”, L=5’</td>
<td>Load: ( P )</td>
<td>lbs</td>
<td>108.2</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Deflection: ( \Delta )</td>
<td>in</td>
<td>0.13</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress: ( \sigma )</td>
<td>psi</td>
<td>472</td>
<td>27600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: ( \tau )</td>
<td>psi</td>
<td>63.8</td>
<td>27600</td>
<td></td>
</tr>
<tr>
<td>Top Tubes: 1”x1”, L=3’</td>
<td>Load: ( P )</td>
<td>lbs</td>
<td>59.3</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Deflection: ( \Delta )</td>
<td>in</td>
<td>0.118</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>
### Tributary Area:
The area of slab that is supported by a particular beam or column is known as the member's tributary area. To determine the dead load transmitted into a column or beam the tributary area is applied. Dead and live load per unit area are generated through its use.

### Tube Specifications:

<table>
<thead>
<tr>
<th>Bottom Tubes: 2&quot;x2&quot;, L=5'</th>
<th>Load: $P$</th>
<th>lbs</th>
<th>418.7</th>
<th>n/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Deflection: $\Delta$</td>
<td>in</td>
<td>0.057</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress: $\sigma$</td>
<td>psi</td>
<td>10742</td>
<td>27600</td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: $\tau$</td>
<td>psi</td>
<td>948</td>
<td>27600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom Tubes: 2&quot;x2&quot;, L=3'</th>
<th>Load: $P$</th>
<th>lbs</th>
<th>228.8</th>
<th>n/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Deflection: $\Delta$</td>
<td>in</td>
<td>0.052</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress: $\sigma$</td>
<td>psi</td>
<td>3522</td>
<td>27600</td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: $\tau$</td>
<td>psi</td>
<td>518</td>
<td>27600</td>
</tr>
</tbody>
</table>
HSS tube dimensions (b, d, h, k) Specify the respective inner and outer dimensions of tube steel. These dimensions are included in the majority of equations applied throughout this analysis. Each dimension and its representation is listed below:

- b: Outer Width
- h: Inner Width
- d: Outer Height
- k: Inner Height

**References:**

| Top/ Bottom Plate Equation(s) | Moment of Inertia  

\[ I = (bt^3) / 12 \]

Maximum Shear  

\[ V = (wL) / 2 \]

Maximum Moment  

\[ M = (wl^2) / 8 \]

Bending Stress  

\[ \sigma = (MC) / l \]

Allowable Stress  

\[ \sigma_{max} = 0.6\sigma_y \]

Deflection  

\[ \Delta = (5wl^4) / (384EI) \]

Allowable Deflection  

\[ \Delta_{max} = L / 240 \]

Shear Stress  

\[ \tau = VQ / It \]

| Variables | Moment of Inertia  

\[ b: Section Length (in.) \]

\[ t: Plate Thickness (in.) \]

Maximum Shear & Maximum Moment  

\[ w: Distributed Load (lbs./ft.) \]

\[ L: Length (ft.) \]
### Sample Calculation

#### Moment of Inertia

\[
I = (bt^3) / 12 \\
= (12\text{in} \times 0.12^3\text{in}) / 12 \\
= 0.00173\text{in}^4
\]

#### Loads

- **Insulation:** 133 lbs
- **Self Weight:** \([5\text{ ft} \times 4\text{ ft}] \times (5\text{ lbs/ft}^2)\) = 100 lbs
- **Total Top weight:** = 233 lbs
- **Weight on 12” slab:** \(223\text{ lbs} \div (20\text{ in} \times 12\text{in}) = 19.42\text{ lbs}
- **Distributed Weight:** \(w = 19.42\text{ lbs} ÷ (20\text{in}/12\text{in}/\text{ft}) = 11.6\text{ lbs/ft} = 0.96695\text{ lbs/in}

#### Maximum Shear

\[
V = (wL) / 2 \\
= [(0.967\text{ lbs/in}) \times (20\text{ in})] / 2 \\
= 9.67\text{ lbs}
\]

#### Maximum Moment

\[
M = (wl^2) / 8 \\
= (0.967\text{ lbs/in} \times (20)^2\text{in}) / 8 \\
= 48.35\text{ ft} \times \text{lbs}
\]

#### Bending Stress

\[
\sigma = (MC) / I = M / S \\
= [(48.35\text{ in lbs}) \times (0.06\text{ in})] / (0.00173\text{ in}^4)
\]
= 1679 psi
 allowable stress
 \[ \sigma_{max} = 0.6\sigma_y \]
 = 0.6 \times 46000 psi
 = 22800 psi

22800 psi \geq 1679 psi \text{ OK}

Deflection
\[ \Delta = \left(5wL^4\right) / \left(384EI\right) \]
\[ = \left(5 \times (0.96695 \text{ lbs/in}) \times (20 \text{ in})^4\right) / \left(384 \times 29 \text{ ksi} \times 0.0017 \text{ in}^4\right) \]
= 0.040 inches

allowable deflection
\[ \Delta_{max} = \frac{L}{240} \]
= \frac{20 \text{ in}}{240} = 0.0833 inches

0.083 inches \geq 0.04 inches \text{ OK}

shear stress
\[ \tau = \frac{VQ}{It} \]
\[ \tau = \frac{(9.7 \times 3)}{(0.0017 \times 0.12)} \]
\[ \tau = 20.14 \text{ psi} \]

20.14 psi \leq 22800 psi \text{ OK}

<table>
<thead>
<tr>
<th>Results</th>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Units</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top/ Bottom Plates: 5’x3’, t=¼”</td>
<td>Load: P</td>
<td>lbs</td>
<td>26.56</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Deflection: (\Delta)</td>
<td>in</td>
<td>0.006</td>
<td>0.083</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress: (\sigma)</td>
<td>psi</td>
<td>4781</td>
<td>22800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: (\tau)</td>
<td>psi</td>
<td>20</td>
<td>22800</td>
<td></td>
</tr>
</tbody>
</table>

Top/ Bottom Plates: 5’x3’, Load: P | lbs | 18.3 | n/a |
<table>
<thead>
<tr>
<th>t=⅛”</th>
<th>Max Deflection: Δ</th>
<th>in</th>
<th>0.038</th>
<th>0.083</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Bending Stress: σ</td>
<td>psi</td>
<td>1585</td>
<td>22800</td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: τ</td>
<td>psi</td>
<td>9.5</td>
<td>22800</td>
</tr>
</tbody>
</table>

**Sketch**

**Notes**

**Tributary Area:**
The area of slab that is supported by a particular beam or column is known as the member’s tributary area. To determine the dead load transmitted into a column or beam the tributary area is applied. Dead and live load per unit area are generated through its use.

**References:**

**Tube Column Equation(s)**

- Moment of Inertia
  \[ I = \frac{(bd^3 - kh^3)}{12} \]

- Cross Sectional Area
  \[ A = (bd - kh) \]

- Radius of Gyration
  \[ r = \sqrt{\frac{I}{A}} \]

- Slenderness Ratio
  \[ \lambda = \frac{L}{r} \]

- Critical Load
  \[ P_{cr} = \frac{\pi^2EI}{L^2} \]

**Variables**

- Moment of Inertia
  \[ b, d: Outside Length & Width \ (in.) \]
  \[ k, h: Inside Length & Width \ (in.) \]

- Radius of Gyration
  \[ I: Moment of Inertia \ (in^4) \]

- Slenderness Ratio
Sample Calculation

Slenderness:

Moment of Inertia: \( I = 0.033 \text{ in}^4 \)

Cross Sectional Area: \( A = (1 \text{ in} \times 1 \text{ in}) - (0.88 \text{ in} \times 0.88 \text{ in}) = 0.226 \text{ in}^2 \)

Radius of gyration: \( r = \sqrt{I/A} = \sqrt{0.33 \text{ in}^4/0.226 \text{ in}^2} = 0.385 \text{ inches} \)

Slenderness Ratio = \( L/r = 60 \text{ inches}/0.385 \text{ inches} = 156 \)
156 \( \geq 140 \) → long, slender column (Euler)

Critical Load:

\[
 P_{cr} = \frac{(\pi^2 EI)}{L^2} = \frac{\pi^2 \times 29 \text{ ksi} \times 0.033 \text{ in}^4}{(60 \text{ in})^2}
\]

\[ P_{cr} = 2652 \text{ lbs} \]

Actual Load:

Insulation: \( = (1/4) \times 133 \text{ lbs} = 33.25 \text{ lbs} \)
Top Plate: \( = (1/4) \times (100 \text{ lbs}) = 25 \text{ lbs} \)
Self weight: \( = 5 \text{ ft} \times 1.44 \text{ lbs/ft} = 7.2 \text{ lbs} \)
Total Weight: \( P = 65.45 \text{ lbs} \)

\[ P_{cr} \geq P \rightarrow 2652 \text{ lbs} \geq 65.45 \text{ lbs} \quad \text{OK} \]

### Results

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Units</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Column: ( 1&quot; \times 1&quot; , L=3' )</td>
<td>Load: ( P )</td>
<td>lbs</td>
<td>72.95</td>
<td>23242 (Pcr)</td>
</tr>
<tr>
<td>Tube Column: ( 1&quot; \times 1&quot; , L=5' )</td>
<td>Load: ( P )</td>
<td>lbs</td>
<td>65.45</td>
<td>23242 (Pcr)</td>
</tr>
</tbody>
</table>

### Sketch

Notes

The total load of the weight from the top of the furnace (insulation, steel plates, steel tubes, self-weight) is distributed evenly through the four columns as shown above.

### References:

Fixed End Beam/Column Calculations for the Furnace Frame

**Equation(s)**

- Maximum Shear \( V_{\text{max}} = \frac{wl}{2} \)
- Maximum Moment \( M_{\text{max}} = \frac{wl^2}{12} \)
- Maximum Deflection \( \Delta_{\text{max}} = \frac{wl^4}{384EI} \)

**Variables**
- \( w \) = distributed load (lbs/ft)
- \( l \) = length of member (ft)
- \( E \) = Elastic Modulus (psi)
- \( I \) = Moment of Inertia (in\(^4\))

**Sample Calculation**

5ft back wall, bottom beam (worst case)

\[ V = \frac{(63.6)(5)}{2} = 159 \text{ lbs} \]
\[ M_{\text{max}} = \frac{(63.6/12\text{in/ft})(5 \times 12\text{in/ft})^2}{12} = 1589 \text{ in} \times \text{lbs} \]
\[ \Delta_{\text{max}} = \frac{(63.6/12\text{in/ft})(5 \times 12\text{in/ft})^4}{384(29000000)(0.0333)} = 0.18 \text{ in.} \]

**Results**

<table>
<thead>
<tr>
<th>5ft Length Side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Distributed Load</strong></td>
</tr>
<tr>
<td>1&quot;x1&quot;x0.12&quot; Top Tubes</td>
</tr>
<tr>
<td>1&quot;x1&quot;x0.12&quot; Bottom Tubes</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
</tbody>
</table>

3ft Length Side

<table>
<thead>
<tr>
<th>1&quot;x1&quot;x0.12&quot; Top Tubes</th>
<th>16.9 lbs/ft</th>
<th>246 in*lbs</th>
<th>0.01 inches</th>
<th>0.15 inches</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>1&quot;x1&quot;x0.12&quot; Bottom Tubes</th>
<th>63.6 lbs/ft</th>
<th>945 in*lbs</th>
<th>0.04 inches</th>
<th>0.15 inches</th>
</tr>
</thead>
</table>

Beam/Column Calculations for the Furnace Frame

**Equation(s)**

Step 1: Determine the available tensile strength of bolts due to combined tension and shear loadings

\[ F'_{nt} = 1.3F_{nt} - \frac{\Omega F_{nt}}{F_{nv}} \cdot f_v \leq F_{nt} \]

Step 2: Determine the bending capacity moment of each connection

\[ \Omega M_n = \Omega F_y Z = 0.9F_y \left(\frac{bt^2}{4}\right) \]

Step 3: Compare bending capacity moment with expected maximum moment at each connection

**Variables**

- \( F_{nt} \): Nominal tensile strength of bolts (psi)
- \( F_{nv} \): Nominal shear strength of bolts (psi)
- \( f_v \): Required shear stress of bolts (psi)
- \( F_y \): Available tensile strength \( (F'_{nt}) \) (psi)
- \( b \): Length of the angle section of connection (in.)
- \( t \): Thickness of the connection (in.)

**Sample Calculation**

5"x5"x.016" angle bracket size

Step 1:

\[ F'_{nt} = 1.3(80,000) - \frac{2(80,000)}{(48,000)} \cdot (10,000) \]

\[ F'_{nt} = 70,667 \text{ psi} \]

Step 2:

\[ \Omega M_n = 0.67(70,667)\left(\frac{5(0.16)^2}{4}\right) \]
\[ \omega M_n = 1,515 \text{ in} \times \text{lbf} \]

Step 3:

Maximum moment per bolt = 795 in \times \text{lbf} \leq 1,515 \rightarrow \text{connection passes}

### Results

<table>
<thead>
<tr>
<th>Corner bracket size</th>
<th>Maximum expected moment on 3' Side</th>
<th>Maximum expected moment on 5' side</th>
<th>Bending moment capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>4''x4''x7/8''x0.12'' thick</td>
<td>212.5 in*lbf</td>
<td>795 in*lbf</td>
<td>682 in*lbf</td>
</tr>
<tr>
<td>5''x5''x1''x0.16'' thick</td>
<td>212.5 in*lbf</td>
<td>795 in*lbf</td>
<td>1,515 in*lbf</td>
</tr>
</tbody>
</table>

### Appendix A.4: Furnace- Dynamic

**Rolling Friction**

**Equation(s)***

\[ p = \frac{wa}{r} \]

**Variables***

\[ p: \text{Applied Force (lbf.)} \]

\[ w: \text{Weight (lbf.)} \]

\[ a: \text{Coefficient of Rolling Resistance (in.)} \]

\[ \text{Polyurethane on Concrete} \]

\[ r: \text{Radius (in.)} \]

**Sample Calculation***

\[ p = \frac{915 \times 0.3}{3} = 91.5 \text{ lbf} \]

**Results***

Furnace

\[ p = 91.5 \text{ lbf} \]

**Static Friction**

**Equation***

\[ P = \mu_s w \]

**Variables***

\[ \mu_s: \text{Coefficient of Static Friction} \]

\[ \text{Polyurethane on Concrete} \]

\[ w: \text{Weight (lbf.)} \]
Sample Calculation

\[ P = 0.7 \times 915 = 640.5 \text{ lbf} \]

Results

Furnace

\[ P = 640.5 \text{ lbf} \]

Critical Load of Furnace Frame Bracing

Equation(s)

\[ P = \frac{4\pi^2EL}{I^2} \]

Variables

\( E \): Elastic Modulus (psi)

\( I \): Moment of inertia (in\(^4\)) of bracing

\( L \): Length (in.)

Sample Calculation

1"x1"x0.12" Steel Tube (actual)

\[ P = \frac{4\pi^2 \times (29000000)(0.0333)}{36^2} = 29,682 \text{ lbs} \]

Significant Results

<table>
<thead>
<tr>
<th>Maximum Live Load (lbf)</th>
<th>Beam/Column Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>Simply Supported</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>L=6’</td>
<td>Max Bending Stress (psi)</td>
<td>16.865</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max Deflection (in)</td>
<td>0.3025</td>
</tr>
</tbody>
</table>

Overall Results
### 3ft Side

<table>
<thead>
<tr>
<th>Bracing</th>
<th>Critical Load (Pcr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>53 lbs</td>
</tr>
<tr>
<td>1” x 1” x 0.12” Tube</td>
<td>29,682 lbs</td>
</tr>
<tr>
<td>½” x ½” x 0.06” Tube</td>
<td>1,842 lbs</td>
</tr>
<tr>
<td>2” x 0.12” (w x t) Plate</td>
<td>254 lbs</td>
</tr>
</tbody>
</table>

### 5ft Side (Back wall)

<table>
<thead>
<tr>
<th>Bracing</th>
<th>Critical Load (Pcr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>53 lbs</td>
</tr>
<tr>
<td>1” x 1” x 0.12” Tube</td>
<td>10,609.1 lbs</td>
</tr>
<tr>
<td>½” x ½” x 0.06” Tube</td>
<td>663 lbs</td>
</tr>
<tr>
<td>2” x 0.12” (w x t) Plate</td>
<td>84 lbs</td>
</tr>
</tbody>
</table>

### Further Analysis of Furnace Frame Bracing

#### Equation(s)

Maximum Shear = \( V_{\text{max}} = \frac{19}{32}P \)

Maximum Moment = \( M_{\text{max}} = \frac{13}{64}Pl \)

Maximum Deflection = \( \Delta_{\text{max}} = \frac{0.015Pl^3}{EI} \)

#### Variables

- \( P \): Pushing load = 320 lbf
- \( E \): Elastic Modulus (psi)
- \( I \): Moment of inertia (in\(^4\)) of bracing
- \( l \): Length (in.)

#### Sample Calculation

\[ V_{\text{max}} = \frac{19}{32}(320) = 190 \text{ lb} \]
\[ M_{\text{max}} = \frac{13}{64} (320)(30) = 1950 \text{ in.}*\text{lbf} \]
\[ \Delta_{\text{max}} = \frac{0.015(320)(30)}{\left(\frac{29000000}{0.033}\right)} = 0.14 \text{ in.} \]

<table>
<thead>
<tr>
<th>Results</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{max}} )</td>
<td>93.42 lb*ft</td>
<td>11,700 lb*ft</td>
</tr>
<tr>
<td>Maximum Bending Stress</td>
<td>16,805 psi</td>
<td>27,600 psi</td>
</tr>
<tr>
<td>( \Delta_{\text{max}} )</td>
<td>0.0025”</td>
<td>0.125”</td>
</tr>
</tbody>
</table>

**Sketch**

**Push Location/Deflection Diagram**

**Notes**

**Push Location/ Deflection Diagram:**
The above sketch represents the most viable location for pushing the furnace when it needs to be moved. The left half of the diagram represents a side of the furnace, with a brace running horizontally. The arrow represents where the furnace should be pushed. All calculations were performed from this position. The right represents a deflection diagram of the column being pushed at the location marked by the arrow.
## Appendix A.5: Furnace- Thermal

### LINEAR EXPANSION

<table>
<thead>
<tr>
<th>Equation</th>
<th>( d_L = \alpha L_o dT )</th>
</tr>
</thead>
</table>

| Variables |  
|----------|----------------|
|  \( d_L \): Elongation (in.) |  
|  \( L_o \): Initial Length (in.) |  
|  \( w \): Weight (lbf.) |  
|  \( \alpha \): Thermal Expansion Coefficient of Carbon Steel \((\frac{\text{in.}}{\text{in.}^0 F})\) |  
|  \( d_T \): Temperature difference \((C^0)\) |  
|  \( A \): Expansion \((\text{in.}^2)\) |  
|  \( A_o \): Initial Area \((\text{in.}^2)\) |  

| Sample Calculation |  \( d_L = (6.5 \times 10^{-6}) \times 60(176 - 73) = 0.40 \) |

<table>
<thead>
<tr>
<th>Results</th>
<th>Tube Elongation in 2” ((23%))</th>
<th>( d_L )</th>
<th>( L_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.083</td>
<td>0.02 in.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.138</td>
<td>0.04 in.</td>
</tr>
</tbody>
</table>

| Notes | - Tube Elongation was chosen for a more conservative analysis, as the elongation in 2”= 35% for the Steel Sheet |

### RESULTANT AXIAL FORCES

| Equations | Axial Load due to Thermal Expansion  \( \sigma_{dt} = \alpha E dT \)  
|-----------|-----------------------------------|
|           |  \( F_T = \sigma_{dt} B_t \)  
|           | Section Area of Screw  \( A = \pi r^2 \)  
|           | Bearing Area of Screw  \( B_t = td \)  
|           | Bearing Area Stress  \( B_t = F/td \)  
|           | Shear Stress Average |
Shear Stress Avg. = \frac{F}{A}

Allowable Stress
Allowable = Ultimate Stress/Ω

### Variables
- Axial Load due to Thermal Expansion
  - \( F_T \): Axial Force (lbf.)
  - \( σ_{dt} \): Stress due to change in temperature (psi)
  - \( d_T \): Temperature difference (°C)
  - \( B_t \): Bearing Area of Screw (in.²)
  - \( α \): Thermal Expansion Coefficient of Carbon Steel (in./in.°F)
  - \( E \): Elastic Modulus of Steel (psi)
- Section Area of Screw
  - \( r \): Nominal radius of screw (in.)
- Bearing Area of Screw
  - \( t \): Thickness of Plate, HSS, Bracket (in.)
  - \( d \): Diameter of screw (in.)
- Bearing Area Stress
  - \( F \): Bearing Force of Screw (lbs.)
- Allowable Stress
  - Ultimate Stress: 60% of the Tensile Strength of the Screw (psi)
  - Ω : 1.67

### Sample Calculation
- Axial Load due to Thermal Expansion
  - \( σ_{dt} = (6.5 \times 10^{-6})(29 \times 10^6)(176 - 73) = 19416 \)
  - \( F_T = \frac{19416(0.03)}{2} = 291 \)
- Section Area of Screw
  - \( A = π(0.13)^2 = 0.049 \)
- Bearing Area of Screw
  - \( B_t = 0.125(0.25) = 0.03 \)
- Bearing Area Stress
  - \( B_t = (291 + 229)/0.03 = 16031 \)
- Shear Stress Average
  - \( Shear Stress Avg. = \frac{521}{.049} = 10614 \)
- Allowable Stress
  - \( Allowable = 120(0.6)/1.67 = 43114 \)
Results

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams &amp; Columns</td>
<td>L=5' Linear Expansion (in)</td>
<td>0.04</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>L=3' Linear Expansion (in)</td>
<td>0.02</td>
<td>0.083</td>
</tr>
<tr>
<td>Screw Type at</td>
<td>8-32 Shear Stress (psi)</td>
<td>27688</td>
<td>28743</td>
</tr>
<tr>
<td>Connection: Plate</td>
<td>10-24 Shear Stress (psi)</td>
<td>24548</td>
<td></td>
</tr>
<tr>
<td>Thickness= 0.25&quot;</td>
<td>1/4&quot;-28 Shear Stress (psi)</td>
<td>17051</td>
<td>43114</td>
</tr>
<tr>
<td>Screw Type at</td>
<td>8-32 Shear Stress (psi)</td>
<td>21088</td>
<td>28743</td>
</tr>
<tr>
<td>Connection: Plate</td>
<td>10-24 Shear Stress (psi)</td>
<td>15977</td>
<td></td>
</tr>
<tr>
<td>Thickness= 0.125&quot;</td>
<td>1/4&quot;-28 Shear Stress (psi)</td>
<td>10614</td>
<td>43114</td>
</tr>
</tbody>
</table>

Sketch

Bracket to Tube:
This diagram represents a corner connection between the furnace frame HSS and an L bracket. The yellow rectangles adjacent to the screws resemble the displacement of the tube steel due to resultant forces of thermal expansion (FT), which are imposed upon the screws in red.

Plate Tube:
The diagram to the right resembles the connection between the furnace frame HSS (light blue) and the steel plate (dark blue). Similarly to the diagram to the left, the yellow rectangles adjacent to the screws resemble the displacement of the tube steel due to resultant forces of thermal expansion (FT), which are imposed upon the screws in red.

References:

Appendix A.6: Specimen Mount-Static

<table>
<thead>
<tr>
<th>DEAD LOADS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Hardware</td>
<td>200 lbs</td>
</tr>
<tr>
<td>Concrete Specimen</td>
<td>1600 lbs</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>Specimen Mount</td>
<td>1800 lbs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>I-Beam</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equations</strong></td>
</tr>
<tr>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>$I = H^3b/12 + 2[h^3B/12 + hB(H + h)^2/4]$</td>
</tr>
<tr>
<td>Maximum Shear</td>
</tr>
<tr>
<td>$V = \text{Total Load}/2$</td>
</tr>
<tr>
<td>Maximum Moment</td>
</tr>
<tr>
<td>$M = (wl^2) \div 8$</td>
</tr>
<tr>
<td>Deflection</td>
</tr>
<tr>
<td>$\Delta = (5wL^4) \div (384EI)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Sample Calculation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loads</strong></td>
</tr>
<tr>
<td>Specimen: = 1600 lbs</td>
</tr>
<tr>
<td>I-Beam: = 28.5 lbs</td>
</tr>
<tr>
<td>Plate: = 51.05 lbs</td>
</tr>
<tr>
<td>Tube: = 4 ft * (2.94 lbs/ft) = 11.76 lbs</td>
</tr>
<tr>
<td>Total: = 1690 lbs</td>
</tr>
<tr>
<td>Distributed: = Total Load / Length of Beam = 1690/5 = 338.26 lbs/ft</td>
</tr>
<tr>
<td><strong>Moment of Inertia</strong></td>
</tr>
<tr>
<td>$I = H^3b/12 + 2[h^3B/12 + hB(H + h)^2/4]$</td>
</tr>
<tr>
<td>$I = 3^3.17/12 + 2[.17^3 \times 2.33/12 + .17 \times 2.33(3 + .17)^2/4]$</td>
</tr>
<tr>
<td>$I = 2.52 \text{ in}^4$</td>
</tr>
<tr>
<td><strong>Maximum Shear</strong></td>
</tr>
<tr>
<td>$V = \text{Total Load}/2$</td>
</tr>
<tr>
<td>$V = 1690/2$</td>
</tr>
<tr>
<td>$V = 845 \text{ lbs}$</td>
</tr>
<tr>
<td>845 lbs $\leq$ 10200 lbs $\text{OK (10,200 = Shear capacity of I beam)}$</td>
</tr>
<tr>
<td><strong>Maximum Moment</strong></td>
</tr>
<tr>
<td>$M = (wl^2) \div 8$</td>
</tr>
<tr>
<td>$M = (338.26 \text{ lbs/ft}) \times (5^2 \text{ ft}) \div 8$</td>
</tr>
<tr>
<td>$M = 1057 \text{ ft} \times \text{ lbs}$</td>
</tr>
<tr>
<td>1057 ft $\times$ lbs $\leq$ 4840 ft $\times$ lbs $\text{OK (4840 = max moment of I beam)}$</td>
</tr>
<tr>
<td><strong>Deflection</strong></td>
</tr>
<tr>
<td>$\Delta = (5wL^4) \div (384EI)$</td>
</tr>
<tr>
<td>$\Delta = (5 \times (4056 \text{ lbs/in}) \times (60\text{ in})^4) \div (384 \times 29 \text{ ksi} \times 2.52 \text{ in}^4)$</td>
</tr>
</tbody>
</table>
= 0.065 inches
0.065 in ≤ 0.25 in OK (0.065 = Deflection capacity of I beam)

<table>
<thead>
<tr>
<th>Results</th>
<th>Specimen Mount Component</th>
<th>Calculation</th>
<th>Units</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Beam</td>
<td>Load: ( P )</td>
<td>lbs</td>
<td>844.5</td>
<td></td>
<td>10200</td>
</tr>
<tr>
<td></td>
<td>Max Deflection: ( \Delta )</td>
<td>in</td>
<td>0.065</td>
<td></td>
<td>0.25</td>
</tr>
</tbody>
</table>

Notes
(references)

Sketch

Notes
**I Beam Dimensions:**
The sketch above is a cross section view of the I Beam included in the specimen mount design. Each dimension and its representation is listed below:
- A: Height
- B: Web Thickness
- C: Flange Width

**Bottom Tubes**

Equations
- Moment of Inertia
  \( I = \frac{(bd^3 - kh^3)}{12} \)
- Maximum Shear
  \( V = \frac{(wL)}{2} \)
- Maximum Moment
  \( M = \frac{(wL^2)}{8} \)
- Bending Stress
  \( \sigma = \frac{(MC)}{I} \)
- Allowable Stress
  \( \sigma_{max} = 0.6\sigma_y \)
- Deflection
  \( \Delta = \frac{(5wL^4)}{(384EI)} \)
- Allowable Deflection
  \( \Delta_{max} = \frac{L}{240} \)
- Shear Stress
  \( \tau = \frac{VQ}{It} \)

Variables
- Moment of Inertia
$b, d$: Outside Length & Width (in.)
$k, h$: Inside Length & Width (in.)
Maximum Shear & Maximum Moment
$w$: Distributed Load (lbs./ft.)
$L$: Length (ft.)

**Bending Stress**

$M$: Max Bending (ft * lbs.)

$C$: 1/2 Tube height/ width (in.)

$I$: Moment of Inertia (in$^4$)

**Allowable Stress**

$\Omega$: 1.67

**Deflection**

$E$: Elastic Modulus of Steel (psi)

**Shear Stress**

$V$: Max Shear (lbs)

$Q$: Second Moment of Area (in$^4$)

$t$: tube thickness (in.)

<table>
<thead>
<tr>
<th>Sample Calc</th>
<th>See Appendix A2: Furnace- Static</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Results</th>
<th><strong>Specimen Component</strong></th>
<th><strong>Calculation</strong></th>
<th>Units</th>
<th>Calculated</th>
<th>Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Tubes: 3.5&quot;x3.5&quot;, L=3'</td>
<td>Load: $P$</td>
<td>lbs</td>
<td>886.22</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Deflection: $\Delta$</td>
<td>in</td>
<td>0.019</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Bending Stress: $\sigma$</td>
<td>psi</td>
<td>7188</td>
<td>35928</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max Shear Stress: $\tau$</td>
<td>psi</td>
<td>1954</td>
<td>35928</td>
<td></td>
</tr>
</tbody>
</table>
## Appendix A.7: Specimen Mount - Dynamic

### Rolling Friction

<table>
<thead>
<tr>
<th>Equation(s)</th>
<th>( P = \frac{w \alpha}{r} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
<td>( P: \text{Applied Force (lbf.)} )</td>
</tr>
<tr>
<td></td>
<td>( w: \text{Weight (lbf.)} )</td>
</tr>
<tr>
<td></td>
<td>( \alpha: \text{Coefficient of Rolling Resistance (in.)} )</td>
</tr>
<tr>
<td></td>
<td>(Polyurethane on Concrete)</td>
</tr>
<tr>
<td><strong>Sample Calculation</strong></td>
<td>( P = \frac{1772 \times 0.3}{3} = 177.2 \text{ lbf} )</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td>Specimen Mount</td>
</tr>
<tr>
<td></td>
<td>( P = 177.2 \text{ lbf} )</td>
</tr>
</tbody>
</table>

### Static Friction

<table>
<thead>
<tr>
<th>Equation</th>
<th>( P = \mu_s w )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
<td>( \mu_s: \text{Coefficient of Static Friction} )</td>
</tr>
<tr>
<td></td>
<td>(Polyurethane on Concrete)</td>
</tr>
<tr>
<td></td>
<td>( w: \text{Weight (lbf.)} )</td>
</tr>
<tr>
<td><strong>Sample Calculation</strong></td>
<td>( P = 0.7 \times 1772 = 1240.4 \text{ lbf} )</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td>Specimen Mount</td>
</tr>
<tr>
<td></td>
<td>( P = 1240.4 \text{ lbf} )</td>
</tr>
</tbody>
</table>

### Notes

Cantilever Beam (Specimen Mount)

| Equation(s) | \( \text{Maximum Deflection} = \Delta \text{max} = \frac{P l^3}{3EI} \) |
Allowable Deflection = \( \Delta \) allowable = \( \frac{l}{240} \)

Variables

- \( P \): Pushing load = 620 lbf
- \( E \): Elastic Modulus (psi)
- \( I \): Moment of inertia (in\(^4\)) of beam
- \( l \): Length (in.)

Sample Calculation

Pushing at top of beam (48 in.)

\[
\Delta \text{ max} = \frac{(620)(48)^3}{3(29000000)(2.01)} = 0.39 \text{ in.}
\]

\[
\Delta \text{ allowable} = \frac{l}{240} = \frac{48}{240} = 0.2 \text{ in.}
\]

0.39 in. \( \geq \) 0.2 in. \( \rightarrow \) Fails

Results

<table>
<thead>
<tr>
<th>Pushing Point Height</th>
<th>( \Delta ) Maximum</th>
<th>( \Delta ) Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>48&quot;</td>
<td>0.39 inches</td>
<td>0.2 inches</td>
</tr>
<tr>
<td>36&quot;</td>
<td>0.17 inches</td>
<td>0.15 inches</td>
</tr>
</tbody>
</table>

Fails due to deflection \( \rightarrow \) Bracing is required

<table>
<thead>
<tr>
<th>Maximum Live Load (lbf)</th>
<th>Beam/Column Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>620</td>
<td>Pin-Roller Connection (With Bracing)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Furnace Component</th>
<th>Calculation</th>
<th>Calculated Value</th>
<th>Allowable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>Max Deflection between supports (in)</td>
<td>0.011</td>
<td>0.2</td>
</tr>
<tr>
<td>Columns</td>
<td>Max Deflection at overhang (in)</td>
<td>0.013</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Sketch

Notes

The two diagrams seen above represent pushing on the specimen mount with no bracing, which results in a failure due to deflection. A diagram representing the specimen mount with required bracing can be found below.
Appendix A.8: Burner Mount

### Static Analysis: Struts

<table>
<thead>
<tr>
<th>Results Provided by Manufacturer:</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Notes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The design loads given for strut beam loads are based on a simple beam condition using an allowable stress of 25,000 psi (Yield Stress of Steel/ Safety Factor). This allowable stress results in a safety factor of ( \frac{W}{1.67} ).</td>
</tr>
<tr>
<td>2.</td>
<td>To determine concentrated load capacity at mid span, multiply uniform load by 0.5 and corresponding deflection by 0.8.</td>
</tr>
<tr>
<td>3.</td>
<td>Loads are applied at the section centroid. Applied effective length factor ( K = 0.8 ) (fixed bottom, pinned top).</td>
</tr>
<tr>
<td>4.</td>
<td>To account for the slots/ holes, loads were reduced to 90% of the original calculations.</td>
</tr>
</tbody>
</table>

Appendix B: Burner Analysis
Appendix B.1: Heat Balance Analysis

A heat balance analysis was conducted to approximate the losses through the interior furnace walls, as well as enthalpy losses expected through the vent. Not only will the results of this analysis give insight on the size of the burner system required for this application, but it also provided intuition on furnace design criteria such as cavity and ventilation size.

Appendix B.1.1: Assumptions

A series of assumptions were made in order to simplify the heat balance analysis of system. These simplifications could be changed or modified, to better suit our understanding of the system. The first assumption made was to assume a quasi-steady state analysis in order to eliminate any storage terms in the energy balance. Specifically, it was determined that all enthalpy flow into the furnace would also be subjected to the walls and exhausted through the vent. Radiation losses through the vent were neglected due to the small surface area of the exhaust gases. The sensible enthalpy from the gases entering the furnace at ambient conditions was neglected.

In order to simplify the heat loss calculation through the furnace walls, it was assumed that the interior gas temperature was uniform resulting from complete stoichiometric combustion. Regarding the radiative heat transfer, furnace wall emissivity’s were assumed to be that of typical construction materials and gas emissivity’s were varied between 0.2 and 0.3 based on Hottel’s $H_2O$ and $CO_2$ emissivity charts. Additionally, the furnace walls and test specimen were assumed to be gray-bodies, and that the entire surface area of each wall was uniform in temperature.

Due to the complexity of determining a convective heat transfer coefficient in a changing thermal environment, the rate of heat transfer via convection was assumed to be a constant value of $50 \frac{W}{m^2 K}$. This approximation was made based upon the conclusions of a parametric analysis of heat transfer in Gypsum Wallboard by NIST.

In order to calculate the radiative losses to the furnace walls, a radiation network between the furnace walls, specimen wall, and hot gases was developed. The gases were assumed to cover the entire surface area within the furnace, therefore, the view factor between the gases and walls was assumed to be one.
The overall energy balance within the furnace is as follows:

**Energy In = Enthalpy of the Fuel + Enthalpy of the Air**

**Energy Out = Enthalpy of the Products Leaving the Vent + Heat Losses to Furnace Walls**

**Heat Source = HRR of the Burners**

Assuming the sensible enthalpy of the products entering the furnace is initially at 0:

\[
HRR = C_p \dot{m}_{total} (T_g - T_l) + \text{Convective Heat Losses} + \text{Radiative Heat Losses}
\]

\[
T_g = \frac{HRR - \text{Total Losses}}{C_p \dot{m}_{total}}
\]

**Convective Heat Loss** = \( H_{conv} A_{Furnace} (T_g - T_f) + H_{conv} A_{Specimen} (T_g - T_s) \)

**Radiative Heat Loss** = \[
\frac{1}{\varepsilon_g A_f F_{fg}} + \frac{1 - \varepsilon_f}{A_f \varepsilon_f} \left( \frac{1}{\varepsilon_g A_s F_{sg}} + \frac{1 - \varepsilon_f}{A_s \varepsilon_s} \right)
\]

Appendix B.1.2: Furnace Heat Balance Analysis and Results

The heat lost to the system was calculated through multiple iterations of the energy balance described above. To begin this process, a radiative heat transfer coefficient needed to be estimated for an accurate representation of heat transfer within the furnace. This value was obtained by assuming a constant gas temperature relative to ASTM E119 time-temperature curve. An initial heat loss was approximated by varying the wall and specimen temperatures 10-150 degrees Celsius below the gas temperature. The resulting radiative heat transfer coefficient was added to the convective heat transfer coefficient in order to approximate a more accurate furnace and specimen wall temperature. Given the furnace walls to be thermally thick, the surface
temperature of the insulation and specimen could be calculated using Drysdale eq. 2.26. To be consistent with the apparatus design, the furnace walls were given the properties of the Cerachem insulation. Furthermore, the specimen was assumed to have the thermal properties of a concrete wall as it would create a large heat sink within the furnace. Following this step, the heat loss to the interior walls of the furnace could be recalculated and used to approximate a heat release rate (HRR) that would satisfy the energy balance for the system and estimate a uniform gas temperature within the furnace.

For this analysis, it was of critical importance to estimate the losses when the interior gas temperatures conformed to the ASTM E119 time-temperature curve. Therefore, this process was iterated to estimate the required HRR to sustain these gas temperatures at specific time intervals. The constant gas temperatures used in the iterations were consistent with the ASTM E119 time-temperature curve as seen in the figure below. Table 9 indicates the resulting heat losses and HRR required at each time interval. Sample calculations for the described process are outlined in the following section.

![Figure 21: Replicated ASTM E119 Time-Temperature Curve and Constant Gas Temperatures used for Iteration Process](image)

The results of the heat balance analysis show that the heat loss to the walls range from 43 kW to 57 kW when the surface area of the inner cavity is approximately 6 $m^2$. A reduction in cavity size resulted in a noticeable decrease in the heat lost to the walls. As expected, the losses peaked during the first 600 seconds due to the rapid temperature rise inside the furnace where convective losses are critical. As the gas temperatures increased, heat loss via radiation became dominant. As such, it is recommended to provide a burner system with an output of 200 kW in order to provide sufficient heat output when conducting standardized or performance based fire testing.
Table 9: Heat Losses and HRR at Different Time Intervals

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Total Heat Transfer Coefficient (W/m² K)</th>
<th>Average Heat Loss to walls (kW)</th>
<th>HRR (kW)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>72</td>
<td>57</td>
<td>101</td>
<td>810</td>
</tr>
<tr>
<td>600</td>
<td>86</td>
<td>56</td>
<td>103</td>
<td>937</td>
</tr>
<tr>
<td>900</td>
<td>94</td>
<td>51</td>
<td>102</td>
<td>1,000</td>
</tr>
<tr>
<td>1,200</td>
<td>98</td>
<td>52</td>
<td>104</td>
<td>1,027</td>
</tr>
<tr>
<td>1,500</td>
<td>100</td>
<td>48</td>
<td>102</td>
<td>1,053</td>
</tr>
<tr>
<td>1,800</td>
<td>106</td>
<td>46</td>
<td>103</td>
<td>1,086</td>
</tr>
<tr>
<td>2,100</td>
<td>108</td>
<td>43</td>
<td>101.5</td>
<td>1,105</td>
</tr>
<tr>
<td>2,400</td>
<td>110</td>
<td>44</td>
<td>102</td>
<td>1,119</td>
</tr>
<tr>
<td>2,700</td>
<td>114</td>
<td>45</td>
<td>102</td>
<td>1,130</td>
</tr>
<tr>
<td>3,000</td>
<td>119</td>
<td>45</td>
<td>104</td>
<td>1,160</td>
</tr>
<tr>
<td>3,300</td>
<td>127</td>
<td>48</td>
<td>105</td>
<td>1,175</td>
</tr>
<tr>
<td>3,600</td>
<td>135</td>
<td>51</td>
<td>110</td>
<td>1,200</td>
</tr>
</tbody>
</table>

Appendix B.1.2.1: Heat Balance Analysis Sample Calculations

**Step 1: Calculate a radiative heat transfer coefficient**

In order to estimate the heat losses under a standard time-temperature curve, the gas temperature was initially assumed to be 810K. According to the ASTM E119 standard time-temperature curve, the first 300 seconds of the test require that the temperatures within the test apparatus be approximately 810K. Tf and Ts were varied from 10-120 °C less than the Tg, to calculate a heat loss due to radiation. The emissivity of the furnace and wall (εf) were kept at 0.8, while the gas emissivity was done at both 0.2 and 0.3, and the results from the calculation were averaged to estimate a radiative heat transfer coefficient. This average value was then added to the convective heat transfer coefficient (50 kW/m² K) to approximate the total heat transfer coefficient within the furnace. An example calculation can be seen below.
The average radiative heat transfer coefficient at 300 seconds was estimated to be 0.022 \( \text{kW}/\text{m}^2\text{K} \). The radiative heat transfer coefficient was then added to the convective heat transfer...
coefficient (0.050 $kW/m^2K$) in order to obtain a total heat transfer coefficient in the test apparatus. A more accurate furnace and specimen wall temperature could then be calculated.

**Step 2: Calculate furnace wall and specimen temperatures**

Surface temperatures were calculated at 30 second intervals up to 300 seconds using a constant gas temperature of 810 °C. Note that $h$ is the total heat transfer coefficient determined in the previous step. A sample calculation of the cerachem insulation temperature can be seen below.

\[
\frac{T_t - T_o}{T_\infty - T_o} = 1 - \exp\left(\frac{at}{(k/h)^2}\right) \text{erfc}\left(\frac{\sqrt{at}}{(k/h)}\right)
\]

**Known Values (Cerachem)**

<table>
<thead>
<tr>
<th>Time</th>
<th>0-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$</td>
<td>810</td>
</tr>
<tr>
<td>$T_o$</td>
<td>293</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>5.67E-08</td>
</tr>
<tr>
<td>$K$</td>
<td>0.51 W/mK</td>
</tr>
<tr>
<td>Density</td>
<td>1250 kg/m$^3$</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>1050 J/kgK</td>
</tr>
<tr>
<td>$hr+hc$</td>
<td>70 W/mK</td>
</tr>
<tr>
<td>Density</td>
<td>1250 kg/m$^3$</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>1050 J/kg K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>2.61 E-06</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\frac{(293 - 293)}{810 - 293} &= 1 - \exp\left(\frac{3.89 \times 10^{-7}t}{(0.51/72)^2}\right) \text{erfc}\left(\frac{\sqrt{2.61 \times 10^{-6} t}}{(0.51/72)}\right) = 550 K \\
\frac{(293 - 293)}{810 - 293} &= 1 - \exp\left(\frac{3.89 \times 10^{-7}t}{(0.51/72)^2}\right) \text{erfc}\left(\frac{\sqrt{2.61 \times 10^{-6} t}}{(0.51/72)}\right) = 575 K \\
\frac{(293 - 293)}{810 - 293} &= 1 - \exp\left(\frac{3.89 \times 10^{-7}t}{(0.51/72)^2}\right) \text{erfc}\left(\frac{\sqrt{2.61 \times 10^{-6} t}}{(0.51/72)}\right) = 750 K
\end{align*}
\]
Step 3: Calculate overall heat loss (convective and radiative)

The estimated furnace and specimen temperatures were used to calculate the combined convective and radiative losses at each time interval (30 – 300 seconds). As stated in the first step of the heat balance analysis, gas emissivities were varied between 0.2 and 0.3. A sample calculation can be seen below.

At time = 30 seconds

\[
Q_{\text{loss}} = \frac{\sigma(810^4 - 500^4)}{0.3 * 5.2} + \frac{\sigma(810^4 - 500)}{0.3 * 1.486} = 29 \, kW
\]

\[
Q_{\text{loss}} = \frac{\sigma(810^4 - 500^4)}{0.2 * 5.2} + \frac{\sigma(810^4 - 500)}{0.2 * 1.486} = 16 \, kW
\]

\[
Q_{\text{loss convective}} = 50 * 5.2 (810 - 500) + 50 * 1.486(810 - 430) = 64 \, kW
\]

Heat loss results from first iteration (constant gas temperature of 810 K)

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Total Heat Loss (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>89</td>
</tr>
<tr>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>90</td>
<td>63</td>
</tr>
<tr>
<td>120</td>
<td>57</td>
</tr>
<tr>
<td>150</td>
<td>53</td>
</tr>
<tr>
<td>180</td>
<td>50</td>
</tr>
<tr>
<td>210</td>
<td>47</td>
</tr>
<tr>
<td>240</td>
<td>45</td>
</tr>
<tr>
<td>270</td>
<td>43</td>
</tr>
<tr>
<td>300</td>
<td>41</td>
</tr>
</tbody>
</table>

Step 4: Recalculate Gas Temperature

After calculating the radiative and convective losses in the furnace, it was necessary to estimate a HRR that would maintain the gas temperature within the furnace relative to the standard time-temperature curve. For the first iteration, the gas temperature is required to be approximately 810 K. A stoichiometric mass flow rate for the combustion of propane and air was determined to be
0.0166 kg/s. The specific heat of air at ambient temperature was used for simplicity. Results from the first iteration can be seen below.

\[ T_{gu} = \frac{HRR - \text{Losses}}{c_p \cdot m} \]

<table>
<thead>
<tr>
<th>HRR:</th>
<th>Input Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_p )</td>
<td>1.01 ( \text{kJ/kg} \cdot \text{K} )</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>0.0166 kg/s (stoichiometric)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Heat Loss</th>
<th>HRR</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>88</td>
<td>115</td>
<td>810</td>
</tr>
<tr>
<td>60</td>
<td>72</td>
<td>100</td>
<td>810</td>
</tr>
<tr>
<td>90</td>
<td>63</td>
<td>90</td>
<td>810</td>
</tr>
<tr>
<td>120</td>
<td>57</td>
<td>86</td>
<td>810</td>
</tr>
<tr>
<td>150</td>
<td>53</td>
<td>83</td>
<td>810</td>
</tr>
<tr>
<td>180</td>
<td>50</td>
<td>79</td>
<td>810</td>
</tr>
<tr>
<td>210</td>
<td>47</td>
<td>74</td>
<td>810</td>
</tr>
<tr>
<td>240</td>
<td>45</td>
<td>71</td>
<td>810</td>
</tr>
<tr>
<td>270</td>
<td>43</td>
<td>69</td>
<td>810</td>
</tr>
<tr>
<td>300</td>
<td>41</td>
<td>67</td>
<td>810</td>
</tr>
</tbody>
</table>
Appendix C: Insulation Analysis

Appendix C.1: Morgan Advanced Materials Simulation

Morgan Advanced Materials gave us access to a program to vary the types of insulation they offer while also varying the thickness of each material and then output various parameters that were used to help guide material selection and served as a point of reference for the hand calculations. The first step in using the simulation is shown in Figure 22, where the program asks for input parameters about the simulated environment. Information needed includes the ambient velocity, emissivity, ambient temperature, and hot face temperature. In this simulation, an ambient velocity was not used (based on the assumption that there would be stagnant air around the furnace), an emissivity of 0.9, and ambient temperature of 27°C, and a hot face temperature of 1000°C.

The next step, shown in Figure 23, requires input of the enclosure geometry, options include a wall, a roof, a floor, and a vertical or horizontal cylinder. The wall, roof, and floor options differ in orientation and the way the heat is expected to flow through each option. If either of the cylinder parameters were used, then further information was required about the diameter of either the inside or outside surface and a diameter input.
The third step in the simulation is the selection of the material desired within the furnace. There is a drop down menu with 16 different material types (blankets, microporous, firebrick, etc.) and specific materials listed under each category. As seen in Figure 24, under the blankets category, various types of Cerablanket are listed with varying density and continuous use limit temperatures. The blue circle to the left of the product name shows more properties about the material, including the thermal conductivity and specific heat.

The final step of the simulation, shown in Figure 25, is calculating the cold face temperature, heat loss, and heat storage will be based on the layers with designated thicknesses, along with the interface temperature between each layer. The resulting numbers are based on the performance
of materials in the manufacturer’s testing. For the insulation layout, the resulting cold face temperature is 74°C, the heat loss is 640.8 W/m², and the heat storage is 11,032.7 kJ/m².

![Figure 25: Final Step of Morgan Simulation: Calculating Temperature, Heat Loss, and Heat Storage](image)

The heat losses and storage were related to the hand calculations by applying an area to the heat flux provided from the simulation, and 2.6 kW of heat were lost and 19 kW of heat were stored. The numbers from the Morgan simulation were used as a base to compare the steady-state hand calculations and a full comparison can be seen in Appendix C.4.
Appendix C.2: No Air Gap Steady-State Calculations
A series of calculations were performed at steady-state conditions to understand the heat loss and heat storage through the walls. Calculation input parameters can be seen in the tables below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m*K)</th>
<th>Length (mm)</th>
<th>Density (kg/m$^3$)</th>
<th>Specific Heat (kJ/kg*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerachem</td>
<td>0.34</td>
<td>25</td>
<td>128</td>
<td>1.13</td>
</tr>
<tr>
<td>Cerablanket</td>
<td>0.34</td>
<td>150</td>
<td>128</td>
<td>1.13</td>
</tr>
<tr>
<td>WDS Ultra</td>
<td>0.04</td>
<td>12</td>
<td>231</td>
<td>0.945</td>
</tr>
<tr>
<td>Steel</td>
<td>51.9</td>
<td>3.175</td>
<td>2400</td>
<td>0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Face</th>
<th>Area (m$^2$)</th>
<th>Volume Cerachem (m$^3$)</th>
<th>Volume Cerablanket (m$^3$)</th>
<th>Volume WDS Ultra (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back wall</td>
<td>2.323</td>
<td>0.0581</td>
<td>0.3485</td>
<td>0.0278</td>
</tr>
<tr>
<td>Sidewall</td>
<td>1.103</td>
<td>0.0275</td>
<td>0.1655</td>
<td>0.0188</td>
</tr>
<tr>
<td>Top/Bottom</td>
<td>0.827</td>
<td>0.0207</td>
<td>0.1241</td>
<td>0.0141</td>
</tr>
</tbody>
</table>

First, the mass of the insulation was calculated to help in the structural analysis portion as well as the storage analysis. The weight was determined by multiplying the volume of each layer by the density of the layer and in the end summed up the weight of each layer on the various wall faces. A sample calculation can be seen below and the table below shows the overall calculations for each layer on each face.

Back wall Cerachem: $0.0581 \text{ m}^3 \times 128 \text{ kg/m}^3 = 7.437 \text{ kg}$

<table>
<thead>
<tr>
<th>Wall Face</th>
<th>Cerachem (kg)</th>
<th>Cerablanket (kg)</th>
<th>WDS Ultra (kg)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back wall</td>
<td>7.437</td>
<td>44.608</td>
<td>6.422</td>
<td>58.467</td>
</tr>
<tr>
<td>Sidewall</td>
<td>3.52</td>
<td>21.184</td>
<td>4.343</td>
<td>29.047</td>
</tr>
<tr>
<td>Top/Bottom</td>
<td>2.65</td>
<td>15.885</td>
<td>3.257</td>
<td>21.791</td>
</tr>
</tbody>
</table>

The total weight of the insulation in the furnace is approximately 160 kg (350 lbs).
Next, we performed calculations for the heat loss through the walls by means of conduction using the equation below

\[ q = \frac{T_h - T_\infty}{\sum R} \text{where } \sum R = \frac{L_n}{k_n} \]

- \( q \) is the heat flux through the walls
- \( T_h \) is the hot face temperature
- \( T_\infty \) is the ambient temperature
- \( L_n \) is the length of the layer
- \( k_n \) is the thermal conductivity of the layer

This analysis was completed on a 5 ft by 5 ft by 3 ft furnace size with 187 mm (7.5 inches) of insulation along with 3.175 mm (1/8 inch) plate of steel. Sample calculations for the conduction through the insulation on the back wall can be seen below using the assumptions the convective heat transfer coefficients are 72 W/m\(^2\)K inside the furnace (based on the heat balance analysis) and 25 W/m\(^2\)K outside the furnace.

<table>
<thead>
<tr>
<th>Resistances</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 ) = ( \frac{L_{\text{cerachem}}}{k_{\text{cerachem}}} ) = ( \frac{0.025 \text{ m}}{0.34 \text{ W/m} \cdot \text{K}} ) = 0.0735 K/W</td>
<td></td>
</tr>
<tr>
<td>( R_2 ) = ( \frac{L_{\text{cerablanket}}}{k_{\text{cerablanket}}} ) = ( \frac{0.15 \text{ m}}{0.34 \text{ W/m} \cdot \text{K}} ) = 0.4412 K/W</td>
<td></td>
</tr>
<tr>
<td>( R_3 ) = ( \frac{L_{\text{WDUitra}}}{k_{\text{WDUitra}}} ) = ( \frac{0.012 \text{ m}}{0.04 \text{ W/m} \cdot \text{K}} ) = 0.3 K/W</td>
<td></td>
</tr>
<tr>
<td>( R_4 ) = ( \frac{L_{\text{steel}}}{k_{\text{steel}}} ) = ( \frac{51.9 \text{ W/m} \cdot \text{K}}{0.003175 \text{ m}} ) = 0.0000612 K/W</td>
<td></td>
</tr>
<tr>
<td>( \sum R = \frac{1}{h_i} + R_1 + R_2 + R_3 + R_4 + \frac{1}{h_0} )</td>
<td></td>
</tr>
<tr>
<td>( \sum R = 0.0735 + 0.4412 + 0.3 + 0.0000612 + 1 )</td>
<td></td>
</tr>
<tr>
<td>( \sum R = 0.8686 )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat Flux</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q = \frac{T_h - T_\infty}{\sum R} ) = ( \frac{1000\degree \text{C} - 27\degree \text{C}}{0.8686} )</td>
<td></td>
</tr>
<tr>
<td>( q = 1120.19 \text{ W} = 1.1 \text{ kW/m}^2 )</td>
<td></td>
</tr>
</tbody>
</table>

Heat loss through each type of wall is determined by multiplying the heat flux by the area of the wall, the results can be seen in Table 13 below.

<table>
<thead>
<tr>
<th>Heat Loss</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q = q \cdot A )</td>
<td></td>
</tr>
<tr>
<td>( Q = 1120.19 \text{ W/m}^2 \cdot 2.323 \text{ m}^2 )</td>
<td></td>
</tr>
<tr>
<td>( Q = 2602.2 \text{ W} = 2.6 \text{ kW} )</td>
<td></td>
</tr>
</tbody>
</table>
Table 13: Heat Loss Through Each Wall Face

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Q (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back wall</td>
<td>2.6</td>
</tr>
<tr>
<td>Sidewall</td>
<td>2.5</td>
</tr>
<tr>
<td>Top/Bottom</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The total heat loss through the walls through a means of conduction is 7 kW. Calculations were also performed on a 60 inch by 60 inch concrete specimen that is 4 inches thick with a thermal conductivity of 0.8 W/m*K. The concrete wall is believed to be the most conservative anticipated specimen.

### Resistances Sample Calculations

\[
R = \frac{1}{\frac{h_i}{h_{o,\text{concrete}}} + \frac{1}{\frac{1}{k_{\text{concrete}}} + \frac{0.1 \text{ m}}{25 \text{ W/m}^2 \cdot \text{K}}}}
\]

\[
R = \frac{72 \text{ W/m}^2 \cdot \text{K}}{0.8 \text{ W/m} \cdot \text{K}} + \frac{1}{25 \text{ W/m}^2 \cdot \text{K}}
\]

\[
R = 0.179
\]

### Heat Loss Sample Calculations

\[
Q = \frac{T_h - T_c}{\sum R} \cdot A
\]

\[
Q = \frac{1000^\circ \text{C} - 27^\circ \text{C}}{0.179} \cdot 2.323 \text{ m}^2
\]

\[
Q = 12,163.636 \text{ W} = 12.2 \text{ kW}
\]

A temperature profile was determined using the heat flux, inside temperature of the furnace, and the resistances. Sample calculations can be seen below and Figure 25 below shows the temperatures between each layer.

### Temperature Profile Sample Calculations

\[
q = \frac{T_h - T_1}{\frac{1}{h_{i,\text{concrete}}} + R_1}
\]

\[
1120.19 \text{ W/m}^2 = \frac{1000^\circ \text{C} - T_1}{\frac{1}{72 \text{ W/m}^2 \cdot \text{K}} + 0.0735 \text{ K/W}}
\]

\[
T_1 = 902.11^\circ \text{C}
\]

\[
q = \frac{T_1 - T_2}{R_2}
\]

\[
1120.19 \text{ W/m}^2 = \frac{902.11^\circ \text{C} - T_2}{0.4412 \text{ K/W}}
\]

\[
T_2 = 407.88^\circ \text{C}
\]
Finally, the heat storage of each layer was determined using the temperatures as shown in the figure below. First, the average temperature change between each layer was calculated and then the mass and the specific heat were used to find the heat storage using the following equation:

\[ Q = \dot{m} c_p T \]

The mass of each blanket on the different wall types was previously calculated, the specific heat is a property of each insulation type, and the average temperature change between the layers is determined below:

\[ T_1 = \frac{1000^\circ C + 902^\circ C}{2} - 27^\circ C = 924^\circ C = 1197 \text{ K} \]
Sample Calculations

\[
T_2 = \frac{902 \degree C + 408 \degree C}{2} - 27 \degree C = 628 \degree C = 901 K
\]

\[
T_3 = \frac{408 \degree C + 72 \degree C}{2} - 27 \degree C = 213 \degree C = 486 K
\]

Heat Storage on Back Wall Sample Calculations

\[
Q_{\text{cerachem}} = 7.437 \text{ kg} \times (1.13 \text{ kJ/kg} \times K) \times 1197 K
\]

\[
Q_{\text{cerachem}} = 10,059.36 \text{ kJ}
\]

\[
Q_{\text{cerablanket}} = 44.608 \text{ kg} \times (1.13 \text{ kJ/kg} \times K) \times 901 K
\]

\[
Q_{\text{cerablanket}} = 45,416.74 \text{ kJ}
\]

\[
Q_{\text{WDS Ultra}} = 6.422 \text{ kg} \times (0.945 \text{ kJ/kg} \times K) \times 486 K
\]

\[
Q_{\text{WDS Ultra}} = 2,949.43 \text{ kJ}
\]

These calculations were performed for each wall type and the total heat storage for all five sides is 159,516.06 kJ, and over a period of 3600 seconds (1 hour), there is 44.31 kW of heat stored. This process was also performed on the 60 inch by 60 inch concrete wall that is 4 inches thick and has a specific heat of 0.75 kJ/kg\(^\circ\)C and a density of 2400 kg/m\(^3\). There is 59.1 kW of heat stored in a 3600 second (1 hour) period.

Heat Storage for Concrete Specimen Sample Calculations

\[
\dot{m} = 2.323 \text{ m}^2 \times 0.1 \text{ m} \times 2400 \text{ kg/m}^3 = 557.52 \text{ kg}
\]

\[
T = \frac{1000 \degree C + 72 \degree C}{2} - 27 \degree C = 509 \degree C = 782 K
\]

\[
Q = 557.52 \text{ kg} \times (0.75 \text{ kJ/kg} \times \degree C) \times 782 K
\]

\[
Q = 326,985.48 \text{ kJ}
\]
Appendix C.3: Three layers and Air Gap Hand Calculations

Similar calculations as above are calculated with a 1 inch air gap behind the WDS Ultra material as an additional insulating layer. The properties of air seen in Table 14 below are from Table A-15 in the *Heat and Mass Transfer Fundamentals & Applications* textbook.

<table>
<thead>
<tr>
<th>Table 14: Select Parameters and Properties of Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>L (m)</td>
</tr>
<tr>
<td>k (W/m*K)</td>
</tr>
<tr>
<td>ν(m²/s)</td>
</tr>
<tr>
<td>α (m²/s)</td>
</tr>
</tbody>
</table>

In the air gap analysis, the Nusselt number is calculated to nondimensionalize the convective equations. The Nusselt number is found by using other nondimensionalized terms based on the properties of the material. First is the Prandtl number found by dividing the molecular diffusivity of momentum by the molecular diffusivity of heat (ν and α respectively). Next, the Grashof number is determined using the temperature conditions and thickness and is 1 divided by the average temperature (represented in Kelvin). Then the Rayleigh number is found by multiplying the Prandtl and Grashof numbers together. These three numbers help determine the Nusselt number equation, which can vary depending on the orientation and geometry of the object being analyzed, in this case, it varies between being horizontal and vertical enclosures. Sample calculations shown below are for the back face wall assuming a vertical enclosure.

<table>
<thead>
<tr>
<th>Vertical Enclosure</th>
<th>Air Gap Sample Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr = \frac{v}{α} = \frac{2.097 * 10^{-5} \text{ m}^2/\text{s}}{2.931 * 10^{-4} \text{ m}^2/\text{s}}</td>
<td></td>
</tr>
<tr>
<td>Pr = 0.7155</td>
<td></td>
</tr>
<tr>
<td>Gr = \frac{g<em>β</em>(T_s - T_∞)*L_c^3}{ν^2}</td>
<td></td>
</tr>
<tr>
<td>Gr = \frac{(9.8 \text{ m/s}^2)(1}{322.5 \text{ K}) \frac{(345 \text{ K} - 300 \text{ K})(0.025)^3}{(2.097 * 10^{-5} \text{ m}^2/\text{s})^2}</td>
<td></td>
</tr>
<tr>
<td>Gr = 48,588.34</td>
<td></td>
</tr>
<tr>
<td>Ra = Pr * Gr = 0.7155 * 48,588.34</td>
<td></td>
</tr>
<tr>
<td>Ra = 34,764.96</td>
<td></td>
</tr>
<tr>
<td>H = 1.524 m</td>
<td></td>
</tr>
<tr>
<td>\frac{L}{0.025 m} = 60.96</td>
<td></td>
</tr>
</tbody>
</table>

Using these parameter along with a tall enclosure (60 inches tall by 1 inch wide), the following Nusselt equation is used:
This equation has the criteria of $10 < \frac{H}{L} < 40$, $1 < Pr < 2 \times 10^4$, and $10^4 < Ra < 10^7$, and although it does not meet the criteria for $\frac{H}{L}$ or the $Pr$ number, it meets the criteria for a $Ra$ number closer than the other equation for tall vertical enclosures. Thus, the $Nu$ number for the back face is:

$$Nu = 0.42 \times Ra^{\frac{1}{4}} \times Pr^{0.012} \times \left(\frac{H}{L}\right)^{-0.3}$$

This $Nu$ number will then be used in the following equation to help determine the heat loss through the gap:

$$q = h(T_1 - T_2) = \frac{k \times Nu(T_1 - T_2)}{L}$$

Since the convective heat transfer coefficient $h = k \times Nu/L$, it can be added to the resistance previously calculated for the three layers plus the steel sheet along with a radiative term that occurs through the gap, which can be found using the equation below:

$$h_{rad} = \varepsilon \sigma(T_1^2 + T_2^2)(T_1 + T_2)$$

Where $\varepsilon$ is the emissivity of the gas, assumed to be 0.8, and $\sigma$ is the Stefan-Boltzmann constant.

In the air gap, there are both convective and radiative resistances, and Table 15 below shows the new heat losses through the walls with an additional air gap. Sample calculations for the back wall as well as the Nusselt numbers, resistances, and resulting heat losses for the vertical walls can be seen below.

<table>
<thead>
<tr>
<th>Radiative Heat Transfer Coefficient Sample Calculations</th>
<th>$h_{rad} = 0.8(5.67 \times 10^{-8} \text{ W/m}^2 \text{K})\left[(345 \text{ K})^2 + (300 \text{ K})^2\right](345 \text{ K} + 300 \text{ K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{rad} = 6.11 \text{ W/m}^2 \text{K}$</td>
<td></td>
</tr>
<tr>
<td>Resistances Sample Calculations</td>
<td>$R_1 = \frac{L_{\text{cerachem}}}{k_{\text{cerachem}}} = \frac{0.025 \text{ m}}{0.34 \text{ W/mK}} = 0.0735 \text{ K/W}$</td>
</tr>
<tr>
<td>$R_2 = \frac{L_{\text{cerablanket}}}{k_{\text{cerablanket}}} = \frac{0.15 \text{ m}}{0.34 \text{ W/mK}} = 0.4412 \text{ K/W}$</td>
<td></td>
</tr>
<tr>
<td>$R_3 = \frac{L_{\text{WDS ultra}}}{k_{\text{WDS ultra}}} = \frac{0.012 \text{ m}}{0.04 \text{ W/mK}} = 0.3 \text{ K/W}$</td>
<td></td>
</tr>
<tr>
<td>$R_4 = \frac{L_{\text{air}}}{k_{\text{air}} + Nu} + \frac{1}{h_{rad}} = \frac{0.025 \text{ m}}{(0.0295 \text{ W/mK}) \times 1.66} + \frac{1}{6.11 \text{ W/m}^2 \text{K}} = 0.123 \text{ K/W}$</td>
<td></td>
</tr>
<tr>
<td>$R_5 = \frac{L_{\text{steel}}}{k_{\text{steel}}} = \frac{0.003175 \text{ m}}{51.9 \text{ W/mK}} = 0.0000612 \text{ K/W}$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma R = \frac{1}{h_i} + R_1 + R_2 + R_3 + R_4 + R_5 + \frac{1}{h_o}$</td>
<td></td>
</tr>
</tbody>
</table>
\[ \Sigma R = \frac{1}{72 \text{W/m}^2 \cdot \text{K}} + 0.0735 + 0.4412 + 0.3 + 0.123 + 0.0000612 \]
\[ + \frac{1}{25 \text{W/m}^2 \cdot \text{K}} \]
\[ \Sigma R = 0.9917 \]

**Heat Flux Sample Calculations**

\[ q = \frac{T_h - T_\infty}{\Sigma R} \]
\[ q = \frac{0.9917}{1000\degree \text{C} - 27\degree \text{C}} \]
\[ q = 981.14 \text{ W} \]

**Heat Loss Sample Calculations**

\[ Q = qA \]
\[ Q = 981.14 \text{ W} \cdot 2.323 \text{ m}^2 \]
\[ Q = 2279.18 \text{ W} = 2.3 \text{ kW} \]

**Table 15: Heat Loss through Vertical Wall Faces**

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Q (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back wall</td>
<td>2.3</td>
</tr>
<tr>
<td>Sidewalls</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The top and bottom walls are horizontal enclosures and will have different Nusselt number equations from the vertical enclosures. The bottom wall will not need a Nusselt number because the hotter surface is on top, thus the Nusselt number will be 1. The equation used to find the Nusselt number for the top plate is based on the Rayleigh number, and in this case \(10^4 < \text{Ra} < 10^7\), so the follow equation is used:

\[ Nu = 0.195 \cdot \text{Ra}^{1/8} \]

Using that equation for the top plate and \( Nu = 1 \) for the bottom wall, the heat loss through the walls can be found. Sample calculations for the top wall as well as the Nusselt numbers, resistances, and resulting heat losses for the horizontal walls can be seen below.

**Nusselt Number Sample Calculations**

\[ Nu = 0.195 \cdot (34,764.96)^{1/8} \]
\[ Nu = 2.66 \]

**Resistance Sample Calculation**

\[ R_4 = \frac{1}{L_{air}^2} \cdot \frac{1}{k_{air} \cdot Nu} \cdot \frac{1}{h_{rad}} \]
\[ = \frac{1}{0.025 \text{ m}} \cdot \frac{1}{(0.0295 \text{ W/m} \cdot \text{K}) \cdot 2.66} + \frac{1}{6.11 \text{ W/m}^2 \cdot \text{K}} \]
\[ R_4 = 0.1073 \]
\[ \Sigma R = 0.9760 \]

**Heat Flux Sample Calculation**

\[ q = \frac{1000\degree \text{C} - 27\degree \text{C}}{0.7960} \]
\[ q = 1222.36 \, W/m^2 \]

Heat Loss Sample Calculation

\[ Q = 1222.36 \, W/m^2 \times 0.827 \, m^2 \]
\[ Q = 1010.89 \, W = 1 \, kW \]

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Nu Number</th>
<th>Q (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>2.66</td>
<td>1</td>
</tr>
<tr>
<td>Bottom</td>
<td>1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 16: Resistance and Heat Loss through Vertical Wall Faces

The total heat loss between the layers with the additional air gap is 3.8 kW. A temperature profile was determined using the heat flux of the back wall, inside temperature of the furnace, and the resistances. Sample calculations can be seen below and Figure 26 shows the temperatures between each layer.

Temperature Profile Sample Calculations

\[ q = \frac{T_h - T_1}{\frac{1}{h_i} + R_1} \]
\[ 981.14 \, W/m^2 = \frac{1000^\circ C - T_1}{\frac{1}{72 \, W/m^2 \times K} + 0.0735 \, K/W} \]
\[ T_1 = 914.25^\circ C \]
\[ q = \frac{T_1 - T_2}{R_2} \]
\[ 981.14 \, W/m^2 = \frac{914.25^\circ C - T_2}{0.4412 \, K/W} \]
\[ T_2 = 481.37^\circ C \]
\[ q = \frac{T_2 - T_3}{R_3} \]
\[ 981.14 \, W/m^2 = \frac{481.37^\circ C - T_3}{0.3 \, K/W} \]
\[ T_3 = 187.03^\circ C \]
\[ q = \frac{T_3 - T_4}{R_4} \]
\[ 981.14 \, W/m^2 = \frac{187.03^\circ C - T_4}{0.123 \, K/W} \]
\[ T_4 = 66.35^\circ C \]
\[ q = \frac{T_4 - T_5}{R_5 + \frac{1}{h_o}} \]
\[ 981.14 \, W/m^2 = \frac{66.35^\circ C - T_4}{0.0000612 \, K/W + \frac{1}{25 \, W/m^2 \times K}} \]
Heat storage of each layer was determined with the additional air gap using the temperatures as shown in the figure above. First, the average temperature change between each layer and then the mass of each wall type were calculated. After those were determined, the heat storage could be calculated.

### Average Temperature Sample Calculations

<table>
<thead>
<tr>
<th>Layer</th>
<th>Temperature Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>[ \frac{1000°C + 914°C}{2} - 27°C = 930°C = 1203 K ]</td>
</tr>
<tr>
<td>$T_2$</td>
<td>[ \frac{914°C + 481°C}{2} - 27°C = 670.5°C = 943.5 K ]</td>
</tr>
<tr>
<td>$T_3$</td>
<td>[ \frac{481°C + 187°C}{2} - 27°C = 307°C = 580 K ]</td>
</tr>
<tr>
<td>$T_4$</td>
<td>[ \frac{187°C + 66°C}{2} - 27°C = 99.5°C = 372.5 K ]</td>
</tr>
</tbody>
</table>

### Mass of Back Wall Sample Calculation

- $m_{\text{back}} = 2.323 m^2 \times 0.025 m \times 0.4565 kg/m^3 = 0.0265 kg$
- $m_{\text{side}} = 1.103 m^2 \times 0.025 m \times 0.4565 kg/m^3 = 0.0126 kg$
- $m_{\text{top/bottom}} = 0.827 m^2 \times 0.025 m \times 0.4565 kg/m^3 = 0.0094 kg$

### Heat Storage on Back wall Sample Calculations

- $Q_{\text{cerachem}} = 7.437 kg \times (1.13 kJ/kg \times K) \times 1203 K$
- $Q_{\text{cerachem}} = 10,109.78 kJ$
- $Q_{\text{cerablanket}} = 44.608 kg \times (1.13 kJ/kg \times K) \times 943.5 K$
- $Q_{\text{cerablanket}} = 47,559.04 kJ$
- $Q_{\text{WDS Ultra}} = 6.422 kg \times (0.945 kJ/kg \times K) \times 580 K$
- $Q_{\text{WDS Ultra}} = 3,519.90 kJ$
- $Q_{\text{air}} = 9.95 kJ$
These calculations were performed for each wall type and the total heat storage for all five sides is 174,428.37 kJ, and over a period of 3600 seconds (1 hour), there is 48.45 kW of heat stored.

Appendix C.4: Comparison of Insulation Analyses

Figure 28 below shows the comparison of the temperature profiles between the simulation and the steady-state calculations. The results are very similar, where multiple points have the same temperature or are within about 40°C. These results further confirm the accuracy of the simulation and give the best representation of how the materials will perform in the furnace.

![Temperature Profile Simulation vs. Steady-State](image)

*Figure 28: Temperature Profile Comparison between Morgan Simulation and Steady-State Hand Calculations*

Table 17 below shows the comparison of results between the Morgan simulation and the steady-state hand calculations without an air gap present. The same properties were used in both cases, as listed in Appendix C.2. The steady-state calculations show that there will be 4.4 kW more heat lost and 24.8 kW more heat stored compared to the simulation. The simulation did not establish a time component, so it was assumed that the results were a steady-state equivalent. The results from the simulation are believed to be the performance of the material when used in a furnace and the hand calculations prepare for the performance with a time component.

<table>
<thead>
<tr>
<th></th>
<th>Morgan Simulation</th>
<th>Steady-State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Losses</td>
<td>2.6 kW</td>
<td>7 kW</td>
</tr>
<tr>
<td>Heat Storage</td>
<td>19 kW</td>
<td>43.8 kW</td>
</tr>
<tr>
<td>Total</td>
<td>21.6 kW</td>
<td>50.8 kW</td>
</tr>
</tbody>
</table>

Figure 29 below shows the two temperature profiles with and without an air gap. The temperature profile of the insulation layout with an air gap is slightly higher than that of the layout without an air gap, however both have temperatures of the outside steel at about 27°C. This difference is caused by the way the heat travels and where the heat is stored through each layer. Less heat is
stored in the second layer with the air gap compared to the same layer without the air gap because the layout with an air gap relies on the additional layer to dissipate the majority of the heat.

Figure 29: Temperature Profile Comparison between Air Gap and No Air Gap

Table 18 below shows a comparison of the heat losses and storage between the insulation layouts with and without an air gap present behind the microporous insulation. The same properties and methods were used in both sets of calculations. With an air gap present, there is about 0.7 kW less heat lost and about 2.1 kW more heat stored. The air gap allows for less heat lost and more heat stored, which means it demands less from the burner and more fuel can be conserved. While there is not a large difference between the heat losses and storage, the air gap also allowed for easier installation of the microporous material to ensure that the bracing was also protected from the elevated temperatures.

<table>
<thead>
<tr>
<th></th>
<th>No Air Gap</th>
<th>Air Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Losses</strong></td>
<td>7 kW</td>
<td>6.3 kW</td>
</tr>
<tr>
<td><strong>Heat Storage</strong></td>
<td>43.8 kW</td>
<td>45.9 kW</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>50.8 kW</td>
<td>52.2 kW</td>
</tr>
</tbody>
</table>
Appendix C.5: Installation Procedure

In the construction of the furnace, the manufacturer recommended an installation procedure to enhance performance and avoid product damage. The manufacture recommended an additional structure to support the microporous material to better allow the storage of heat, rather than letting it flow through microcracks in a weakened board.

1. Weld the Inconel 601 studs to the steel sheets that encase the furnace, spaced approximately 12 inches apart.
2. Place the perforated steel on the studs, resting against the bracing around the furnace, which will create a 25 mm (1 inch) air gap between the perforated steel and the solid steel sheets encasing the furnace.
3. Cut microporous material to size and place tape over plastic packaging to seal material.
4. Make small cut into microporous material where the studs will pierce and gently place the 12 mm (1/2 inch) boards on the studs, careful to avoid damage or create cracks in the material.
5. Cut Cerabrand to size, there will be six layers of 25 mm (1 inch) thick blanket on each wall, with the back wall having five layers.
6. Push the Cerabrand onto the studs.
7. Cut Cerachem blanket to size, there is a single layer of 25 mm (1 inch) thick blanket on each wall, with the back wall having two layers.
8. Push the Cerachem blanket onto the studs.
9. Push washers onto studs and rotate 90° to lock all materials in place. The materials behind the washer will be in compression to hold the washer in place.
10. Cut four strips of 2 inch wide by 60 inches long and four strips of 2 inch wide by 56 inches long of Cerachem blanket to create a 2 inch thick gasket around the open face of the furnace.
11. Secure the insulation for the gasket.
Appendix D: CFD Modeling
Appendix D.1: Solidworks Flow Simulation - Equations

Overall governing equations for fluid flow and heat transfer in the program can be seen below:

**FAVRE-AVERAGED NAVIER STOKES EQ.**

**Mass:**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0
\]

Mass Density, 
\( u = \) fluid velocity, Chain rule of acceleration

**Momentum:**

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) + \frac{\partial p}{\partial x_i} = \frac{\partial}{\partial x_j} (\tau_{ij} + \tau_{ij}^R) + S_i, \quad i = 1, 2, 3
\]

\( S_i \) = mass-distributed external force per unit mass due to a porous media resistance: \( (S_{i}^{\text{Porous}}) \), a buoyancy \( (S_{i}^{\text{Gravity}} = -g_i) \) where \( g_i \) is the gravitational acceleration component along the \( i \)-th coordinate direction, and the systems rotation \( (S_{i}^{\text{Rotation}}) \)

**Energy:**

\[
\frac{\partial \rho H}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i H) = \frac{\partial}{\partial x_j} (u_j (\tau_{ij} + \tau_{ij}^R) + q_i) + \frac{\partial p}{\partial x_j} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho c + S_i u_i + Q_H
\]

\[ H = h + \frac{u^2}{2} \]

\( H \) = thermal enthalpy, 
\( Q_H \) = Heat source or sink per unit volume 
\( \tau_{ij} \) = viscous shear stress tensor 
\( q_i \) = diffusive heat flux

**HEAT TRANSFER**

The energy equation above is also used to describe heat transfer through fluids. The diffusive heat flux, \( q_i \), is defined by the equation below.

Diffusive Heat Flux, \( q_i \):

\[
q_i = \left( \frac{\mu}{Pr} + \frac{\mu_t}{\sigma_c} \right) \frac{\partial h}{\partial x_i}, \quad i = 1, 2, 3
\]

\( \sigma_c = 0.9 \) 
\( Pr = \) Prandtl number
h = thermal enthalpy

Heat conduction in solid is given by the equation below:
\[ \frac{\partial \rho e}{\partial t} = \frac{\partial}{\partial x_i} \left( \lambda_i \frac{\partial T}{\partial x_i} \right) + Q_H \]

e = c \times T = specific internal energy where c is the specific heat
Q_H = specific heat release per unit volume
\( \lambda_i \) = eigenvalues

RADIATION:
Flow Simulation has two models for radiation, Ray Tracing Method and Discrete Ordinates. The general assumptions of the Ray Tracing Method are:

➢ heat radiation from solid surface is assumed diffuse (obey Lambert law)
➢ the propagating heat radiation passes through a solid specified as radiation transparent without any refraction and/or absorption
➢ Project fluids neither emit or absorb heat radiation (transparent) so the heat radiation concerns solid surfaces only
➢ Radiative solid surfaces which are not specified as a black body or white body are assumed an ideal gray body

The general assumptions of the discrete ordinates model are:

➢ radiation absorptive (semi-transparent) solids absorb and emit heat radiation in accordance with the specified solid material absorption coefficient
➢ Scattering is not considered
➢ Surfaces of opaque solids absorb incident heat radiation in accordance with their specified emissivity coefficients. The rest of incident radiation is reflected specularly or diffusively, or both
➢ Radiation absorptive solids reflect radiation specularly, the radiation is refracted in accordance with the specified refraction indices of the solid and adjacent medium

For the simulations done for the project, the Ray Tracing model was used.
Appendix D.2: Solidworks Flow Simulation – Model & Computational Domain

Figure 30: Solidworks Simulation Furnace Model & Computational Domain
Appendix D.3: Solidworks Flow Simulation - Temperature Plots

Side Vent: Concrete Surface Temperature Cut Plot

Temperature Cut Plot
Top Vent: Temperature Cut Plot
Appendix D.4: Solidworks Flow Simulation - Input Summary

Input Data:

Global Mesh Settings
  Automatic initial mesh: On
  Result resolution level: 3
  Advanced narrow channel refinement: Off
  Refinement in solid region: Off

Geometry Resolution
  Evaluation of minimum gap size: Automatic
  Evaluation of minimum wall thickness: Automatic

Computational Domain

Size
  X min: -0.447 m
  X max: 0.469 m
  Y min: 0.156 m
  Y max: 1.683 m
  Z min: 0.616 m
  Z max: 2.143 m

Boundary Conditions
  2D plane flow: None
  At X min: Default
  At X max: Default
  At Y min: Default
  At Y max: Default
  At Z min: Default
  At Z max: Default

Physical Features
  Heat conduction in solids: On
  Heat conduction in solids only: Off
  Radiation: On
  Time dependent: On
  Gravitational effects: On
  Rotation: Off
  Flow type: Laminar and turbulent
  High Mach number flow: Off
  Default roughness: 0 micrometer
Gravitational Settings
   X component: 0 m/s^2
   Y component: -9.81 m/s^2
   Z component: 0 m/s^2

Radiation
   Default wall radiative surface: Blackbody wall
   Radiation model: Ray Tracing
   Default outer wall radiative surface: Blackbody wall

Environment radiation
   Environment temperature: 293.20 K
   Spectrum: Blackbody

Default outer wall condition
   Heat transfer coefficient: 50.000 W/m^2/K
   External fluid temperature: 293.20 K

Initial Conditions

   Thermodynamic parameters
      Static Pressure: 101325.00 Pa
      Temperature: 293.20 K

   Velocity parameters
      Velocity vector
      Velocity in X direction: 0 m/s
      Velocity in Y direction: 0 m/s
      Velocity in Z direction: 0 m/s

   Solid parameters
      Default material: Steel Stainless 321
      Initial solid temperature: 293.20 K
      Radiation Transparency: Opaque

Concentrations
   Substance fraction by mass
      Steam
      0
      Carbon dioxide
      0
      Nitrogen
Material Settings

Fluids
  Steam
  Carbon dioxide
  Nitrogen
  Air
  Oxygen

Solids
  Steel Stainless 321
  Microporous
  Concrete
  Cast concrete
  CeraChem

Solid Materials

Steel Stainless 321 Solid Material 1
  Components: Outside steel wall-1@5x5x3_Furnace_WallSpecimen_Insulation,
  Outside steel wall (30in)_SideVent-1@5x5x3_Furnace_WallSpecimen_Insulation, 5x5x3
  Furnace (Insulation)-1@5x5x3_Furnace_WallSpecimen_Insulation, Outside steel wall (top and
  bottom)-2@5x5x3_Furnace_WallSpecimen_Insulation, Outside steel wall (30in)-1@5x5x3_Furnace_WallSpecimen_Insulation
  Solid substance: Steel Stainless 321
  Radiation Transparency: Opaque

Microporous Solid Material 1
  Components: Insulation (Micro_30in_top&bottom))-3@5x5x3_Furnace_WallSpecimen_Insulation, Insulation_Micro_SideVent-
  1@5x5x3_Furnace_WallSpecimen_Insulation, Insulation-
  2@5x5x3_Furnace_WallSpecimen_Insulation, Insulation (Micro_30in)-
  4@5x5x3_Furnace_WallSpecimen_Insulation
  Solid substance: Microporous
  Radiation Transparency: Opaque

Concrete Solid Material 1
Components: Wall Specimen-1@5x5x3_Furnace_WallSpecimen_Insulation
Solid substance: Concrete
Radiation Transparency: Opaque

CeraChem Solid Material 1
Components: Insulation-4@5x5x3_Furnace_WallSpecimen_Insulation,
Insulation_SideVent-1@5x5x3_Furnace_WallSpecimen_Insulation, Insulation
(30in_top&bottom)-1@5x5x3_Furnace_WallSpecimen_Insulation, Insulation (30in)-1@5x5x3_Furnace_WallSpecimen_Insulation
Solid substance: CeraChem
Radiation Transparency: Opaque

Boundary Conditions

Burner
Type: Inlet Mass Flow
Faces: Face<9>@5x5x3 Furnace (Insulation)-1, Face<10>@5x5x3 Furnace (Insulation)-1
Coordinate system: Global coordinate system
Reference axis: X

Flow parameters
Flow vectors direction: Normal to face
Mass flow rate: 0.0087 kg/s
Fully developed flow: No
Inlet profile: 0

Thermodynamic parameters
Approximate pressure: 6500.00 Pa
Temperature: 2470.00 K

Concentrations
Substance fraction by mass
Steam
0.1020
Carbon dioxide
0.1860
Nitrogen
0.7120
Air
0
Oxygen
0
Boundary layer parameters
  Boundary layer type: Turbulent

Outer Walls
  Type: Real wall
  Faces:
  Coordinate system: Global coordinate system
  Reference axis: X
  Heat transfer coefficient: 50.000 W/m^2/K
  Fluid temperature: 293.20 K

CeraChem
  Type: Real wall
  Faces: Face<2>@5x5x3 Furnace (Insulation)-1
  Coordinate system: Global coordinate system
  Reference axis: X
  Wall temperature: Table from time

SideVent
  Type: Environment Pressure
  Faces: Face<7>@LID1-1
  Coordinate system: Face Coordinate System
  Reference axis: X

Thermodynamic parameters
  Environment pressure: 101325.00 Pa
  Temperature: 293.20 K

Concentrations
  Substance fraction by mass
  Steam
  0
  Carbon dioxide
  0
  Nitrogen
  0
  Air
  1.0000
  Oxygen
  0

Boundary layer parameters
Boundary layer type: Turbulent

Radiative Surfaces

CeraChem,
Faces: Face<4>@5x5x3 Furnace (Insulation)-1, Face<1>@5x5x3 Furnace (Insulation)-1, Face<2>@5x5x3 Furnace (Insulation)-1, Face<5>@5x5x3 Furnace (Insulation)-1, Face<3>@5x5x3 Furnace (Insulation)-1
Type: CeraChem

Concrete
Faces: Wall Specimen-1@5x5x3_Furnace_WallSpecimen_Insulation
Type: Concrete

Goals

Global Goals

Avg. Temp. Fluid
Type: Global Goal
Goal type: Temperature (Fluid)
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.00 K
Use in convergence: On

GG Mass Flow Rate 1
Type: Global Goal
Goal type: Mass Flow Rate
Coordinate system: Global coordinate system
Criteria: 1.0000 kg/s
Use in convergence: On

GG Av Heat Flux 1
Type: Global Goal
Goal type: Heat Flux
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.000 W/m^2
Use in convergence: On

GG Av Surface Heat Flux (Convective) 1
Type: Global Goal
Goal type: Surface Heat Flux (Convective)
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.000 W/m^2
Use in convergence: On

GG Av Wall Temperature 1
Type: Global Goal
Goal type: Wall Temperature
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.00 K
Use in convergence: On

GG Total Enthalpy Rate 1
Type: Global Goal
Goal type: Total Enthalpy Rate
Coordinate system: Global coordinate system
Criteria: 1.000 W
Use in convergence: On

GG Av Temperature (Solid) 1
Type: Global Goal
Goal type: Temperature (Solid)
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.00 K
Use in convergence: Off

Point Goals

PG Temperature (Solid) 1
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.380 m
Y: 0.875 m
Z: 1.456 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 2
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.330 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 5
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.320 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 6
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.350 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 7
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.370 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 8
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.390 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 9
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.410 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 10
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.430 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 11
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.450 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence: On

PG Temperature (Solid) 3
Type: Point Goal
Goal type: Temperature (Solid)
Coordinate system: Global coordinate system
X: 0.316 m
Y: 0.875 m
Z: 1.476 m
Criteria: 1.00 K
Use in convergence :  On

Surface Goals

Avg. Surface Temp. Concrete
Type: Surface Goal
Goal type: Wall Temperature
Calculate: Average value
Faces: Face<1>@Wall Specimen-1
Coordinate system: Global coordinate system
Criteria: 1.00 K
Use in convergence : On

SG Av Heat Flux 1
Type: Surface Goal
Goal type: Heat Flux
Calculate: Average value
Faces: Face<1>@5x5x3 Furnace (Insulation)-1, Face<3>@5x5x3 Furnace (Insulation)-1, Face<2>@5x5x3 Furnace (Insulation)-1, Face<4>@5x5x3 Furnace (Insulation)-1
Coordinate system: Global coordinate system
Criteria: 1.000 W/m²
Use in convergence : On

SG Av Surface Heat Flux (Convective) 1
Type: Surface Goal
Goal type: Surface Heat Flux (Convective)
Calculate: Average value
Faces: Face<3>@5x5x3 Furnace (Insulation)-1, Face<5>@5x5x3 Furnace (Insulation)-1, Face<1>@5x5x3 Furnace (Insulation)-1, Face<4>@5x5x3 Furnace (Insulation)-1, Face<2>@5x5x3 Furnace (Insulation)-1
Coordinate system: Global coordinate system
Criteria: 1.000 W/m²
Use in convergence : On

SG Av Surface Heat Flux (Conductive) 1
Type: Surface Goal
Goal type: Surface Heat Flux (Conductive)
Calculate: Average value
Faces: Face<1>@5x5x3 Furnace (Insulation)-1, Face<3>@5x5x3 Furnace (Insulation)-1, Face<2>@5x5x3 Furnace (Insulation)-1, Face<4>@5x5x3 Furnace (Insulation)-1
Coordinate system: Global coordinate system
Criteria: 1.000 W/m²
Use in convergence : On
Avg. Temp Interior Walls
Type: Surface Goal
Goal type: Temperature (Solid)
Calculate: Average value
Faces: Face<4>@5x5x3 Furnace (Insulation)-1, Face<1>@5x5x3 Furnace (Insulation)-1, Face<2>@5x5x3 Furnace (Insulation)-1, Face<3>@5x5x3 Furnace (Insulation)-1

Coordinate system: Global coordinate system
Criteria: 1.00 K
Use in convergence: On

Calculation Control Options

Finish Conditions
Finish Conditions: If one is satisfied
Maximum physical time: 3600.000 s

Solver Refinement
Refinement: Disabled

Results Saving
Save before refinement: On

Advanced Control Options

Flow Freezing
Flow freezing strategy: Disabled
Manual time step (Freezing): Off
Manual time step: 0.500 s
View factor resolution level:
Appendix D.5: FDS Model

Appendix D.5.1: Adiabatic Flame Temperature Calculation

\[ H_{f_{C3H8}} * N_{C3H8} + H_{f_{CO2}} * N_{CO2} + H_{f_{H2O}} * N_{H2O} + \Delta T \sum C_{P_{x}} * N_{x} \]

\[ \sum C_{P_{x}} * N_{x} = C_{P_{CO2}} * N_{CO2} + C_{P_{H2O}} * N_{H2O} + C_{P_{N2}} * N_{N2} \]

\[ H_{f_{C3H8}} = -103850 \text{ kJ/kmol} \quad N_{C3H8} = 1 \text{ kmol} \]

\[ H_{f_{CO2}} = -393522 \text{ kJ/kmol} \quad N_{CO2} = 3 \text{ kmol} \quad C_{P_{CO2}} = 45 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}} \]

\[ H_{f_{H2O}} = -241827 \frac{\text{kJ}}{\text{kmol}} \quad N_{H2O} = 4 \text{ kmol} \quad C_{P_{H2O}} = 35 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}} \]

\[ \Delta T = (T_f - 298K) \]

\[ T_f = 2138.23 K \]

Appendix D.5.2: Species Mass Flux Calculation

\[ C_{3H6} + 5(CO_2 + 3.76N_2) = 3CO_2 + 4H_2O + 18.8N_2 \]

\[ 3CO_2 = 72g \]

\[ 4H_2O = 46.8g \]

\[ 18.8N_2 = 132g \]

Mass Fraction of CO₂ = 0.287
Mass Fraction of H₂O = 0.186
Mass Fraction of N₂ = 0.526

Appendix D.5.3: Species Mass Flux Calculation

The manufacture provided air and propane flow rates from experimental measurements of the purchased burner system. These measurements were used to calculate the mass flux of the species entering the furnace.

\[ 2 \times \left( 7160 \frac{ft^3}{hr} \text{ air} + 286 \frac{ft^3}{hr} \text{ propane} \right) = 0.112 \frac{m^3}{s} \]

Mass flux through each burner (surface area of pine ridge burners approximately 0.05m²):

\[ 0.056 \frac{m^3}{s} * 1.225 \frac{kg}{m^3} = 0.06 \frac{kg}{s} \]

\[ 0.06 \frac{kg}{s} + 0.05m^2 = 0.70 \frac{kg}{m^3 \cdot s} \]
Appendix D.5.4: Simulation Temperature Slice File
Appendix D.5.5: Simulation Velocity Slice Files
Appendix D.5.6: Computation Domain
Appendix D.5.6: FDS Input File

```plaintext
[HEAD]
CHID='MUP_SIM', TITLE='SIMULATION_2'
/

[MESH]
N=18, 20, 20, XB=-0.30, 1.21, -0.30, 1.52, -0.30, 1.52/
NISC THICKER_OBSTRUCTIONS =.TRUE., SURF_DEFAULT='FURNACE_INSULATION'/

[TIME]
T_END=3600/

&MAT ID=
  ID = 'CERACHEM'
  CONDUCTIVITY = 0.34
  DENSITY = 128
  SPECIFIC_HEAT = 1.846/

&MAT ID=
  ID = 'MICROPOROUS'
  CONDUCTIVITY = 0.04
  DENSITY = 231
  SPECIFIC_HEAT = 1.046/

&MAT ID=
  ID = 'CONCRETE'
  CONDUCTIVITY = 0.80
  DENSITY = 2400

&MAT ID=
  ID = 'STEEL'
  CONDUCTIVITY = 50.
  SPECIFIC_HEAT = 0.5
  DENSITY = 6000/

&SURF ID=
  ID = 'FURNACE_INSULATION'
  COLOR = 'GRAY 75'
  MAT_ID = 'CERACHEM', 'MICROPOROUS'
  THICKNESS = 0.155, 0.25
  BACKING = 'EXPOSED'/

&SURF ID=
  ID = 'CONCRETE WALL'
  MAT_ID = 'CONCRETE'
  COLOR = 'YELLOW'
  THICKNESS = 0.14
  BACKING = 'EXPOSED'/

&SURF ID=
  ID = 'plate'
  MAT_ID = 'STEEL'
  HEAT_TRANSFER_COEFFICIENT=10.
  COLOR = 'BLACK'
  THICKNESS = 0.0001
  BACKING = 'INSULATED'
  EMISSIVITY = 0.9/

&AVENT MB=MIN, SURF_ID='OPEN'/
&AVENT MB=MAX, SURF_ID='OPEN'/
&AVENT MB+MIN, SURF_ID='OPEN'/
&AVENT MB+MAX, SURF_ID='OPEN'/
&AVENT MB-MIN, SURF_ID='OPEN'/
&AVENT MB-MAX, SURF_ID='OPEN'/

&OBST XB=0.0, 0.01, 0.0, 0.0, 1.22, 1.22, 1.22, 1.22, SURF_ID='FURNACE_INSULATION' /Ceiling
&OBST XB=0.0, 0.01, 0.0, 1.22, 0.0, 0.0, 0.0, 0.0, SURF_ID='FURNACE_INSULATION' /Floor
&OBST XB=0.0, 0.91, 0.91, 0.0, 1.22, 0.0, 1.22, SURF_ID='CONCRETE WALL' /MAX WALL
&OBST XB=0.0, 0.0, 0.0, 0.0, 1.22, 0.0, 1.22, SURF_ID='FURNACE_INSULATION' /MIN WALL
&OBST XB=0.0, 0.91, 1.22, 1.22, 0.0, 0.0, 0.0, 0.0, SURF_ID='FURNACE_INSULATION' /MAX WALL
&OBST XB=0.0, 0.91, 1.22, 1.22, 0.0, 0.0, 0.0, 0.0, SURF_ID='FURNACE_INSULATION' /MIN WALL

&OBST XB=0.81, 0.81, 0.99, 1.04, 0.99, 1.04, SURF_ID='plate' /PT1
&OBST XB=0.81, 0.81, 0.59, 0.64, 0.99, 1.04, SURF_ID='plate' /PT2
&OBST XB=0.81, 0.81, 0.19, 0.24, 0.99, 1.04, SURF_ID='plate' /PT3
&OBST XB=0.81, 0.81, 0.99, 1.04, 0.59, 0.64, SURF_ID='plate' /PT4
&OBST XB=0.81, 0.81, 0.99, 1.04, 0.59, 0.64, SURF_ID='plate' /PT5
&OBST XB=0.81, 0.81, 0.99, 1.04, 0.59, 0.64, SURF_ID='plate' /PT6
&OBST XB=0.81, 0.81, 0.19, 0.24, 0.59, 0.64, SURF_ID='plate' /PT7
&OBST XB=0.81, 0.81, 0.19, 0.24, 0.59, 0.64, SURF_ID='plate' /PT8
&OBST XB=0.81, 0.81, 0.19, 0.24, 0.59, 0.64, SURF_ID='plate' /PT9
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108
SPEC ID = "PRODUCTS",
SPEC_ID(1)="WATER VAPOR", MASS_FRACTION(1)=0.287
SPEC_ID(2)="CARBON DIOXIDE", MASS_FRACTION(2)=0.186
SPEC_ID(3)="NITROGEN", MASS_FRACTION(3)=0.527

SPEC ID = "INLET",
SPEC ID = "PRODUCTS"
MASS_Flux = 0.70,
TEMP_FRONT=1995,
RAMP_T="TEMP_RAMP",
COLOR="RED"/

RAMP ID="TEMP_RAMP", T= 0.0, F= 0.00/
RAMP ID="TEMP_RAMP", T= 5.0, F= 0.10/
RAMP ID="TEMP_RAMP", T= 50.0, F= 0.15/
RAMP ID="TEMP_RAMP", T= 100.0, F= 0.25/
RAMP ID="TEMP_RAMP", T= 150.0, F= 0.35/
RAMP ID="TEMP_RAMP", T= 200.0, F= 0.45/
RAMP ID="TEMP_RAMP", T= 250.0, F= 0.50/
RAMP ID="TEMP_RAMP", T= 600.0, F= 0.55/
RAMP ID="TEMP_RAMP", T= 900.0, F= 0.57/
RAMP ID="TEMP_RAMP", T= 1500.0, F= 0.58/

EVT 1 X= 0.0, Y= 0.0, Z= 0.435, 0.785, 0.30, 0.40, SURF_ID="INLET"/
EVT 2 X= 0.0, Y= 0.0, Z= 0.435, 0.785, 0.65, 0.75, SURF_ID="INLET"/

HOLE 1 X=0.1,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 3" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 3", SETPOINT= 100.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

HOLE 2 X=0.1,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 4" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 4", SETPOINT= 100.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

HOLE 3 X=0.2,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 5" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 5", SETPOINT= 100.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

HOLE 4 X=0.2,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 6" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 6", SETPOINT= 100.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

HOLE 5 X=0.2,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 7" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 7", SETPOINT= 10000.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

HOLE 6 X=0.2,1.0,1.5,2.75,1.05,0.70,0.75, COLOR="RED", TRANSPARENCY=0.75, DEC_ID="timer 8" /
DEV XY=1.0,1.0,1.0,1.0, ID="timer 8", SETPOINT= 20000.0, QUANTITY="TIME", INITIAL_STATE=FALSE /

DEVIC Id="WALL_MID_TEMP1", XYZ= 0.9, 0.61, 0.61, QUANTITY="WALL_TEMPERATURE",10=1 /
DEVIC Id="WALL_MID_TEMP1", XYZ= 0.9, 0.61, 0.61, QUANTITY="WALL_TEMPERATURE",10=3 /

SLCF QUANTITY="TEMPERATURE", PBY=0.61/
SLCF QUANTITY="TEMPERATURE", PBY=0.61/
SLCF QUANTITY="TEMPERATURE", PBY=0.61/

SLCF QUANTITY="VELOCITY", PBY=0.61/
SLCF QUANTITY="VELOCITY", PBY=0.61/
SLCF QUANTITY="VELOCITY", PBY=0.61/

SLCF QUANTITY="DENSITY" /
SLCF QUANTITY="PRESSURE" /
SLCF QUANTITY="PRESSURE" /

DEVIC Id="VOLUME FLOW", X=0.001, 0.001, 0.435, 0.785, 0.30, 0.40, QUANTITY="VOLUME FLOW", BURNER 1 /
DEVIC Id="VOLUME FLOW", X=0.001, 0.001, 0.435, 0.785, 0.65, 0.75, QUANTITY="VOLUME FLOW", BURNER 2 /

DEVIC Id="NH3_toleft", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
DEVIC Id="NH3_topmid", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
DEVIC Id="NH3_topright", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
DEVIC Id="NH3_midleft", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
DEVIC Id="NH3_midright", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
DEVIC Id="NH3_botleft", QUANTITY="NET HEAT FLOW", XYZ=0.81,1.015,1.015, 10=1 /
Appendix E: System Design
Appendix E.1: Furnace Design
Appendix E.2: Specimen Mount Design
Appendix E.3: Burner System Design

Pipe sizing needed to be estimated in order to complete the system. It was recommended by the manufacturer to design the manifold so that it is symmetric with as minimal piping. The concept here is to have an even distribution of an air and gas mixture with as little resistance to flow as possible. A stoichiometric combustion reaction with maximum heat output from the system is desired. The piping required to meet the size of the system is as follows:

- 2" Diameter - 3" Length Black Malleable Pipe (4)
- 2" Diameter - 4" Length Black Malleable Pipe (2)
- 2" Diameter - 3" Length PVC Pipe (4)
- 2" Diameter - 12" Length PVC Pipe (1)
- 2" Diameter - 10" Length Black Malleable Pipe (2)
- ¾" Diameter - 4" Length Black Malleable Pipe (4)
- 2" Diameter - 2.5" Length Black Malleable Threaded Fittings (2)
- 2" Diameter - 90 degree elbows (4)

In addition, the temperature control system must be wired correctly in order to control the output from the variable speed blower. The figure below displays the wiring diagram between the programmable unit, variable speed blower, and Type-K thermocouple:
Appendix F: Instrumentation

Appendix F.1: Construction Details for the Plate Thermometers

The plate thermometers to be used for the initial calibration and heat flux calculations were constructed as follows. Type K wire was welded to a 2 in by 2 in steel plate. Two layers of insulation and a layer of dry wall were placed on top of the steel plate with the welded wire, and a thermocouple was placed in between the insulation layers. The plate thermometers are held together with screws. The image below shows the constructed plate thermometer.

![Plate Thermometer Visual](image)

The plate thermometers for the furnace were constructed in a similar way with a few adjustments. Type K wire was welded to a 4 in by 4 in Inconel steel plate. This weld was topped with three layers of insulation with the thermocouple placed between the top two layers. The dry wall was eliminated from the design for the furnace as it will not be able to withstand the high temperatures. The plate thermometers for the furnace are held together with bolts and nuts. They are attached to the instrumentation piping by brackets, which help the thermocouples to remain securely together. A constructed plate thermometer for the furnace is shown below in Figure 32.
The plate thermometers were then attached to a 3/4 inch steel pipe, which was capped at one end. The two thermocouple wires were then threaded through a hole drilled into a pipe and out the uncapped end of the pipe. The pipes with the plate thermometers bracketed to it were then attached to the furnace via flanges bolted into the bottom steel skin of the furnace 4 inches away from the open furnace face.

Appendix F.2: Plate Thermometer Heat Flux Calibration

Heat Flux Calculation

\[ q''_{\text{net}} = \varepsilon q''_{\text{incident}} + q''_{\text{conv}} + q''_{\text{rad}} + q''_{\text{cond}} \]

\[ q''_{\text{incident}} = \frac{q''_{\text{net}} + q''_{\text{conv}} + q''_{\text{rad}} + q''_{\text{cond}}}{\varepsilon} \]
\[ \dot{q}''_{\text{net}} = \rho c_p \delta \frac{dT}{dt} \quad \dot{q}''_{\text{conv}} = h(T_s + T_g) \quad \dot{q}''_{\text{rad}} = \varepsilon \sigma T_s^4 \quad \dot{q}''_{\text{cond}} = \frac{(T_s - T_{\text{insulated}})}{\frac{1}{r_c} + \frac{1}{k}} \]

The equation for incident heat flux uses the radiative heat transfer and convective heat transfer to account for the net heat transfer between the furnace and the steel plate, and accounts for the heat lost from the steel plate to the insulation of the plate thermometer through conductive heat transfer.

**Cone and Heat Flux Calculation Results for Initial Test Plate Thermometers**

The table below shows the temperature results from the cone calorimeter tests and the incident heat flux calculated from the temperature results.

<table>
<thead>
<tr>
<th>Plate Thermometer</th>
<th>Test</th>
<th>Temperature vs Time</th>
<th>Incident Heat Flux vs Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td><img src="image1.png" alt="Plate Thermometer Temp vs Time" /></td>
<td><img src="image2.png" alt="Incident Heat Flux vs Time" /></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td><img src="image3.png" alt="Plate Thermometer Temp vs Time" /></td>
<td><img src="image4.png" alt="Incident Heat Flux vs Time" /></td>
</tr>
</tbody>
</table>
Table 19: Measured Temperature and Calculated Heat Flux of Test Plate Thermometers

<table>
<thead>
<tr>
<th>Plate Thermometer</th>
<th>Test</th>
<th>Measured Temperature [°C (K)]</th>
<th>Calculated Heat Flux [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>690 (963)</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>680 (953)</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>670 (943)</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>670 (943)</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>660 (933)</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>675 (948)</td>
<td>67</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>680 (953)</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>670 (643)</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>665 (938)</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>665 (938)</td>
<td>63</td>
</tr>
</tbody>
</table>

The following is the MATLAB script that was used in the calculation of the incident heat flux of the initial test plate thermometers.

clear all
close all
click

sigma= 5.67e-8; %[W/m2K4]
epsilon= 0.8; %
\( h= 20, \text{ [W/m2 K]} \)
\( \rho= 7600, \text{ [kg/m}^3\text{]} \) density of stainless steel
\( c_p= 510, \text{ [J/kg K]} \) specific heat of stainless steel
\( \delta= 0.00158, \text{ [m]} \) thickness of stainless steel 1/16 inch
\( T_g= 298, \text{ [K]} \)
\( \text{num_pt_ave}= 8; \text{ % number of points being averaged} \)
\( \text{perc_net}= 0.3; \text{ %percentage of incident or net heat flux} \)
\( \text{perc_inc}= 0.05; \text{ %} \)
\( \text{perc_time} = 0.1; \)

data = xlsread('C:\Users\Lynn\Documents\MQP\Cone Results\TC25T&~1.XLS') ;
%6

time1= data(1,1);
TSC_temp = data(:,2) +273 ;
tempp = data(:,3) +273 ;
time_start = [230 1540 2415] ;
time_steady = [600 2000 2690] ;
time_stop= [815 2120 2915] ;
time_test= time_stop-time_start+1 ;

for count = 1:length(time_start)
    time(1:time_stop(count)-time_start(count),count) = time1(1:time_stop(count)-time_start(count)) ; % time stamp
    TSC_temp(1:time_stop(count)-time_start(count)-1),count) = TSC_temp1(1:time_stop(count)-time_start(count)-1),count) ; % Thin skin calorimeter temperature
    temp(1:time_stop(count)-time_start(count)-1),count) = temp1(1:time_stop(count)-time_start(count)-1),count) ; % insulated temperature
end

dt = 1 ; %[s]
dT_dt = (TSC_temp(2:end,:)- TSC_temp(1:end-1,:))/dt ; %[K/s]
T_s = TSC_temp(1:length(T_T_dt),:) ; %[K]
T_ins = temp(1:length(dT_dt),:) ; %[K]
q_net = rho.*c_p.*delta.*dT_dt ; %[kW]
q_conv = k.*(T_s-T_g) ; %[kW]
q_rad = epsilon.*sigma.*T_s.^4 ; %[kW]

k = 0.135 ; %[W/(m K)] insulation
L = 0.00635 ; %[m] length of substrate
h_s = 150 ;
q_cond_k = (T_s-T_ins)/(1/h_s+L/k) ; %[W]
q_inc_03 = ((q_net + q_conv + q_rad + q_cond_k)./epsilon )./1000 ; %[kW]

for ii = num_pt_ave+1:length(q_inc_03)-num_pt_ave+1
    q_inc_03(ii-num_pt_ave,:) = mean(q_inc_03(ii-num_pt_ave : ii+num_pt_ave,: ) ) ;
end
q_inc_80ave = mean(q_inc_03(1:400,1)) ;

%% Plotting results
figure
hold on
plot(time(1:time_test(1)-63,1),TSC_temp(1:time_test(1)-63,1),'.b')
plot(time(1:time_test(1)-63,1),temp(1:time_test(1)-63,1),'-b')
xlabel('Time (s)')
ylabel('Thin Skin Temp (K)')
axis([0 900 0 1500])
legend('plate','insulation')
hold off

% All three heat fluxes
figure
hold on
plot(time(1:time_test(1)-64,1),q_inc_03(1:time_test(1)-64,1),'.b','LineWidth',2)
xlabel('Time (s)')
ylabel('Incident Heat flux (kW/m2)')
axis([0 400 0 80])
% grid on
legend('80kW Coef','Location','SouthEast')
hold off

legend('80kW/m2','Location','SouthEast')
hold off

Cone and Heat Flux Calculation Results for Furnace Plate Thermometers

| Plate Thermometer | Temperature vs Time | Incident Heat Flux vs Time |
The following is the MATLAB script that was used in the calculation of the incident heat flux of the plate thermometers for the actual furnace.

```matlab
clear all
close all
clc

sigma = 5.67e-8; % [W/m²K⁴]
epsilon = 0.3;

h = 20; % [W/(m² K)]
density = 8440; % [kg/m³] density of Inconel 625
specific_heat = 410; % [J/(kg K)] specific heat of Inconel 625
thickness = 0.0007112; % [m] thickness of Inconel 625 1/16 inch
T_g = 298; % [K]
num_pt_ave = 8; % number of points being averaged
perc_net = 0.3; % percentage of incident or net heat flux
perc_inc = 0.05;
perc_time = 0.1;

data = xlsread(’C:\Users\Lynn\Documents\MQP\Furnace PT\PT5-1.XLS’);

for count = 1:length(time_start)
    TSC_temp(count,:) = TSC_temp(1:length(time_start(count)),count) - TSC_temp(1:length(time_start(count))-1,count) + TSC_temp(count)
end

time = (time_stop - time_start+1);
dt = 1 ; %[s]
dT_dt = (TSC_temp(2:end,:)) - TSC_temp(1:end-1,:))/dt ; %[K/s]

T_s = TSC_temp(1:length(dT_dt,:)); %[K]
T_ins = temp(1:length(dT_dt,:)); %[K]

q_net = rho.*c_p.*delta.*dT_dt ; %[KW]
q_conv = h.*(T_s - T_g) ; %[KW]
q_rad = epsilon.*sigma.*T_s.^4 ; %[KW]

for ii = num_pt_ave+1:length(q_inc_03) num_pt_ave+1)
    q_inc_03(ii) = mean(q_inc_03(ii-1:length(q_inc_03))); %=mean(q_inc_03(11-1:400,1))
end

q_inc_80ave = mean(q_inc_03(1:400,1));
```

This MATLAB script calculates the incident heat flux of the plate thermometers for the actual furnace.
%% Plotting results
figure
hold on
plot(time(1:time_test(1)-63,1),TSC_temp(1:time_test(1)-63,1),'.b')

plot(time(1:time_test(1)-63,1),temp(1:time_test(1)-63,1),'-b')

xlabel('Time (s)')
ylabel('Thin Skin Temp (K)')
axis([0 900 0 1500])
legend('plate','insulation')
hold off

% All three heat fluxes
figure
hold on
plot(time(1:time_test(1)-64,1),q_inc_03(1:time_test(1)-64,1),'-b','LineWidth',2)

xlabel('Time (s)')
ylabel('Incident Heat flux (kW/m2)')
axis([0 400 0 80])
% grid on
legend('80kW Coef','Location','SouthEast')
hold off

legend('80kW/m2','Location','SouthEast')
hold off