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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

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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
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2.0 Structural Analysis	Kevin Lynch, Dylan Martel
3.0 Insulation Selection	Alex Ing, Tara Sharp
4.0 CFD Modeling	Joe Igoe, Austin Smith
5.0 Instrumentation	Joe Igoe, Alex Ing, Lynn Renner

Table of Contents

Table of Figures

Table of Tables

Table of Equations

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 off 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 4ft 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[7]. 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*[8]. 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[9]. 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.

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[10]. Diagrams associated with these components of the analysis are represented in Figure 2.

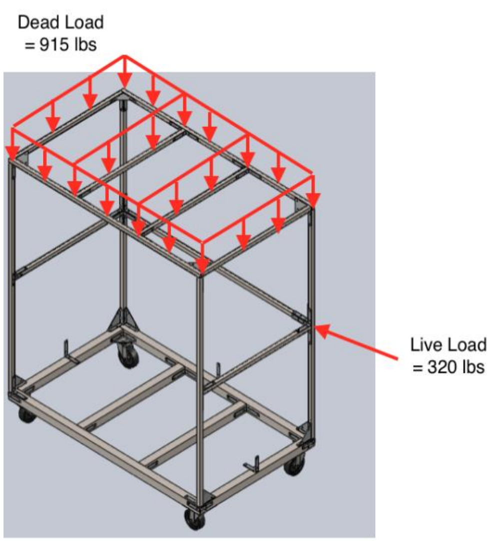


Figure 1: Furnace - Load Distribution

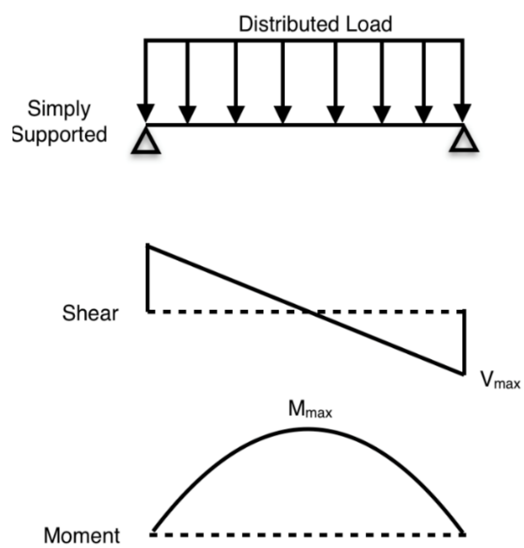


Figure 2: Shear and Moment Diagrams

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[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 1: Static Analysis- Furnace Frame

Furnace Frame				
Maximum Dead Load (lbf)			***Beam/ Column Interpretation***	
915			Simply Supported & Fixed	
Furnace Component		***Calculation***	***Calculated Value***	***Allowable Value***
Top Beams	L=5’	Max Deflection (in)	0.13	0.2
		Max Bending Stress (psi)	472	27600
		Max Shear Stress (p si)	64	
	L=3’	Max Deflection (in)	0.12	0.2
		Max Bending Stress (psi)	4001	27600
		Max Shear Stress (psi)	6259	
Bottom Beams	L=5’	Max Deflection (in)	0.057	0.2
		Max Bending Stress (psi)	10742	27600
		Max Shear Stress (psi)	948	
	L=3’	Max Deflection (in)	0.052	0.2
		Max Bending Stress (psi)	3552	
		Max Shear Stress (psi)	518	27600
Columns	L=5’	Load Applied (lbf)	66	23242
Brackets	5”x5”	Max Moment (in*lbf)	795	1515
Plates	5’x3’, t= 1/8”	Max Deflection (in)	0.038	0.083
		Max Bending Stress (psi)	1585	22800
	5’x3’, t= 1/4”	Max Deflection (in)	0.006	0.083
		Max Bending Stress (psi)	4781	22800

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.

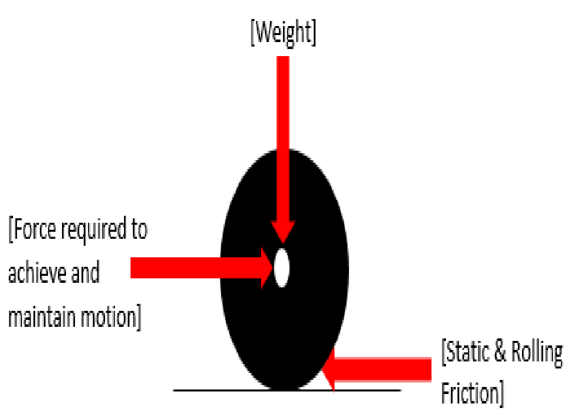


Figure 3: Required Dynamic Loads

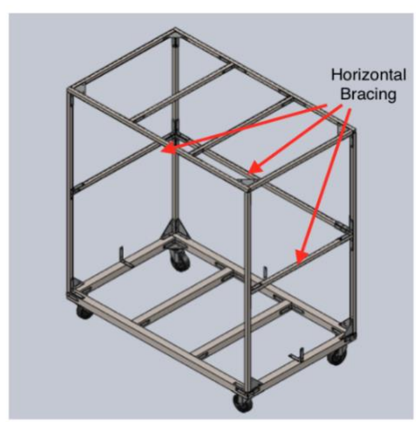


Figure 4: Furnace Frame Bracing

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[12]. 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.[13] 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^{o}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.[14]

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[15]. 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.

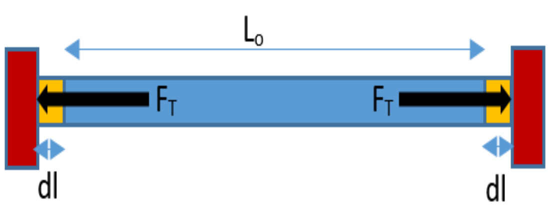


Figure 5: Linear Thermal Expansion

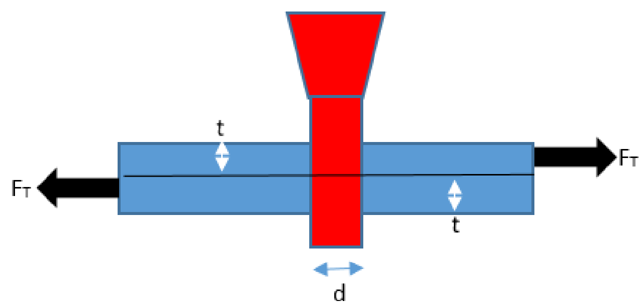


Figure 6: Single Shear Analysis

Due to the displacement caused by thermal expansion, structural members within the design impose and are subjected to resultant axial forces[16]. 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 2: Static Analysis- Specimen Mount

Specimen Mount				
Maximum Dead Load (lbf)			***Beam/ Column Interpretation***	
1800			Simply Supported	
Furnace Component		***Calculation***	***Calculated Value***	***Allowable Value***
I Beam		Max Deflection	0.065	0.25
Bottom Beams	3.5”x3.5” L=3’	Max Deflection (in)	0.019	0.19
		Max Bending Stress (psi)	7188	35928
		Max Shear Stress (psi)	1954	

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.

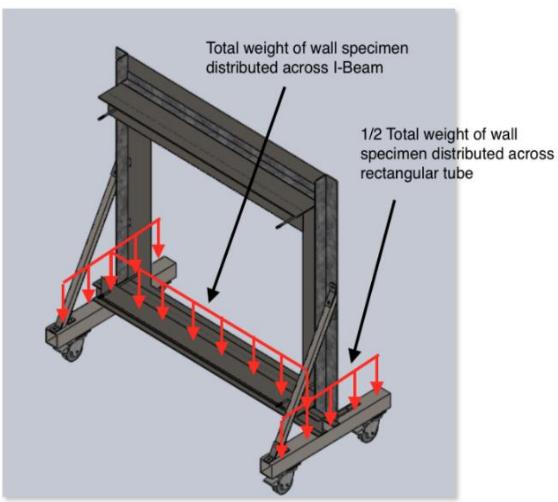


Figure 7: Specimen Mount - Load Distribution

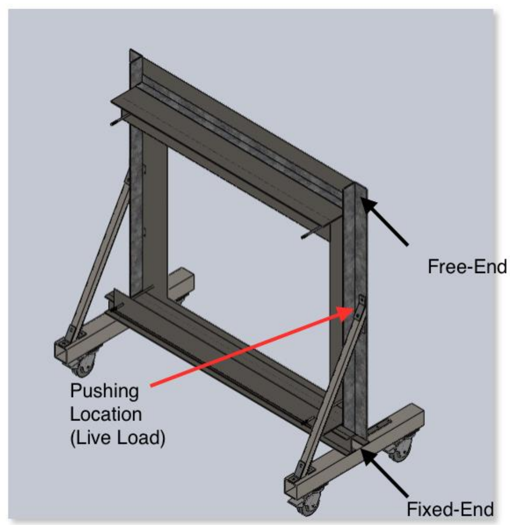


Figure 8: Specimen Mount – Cantilever Interpretation

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 3: Static Analysis- Burner Frame

Burner Frame				
Maximum Dead Load (lbf)			***Beam/ Column Interpretation***	
150			Simply Supported	
Furnace Component		***Calculation***	***Calculated Value***	***Allowable Value***
Beams	L=3’	Max Load to Shear (lbf)	150	499
		Max Load to Max Deflection(lbf)		464
	L=5’	Max Load to Shear (lbf)	150	297
		Max Load to Max Deflection(lbf)		167
Columns	L=5’ L=3’	Column Load (lbf)	200	4023

3.0 Insulation Selection

3.1 Material Selection

While in operation, the testing furnace will reach up to 1000^{o} 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^{o} 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.

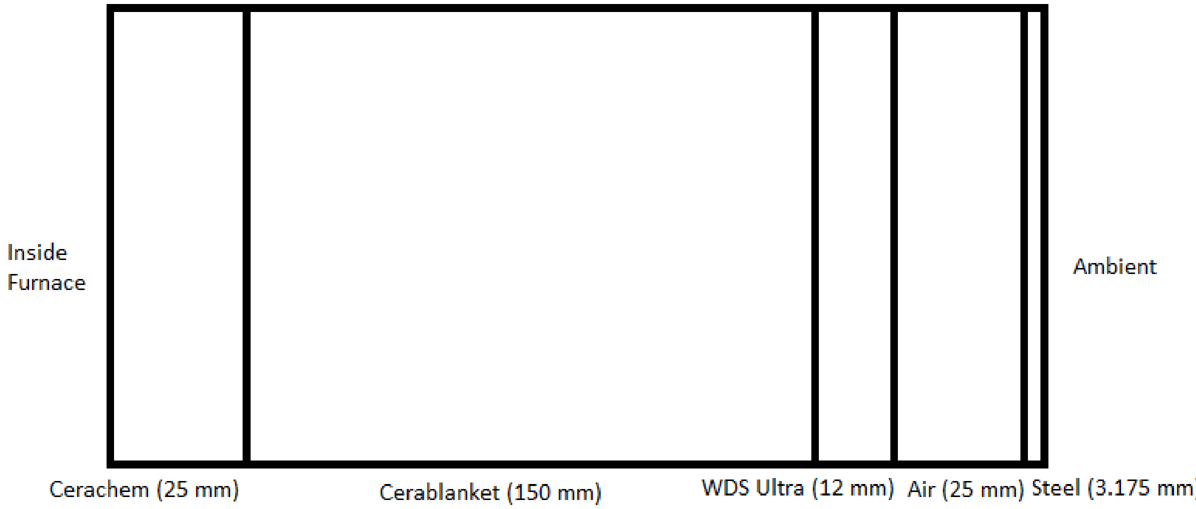


Figure 9: Layers of insulation inside the furnace

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).

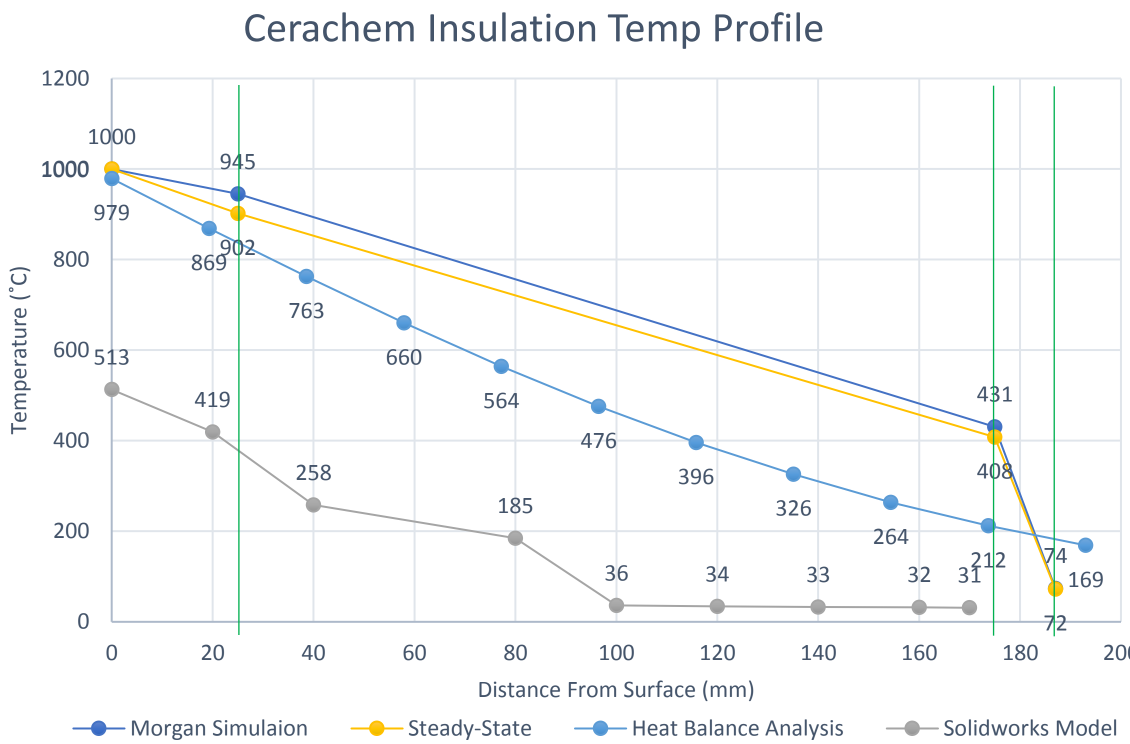


Figure 10: Temperature Profile Comparison

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 4: Comparison of Analyses between the Morgan Simulation, Steady State Analysis, Heat Balance Analysis, and Solidworks Model for Heat Loss to the Walls

	Morgan Simulation	Steady State Analysis	Heat Balance Analysis	Solidworks Model
Total Heat Losses and Storage	21.6 kW	50.8 kW	50 kW	87 kW

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[18]. 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[19]. The second model used was the Fire Dynamics Simulator (FDS) which was developed by National Institute of Standards and Technology[20]. 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 5: ASTM E119 Time-Temperature Curve Simulation

Time (s)	Percentage of Adiabatic Flame Temperature	Simulation Gas Temperature (˚C)
5	0.10	100
50	0.15	300
100	0.25	500
150	0.35	700
200	0.45	900
250	0.50	1,000
600	0.55	1,100
900	0.57	1,140
1500	0.58	1,160

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.

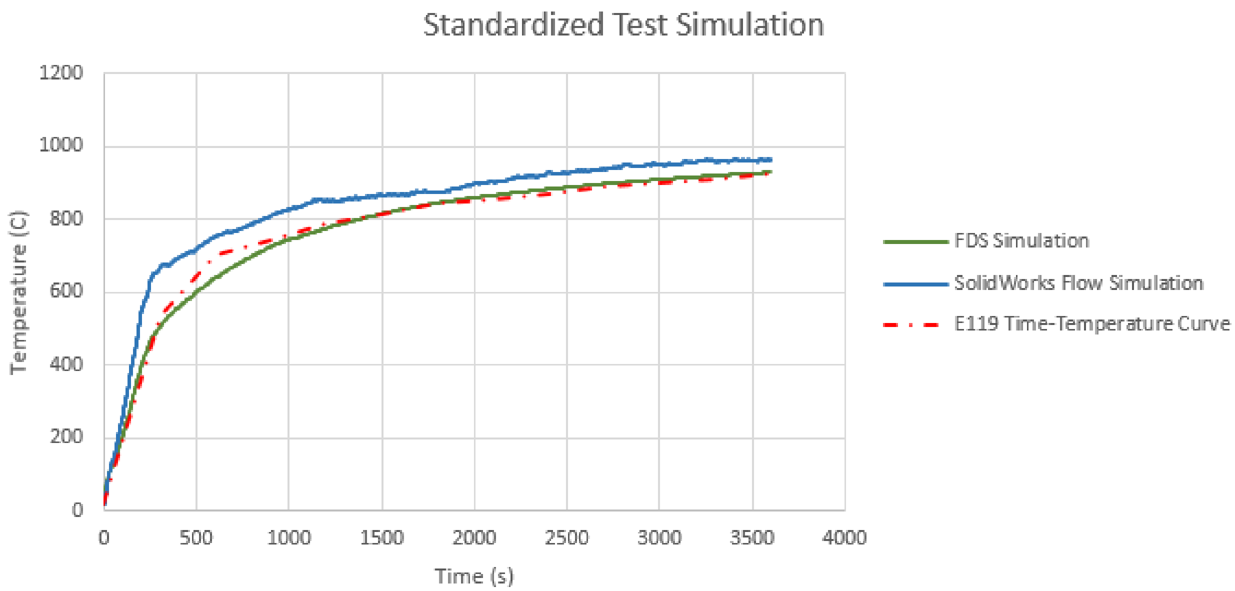


Figure 11: ASTM E119 Fire Resistance Test Simulation Using CFD Models

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/m^2. The cut plot below displays the resulting temperature distribution within the furnace and across the concrete specimen.

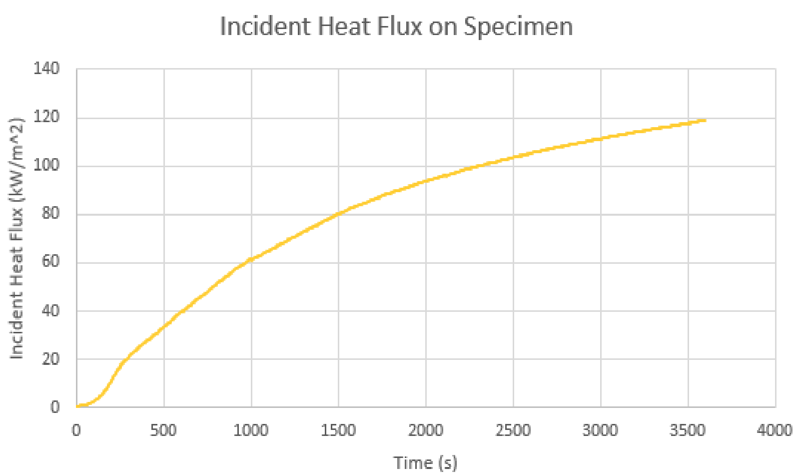


Figure 12: Incident Heat Flux on Specimen

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.

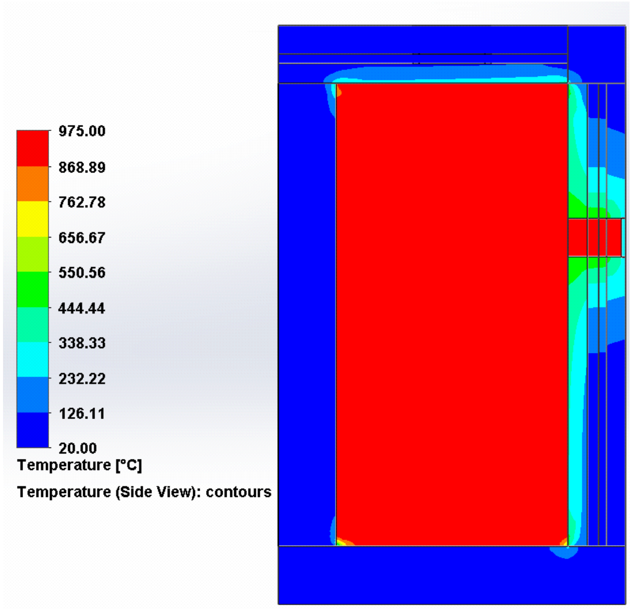


Figure 13: Temperature distribution in Solidworks Flow Simulation Model

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.

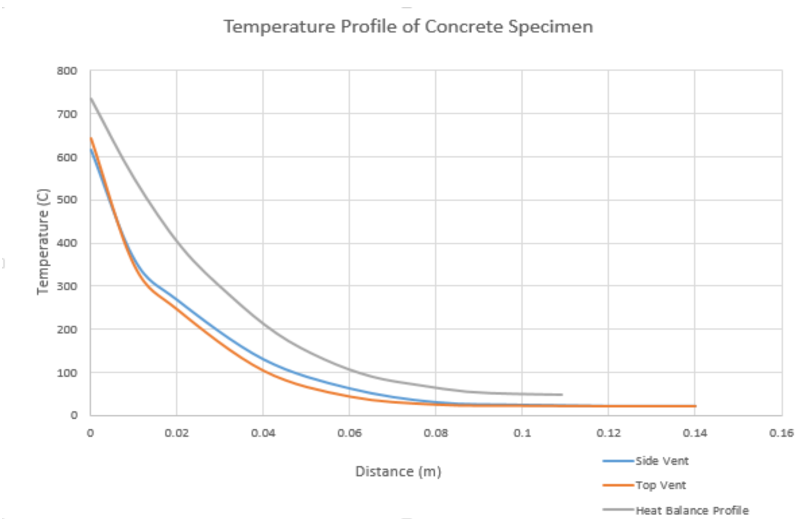


Figure 14: Temperature Profile of Concrete Specimen (HBA & Flow Simulation) After 1 Hour

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 6: Verification for Estimated Heat Loss

	Heat Balance Analysis	**FDS**	**Flow Simulation**
Heat Loss (kW)	65	73	76

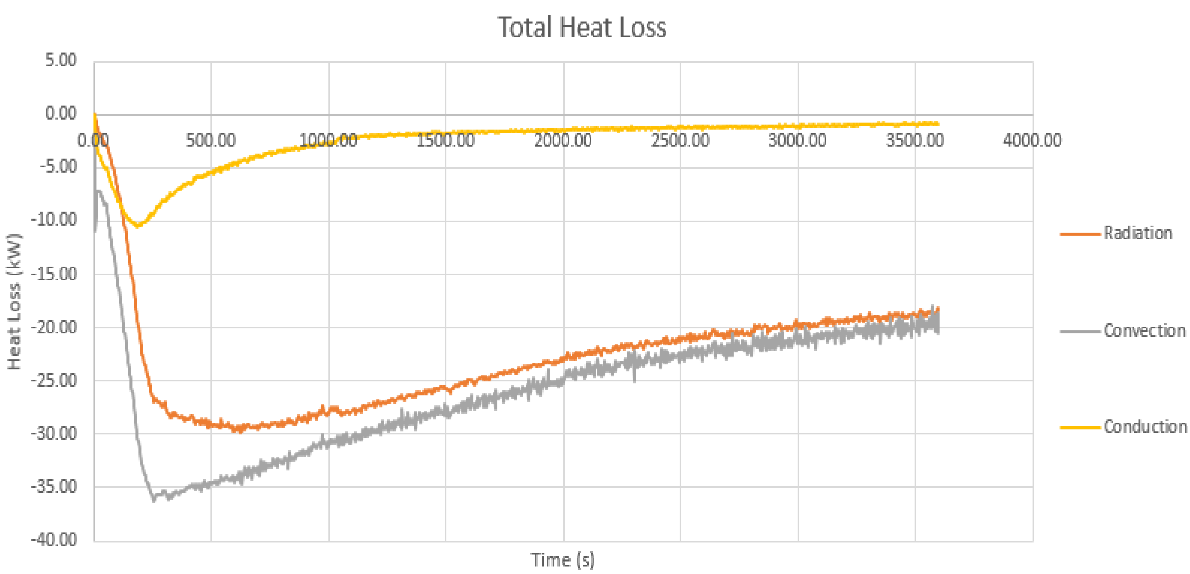


Figure 15. Heat Loss by Each Mode of Heat Transfer

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.

Table 7: Table of Vent Opening

Vent #	Time when opened during simulation (s)
1	5
2	50
3	300
4	600
5	1,000
6	2,000

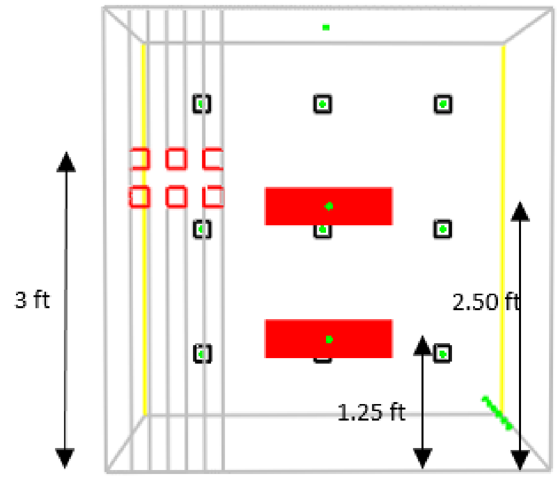


Figure 16: FDS Instrumentation Placement

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.

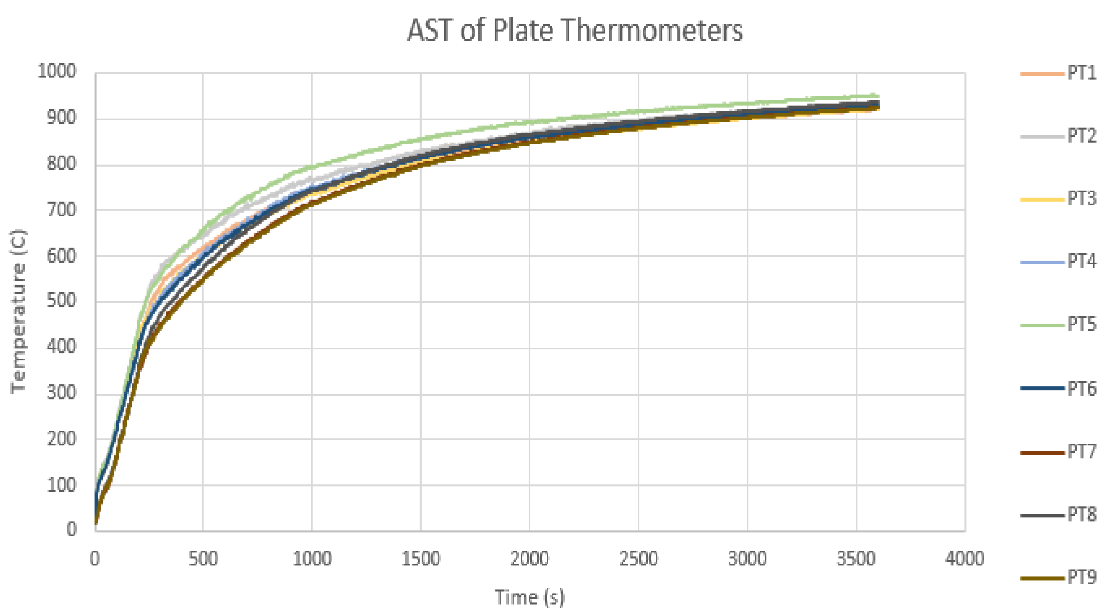


Figure 17: AST of Plate Thermometers

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[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[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.

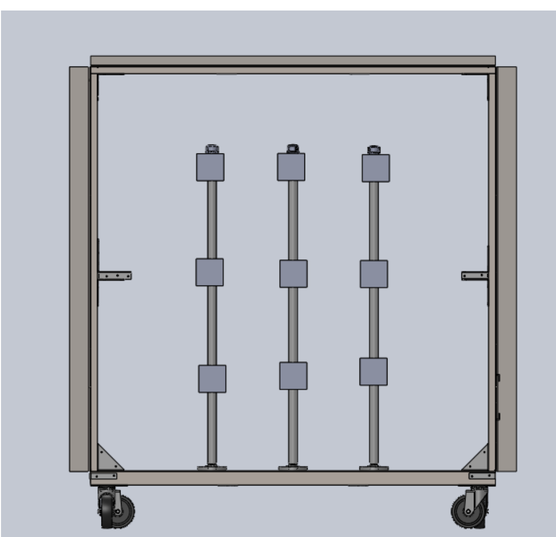


Figure 18:View from the Burner of PT Placement

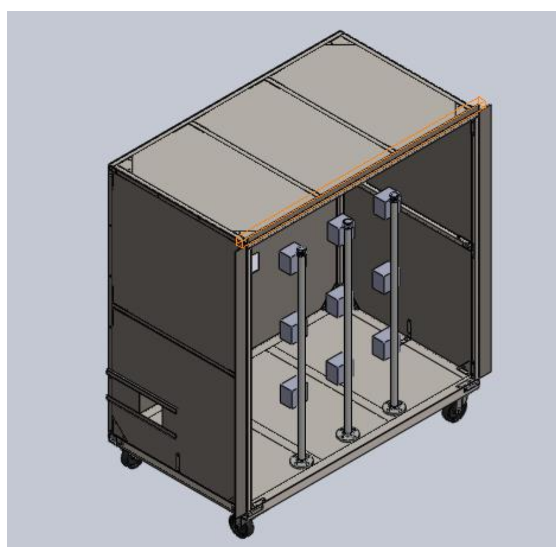


Figure 19:Isomeric View of PT Placement

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/m^2, 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

$$Cone\ Temperature = -0.05035y^2 + 10.92y + 189$$

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[23]

$$\dot{q}''_{incident} = \frac{\rho c_p \delta \frac{dT}{dt} + h\left(T_s + T_g\right) + \varepsilon\sigma T_s^4 + \frac{(T_s - T_{insulated})}{\frac{1}{h_c} + \frac{L}{k}}}{\varepsilon}$$

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[24]. 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

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

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[25]. 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

[1] *2012 International Building Code*. Country Club Hills, Ill: ICC, 2011. Print.
[2] National Fire Protection Association., and Ron Coté. *Life Safety Code Handbook: With the Complete Text of the 2015 Edition of NFPA 101, Life Safety Code*. Quincy, Mass.: National Fire Protection Association, 2015.
[3] Cote, Arthur E. *Fire Protection Handbook*. Quincy, MA: National Fire Protection Association, 2008. Print.
[4] ASTM E119-16a Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/E0119-16A
[5] ASTM E119-16a Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/E0119-16A
[6] ASTM E119-16a Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/E0119-16A
[7] Correll, Charles. *Control of Forced Air and Gas Burner Systems*. Rep. Correll Glass Studio, Web. 29 Mar. 2017
[8] AISC.*Manual of Steel Construction: Allowable Stress Design*. Vol. 2nd Rev. of the 9th. Chicago, Ill: American Institute of Steel Construction, 1995.
[9] Hibbeler, R C. *Mechanics of Materials*. 8th ed., New Jersey, Pearson Prentice Hall, 2011
[10] Hibbeler, R C. Engineering Mechanics Statics. 13th ed., New Jersey, Pearson Prentice Hall, 2013.
[11] Atlas Tube. Material Test Report. N.p.: n.p., 1 Jan. 2017. PDF.
[12] Young, W. C., Budynas, R. G.(2002). Roark's Formulas for Stress and Strain . 7nd Edition, McGraw-Hill
[13] Amesweb. "HOMEPAGE." Amesweb. N.p., n.d. Web. 04 Mar. 2017.
[14] Edge, LLC. Engineers. "Reference Data for Engineers | GD&T ASME Training | GD&T Training | DFM DFA Training | Engineering Supplies Store | Engineering Tools for Productivity." Engineers Edge.
[15] Kloeckner Metals Corp. Material Test Report. N.p.: n.p., 13 Feb. 2017. PDF.
[16] "Engineering ToolBox." The Engineering ToolBox. N.p., n.d. Web. 04 Mar. 2017
[17] Cutter, P. A., Shenoi, R. A., Phillips, H. J., & Moy, S. J. (2015, November 02). A new small scale fire resistance test method for composite materials. Retrieved from https://www.researchgate.net/publication/283135765_A_new_small_scale_fire_resistance_test_method_for_composite_materials
[18] *Solidworks Flow Simulation 2012 Technical Reference* [PDF]. (2012). Dassault Systemes
[19] *Solidworks Flow Simulation 2012 Technical Reference* [PDF]. (2012). Dassault Systemes
[20] McGrattan, Kevin B., and Randall J. McDermott. “FDS and Smokeview.” *NIST.* National
[21] Wickstrom, Ulf. “Adiabatic Surface Temperature and the Plate Thermometer for Calculating Heat Transfer and Controlling Fire Resistance Furnaces. *SP Technical Research Institute of Sweden, Department of Fire Technology,* 1985.
[22] ASTM E119-16a Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/E0119-16A
[23] Alston, Jarrod. “This Skin Calorimeter – Fire Science Tools.” *Google Sites.* Fire Science Tools, n.d. Web. 31 Mar. 2017
[24] Alston, Jarrod. “This Skin Calorimeter – Heat Flux Calculation Script.” *Google Sites.* Fire Science Tools, n.d. Web. 31 Mar. 2017

[25] Beyler, Craig, Jesse Beitel, Nestor Iwankiw, and Brian Lattimer. *Fire Resistance Testing For Performance-Based Design of Buildings.* Rep. Quincy, MA: Fire Protection Research Foundation, 2007. Print
[26] Hottel, Hoyt C., and Adel F. Sarofim. Radiative Transfer. New York: McGraw-Hill, 1967. Print

Appendix A: Structural Analysis

Appendix A.1 ASD

Limitation	Variables	
$R_a \leq \frac{R_n}{\Omega}$	R_a= Required Strength (Dead or Live; Force, Moment, Stress) R_n= Nominal Strength Specified Ω= Safety Factor	
	Factors of Safety (applied in order to limit the stresses for allowable stress values)	
	Bending (Braced Member, $L_b < L_p$)	Ω=1.67
	Bending (Unbraced Member, $L_b < L_p$ &$L_b < L_r$)	Ω=1.67
	Shear (Beams)	Ω=1.67
	Shear (Bolts)	Ω=2.00

Appendix A.2: Construction Procedure

Appendix A.2.1: Construction Procedure-Furnace Frame

Furnace Frame	
Procedure Specifications	
Phase No.	**Process**
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

<table>
<tr><td></td><td>Note:
Refer to Drawings for cut lengths.</td></tr>
<tr><td>3</td><td>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.
<table>
<tr><th colspan="5">3.A: 1” STEEL TUBE</th></tr>
<tr><th>ID</th><th>Length</th><th>ID Dimension</th><th>Drill Size</th><th>Tap Size</th></tr>
<tr><td>V1</td><td rowspan="4">59”</td><td rowspan="15">1”x1”x1/8” (A 513)

1”x1”x1/8” (A 513)</td><td rowspan="15">7

7</td><td rowspan="15">¼”-20

¼”-20</td></tr>
<tr><td>V2</td></tr>
<tr><td>V3</td></tr>
<tr><td>V4</td></tr>
<tr><td>TS1</td><td rowspan="8">34”</td></tr>
<tr><td>TS2</td></tr>
<tr><td>TB1</td></tr>
<tr><td>TB2</td></tr>
<tr><td>SB1</td></tr>
<tr><td>SB2</td></tr>
<tr><td>TB1</td></tr>
<tr><td>TB2</td></tr>
<tr><td>TFH</td><td rowspan="2">60”</td></tr>
<tr><td>TBH</td></tr>
<tr><td>BHB</td><td>58”</td></tr>
<tr><th colspan="5">3B: 2” STEEL TUBE</th></tr>
<tr><th>ID</th><th>Length</th><th>ID Dimension</th><th>Drill Size</th><th>Tap Size</th></tr>
<tr><td>BS1</td><td rowspan="4">32”</td><td rowspan="6">2”x2”</td><td rowspan="6">7</td><td rowspan="6">¼” -20</td></tr>
<tr><td>BS2</td></tr>
<tr><td>BB1</td></tr>
<tr><td>BB2</td></tr>
<tr><td>BFH</td><td rowspan="2">60”</td></tr>
<tr><td>BBH</td></tr>
<tr><th colspan="5">3C: STEEL SHEET</th></tr>
<tr><th>ID</th><th colspan="2">ID Dimension</th><th>Drill Size</th><th>Tap Size</th></tr>
<tr><td>TSH</td><td colspan="2" rowspan="4">5’x3’, t=1/8”</td><td rowspan="5">5/16”</td><td rowspan="5">Thru</td></tr>
<tr><td>BSH</td></tr>
<tr><td>LSH</td></tr>
<tr><td>RSH</td></tr>
<tr><td>BKSH</td><td colspan="2">5’x5’, t=1/8”</td></tr>
</table>
Note:
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.</td></tr>
</table>

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				
ID	**Coincident Members**	**ID Dimension**	**Drill Size**	**Tap Size**
1.1	TS1, V1	5"x5"x7/8" t=1/8"	16	12-24
1.2	SB1, V1			
1.3	SB1, V1			
1.4	TFH, V1			
2.1	TS1, V2	5"x5"x7/8" t=1/8"	16	12-24
2.2	SB1, V2			
2.3	SB1, V2			
2.4	TBH, V2			
2.5	BHB, V2			
2.6	BHB, V2			
3.1	TS2, V3			
3.2	SB2, V3			
3.3	SB2, V3			
3.4	TBH, V3			
3.5	BHB. V3			
3.6	BHB, V3			
4.1	TS2, V4			
4.2	SB2, V4			
4.3	SB2, V4			
4.4	TFH, V4			
T1.1	TBH, TB1			
T1.2	TFH, TB1			
T1.3	TBH, TB1			
T1.4	TFH, TB1			
T2.1	TBH, TB2			
T2.2	TFH, TB2			
T2.3	TBH, TB2			
T2.4	TFH, TB2			
4B: L-BRACKET TO 2" STEEL TUBE				
ID	**Coincident Members**	**ID Dimension**	**Drill Size**	**Tap Size**
1.1	BFH, BS1	5"x5"x7/8" t=1/8"	16	12-24
1.2	BFH, BB1			
1.3	BFH, BB1			
1.4	BFH, BB2			
1.5	BFH, BB2			
1.6	BFH, BS2			
2.1	BBH, BS1			
2.2	BBH, BB1		16	12-24
2.3	BBH, BB1	5"x5"x7/8"		

		2.4	BBH, BB2	t=1/8”		
		2.5	BBH, BB2			
		2.6	BBH, BS2			

4C: L-BRACKET TO BOTTOM STEEL SHEET & 2” STEEL TUBE

ID	Coincident Components	ID Dimension	Drill Size	Tap Size
1.5	BSH, BFH, V1	5”x5”x7/8” t=1/8”	16	12-24
4.5	BSH, BFH, V4			

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

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

5B: T BRACKET TO 2” STEEL TUBE

ID	Coincident Members	ID Dimension	Drill Size	Tap Size
3.1	BBH, BB1	3”x3”x7/8” t=1/8”	29	8-32
3.2	BFH, BB2			
3.3	BBH, BB2			
3.4	BBH, BB1			

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

ID	Coincident Members	ID Dimension	Drill Size	Tap Size
1.1	TS1, TFH	4”x4”x7/8”	29	8-32

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				
ID	**Coincident Components**	**ID Dimension**	**Drill Size**	**Tap Size**
1.2	BSH, BS1, V2	4”x4”x7/8” t=1/8”	29	8-32
1.3	BSH, BS1, V1			
1.4	BSH, BBH, V3			
1.5	BSH, BBH, V2			
1.6	BSH, BS2, V4			
1.7	BSH, BS2, V3			

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.

7A: CASTER TO 2” STEEL TUBE				
ID	**Coincident Members**	**ID Dimension**	**Drill Size**	**Tap Size**
1.1	BFH, BS1	4 1/8”x 4 1/8” x 1 1/4” t= 1/8”	18	5/16”
1.2	BBH, BS1			
1.3	BBH, BS2			
1.4	BBH, BS2			

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.

8: Angle Iron to Steel Sheet & 1”Tube

ID	Coincident Components	ID Dimension	Drill Size	Tap Size
1.1	LSH, V1	3”x2”x3/16”	7	Thru
1.2	TSH, TFH			
1.3	LSH, V4			

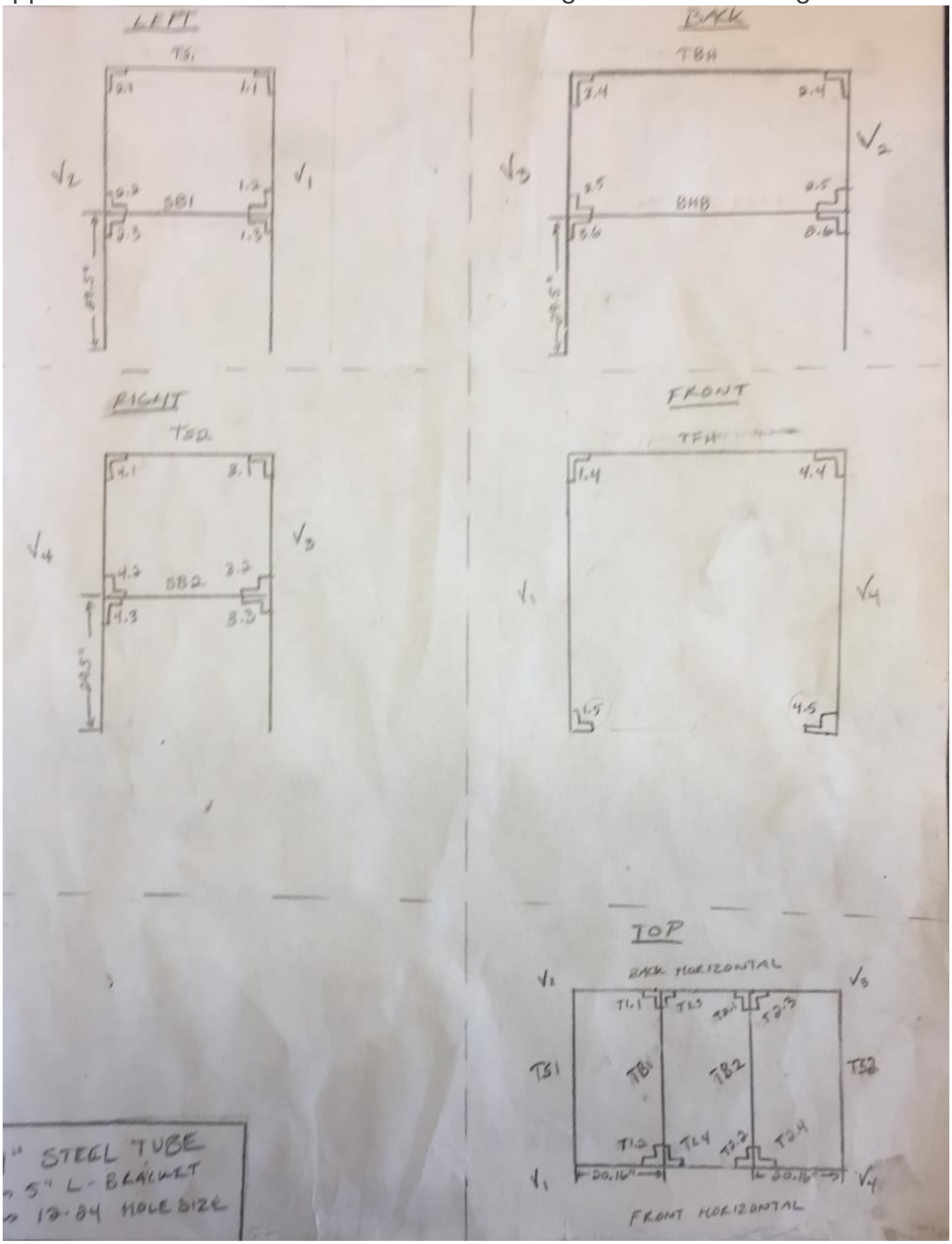
Note:
Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

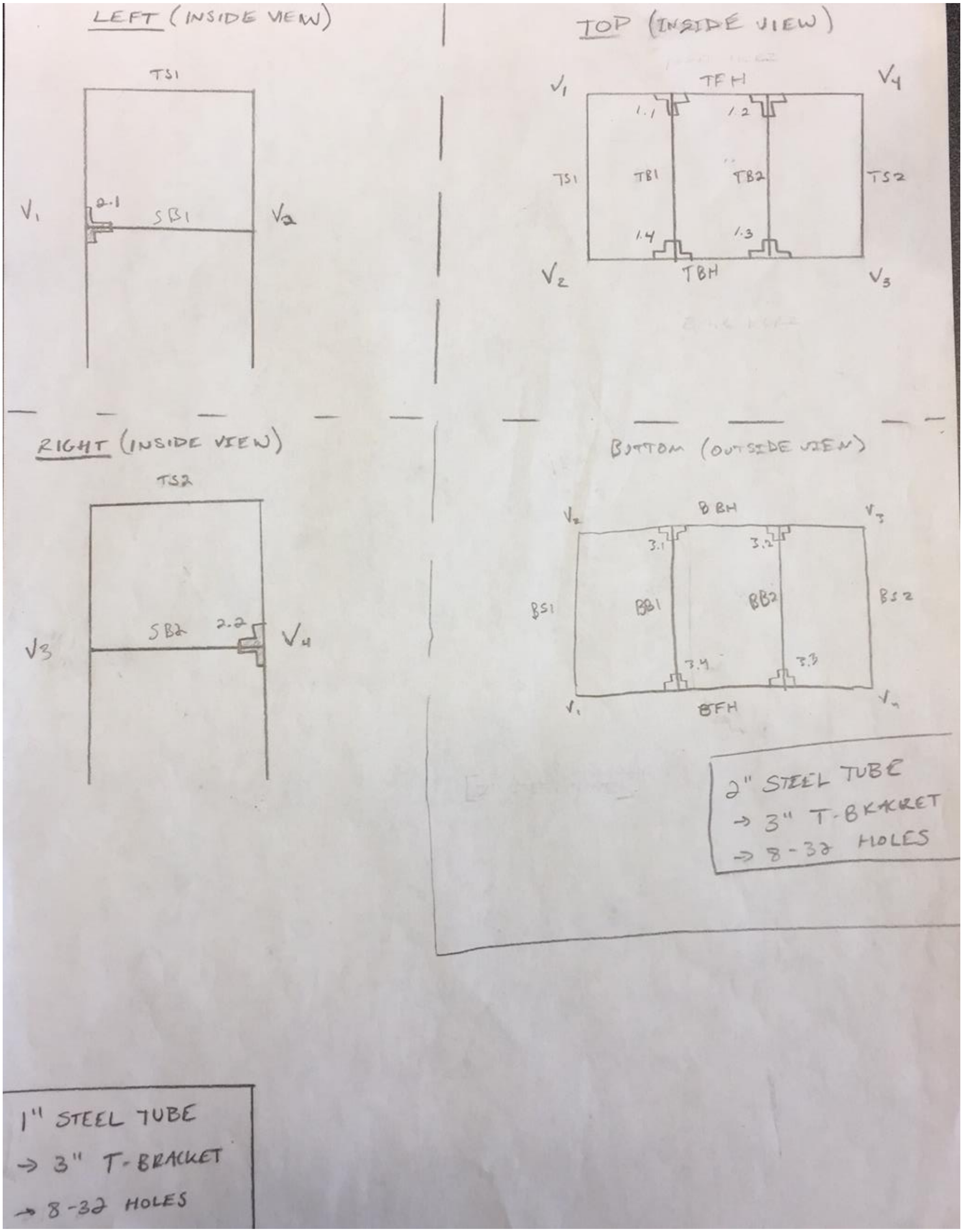
ID Legend	V: Columns TS: Top Side Beam TB: Top Brace SB: Side Brace TFH: Top Front Horizontal Beam TBH: Top Back Horizontal Beam BHB: Back Horizontal Brace BS: Bottom Side Beam BB: Bottom Brace BFH: Bottom Front Horizontal Beam BBH: Bottom Back Horizontal Beam TSH: Top Steel Sheet BSH: Bottom Steel Sheet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

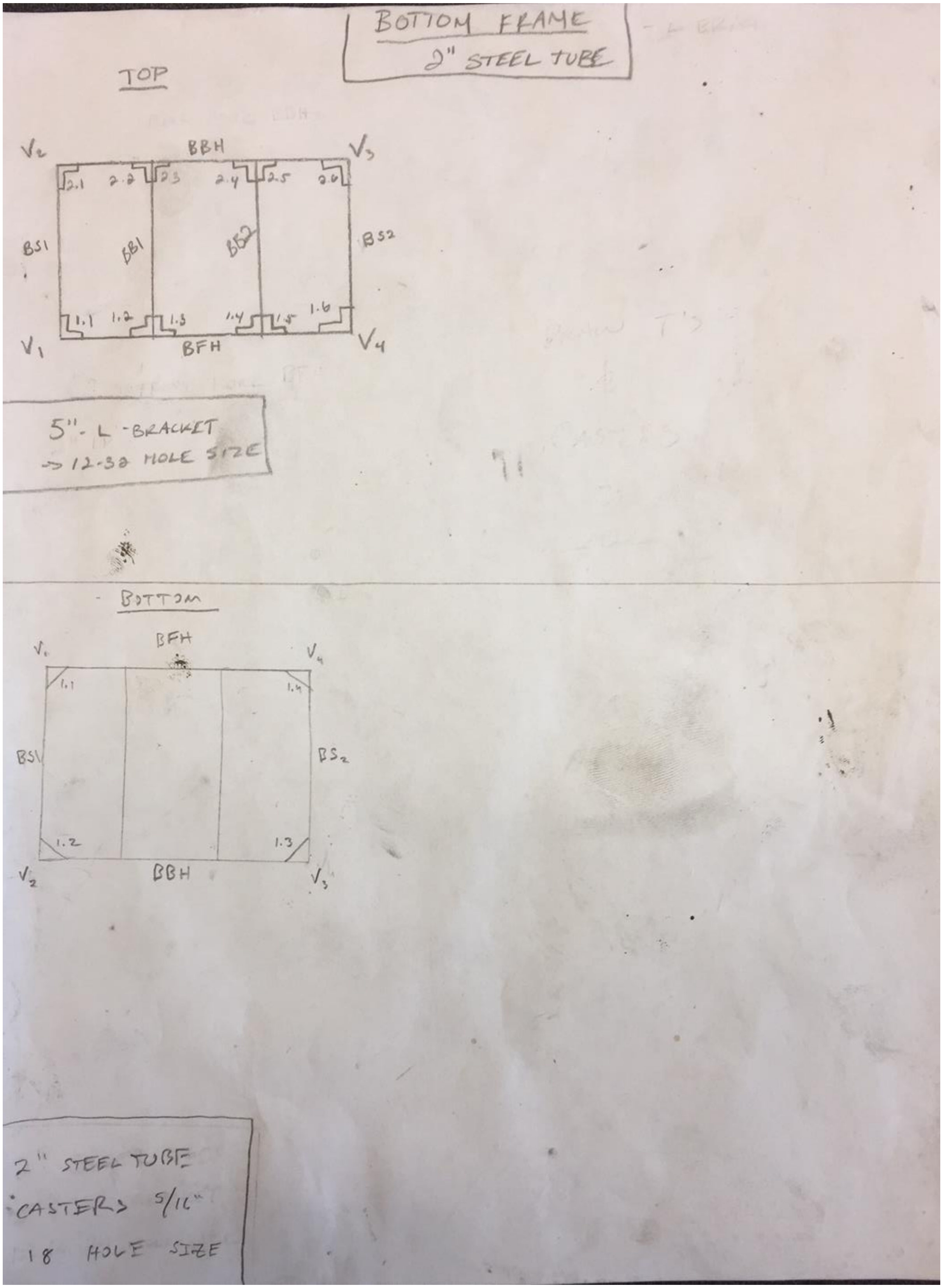
Procedure Order

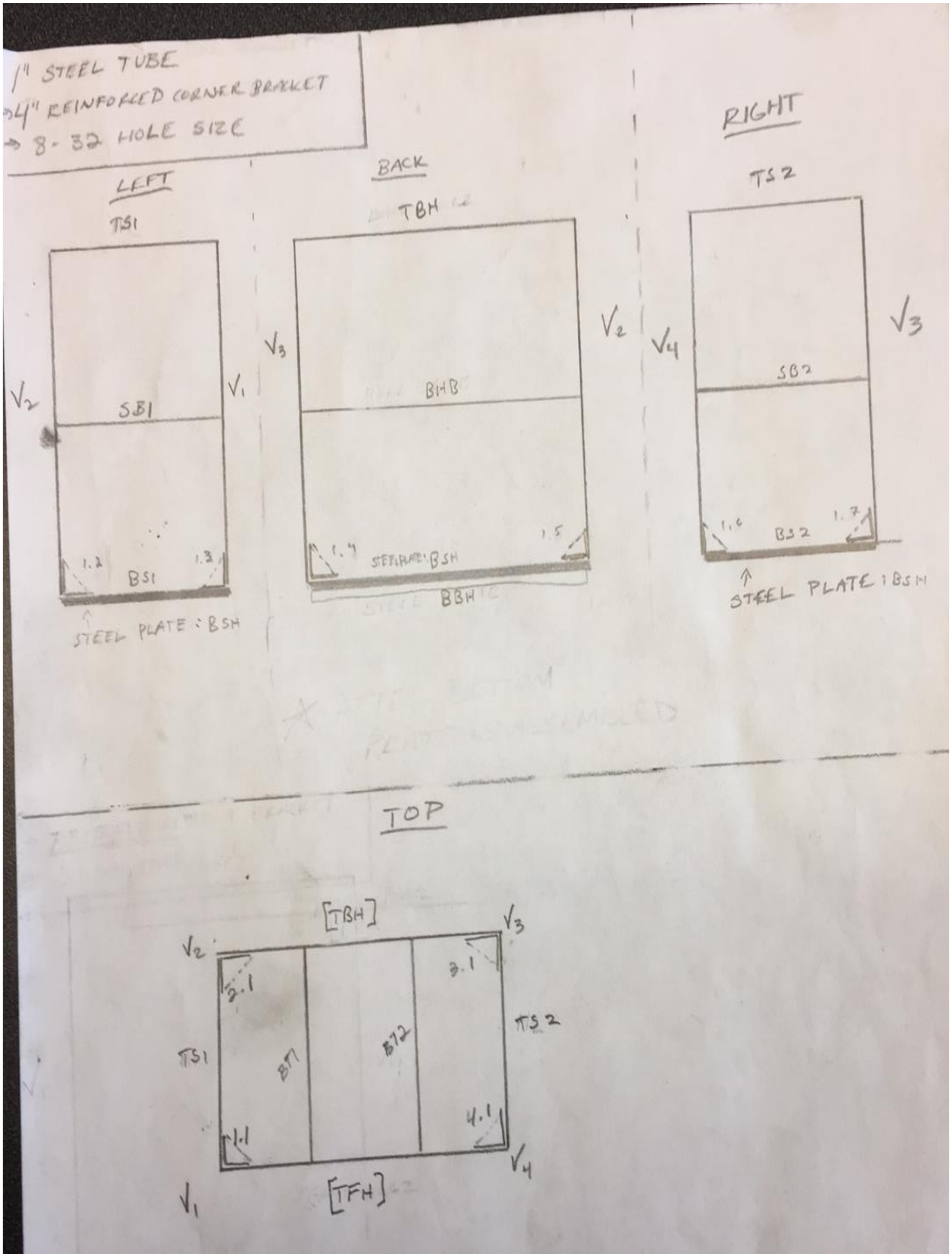
1. Phase 1
2. Phase 2
3. Phase 3A
4. Phase 4A
5. Phase 5A
6. Phase 6A
7. Assembly 1: V1, V2, V3, V4, TS1, TS2, TB1, TB2, SB1, SB2, TFH, TBH, BHB
8. Phase 3B
9. Phase 4B
10. Phase 5B
11. Phase 6B
12. Phase 7A
13. Phase 4C
14. Assembly 2: BS1, BS2, BB1, BB2, BFH, BBH, BSH
15. Assembly 3: Assembly 1 & 2
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




LEFT (INSIDE VIEW)
TS1
2.1
SB1
V1
V2
TOP (INSIDE VIEW)
V1
TFH
V4
1.1
1.2
TS1
TB1
TB2
TS2
1.4
1.3
V2
TBH
V3
RIGHT (INSIDE VIEW)
TS2
SB2
2.2
V3
V4
BOTTOM (OUTSIDE VIEW)
V2
BBH
V3
3.1
3.2
BS1
BB1
BB2
BS2
3.4
3.3
V1
BFH
V4
2" STEEL TUBE
→ 3" T-BRACKET
→ 8-32 HOLES
1" STEEL TUBE
→ 3" T-BRACKET
→ 8-32 HOLES


BOTTOM FRAME
2" STEEL TUBE
TOP
V2
BBH
V3
2.1
2.2
2.3
2.4
2.5
2.6
BS1
BB1
BS2
1.1
1.2
1.3
1.4
1.5
1.6
V1
BFH
V4
5"- L -BRACKET
→ 12-32 HOLE SIZE
BOTTOM
V1
BFH
V4
1.1
1.4
BS1
BS2
1.2
1.3
V2
BBH
V3
2" STEEL TUBE
CASTERS 5/16"
18 HOLE SIZE


1" STEEL TUBE
4" REINFORCED CORNER BRACKET
8-32 HOLE SIZE
LEFT
BACK
RIGHT
TS1
TBH
TS2
SB1
BHB
SB2
BS1
BS2
STEEL PLATE : BSH
BBH
TOP
[TBH]
[TFH]
BT1
BT2

Appendix A.2.3: Construction Procedure – Specimen Mount

Specimen Mount Design

Procedure Specifications

Phase No.	Process
1	**Cut Steel Tube:** 1 ½ " x1 ½ " x 1/8" (A 513) 3 ½ " x3 ½ " x 3/16" (A500) **Cut Angle Iron:** 2"x2"x 1/8" (A36) 3 ½" x 3 ½" x ¼" (A36) **Cut I Beam:** S 4*7.7 lb (A36) **Cut U- Channel:** 4x5.4 lb (A36) **Note:** Refer to Drawing for cut lengths.
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 ¼" 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.

3.A: U-CHANNEL				
ID	**Length**	**ID Dimension**	**Drill Size**	**Tap Size**
U1	68.5"	4" X 1.584" X .184" (A36)	N	Thru
Holes connecting to steel tube			F	5/16"-18
3B: I-BEAM				
ID	**Length**	**ID Dimension**	**Drill Size**	**Tap Size**
I1	68.5"	4.00"x0.193"x2.663" (A36)	N	Thru
Holes connecting to steel tube			F	5/16"-18
3C: ANGLE IRON				
ID	**Length**	**ID Dimension**	**Drill Size**	**Tap Size**
AB	61.5"	2"x2"x1/8" (A36)	16	12-24
3D: 3.5" STEEL TUBE				

	S1	36”	3 ½ ” x3 ½ ” x 3/16” (A500)	F	5/16”-18
	S2	36”	3 ½ ” x3 ½ ” x 3/16” (A500)	F	5/16”-18

3E: STEEL PLATE			
ID	**ID Dimension**	**Drill Size**	**Tap Size**
BSH	60”x10”, t=1/4” (A36)	N	Thru
TSH	60”x10”, t=0.12” (11 Gauge)	N	Thru

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			
ID	**Coincident Members**	**Drill Size**	**Tap Size**
1.1	S1, A1	16	12-24
1.2	S2, A2	16	12-24

4B: ANGLE IRON				
ID	**Length**	**ID Dimension**	**Drill Size**	**Tap Size**
VA1	60”	3 ½” x 3 ½” x ¼” (A36)	16	12-24
VA2	60”	3 ½” x 3 ½” x ¼” (A36)	16	12-24

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				
ID	**Length**	**ID Dimension**	**Drill Size**	**Tap Size**
U1	68.5”	4” X 1.584” X .184” (A36)	F	5/16”-18
5B: STEEL SHEET FRAME				

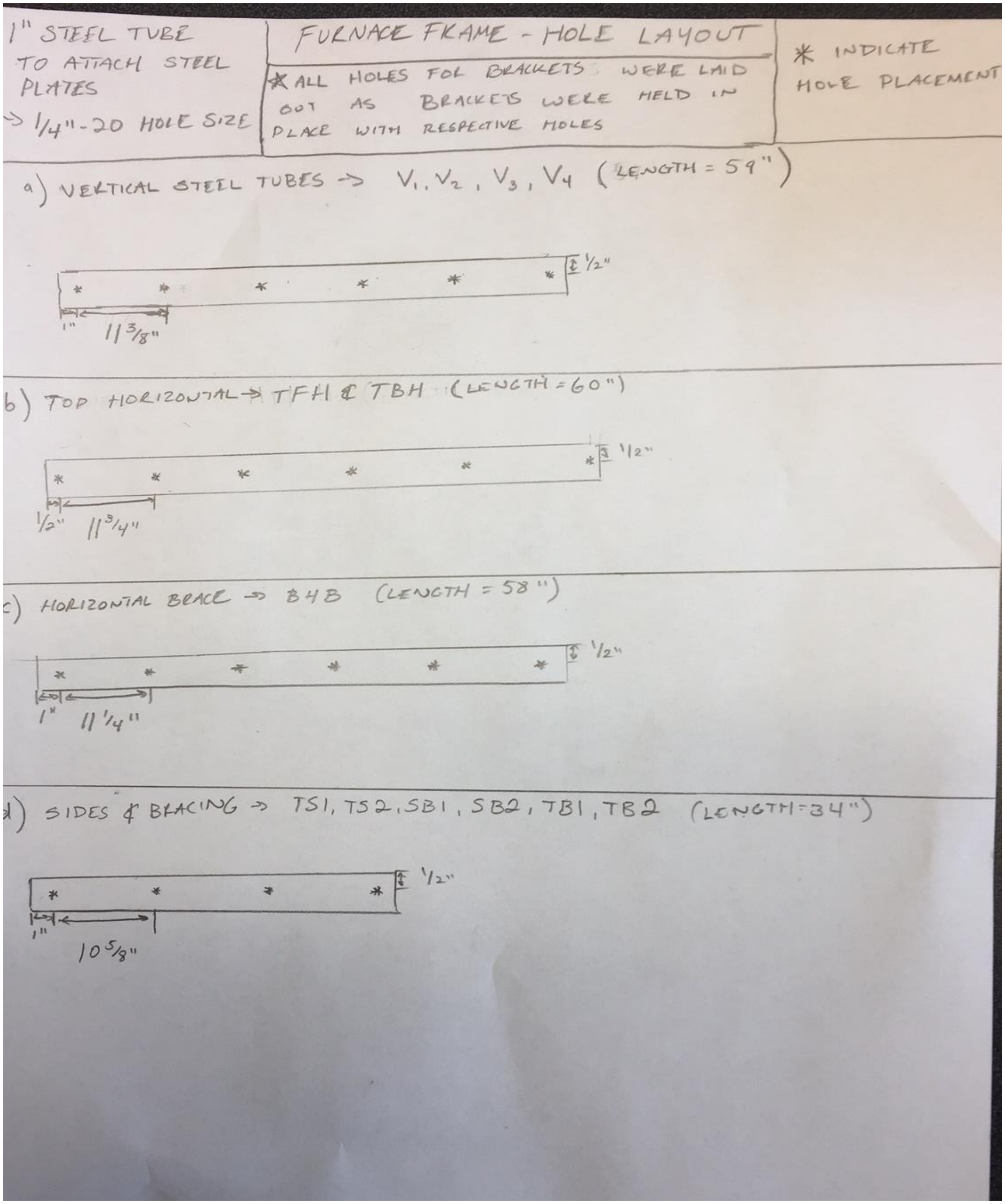
	<table><tr><th>ID</th><th>Length</th><th>ID Dimension</th><th>Drill Size</th><th>Tap Size</th></tr><tr><td>FSH</td><td>68.5”</td><td>60”x60”, t=0.12” (11Gauge)</td><td>N</td><td>Thru</td></tr></table> **Note:** Design Drawings show hole sizing to be cut in order for correct dimensions of specimen to be tested. Refer to Drawing for a visual of each member assembled, respective hole placement and amount.

6	**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><tr><th colspan="5">6A: CASTER TO 2” STEEL TUBE</th></tr><tr><th>ID</th><th>Coincident Members</th><th>ID Dimension</th><th>Drill Size</th><th>Tap Size</th></tr><tr><td>1.1</td><td>S1</td><td rowspan="4">4 ½”x 4”, t=1/4” Wheel Size: DIa=5”, Width= 1 ½”</td><td rowspan="4">5/16”</td><td rowspan="4">3/8”-16</td></tr><tr><td>1.2</td><td>S1</td></tr><tr><td>2.1</td><td>S2</td></tr><tr><td>2.2</td><td>S2</td></tr></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

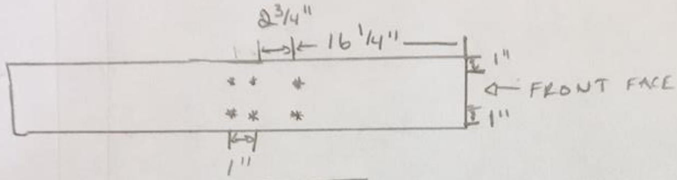
12. Phase 5B
13. Phase 6A

Appendix A.2.4: Construction Procedure Diagrams and Drawings – Specimen Mount



HOLE LAYOUT - SPECIMEN MOUNT

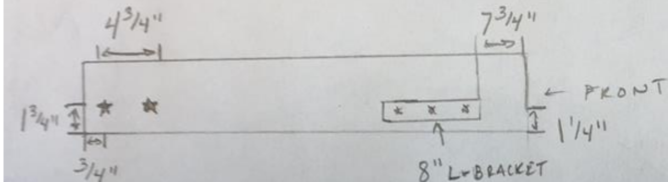
a) 3.5" x 3.5" STEEL TUBE -> S1, S2 (LENGTH = 36") (TOP VIEW)
-> TO CONNECT U-CHANNEL & I-BEAM



TOP VIEW

*5/16"-18 HOLE SIZE
-> THREADED IN STEEL TUBE

b) 3.5" x 3.5" STEEL TUBE -> S1, S2 (TOP VIEW)
-> CONNECT VERTICAL ANGLE & ANGLED BRACING

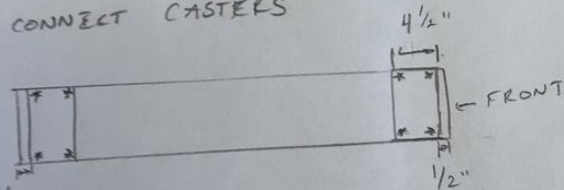


TOP VIEW

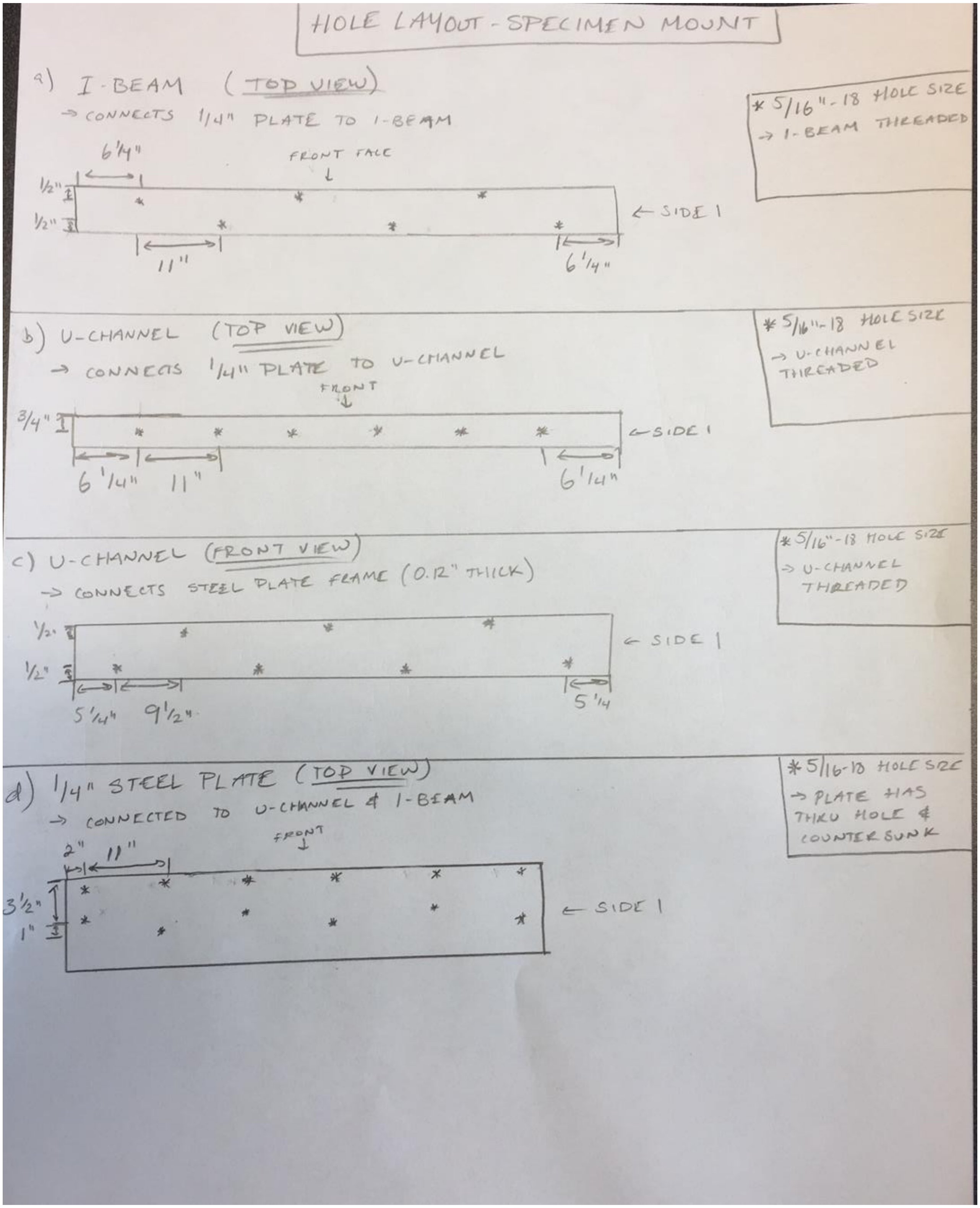
* 12-24 HOLE SIZE
-> CONNECT 8" L-BRACKET

☆ 9/16"-12 HOLE SIZE
-> CONNECT ANGLED 30°/60° BRACING

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



* 3/8"-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
6 1/4"
FRONT FACE
1/2"
1/2"
← SIDE 1
11"
6 1/4"
* 5/16"-18 HOLE SIZE
→ I-BEAM THREADED
b) U-CHANNEL (TOP VIEW)
→ CONNECTS 1/4" PLATE TO U-CHANNEL
FRONT
3/4"
← SIDE 1
6 1/4"
11"
6 1/4"
* 5/16"-18 HOLE SIZE
→ U-CHANNEL THREADED
c) U-CHANNEL (FRONT VIEW)
→ CONNECTS STEEL PLATE FRAME (0.12" THICK)
1/2"
1/2"
← SIDE 1
5 1/4"
9 1/2"
5 1/4
* 5/16"-18 HOLE SIZE
→ U-CHANNEL THREADED
d) 1/4" STEEL PLATE (TOP VIEW)
→ CONNECTED TO U-CHANNEL & I-BEAM
FRONT
2"
11"
3 1/2"
1"
← SIDE 1
* 5/16-18 HOLE SIZE
→ PLATE HAS THRU HOLE & COUNTER SUNK

Appendix A.3: Furnace- Static

<table>
<tr><td colspan="4">DEAD LOADS</td></tr>
<tr><td colspan="2">Framing Material</td><td colspan="2">Insulation</td></tr>
<tr><td>Outer Frame</td><td>3’ x ‘5 x 5’</td><td>Inner Cavity</td><td>4’x 4’x2’</td></tr>
<tr><td>Steel Sheets</td><td>425 lbs</td><td>Wall Type</td><td>Weight (lbs.)</td></tr>
<tr><td>Tube Steel</td><td>140 lbs</td><td>Back wall</td><td>131.6</td></tr>
<tr><td rowspan="3">Total Weight of Frame</td><td rowspan="3">565 lbs</td><td>Sidewalls</td><td>125</td></tr>
<tr><td>Top/Bottom</td><td>93.7</td></tr>
<tr><td>Total</td><td>350.3</td></tr>
<tr><td colspan="4">Total Weight</td></tr>
<tr><td colspan="2">Furnace</td><td colspan="2">915 lbs</td></tr>
<tr><td colspan="4">SIMPLY SUPPORTED BEAM/ COLUMN CALCULATIONS FOR THE FURNACE FRAME</td></tr>
<tr><td>Top/ Bottom HSS Tube Equation(s)</td><td colspan="3">Moment of Inertia
$I = (bd^3 - kh^3) \div 12$
Maximum Shear
$V = (wL) \div 2$
Maximum Moment
$M = (wL^2) \div 8$
Bending Stress
$\sigma = (MC) \div I$
Allowable Stress
$\sigma\, max = 0.6\sigma y$
Deflection
$\Delta = (5wL^4) \div (384EI)$
Allowable Deflection
$\Delta max = L \div 240$
Shear Stress
$\tau = VQ/It$</td></tr>
</table>

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 $V: Max\ Shear\ (lbs)$ $Q: Second\ Moment\ of\ Area\ (in^4)$ $t: tube\ thickness\ (in.)$
Sample Calculation	Moment of Inertia $I\ =\ (bd^3 -\ kh^3) \div 12$ $=\ (1in * 1^3 in - 0.88in * 0.88^3 in) \div 12$ $=\ 0.0334\ in^4$ Loads Insulation: $= (1/3) * (133\ lbs)\ = 44.33\ lbs$ Top Plate: $=\ (1/3)\ *\ [(5\ ft * 4\ ft) * (5\ lbs/ft^2)] = 33.33\ lbs$ Self weight: $=\ 4\ ft\ *\ (1.44\ lbs/ft)\ =\ 5.76\ lbs$ Total: $=\ 83.42\ lbs$ Distributed: $w =\ (83.42\ lbs\ \div\ 4\ ft)\ =\ 20.86\ lbs/ft$ Maximum Shear $V\ =\ (wL) \div 2$ $= [(20.86\ lbs/ft) * (4\ ft)] \div 2$ $= 41.71\ lbs$ Maximum Moment $M\ =\ (wL^2) \div 8$ $=\ (20.86\ lbs/ft\ *\ 4^2 ft) \div 8$ $=\ 41.71\ ft * lbs$

Bending Stress

$\sigma = (MC) \div I = M \div S$

$= [((41.71\ ft\ lbs * (12in/ft)) * (0.5\ in)] \div (0.0334\ in^4)$

$= 7502\ psi$

Allowable Stress

$\sigma\ max = 0.6\sigma y$

$= 0.6 * 46000\ psi$

$= 27600\ psi$ OK

Deflection

$\Delta = (5wL^4) \div (384EI)$

$= (5 * (20.86\ lbs/ft \div 12in/ft) * (4\ ft \div 12in/ft)^4) \div (384 * 29\ ksi * 0.0334\ in^4)$

$= 0.124\ inches$

Allowable Deflection

$\Delta max = L \div 240$

$= (4ft * 12in/ft) \div 240$

$= 0.20\ inches$ OK

Shear Stress

$\tau = VQ/It$

$\tau = (41.7 * 0.070)/(0.033 * 0.12)$

$\tau = 363.8\ psi$

$363.8\ psi \leq 27600\ psi$ OK

Results	**Furnace Component**	**Calculation**	**Units**	**Calculated**	**Allowable**
	Top Tubes: 1”x1”, L=5’	Load: P	lbs	108.2	n/a
		Max Deflection: Δ	in	0.13	0.2
		Max Bending Stress: σ	psi	472	27600
		Max Shear Stress: τ	psi	63.8	27600
	Top Tubes: 1”x1”, L=3’	Load: P	lbs	59.3	n/a
		Max Deflection: Δ	in	0.118	0.15

		Max Bending Stress: σ	psi	4001	27600
		Max Shear Stress: τ	psi	6259	27600
	Bottom Tubes: 2”x2”, L=5’	Load: P	lbs	418.7	n/a
		Max Deflection: Δ	in	0.057	0.2
		Max Bending Stress: σ	psi	10742	27600
		Max Shear Stress: τ	psi	948	27600
	Bottom Tubes: 2”x2”, L=3’	Load: P	lbs	228.8	n/a
		Max Deflection: Δ	in	0.052	0.15
		Max Bending Stress: σ	psi	3522	27600
		Max Shear Stress: τ	psi	518	27600
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. **Tube Specifications:**				

	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:** Atlas Tube. Material Test Report. N.p.: n.p., 1 Jan. 2017. PDF. Amesweb. "HOMEPAGE." Amesweb. N.p., n.d. Web. 04 Mar. 2017. Edge, LLC. Engineers. "Reference Data for Engineers | GD&T ASME Training | GD&T Training | DFM DFA Training | Engineering Supplies Store | Engineering Tools for Productivity." Engineers Edge. N.p., n.d. Web. 04 Mar. 2017 "Engineering ToolBox." The Engineering ToolBox. N.p., n.d. Web. 04 Mar. 2017 Hibbeler, R C. Engineering Mechanics Statics. 13th ed., New Jersey, Pearson Prentice Hall, 2013. Young, W. C., Budynas, R. G.(2002). Roark's Formulas for Stress and Strain . 7nd Edition, McGraw-Hill
Top/ Bottom Plate Equation(s)	Moment of Inertia $I = (bt^3) \div 12$ Maximum Shear $V = (wL) \div 2$ Maximum Moment $M = (wL^2) \div 8$ Bending Stress $\sigma = (MC) \div I$ Allowable Stress $\sigma\, max = 0.6\sigma y$ Deflection $\Delta = (5wL^4) \div (384EI)$ Allowable Deflection $\Delta max = L \div 240$ Shear Stress $\tau = VQ/It$
Variables	Moment of Inertia $b: Section\ Length\ (in.)$ $t: Plate\ Thickness\ (in.)$ Maximum Shear & Maximum Moment $w: Distributed\ Load\ (lbs./ft.)$ $L: Length\ (ft.)$

	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 $V: Max\ Shear\ (lbs)$ $Q: Second\ Moment\ of\ Area\ (in^4)$ $t: tube\ thickness\ (in.)$
Sample Calculation	Moment of Inertia $I = (bt^3) \div 12$ $= (12in * 0.12^3 in) \div 12$ $= 0.00173\ in^4$ Loads Insulation: $= 133\ lbs$ Self Weight: $= [(5\ ft * 4\ ft) * (5\ lbs/ft^2)] = 100\ lbs$ Total Top weight: $= 233\ lbs$ Weight on 12" slab: $= (223\ lbs) * [((20in * 12in) \div 144in^2) \div 20\ ft^2] = 19.42\ lbs$ Distributed Weight: $w = 19.42\ lbs \div (20in/12in/ft) = 11.6\ lbs/ft = 0.96695\ lbs/in$ Maximum Shear $V = (wL) \div 2$ $= [(0.967\ lbs/in) * (20\ in)] \div 2$ $= 9.67\ lbs$ Maximum Moment $M = (wL^2) \div 8$ $= (0.967\ lbs/in * (20)^2 in) \div 8$ $= 48.35\ ft * lbs$ Bending Stress $\sigma = (MC) \div I = M \div S$ $= [((48.35\ in\ lbs) * (0.06\ in)] \div (0.00173\ in^4)$

	$= 1679\, psi$ Allowable Stress $\sigma\, max = 0.6\sigma y$ $= 0.6 * 46000\, psi$ $= 22800\, psi$ $22800\, psi \geq 1679\, psi$ OK Deflection $\Delta = (5wL^4) \div (384EI)$ $= (5 * (0.96695\, lbs/in) * (20in)^4) \div (384 * 29\, ksi * 0.0017\, in^4)$ $= 0.040\, inches$ Allowable Deflection $\Delta max = L \div 240$ $= (20\, in) \div 240$ $= 0.0833\, inches$ $0.083\, inches \geq 0.04\, inches$ OK Shear Stress $\tau = VQ/It$ $\tau = (9.7 * 3)/(0.0017 * 0.12)$ $\tau = 20.14\, psi$ $20.14\, psi \leq 22800\, psi$ OK				
Results	**Furnace Component**	**Calculation**	**Units**	**Calculated**	**Allowable**
	Top/ Bottom Plates: 5'x3', t=¼"	Load: P	lbs	26.56	n/a
		Max Deflection: Δ	in	0.006	0.083
		Max Bending Stress: σ	psi	4781	22800
		Max Shear Stress: τ	psi	20	22800
	Top/ Bottom Plates: 5'x3',	Load: P	lbs	18.3	n/a

	t=⅛”	Max Deflection: Δ	in	0.038	0.083
		Max Bending Stress: σ	psi	1585	22800
		Max Shear Stress: τ	psi	9.5	22800
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:** Hibbeler, R C. Engineering Mechanics Statics. 13th ed., New Jersey, Pearson Prentice Hall, 2013. Hibbeler, R C. *Mechanics of Materials*. 8th ed., New Jersey, Pearson Prentice Hall, 2011 Young, W. C., Budynas, R. G.(2002). Roark's Formulas for Stress and Strain . 7nd Edition, McGraw-Hill				
Tube Column Equation(s)	Moment of Inertia $I = (bd^3 - kh^3) \div 12$ Cross Sectional Area $A = (bd - kh)$ Radius of Gyration $r = \sqrt{I/A}$ Slenderness Ratio $\lambda = L/r$ Critical Load $Pcr = (\pi^2 EI)/L^2$				
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				

<table>
<tr><td></td><td>$L: Length\ (in.)$
Critical Load
$E: Elastic\ Modulus\ of\ Steel\ (psi)$</td></tr>
<tr><td>Sample Calculation</td><td>Slenderness:
$Moment\ of\ Inertia: I = 0.033\ in^4$
$Cross\ Sectional\ Area: A = (1\ in * 1\ in) - (0.88\ in * 0.88\ in) = 0.226\ in^2$
$Radius\ of\ gyration: r = \sqrt{I/A} = \sqrt{0.33\ in^4/0.226\ in^2} = 0.385\ inches$
$Slenderness\ Ratio = L/r = 60\ inches/0.385\ inches = 156$
$156 \geq 140 \rightarrow long, slender\ column\ (Euler)$
Critical Load:
$Pcr = (\pi^2 EI)/L^2$
$= (\pi^2 * 29ksi * 0.033\ in^4)/(60^2\ in)$
$Pcr = 2652\ lbs$

Actual Load:
Insulation: $= (1/4) * 133\ lbs = 33.25\ lbs$
Top Plate: $= (1/4) * (100\ lbs) = 25\ lbs$
Self weight: $= 5\ ft * 1.44\ lbs/ft = 7.2\ lbs$
Total Weight: $P = 65.45\ lbs$
$Pcr \geq P \rightarrow 2652\ lbs \geq 65.45\ lbs$ OK</td></tr>
<tr><td>Results</td><td><table>
<tr><th>Furnace Component</th><th>Calculation</th><th>Units</th><th>Calculated</th><th>Allowable</th></tr>
<tr><td>Tube Column: 1”x1”, L=3’</td><td>Load: P</td><td>lbs</td><td>72.95</td><td>23242 (Pcr)</td></tr>
<tr><td>Tube Column: 1”x1”, L=5’</td><td>Load: P</td><td>lbs</td><td>65.45</td><td>23242 (Pcr)</td></tr>
</table></td></tr>
<tr><td>Sketch</td><td></td></tr>
<tr><td>Notes</td><td>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:
Beer.F.P. , Johnston.E.R. (1992). Mechanics of Materials , 2nd edition. McGraw-Hill</td></tr>
</table>

Atlas Tube. Material Test Report. N.p.: n.p., 1 Jan. 2017. PDF.
Amesweb. "HOMEPAGE." Amesweb. N.p., n.d. Web. 04 Mar. 2017.
AISC.*Manual of Steel Construction: Allowable Stress Design*. Vol. 2nd Rev. of the 9th. Chicago, Ill: American Institute of Steel Construction, 1995.

Fixed End Beam/Column Calculations for the Furnace Frame

Equation(s)

$$Maximum\ Shear = Vmax = \frac{wl}{2}$$

$$Maximum\ Moment = M\ max = \frac{wl^2}{12}$$

$$Maximum\ Deflection = \Delta\ max = \frac{wl^4}{384EI}$$

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)

$$V = \frac{(63.6)(5)}{2} = 159\ lbs$$

$$M\ max = \frac{(63.6/12in/ft)(5 * 12in/ft)^2}{12} = 1589\ in * lbs$$

$$\Delta\ max = \frac{(63.6/12in/ft)(5 * 12in/ft)^4}{384(29000000)(0.0333)} = 0.18\ in.$$

Results

5ft Length Side

	Distributed Load	Maximum Moment	Maximum Deflection	Allowable Deflection
1”x1”x0.12” Top Tubes	16.9 lbs/ft	425 in*lbs	0.05 inches	0.25 inches

1”x1”x0.12” Bottom Tubes	63.6 lbs/ft	1589 in*lbs	0.18 inches	0.25 inches

3ft Length Side				
1”x1”x0.12” Top Tubes	16.9 lbs/ft	246 in*lbs	0.01 inches	0.15 inches
1”x1”x0.12” Bottom Tubes	63.6 lbs/ft	945 in*lbs	0.04 inches	0.15 inches

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 $F'_{nt} = 1.3F_{nt} - \frac{\Omega F_{nt}}{F_{nv}} * f_v \leq F_{nt}$ Step 2: Determine the bending capacity moment of each connection $_{\Omega}M_n = \Omega F_y Z = 0.9F_y(\frac{bt^2}{4})$ Step 3: Compare bending capacity moment with expected maximum moment at each connection
Variables	$F_{nt}: Nominal\ tensile\ strength\ of\ bolts\ (psi)$ $F_{nv}: Nominal\ shear\ strength\ of\ bolts\ (psi)$ $f_v: Required\ shear\ stress\ of\ bolts\ (psi)$ $Fy:\ Available\ tensile\ strength\ (F'_{nt})\ (psi)$ $b: Length\ of\ the\ angle\ section\ of\ connection\ (in.)$ $t:\ thickness\ of\ the\ connection\ (in.)$
Sample Calculation	5”x5”x.016” angle bracket size Step 1: $F'_{nt} = 1.3(80{,}000) - \frac{2(80{,}000)}{(48{,}000)} * (10{,}0000)$ $F'_{nt} = 70{,}667\ psi$ Step 2: $_{\Omega}M_n = 0.67(70{,}667)(\frac{(5)(0.16)^2}{4})$

	$\Omega M_n = 1{,}515\ in * lbf$ Step 3: $Maximum\ moment\ per\ bolt\ =\ 795\ in * lbf \leq 1{,}515\ \rightarrow\ connection\ passes$
Results	

Corner bracket size	Maximum expected moment on 3' Side	Maximum expected moment on 5' side	Bending moment capacity
4"x4"x7/8"x0. 12"thick	212.5 in*lbf	795 in*lbf	682 in*lbf
5"x5"x1"x0.1 6"thick	212.5 in*lbf	795 in*lbf	1,515 in*lbf

Appendix A.4: Furnace- Dynamic

Rolling Friction	
Equation(s)	$P = \frac{w\alpha}{r}$
Variables	$P: Applied\ Force\ (lbf.)$ $w: Weight\ (lbf.)$ $\alpha: Coefficient\ of\ Rolling\ Resistance\ (in.)$ $(Polyurethane\ on\ Concrete\ )$ $r: Radius\ (in.)$
Sample Calculation	$P = \frac{915 * 0.3}{3} = 91.5\ lbf$
Results	**Furnace**
	$P = 91.5\ lbf$
Static Friction	
Equation	$P = \mu_s w$
Variables	μ_s: $\boldsymbol{Coefficient\ of\ Static\ Friction}$ $(\boldsymbol{Polyurethane\ on\ Concrete})$ $\boldsymbol{w}: \boldsymbol{Weight}\ (\boldsymbol{lbf}.)$

<table>
<tr><td>Sample Calculation</td><td>$P = 0.7 * 915 = 640.5\ lbf$</td></tr>
<tr><td rowspan="2">Results</td><td>Furnace</td></tr>
<tr><td>$P = 640.5\ lbf$</td></tr>
<tr><td colspan="2">Critical Load of Furnace Frame Bracing</td></tr>
<tr><td>Equation(s)</td><td>$P = \frac{4\pi^2 EI}{L^2}$</td></tr>
<tr><td>Variables</td><td>$E: Elastic\ Modulus\ (psi))$
$I: Moment\ of\ inertia\ (in^4)\ of\ bracing$
$L:\ Length\ (in.)$</td></tr>
<tr><td>Sample Calculation</td><td>1”x1”x0.12” Steel Tube (actual)
$P = \frac{4\pi^2 * (29000000)(0.0333)}{36^2} = 29{,}682\ lbs$</td></tr>
<tr><td>Significant Results</td><td>
<table>
<tr><td colspan="3">Maximum Live Load (lbf)</td><td colspan="2">Beam/ Column Interpretation</td></tr>
<tr><td colspan="3">320</td><td colspan="2">Simply Supported</td></tr>
<tr><td colspan="2">Furnace Component</td><td>Calculation</td><td>Calculated Value</td><td>Allowable Value</td></tr>
<tr><td rowspan="2">Columns</td><td rowspan="2">L=5'</td><td>Max Bending Stress (psi)</td><td>16,805</td><td>27600</td></tr>
<tr><td>Max Deflection (in)</td><td>0.0025</td><td>0.125</td></tr>
</table>
</td></tr>
<tr><td>Overall Results</td><td></td></tr>
</table>

3ft Side	
Bracing	**Critical Load (Pcr)**
None	53 lbs
1” x 1” x 0.12” Tube	29,682 lbs
½” x ½” x 0.06” Tube	1,842 lbs
2” x 0.12” (w x t) Plate	254 lbs

5ft Side (Back wall)	
Bracing	**Critical Load (Pcr)**
None	53 lbs
1” x 1” x 0.12” Tube	10,609.1 lbs
½” x ½” x 0.06” Tube	663 lbs
2” x 0.12” (w x t) Plate	84 lbs

Further Analysis of Furnace Frame Bracing

Equation(s)	$Maximum\ Shear\ = Vmax = \frac{19}{32}P$ $Maximum\ Moment\ =\ M\ max\ = \frac{13}{64}Pl$ $Maximum\ Deflection\ = \Delta\ max\ = \frac{0.015Pl^3}{EI}$
Variables	$P:\ Pushing\ load\ =\ 320\ lbf$ $E: Elastic\ Modulus\ (psi)$ $I: Moment\ of\ inertia\ (in^4)\ of\ bracing$ $l:\ Length\ (in.)$
Sample Calculation	$Vmax = \frac{19}{32}(320)\ = 190\ lb$

<table>
<tr><td></td><td>

$$M\ max\ = \frac{13}{64}(320)(30)\ = 1950\ in.*\ lbf$$

$$\Delta max\ = \frac{0.015(320)(30)^3}{(29000000)(0.033)} = 0.14\ in.$$

</td></tr>
<tr><td>Results</td><td>
<table>
<tr><th></th><th>Calculated</th><th>Allowable</th></tr>
<tr><td>Mmax</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>Δ max</td><td>0.0025”</td><td>0.125”</td></tr>
</table>
</td></tr>
<tr><td>Sketch</td><td>Push Location/Deflection Diagram</td></tr>
<tr><td>Notes</td><td>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.</td></tr>
</table>

Appendix A.5: Furnace- Thermal

LINEAR EXPANSION			
Equation	$d_L = \alpha L_o dT$		
Variables	d_L: $Elongation\ (in.)$ L_o: $Initial\ Length\ (in.)$ w: $Weight\ (lbf.)$ α: $Thermal\ Expansion\ Coefficient\ of\ Carbon\ Steel\ \left(\frac{in.}{in.^o\ F}\right)$ d_T: $Temperature\ difference\ (C^o)$ A: $Expansion\ (in.^2)$ A_o: $Initial\ Area\ (in.^2)$		
Sample Calculation	$d_L = (6.5 * 10^{-6})\ 60(176 - 73) = 0.40$		
Results	Tube Elongation in 2" (23%)	$\boldsymbol{d_L}$	$\boldsymbol{L_o}$
	$\mathbf{0.083}$	$\mathbf{0.02\ in.}$	$\mathbf{36}$
	$\mathbf{0.138}$	$\mathbf{0.04\ in.}$	$\mathbf{60}$
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 $Allowable = \ Ultimate\ Stress/\Omega$
Variables	Axial Load due to Thermal Expansion F_T: $Axial\ Force\ (lbf.)$ σ_{dt} : $Stress\ due\ to\ change\ in\ temperature\ \ (psi)$ d_T: $Temperature\ difference\ (C^o\ )$ B_t: $Bearing\ Area\ of\ Screw\ (in.^2\ )$ α: $Thermal\ Expansion\ Coefficient\ of\ Carbon\ Steel\ (in./in.^o\ F)$ 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 $\sigma_{dt}\ = (6.5 * 10^{-6})(29 * 10^6)(176 - 73) = 19416$ $F_T\ = \frac{19416(0.03)}{2} = 291$ Section Area of Screw $A = \pi(0.13)^2 = 0.049$ 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

Maximum Thermal Load (lbf)			Beam/ Column Interpretation	
837			Fixed	
Furnace Component		**Calculation**	**Calculated Value**	**Allowable Value**
Beams & Columns	L=5'	Linear Expansion (in)	0.04	0.14
	L=3'	Linear Expansion (in)	0.02	0.083
Screw Type at Connection; Plate Thickness= 0.25"	8-32	Shear Stress (psi)	27668	28743
	10-24	Shear Stress (psi)	24548	
	1/4"-28	Shear Stress (psi)	17051	43114
Screw Type at Connection; Plate Thickness= 0.125"	8-32	Shear Stress (psi)	21088	28743
	10-24	Shear Stress (psi)	15977	
	1/4"-28	Shear Stress (psi)	10614	43114

Sketch

Notes

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, he 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:

Edge, LLC. Engineers. "Reference Data for Engineers | GD&T ASME Training | GD&T Training | DFM DFA Training | Engineering Supplies Store | Engineering Tools for Productivity." Engineers Edge. N.p., n.d. Web. 04 Mar. 2017

Amesweb. "HOMEPAGE." Amesweb. N.p., n.d. Web. 04 Mar. 2017.

"Engineering ToolBox." The Engineering ToolBox. N.p., n.d. Web. 04 Mar. 2017

Appendix A.6: Specimen Mount-Static

DEAD LOADS	
Steel Hardware	200 lbs
Concrete Specimen	1600 lbs

Total Weight	
Specimen Mount	1800 lbs
I-Beam	

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

	$= 0.065\ inches$ $0.065\ in\ \leq 0.25\ in$OK($0.065 = Deflection\ capacity\ of\ I\ beam$)				
Results	**Specimen Mount Component**	**Calculation**	**Units**	**Calculated**	**Allowable**
	I Beam	Load: P	lbs	844.5	10200
		Max Deflection: Δ	in	0.065	0.25
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 $I\ =\ (bd^3 -\ kh^3) \div 12$ Maximum Shear $V\ =\ (wL) \div 2$ Maximum Moment $M\ =\ (wL^2) \div 8$ Bending Stress $\sigma\ =\ (MC) \div I$ Allowable Stress $\sigma\ max\ = 0.6\sigma y$ Deflection $\Delta\ =\ (5wL^4) \div (384EI)$ Allowable Deflection $\Delta max\ =\ L \div 240$ Shear Stress $\tau\ = VQ/It$				
Variables	Moment of Inertia				

<table>
<tr><td></td><td colspan="5">$b, d: Outside\ Length\ \&\ Width\ \ (in.)$
$k\ , h: Inside\ Length\ \&\ Width\ (in.)$
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
Ω: 1.67
Deflection
$E: Elastic\ Modulus\ of\ Steel\ (psi)$
Shear Stress
$V: Max\ Shear\ (lbs)$
$Q: Second\ Moment\ of\ Area\ (in^4)$
$t: tube\ thickness\ (in.)$</td></tr>
<tr><td>Sample Calc</td><td colspan="5">See Appendix A2: Furnace- Static</td></tr>
<tr><td rowspan="5">Results</td><td>Specimen Component</td><td>Calculation</td><td>Units</td><td>Calculated</td><td>Allowable</td></tr>
<tr><td rowspan="4">Top Tubes: 3.5”x3.5”, L=3’</td><td>Load: P</td><td>lbs</td><td>886.22</td><td>n/a</td></tr>
<tr><td>Max Deflection: Δ</td><td>in</td><td>0.019</td><td>0.15</td></tr>
<tr><td>Max Bending Stress: σ</td><td>psi</td><td>7188</td><td>35928</td></tr>
<tr><td>Max Shear Stress: τ</td><td>psi</td><td>1954</td><td>35928</td></tr>
</table>

Appendix A.7: Specimen Mount- Dynamic

Rolling Friction	
Equation(s)	$P = \frac{w\alpha}{r}$
Variables	P: $Applied\ Force\ (lbf.)$ w: $Weight\ (lbf.)$ α: $Coefficient\ of\ Rolling\ Resistance\ (in.)$ $(Polyurethane\ on\ Concrete\ )$
Sample Calculation	$P = \frac{1772 * 0.3}{3} = 177.2\ lbf$
Results	**Specimen Mount**
	$P = 177.2\ lbf$
Static Friction	
Equation	$P = \mu_s w$
Variables	μ_s: $Coefficient\ of\ Static\ Friction$ $(Polyurethane\ on\ Concrete)$ w: $Weight\ (lbf.)$
Sample Calculation	$P = 0.7 * 1772 = 1240.4\ lbf$
Results	**Specimen Mount**
	$P = 1240.4\ lbf$
Notes	
Cantilever Beam (Specimen Mount)	
Equation(s)	$Maximum\ Deflection\ = \Delta\ max\ = \frac{Pl^3}{3EI}$

	$Allowable\ Deflection\ = \Delta\ allowable\ = \dfrac{l}{240}$
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.) $\Delta\ max\ = \dfrac{(620)(48)^3}{3(29000000)(2.01)} = 0.39\ in.$ $\Delta\ allowable\ = \dfrac{l}{240} = \dfrac{48}{240} =\ 0.2\ in.$ $0.39\ in. \geq\ 0.2\ in. \rightarrow Fails$
Results	(see tables below)
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.

Results:

Pushing Point Height	***Δ Maximum***	***Δ Allowable***
48”	0.39 inches	0.2 inches
36”	0.17 inches	0.15 inches

Fails due to deflection →Bracing is required

Maximum Live Load (lbf)		*Beam/ Column Interpretation*	
620		Pin-Roller Connection (With Bracing	
Furnace Component	*Calculation*	*Calculated Value*	*Allowable Value*
Columns	Max Deflection between supports (in)	0.011	0.2
Columns	Max Deflection at overhang (in)	0.033	0.2

Appendix A.8: Burner Mount

Static Analysis: Struts	
Results Provided by Manufacturer:	
Notes	1. 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 W=1.67. 2. To determine concentrated load capacity at mid span, multiply uniform load by 0.5 and corresponding deflection by 0.8. 3. Loads are applied at the section centroid. Applied effective length factor K=0.8 (fixed bottom, pinned top). 4. To account for the slots/ holes, loads were reduced to 90% of the original calculations.
References	Strut Flex Material Test Report. N.p.: n.p., 1 Jan. 2017. PDF.

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[26]. 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 $50\frac{W}{m^2K}$. 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.

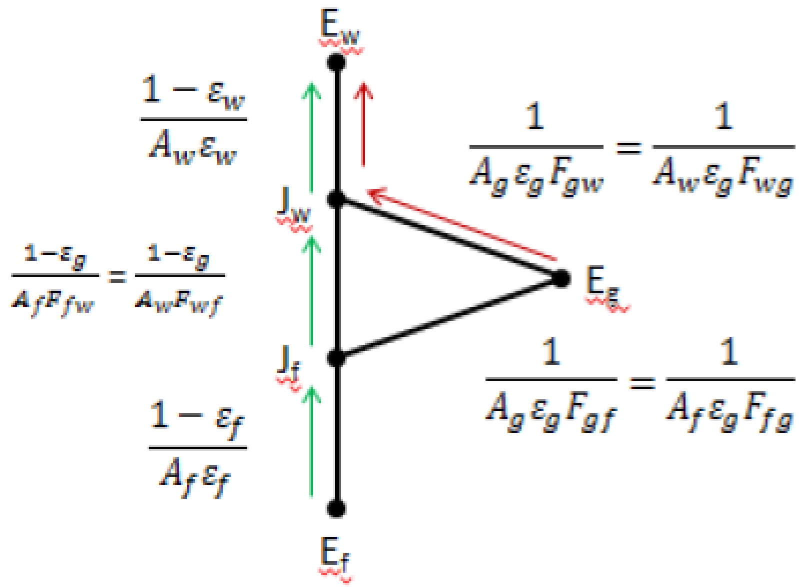


Figure 20:Radiation Network for Calculation of Heat Lost to the Furnace Walls and Test Specimen

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:
$HRR = Enthalpy\ of\ the\ Products\ Leaving\ the\ Vent + Heat\ Losses\ to\ Furnace\ Walls$
$HRR = C_p\dot{m}_{total}(T_g - T_i) + Convective\ Heat\ Losses + Radiative\ Heat\ Losses$

$$T_g = \frac{HRR - Total\ Losses}{C_p\dot{m}_{total}}$$

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

$$Radiative\ Heat\ Loss = \frac{\sigma(T_g^4 - T_f^4)}{\left(\frac{1}{\epsilon_g A_f F_{fg}}\right) + (\frac{1-\epsilon_f}{A_f\epsilon_g})} + \frac{\sigma(T_g^4 - T_s^4)}{\left(\frac{1}{\epsilon_g A_s F_{sg}}\right) + (\frac{1-\epsilon_f}{A_s\epsilon_s})}$$

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[27]. 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.

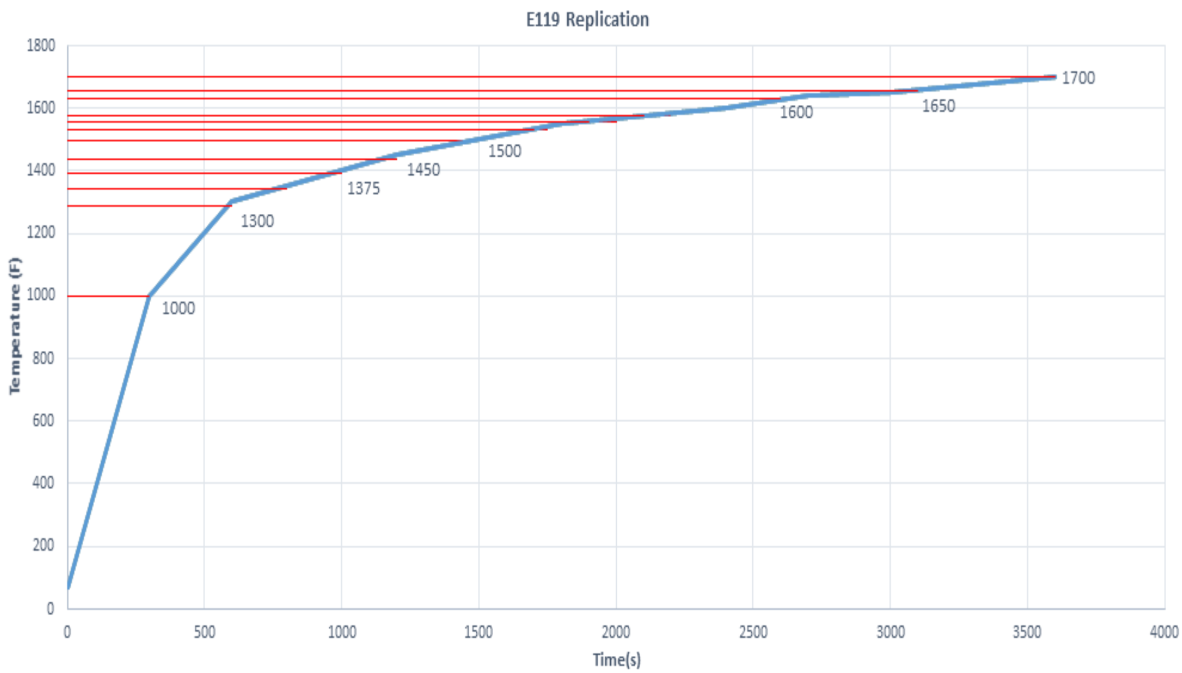


Figure 21:Replicated ASTM E119 Time-Temperature Curve and Constant Gas Temperatures used for Iteration Process

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

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

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/m^2 K) to approximate the total heat transfer coefficient within the furnace. An example calculation can be seen below.

Known Values	
Time	300 s
Tg	810 K
To	293 K
Tf	690-800 K
Ts	690-800 K
ϵg	0.2-0.3
ϵf	0.8
ϵs	0.8
σ	5.67E-08
Af	5.2m^2
As	1.486m^2
hc	50

$$Radiative\ Heat\ Losses = \frac{\sigma(T_g^4 - T_f^4)}{\left(\frac{1}{\epsilon_g A_f F_{fg}}\right) + \left(\frac{1-\epsilon_W}{A_f \epsilon_f}\right)} + \frac{\sigma(T_g^4 - T_s^4)}{\left(\frac{1}{\epsilon_g A_s F_{sg}}\right) + \left(\frac{1-\epsilon_s}{A_s \epsilon_s}\right)}$$

$$Radiative\ Heat\ Transfer\ Coefficent\ (h_r) = \frac{Radiative\ Losses}{(T_g - T_f)}$$

$$Q_{loss} = \frac{\sigma(810^4 - 800^4)}{\frac{1}{0.3 * 5.2} + \frac{1-0.3}{5.2 * 0.3}} + \frac{\sigma(810^4 - 800^4)}{\frac{1}{0.3 * 1.486} + \frac{1-0.3}{1.486 * .3}} = 3.1\ kW$$

$$Q_{loss} = \frac{\sigma(810^4 - 800)}{\frac{1}{0.2 * 5.2} + \frac{1-0.2}{5.2 * 0.2}} + \frac{\sigma(810^4 - 800^4)}{\frac{1}{0.2 * 1.486} + \frac{1-0.2}{1.486 * 0.2}} = 2.7\ kW$$

$$h_r = \frac{3.1\ kW}{(810 - 800)} = 0.035\ kW/m^2K$$

$$h_r = \frac{2.7\ kW}{(810 - 800)} = 0.030\ kW/m^2K$$

$$Q_{loss} = \frac{\sigma(810^4 - 790^4)}{\frac{1}{0.3 * 5.2} + \frac{1-0.3}{5.2 * 0.3}} + \frac{\sigma(810^4 - 790^4)}{\frac{1}{0.3 * 1.486} + \frac{1-0.3}{1.486 * .3}} = 5.2\ kW$$

$$Q_{loss} = \frac{\sigma(810^4 - 790)}{\frac{1}{0.2 * 5.2} + \frac{1-0.2}{5.2 * 0.2}} + \frac{\sigma(810^4 - 790^4)}{\frac{1}{0.2 * 1.486} + \frac{1-0.2}{1.486 * 0.2}} = 4.1\ kW$$

$$h_r = \frac{5.2\ kW}{(810 - 790)} = 0.029\ kW/m^2K$$

$$h_r = \frac{4.1\ kW}{(810 - 790)} = 0.023\ kW/m^2K$$

$$Q_{loss} = \frac{\sigma(810^4 - 690^4)}{\frac{1}{0.3 * 5.2} + \frac{1-0.3}{5.2 * 0.3}} + \frac{\sigma(810^4 - 690^4)}{\frac{1}{0.3 * 1.486} + \frac{1-0.3}{1.486 * .3}} = 22.1\ kW$$

$$Q_{loss} = \frac{\sigma(810^4 - 690)}{\frac{1}{0.2 * 5.2} + \frac{1-0.2}{5.2 * 0.2}} + \frac{\sigma(810^4 - 690^4)}{\frac{1}{0.2 * 1.486} + \frac{1-0.2}{1.486 * 0.2}} = 15.6\ kW$$

$$h_r = \frac{22.1\ kW}{(810 - 800)} = 0.020\ kW/m^2K$$

$$h_r = \frac{15.6\ kW}{(810 - 800)} = 0.015\ kW/m^2K$$

The average radiative heat transfer coefficient at 300 seconds was estimated to be 0.022 kW/m^2K. 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

Known Values (Cerachem)	
Time	0-300
Tg	810
To	293
σ	5.67E-08
K	0.51 W/mK
Density	1250 kg/m^3
Specific Heat	1050 J/kgK
hr+hc	70 W/mK
Density	1250 kg/m^3
Specific Heat	1050 j/kg K
α	2.61 E-06

$$\frac{\theta_s}{\theta_\infty} = \frac{T_s - T_o}{T_\infty - T_o} = 1 - \exp\left(\frac{\alpha t}{(k/h)^2}\right) erfc\left(\frac{\sqrt{\alpha t}}{(k/h)}\right)$$

$$\frac{(293-293)}{810-293} = 1 - EXP\left(\frac{3.89 * 10^{-7} t}{\left(\frac{.51}{72}\right)^2}\right) ERFC\left(\frac{SQRT(2.61 * 10^{-6} * 30)}{\left(\frac{.51}{72}\right)}\right) = 550\ K$$

$$\frac{(293-293)}{810-293} = 1 - EXP\left(\frac{3.89 * 10^{-7} t}{\left(\frac{.51}{72}\right)^2}\right) ERFC\left(\frac{SQRT(2.61 * 10^{-6} * 60)}{\left(\frac{.51}{72}\right)}\right) = 575\ K$$

$$\frac{(293-293)}{810-293} = 1 - EXP\left(\frac{3.89 * 10^{-7} t}{\left(\frac{.51}{72}\right)^2}\right) ERFC\left(\frac{SQRT(2.61 * 10^{-6} * 300)}{\left(\frac{.51}{72}\right)}\right) = 750\ K$$

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

$$Q_{loss} = \frac{\sigma(810^4 - 500^4)}{\frac{1}{0.3*5.2} + \frac{1-0.3}{5.2*0.3}} + \frac{\sigma(810^4 - 500)}{\frac{1}{0.3*1.486} + \frac{1-0.3}{1.486*.3}} = 29\ kW$$

$$Q_{loss} = \frac{\sigma(810^4 - 500^4)}{\frac{1}{0.2*5.2} + \frac{1-0.2}{5.2*0.2}} + \frac{\sigma(810^4 - 500)}{\frac{1}{0.2*1.486} + \frac{1-0.2}{1.486*0.2}} = 16\ kW$$

$$Q_{loss\ conective} = 50*5.2\ (810-500) + 50*1.486(810-430) = 64\ kW$$

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

Time (s)	Total Heat Loss (kW)
30	89
60	72
90	63
120	57
150	53
180	50
210	47
240	45
270	43
300	41

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.

HRR:	Input Value
c_p	1.01kj/kg*K
$\dot{m}$	0.0166 kg/s (stoichiometric)

$$T_{gu} = \frac{HRR - Losses}{c_p * \dot{m}}$$

Time (s)	Heat Loss	HRR	Gas Temperature (K)
30	88	115	810
60	72	100	810
90	63	90	810
120	57	86	810
150	53	83	810
180	50	79	810
210	47	74	810
240	45	71	810
270	43	69	810
300	41	67	810

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℃, and a hot face temperature of 1000℃.

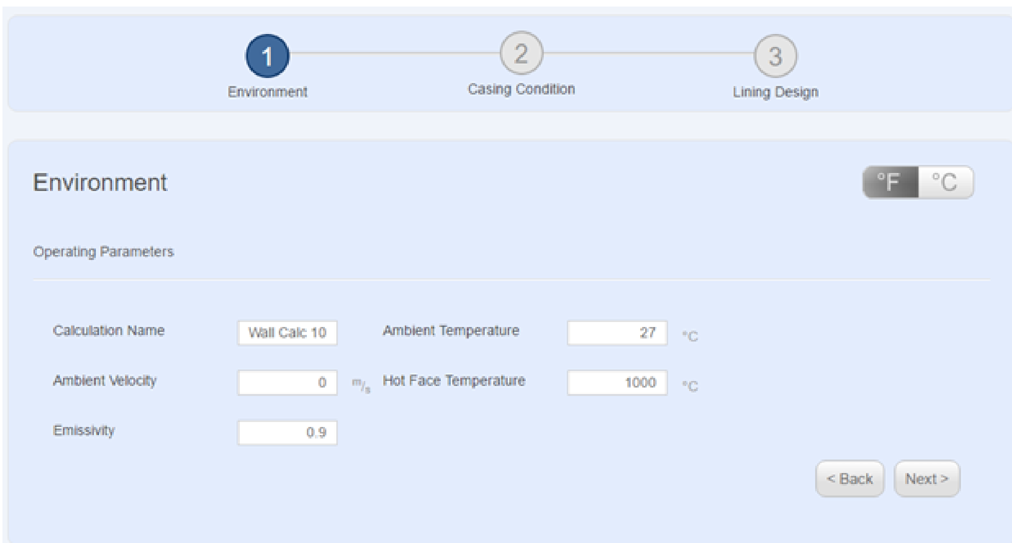


Figure 22: First step of Morgan Simulation- Input Parameters

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.

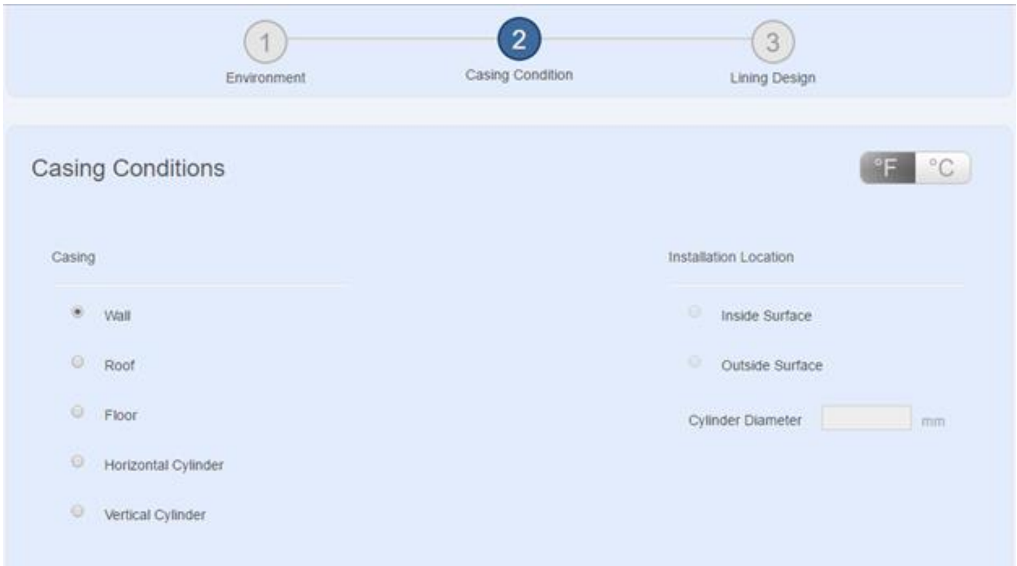


Figure 23: Second Step of Morgan Simulation-Enclosure Conditions

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.

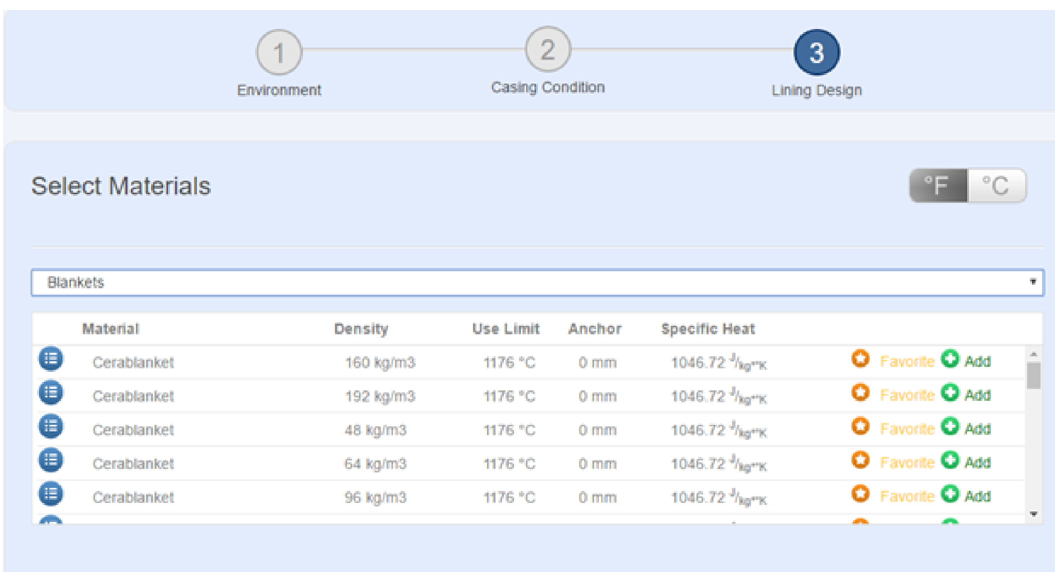


Figure 24: Step three of the Morgan Simulation- Material Selection

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℃, the heat loss is 640.8 W/m^2, and the heat storage is 11,032.7 kJ/m^2.

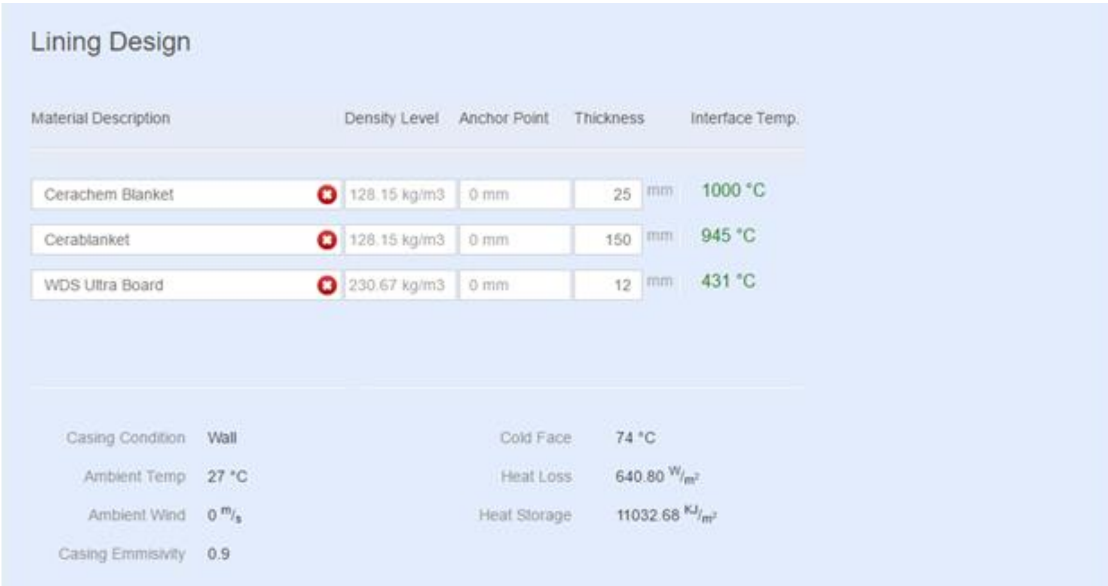


Figure 25: Final Step of Morgan Simulation: Calculating Temperature, Heat Loss, and Heat Storage

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 10: Input parameters: Material Properties of Insulation

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

Table 11: Input parameters: Area and Volume of the Different Faces of the Furnace

Wall Face	Area (m^2)	Volume Cerachem (m^3)	Volume Cerablanket (m^3)	Volume WDS Ultra (m^3)
Back wall	2.323	0.0581	0.3485	0.0278
Sidewall	1.103	0.0275	0.1655	0.0188
Top/Bottom	0.827	0.0207	0.1241	0.0141

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: $0.0581\ m^3 * 128\ kg/m^3 = 7.437\ kg$

Table 12: Mass of Each Layer on the Vary Wall Type

Wall Face	Cerachem (kg)	Cerablanket (kg)	WDS Ultra (kg)	Total
Back wall	7.437	44.608	6.422	58.467
Sidewall	3.52	21.184	4.343	29.047
Top/Bottom	2.65	15.885	3.257	21.791

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

$$q = \frac{T_h - T_\infty}{\sum R} \ where \ \Sigma R = \frac{L_n}{k_n}$$

q is the heat flux through the walls
T_h is the hot face temperature
T_∞ 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.

Resistances Sample Calculations	$R_1 = \frac{L_{cerachem}}{k_{cerachem}} = \frac{0.025\, m}{0.34\, W/m * K} = 0.0735 \ K/W$ $R_2 = \frac{L_{cerablanket}}{k_{cerablanket}} = \frac{0.15\, m}{0.34\, W/m * K} = 0.4412\, K/W$ $R_3 = \frac{L_{WDS\ Ultra}}{k_{WDS\ Ultra}} = \frac{0.012\, m}{0.04\, W/m * K} = 0.3\, K/W$ $R_4 = \frac{L_{steel}}{k_{steel}} = \frac{0.003175\, m}{51.9\, W/m * K} = 0.0000612\, K/W$ $\Sigma R = \frac{1}{h_i} + R_1 + R_2 + R_3 + R_4 + \frac{1}{ho}$ $\Sigma R = \frac{1}{72\, W/m^2 * K} + 0.0735 + 0.4412 + 0.3 + 0.0000612 + \frac{1}{25\, W/m^2 * K}$ $\Sigma R = 0.8686$
Heat Flux Sample Calculations	$q = \frac{T_h - T_\infty}{\sum R}$ $q = \frac{1000℃ - 27℃}{0.8686}$ $q = 1120.19\, W = 1.1 \ kW/m^2$

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.

Heat Loss Sample Calculations	$Q = q * A$ $Q = 1120.19 \ W/m^2 * 2.323\, m^2$ $Q = 2602.2\, W = 2.6\, kW$

Table 13: Heat Loss Through Each Wall Face

Wall Type	Q (kW)
Back wall	2.6
Sidewall	2.5
Top/Bottom	1.9

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	$R = \frac{1}{h_i} + \frac{L_{concrete}}{k_{concrete}} + \frac{1}{h_o}$ $R = \frac{1}{72\, W/m^2 * K} + \frac{0.1\, m}{0.8\, W/m * K} + \frac{1}{25\, W/m^2 * K}$ $R = 0.179$ $R = \frac{1}{72\, W/m^2 * K} + \frac{0.1\, m}{0.8\, W/m * K} + \frac{1}{25\, W/m^2 * K}$ $R = 0.179$
Heat Loss Sample Calculations	$Q = \frac{T_h - T_c}{\Sigma R} * A$ $Q = \frac{1000℃ - 27℃}{0.179} * 2.323\, m^2$ $Q = 12{,}1636.36\, W = 12.2\, kW$

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	$q = \frac{T_h - T_1}{\frac{1}{h_i} + R_1}$ $1120.19\, W/m^2 = \frac{1000℃ - T_1}{\frac{1}{72\, W/m^2 * K} + 0.0735\, K/W}$ $T_1 = 902.11℃$ $q = \frac{T_1 - T_2}{\mathrm{R}_2}$ $1120.19\, W/m^2 = \frac{902.11℃ - T_2}{0.4412\, K/W}$ $T_2 = 407.88℃$

	$q = \frac{T_2 - T_3}{R_3}$ $1120.19\, W/m^2 = \frac{407.88℃ - T_3}{0.3\, K/W}$ $T_3 = 71.82℃$ $q = \frac{T_3 - T_4}{R_4 + \frac{1}{h_o}}$ $1120.19\, W/m^2 = \frac{71.82℃ - T_4}{0.0000612\ K/W + \frac{1}{25\, W/m^2 * K}}$ $T_4 = 27.01℃$

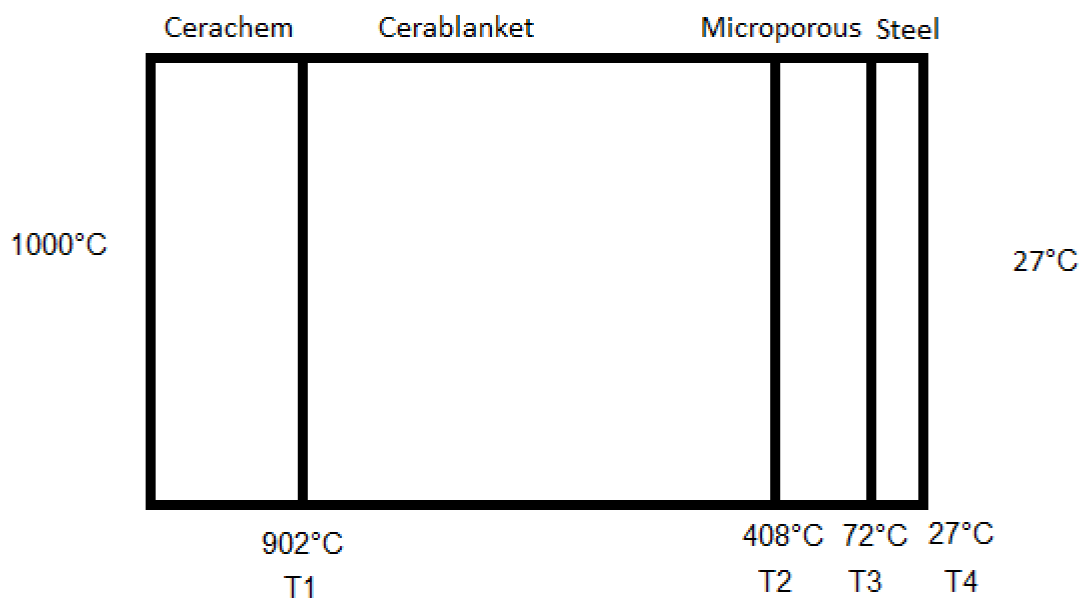


Figure 26: Temperature Profile of Insulation Layers

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:

Average Temperature	$T_1 = \frac{1000℃ + 902℃}{2} - 27℃ = 924℃ = 1197\ K$

Sample Calculations	$T_2 = \frac{902℃ + 408℃}{2} - 27℃ = 628℃ = 901\,K$ $T_3 = \frac{408℃ + 72℃}{2} - 27℃ = 213℃ = 486\,K$
Heat Storage on Back Wall Sample Calculations	$Q_{cerachem} = 7.437\,kg * (1.13\,kJ/kg * K) * 1197\,K$ $Q_{cerachem} = 10{,}059.36\,kJ$ $Q_{cerablanket} = 44.608\,kg * (1.13\,kJ/kg * K) * 901\,K$ $Q_{cerablaket} = 45{,}416.74\,kJ$ $Q_{WDS\ Ultra} = 6.422\,kg * (0.945\,kJ/kg * K) * 486\,K$ $Q_{WDS\ Ultra} = 2{,}949.43\,kJ$

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*℃ 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	$\dot{m} = 2.323\,m^2 * 0.1\,m * 2400\,kg/m^3 = 557.52\,kg$ $T = \frac{1000℃ + 72℃}{2} - 27℃ = 509℃ = 782\,K$ $Q = 557.52\,kg * (0.75\,kJ/kg * ℃) * 782\,K$ $Q = 326{,}985.48\,kJ$

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*[1] textbook.

Table 14: Select Parameters and Properties of Air

Parameter	Value
L (m)	0.025
k (W/m*K)	0.0295
ν(m^2/s)	2.097*10^{-5}
α (m^2/s)	2.931*10^{-5}

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 (υ 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.

Vertical Enclosure Air Gap Sample Calculations	$Pr = \frac{\upsilon}{\alpha} = \frac{2.097 * 10^{-5}\, m^2/s}{2.931 * 10^{-4}\, m^2/s}$ $Pr = 0.7155$ $Gr = \frac{g * \beta * (T_s - T_\infty) * L_c^3}{\upsilon^2}$ $Gr = \frac{(9.8\ m/s^2)\left(\frac{1}{322.5\ K}\right)(345\ K - 300\ K)(0.025)^3}{(2.097 * 10^{-5}\, m^2/s)^2}$ $Gr = 48{,}588.34$ $Ra = Pr * Gr = 0.7155 * 48{,}588.34$ $Ra = 34{,}764.96$ $\frac{H}{L} = \frac{1.524\ m}{0.025\ m} = 60.96$

Using these parameter along with a tall enclosure (60 inches tall by 1 inch wide), the following Nusselt equation is used:

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

This equation has the criteria of 10 < H/L < 40, 1 < Pr < 2*10^4, and 10^4 < Ra < 10^7, and although it does not meet the criteria for 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:

$$Nu = 0.42 * (34{,}764.96)^{\frac{1}{4}} * (0.7155)^{0.012} * (60.96)^{-0.3}$$
$$Nu = 1.66$$

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

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

Since the convective heat transfer coefficient $h = k * Nu/L$, 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:

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

Where ε is the emissivity of the gas, assumed to be 0.8, and σ 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.

Radiative Heat Transfer Coefficient Sample Calculations	$h_{rad} = 0.8(5.67 * 10^{-8}\ W/m^2 * K^4)\ [(345\ K)^2 + (300\ K)^2](345\ K + 300\ K)$ $h_{rad} = 6.11\ W/m^2 * K$
Resistances Sample Calculations	$R_1 = \frac{L_{cerachem}}{k_{cerachem}} = \frac{0.025\ m}{0.34W/m*K} = 0.0735\ K/W$ $R_2 = \frac{L_{cerablanket}}{k_{cerablanket}} = \frac{0.15\ m}{0.34\ W/m * K} = 0.4412\ K/W$ $R_3 = \frac{L_{WDS\ Ultra}}{k_{WDS\ Ultra}} = \frac{0.012\ m}{0.04\ W/m * K} = 0.3\ K/W$ $R_4 = \frac{1}{\frac{L_{air}}{k_{air} * Nu} + \frac{1}{h_{rad}}} = \frac{1}{\frac{0.025\ m}{(0.0295\ W/m * K) * 1.66} + \frac{1}{6.11\ W/m^2 * K}}$ $= 0.123\ K/W$ $R_5 = \frac{L_{steel}}{k_{steel}} = \frac{0.003175\ m}{51.9\ W/m * K} = 0.0000612\ K/W$ $\Sigma R = \frac{1}{h_i} + R_1 + R_2 + R_3 + R_4 + R_5 + \frac{1}{ho}$

	$\Sigma R = \frac{1}{72\, W/m^2 * K} + 0.0735 + 0.4412 + 0.3 + 0.123 + 0.0000612 + \frac{1}{25\, W/m^2 * K}$ $\Sigma R = 0.9917$
Heat Flux Sample Calculations	$q = \frac{T_h - T_\infty}{\sum R}$ $q = \frac{1000℃ - 27℃}{0.9917}$ $q = 981.14\, W$
Heat Loss Sample Calculations	$Q = q * A$ $Q = 981.14\, W * 2.323\, m^2$ $Q = 2279.18\, W = 2.3\, kW$

Table 15: Heat Loss through Vertical Wall Faces

Wall Type	Q (kW)
Back wall	2.3
Sidewalls	2.2

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 $10^4 < Ra < 10^7$, so the follow equation is used:

$$Nu = 0.195 * Ra^{\frac{1}{4}}$$

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	$Nu = 0.195 * (34{,}764.96)^{\frac{1}{4}}$ $Nu = 2.66$
Resistance Sample Calculation	$R_4 = \frac{1}{\frac{L_{air}}{k_{air} * Nu} + \frac{1}{h_{rad}}} = \frac{1}{\frac{0.025\, m}{(0.0295\, W/m * K) * 2.66} + \frac{1}{6.11\, W/m^2 * K}}$ $R_4 = 0.1073$ $\Sigma R = 0.9760$
Heat Flux Sample Calculation	$q = \frac{1000℃ - 27℃}{0.7960}$

	$q = 1222.36\ W/m^2$
Heat Loss Sample Calculation	$Q = 1222.36\, W/m^2 * 0.827\ m^2$ $Q = 1010.89\, W = 1\, kW$

Table 16: Resistance and Heat Loss through Vertical Wall Faces

Wall Type	Nu Number	Q (kW)
Top	2.66	1
Bottom	1	0.8

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 below shows the temperatures between each layer.

Temperature Profile Sample Calculations	$q = \dfrac{T_h - T_1}{\frac{1}{h_i} + R_1}$ $981.14\, W/m^2 = \dfrac{1000℃ - T_1}{\frac{1}{72\, W/m^2 * K} + 0.0735\, K/W}$ $T_1 = 914.25℃$ $q = \dfrac{T_1 - T_2}{\mathrm{R}_2}$ $981.14\, W/m^2 = \dfrac{914.25℃ - T_2}{0.4412\, K/W}$ $T_2 = 481.37℃$ $q = \dfrac{T_2 - T_3}{\mathrm{R}_3}$ $981.14\, W/m^2 = \dfrac{481.37℃ - T_3}{0.3\, K/W}$ $T_3 = 187.03℃$ $q = \dfrac{T_3 - T_4}{\mathrm{R}_4}$ $981.14\, W/m^2 = \dfrac{187.03℃ - T_4}{0.123\, K/W}$ $T_4 = 66.35℃$ $q = \dfrac{T_4 - T_5}{R_5 + \frac{1}{h_o}}$ $981.14\, W/m^2 = \dfrac{66.35℃ - T_4}{0.0000612\ K/W + \frac{1}{25\, W/m^2 * K}}$

	$T_5 = 27.04°C$

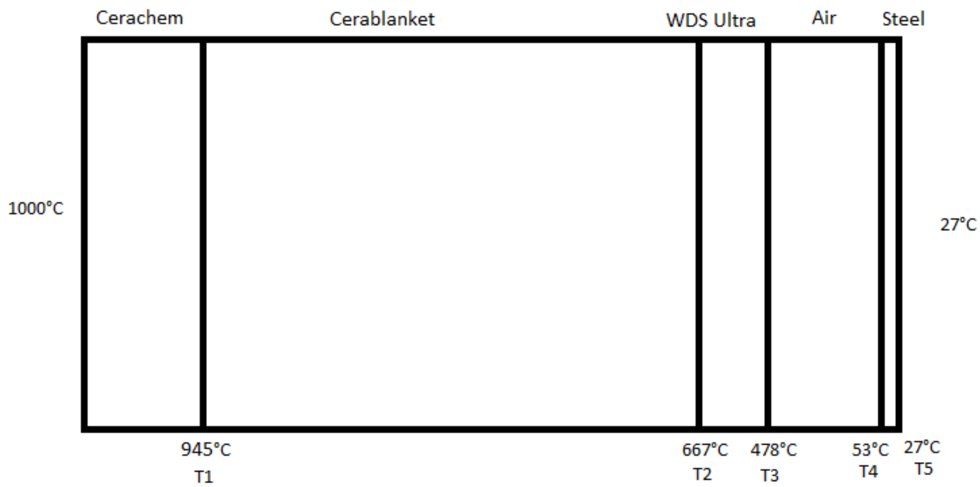


Figure 27: Temperature Profile of Insulation Layers

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	$T_1 = \frac{1000°C + 914°C}{2} - 27°C = 930°C = 1203\ K$ $T_2 = \frac{914°C + 481°C}{2} - 27°C = 670.5°C = 943.5\ K$ $T_3 = \frac{481°C + 187°C}{2} - 27°C = 307°C = 580\ K$ $T_4 = \frac{187°C + 66°C}{2} - 27°C = 99.5°C = 372.5\ K$
Mass of Back Wall Sample Calculation	$\dot{m}_{back} = 2.323\ m^2 * 0.025\ m * 0.4565\ kg/m^3 = 0.0265\ kg$ $\dot{m}_{side} = 1.103\ m^2 * 0.025\ m * 0.4565\ kg/m^3 = 0.0126\ kg$ $\dot{m}_{top/bottom} = 0.827\ m^2 * 0.025\ m * 0.4565\ kg/m^3 = 0.0094\ kg$
Heat Storage on Back wall Sample Calculations	$Q_{cerachem} = 7.437\ kg * (1.13\ kJ/kg * K) * 1203\ K$ $Q_{cerachem} = 10{,}109.78\ kJ$ $Q_{cerablanket} = 44.608\ kg * (1.13\ kJ/kg * K) * 943.5\ K$ $Q_{cerablaket} = 47{,}559.04\ kJ$ $Q_{WDS\ Ultra} = 6.422\ kg * (0.945\ kJ/kg * K) * 580\ K$ $Q_{WDS\ Ultra} = 3{,}519.90\ kJ$ $Q_{air} = 0.0265\ kg * (1.008\ kJ/kg * K) * 372.5\ K$ $Q_{air} = 9.95\ kJ$

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.

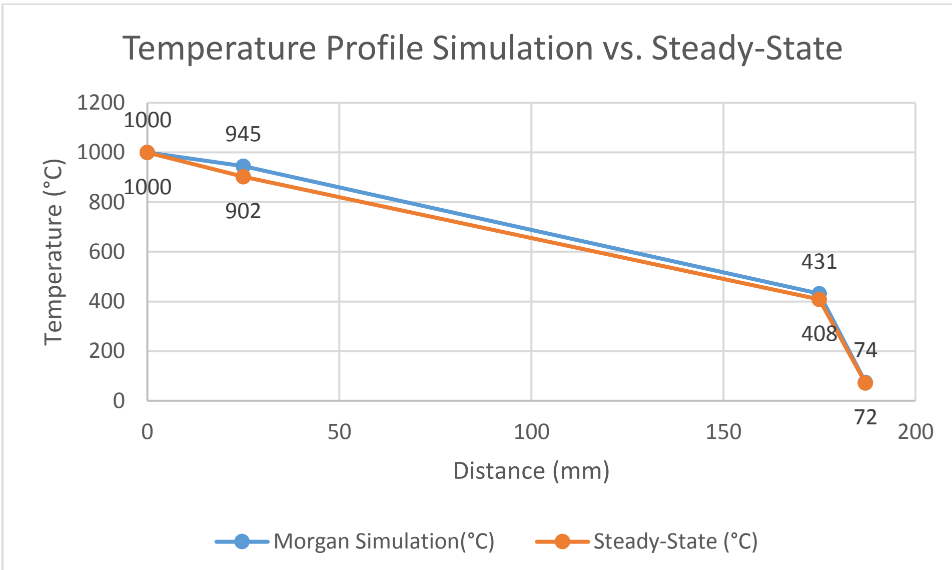


Figure 28: Temperature Profile Comparison between Morgan Simulation and Steady-State Hand Calculations

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 17: Comparison of results from the Morgan Simulation and Steady-State Hand Calculations

	Morgan Simulation	Steady-State
Heat Losses	2.6 kW	7 kW
Heat Storage	19 kW	43.8 kW
Total	21.6 kW	50.8 kW

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.

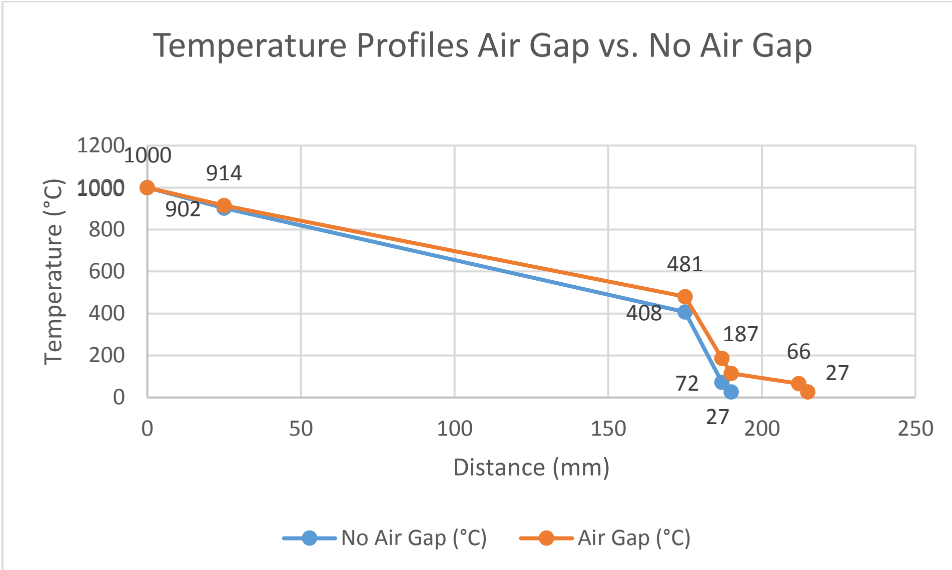


Figure 29: Temperature Profile Comparison between Air Gap and No Air Gap

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 18: Comparison of Results between an Air Gap and No Air Gap

	No Air Gap	**Air Gap**
Heat Losses	7 kW	6.3 kW
Heat Storage	43.8 kW	45.9 kW
Total	50.8 kW	52.2 kW

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 Cerablanket 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 Cerablanket 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^{Porous}), a buoyancy ($S_i^{Gravity}$=-g_i) where g_i is the gravitational acceleration component along the i-th coordinate direction, and the systems rotation ($S_i^{Rotation}$)

Energy:

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}\left(u_j(\tau_{ij} + \tau_{ij}^R) + q_i\right) + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H$$

$$H = h + \frac{u^2}{2},$$

H = thermal enthalpy,
Q_h= Heat source or sink per unit volume
τ_{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 :

$$q_i = \left(\frac{\mu}{\Pr} + \frac{\mu_t}{\sigma_c}\right)\frac{\partial h}{\partial x_i}, \; i = 1,\, 2,\, 3.$$

σ_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 x T = specific internal energy where c is the specific heat
Q_H = specific heat release per unit volume
λ_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 hte 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

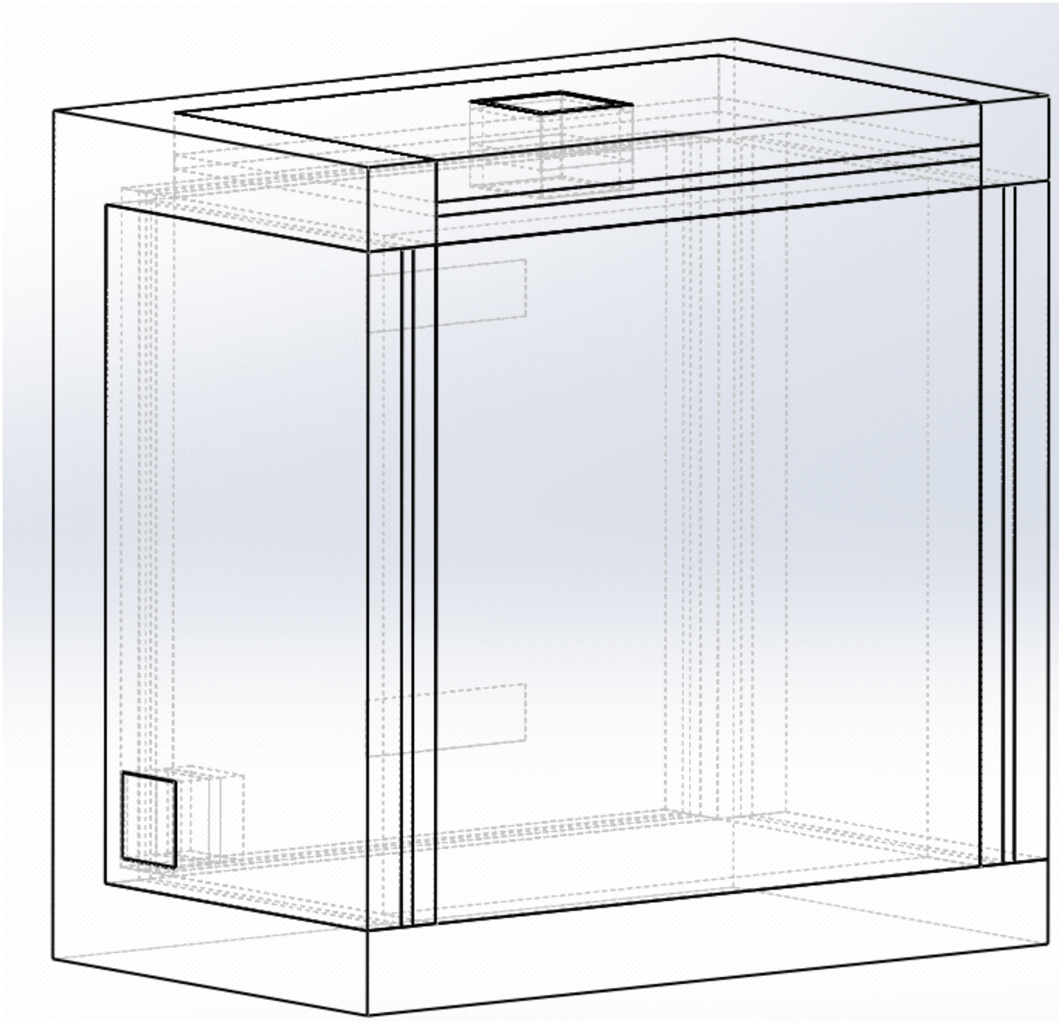
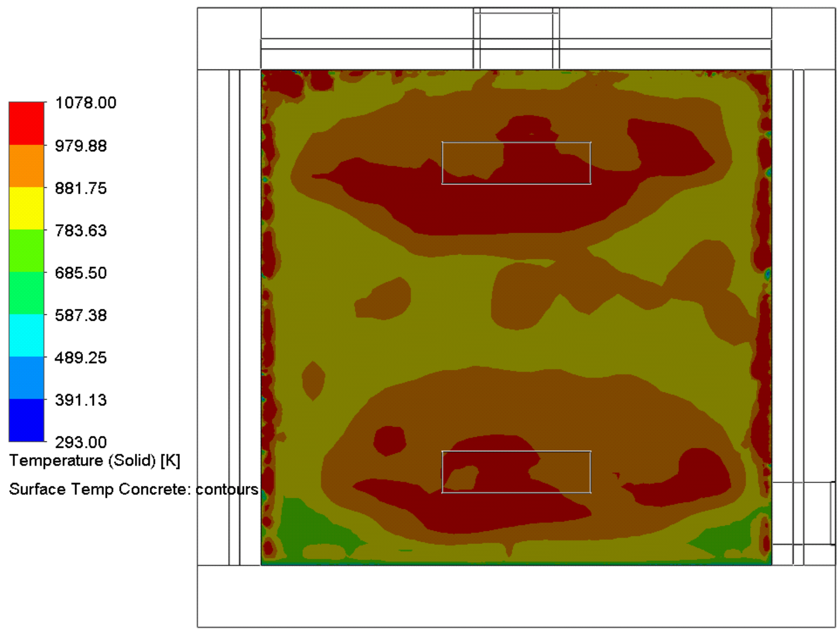


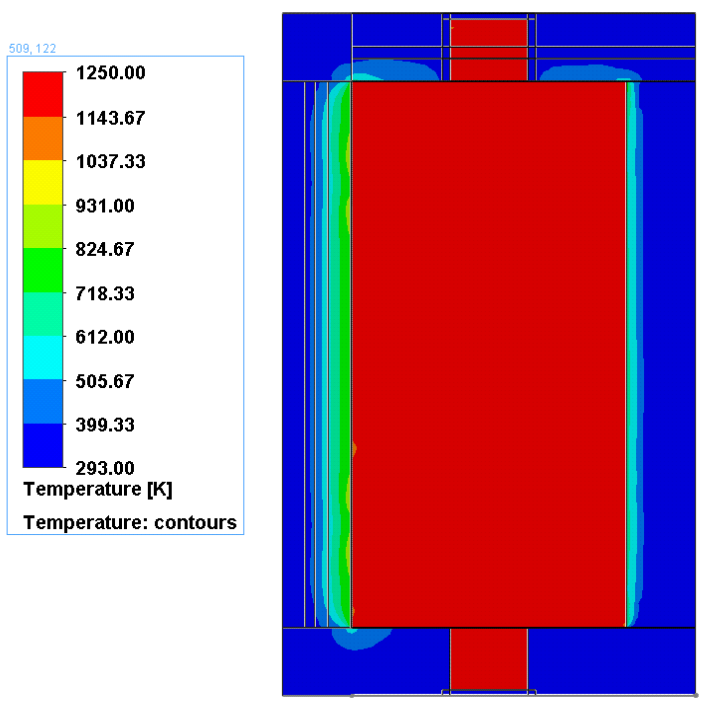
Figure 30: Solidworks Simulation Furnace Model & Computational Domain

Appendix D.3: Solidworks Flow Simulation - Temperature Plots

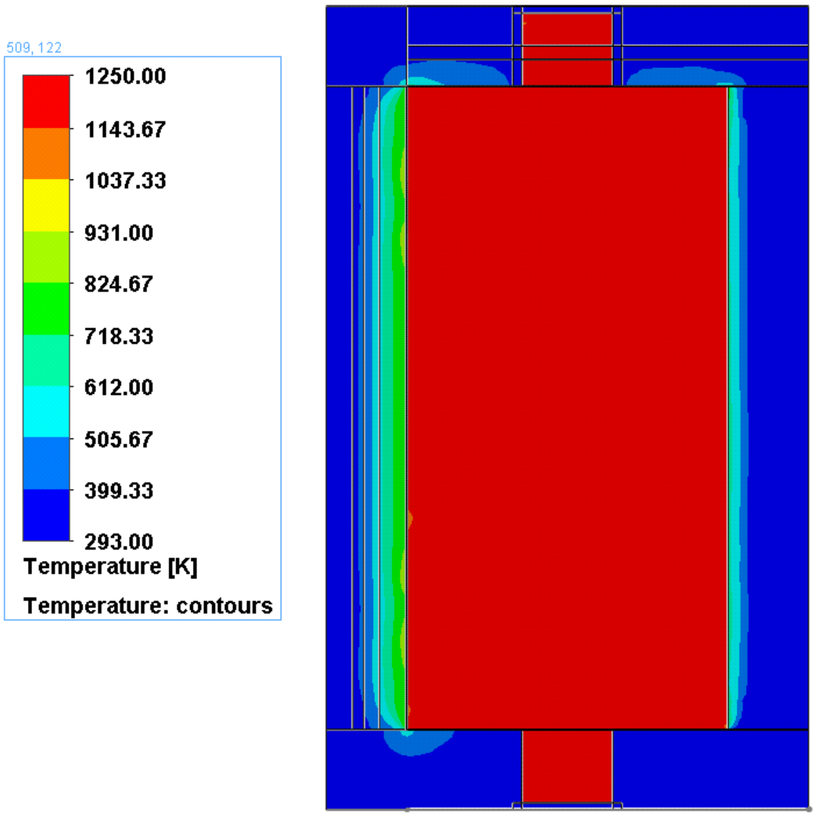
Side Vent: Concrete Surface Temperature Cut Plot



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

0
Air
1
Oxygen
0

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/m^2
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/m^2
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/m^2
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<5>@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

$$Hf_{C3H8} * N_{C3H8} = Hf_{CO2} * N_{CO2} + Hf_{H2O} * N_{H2O} + \Delta T \sum Cp_x * N_x$$

$$\sum Cp_x * N_x = Cp_{CO2} * N_{CO2} + Cp_{H2O} * N_{H2O} + Cp_{N2} * N_{N2}$$

$$Hf_{C3H8} = -103850\ kJ/kmol \quad N_{C3H8} = 1\ kmol$$

$$Hf_{CO2} = -393522\ kJ/kmol \quad N_{CO2} = 3\ kmol \quad Cp_{CO2} = 45\frac{kJ}{kmol\ K}$$

$$Hf_{H2O} = -241827\frac{kJ}{kmol} \quad N_{H2O} = 4\ kmol \quad Cp_{H2O} = 35\ \frac{kJ}{kmol\ K}$$

$$N_{N2} = 18.8\ kmol \quad Cp_{N2} = 30\ \frac{kJ}{kmol\ K}$$

$$\Delta T = (Tf - 298K)$$

$$Tf = 2138.23\ K$$

Appendix D.5.2: Species Mass Flux Calculation

$$C_3H_8 + 5(O_2 + 3.76N_2) = 3CO_2 + 4H_2O + 18.8N_2$$

$$3CO_2 = 72g$$

$$4H_2O = 46.8g$$

$$18.8N_2 = 132g$$

$$Mass\ Fraction\ of\ CO_2 = 0.287$$

$$Mass\ Fraction\ of\ H_2O = 0.186$$

$$Mass\ Fraction\ of\ N_2 = 0.526$$

Appendix D.5.3: Species Mass Flux Calculation

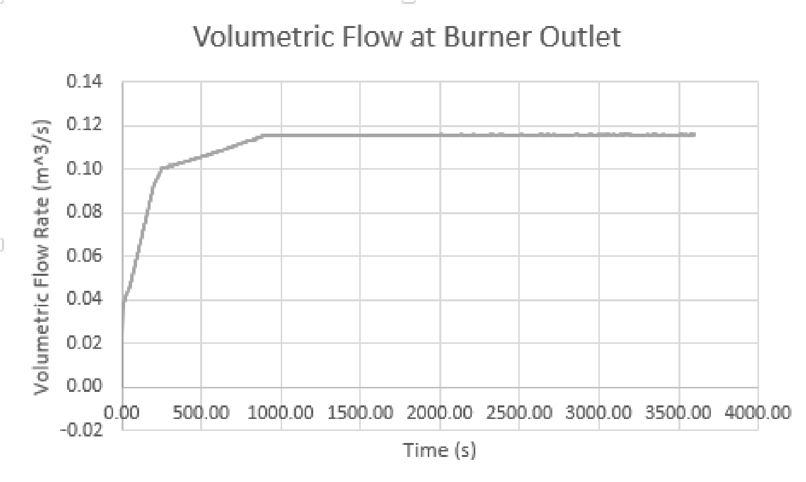
The manufacture provided air and propane flow rates from experimental measurements of the purchased burner system. These measurements were used to calculate the mass flux of the species entering the furnace.

$$2 * \left(7160\frac{ft^3}{hr}air + 286\frac{ft^3}{hr}\ propane\right) = 0.112\frac{m^3}{s}$$

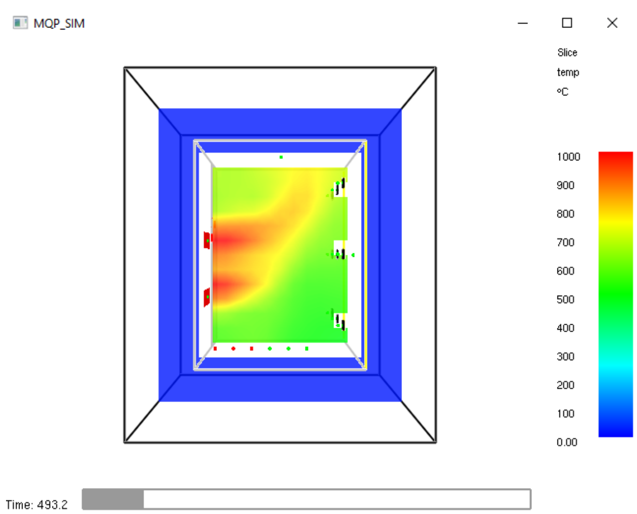
Mass flux through each burner (surface area of pine ridge burners approximately $0.05m^2$):

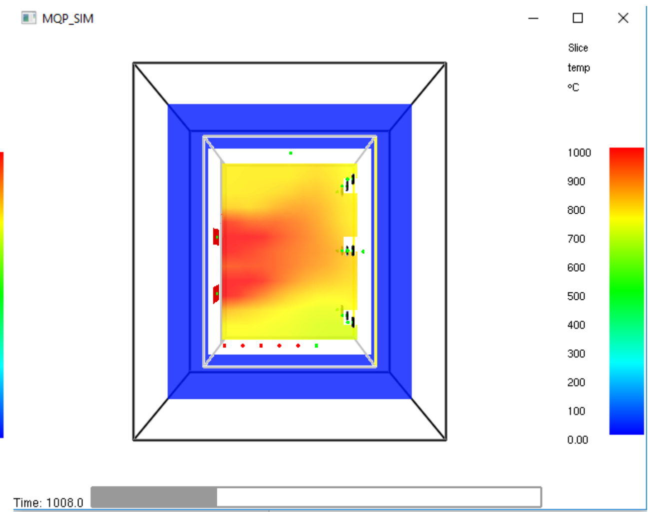
$$0.056\frac{m^3}{s} * 1.225\frac{kg}{m^3} = 0.06\frac{kg}{s}$$

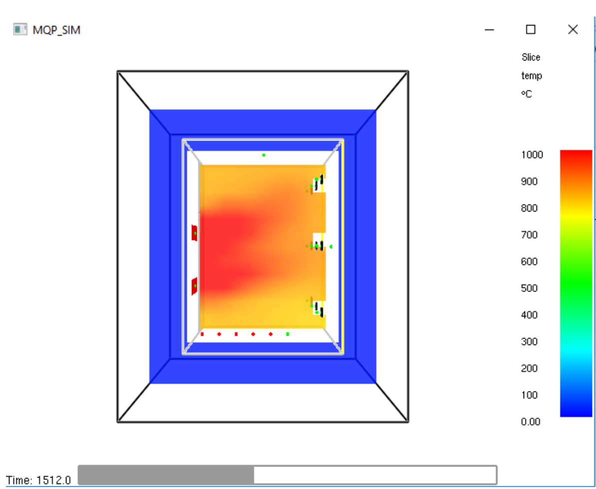
$$0.06\frac{kg}{s} \div 0.05m^2 = 0.70\frac{kg}{m^3 * s}$$

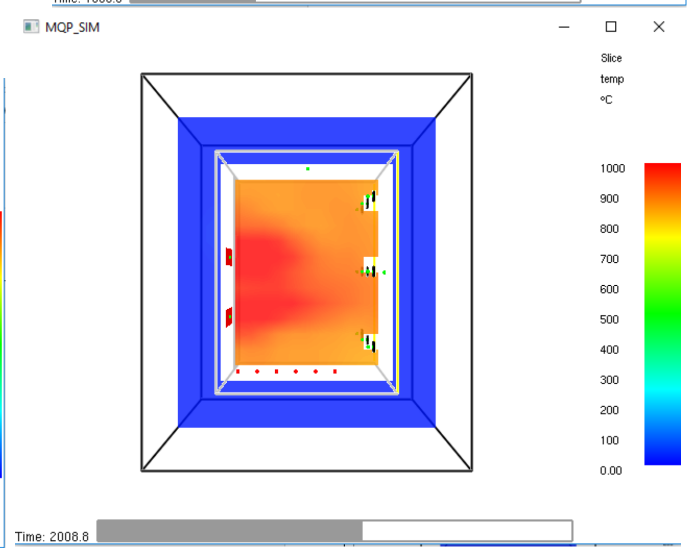

Volumetric Flow at Burner Outlet
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
Volumetric Flow Rate (m^3/s)
0.00
500.00
1000.00
1500.00
2000.00
2500.00
3000.00
3500.00
4000.00
Time (s)

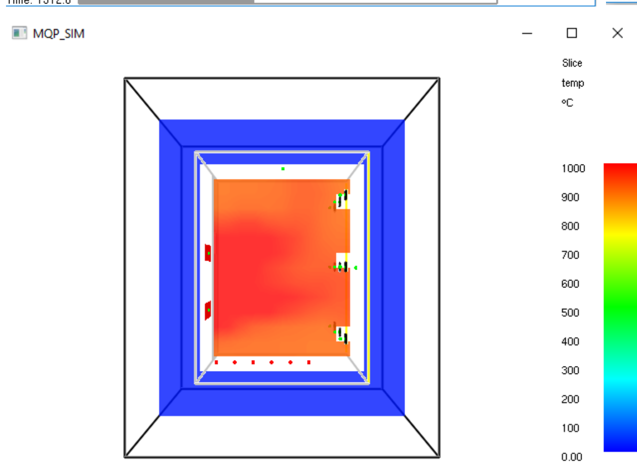
Appendix D.5.4: Simulation Temperature Slice File

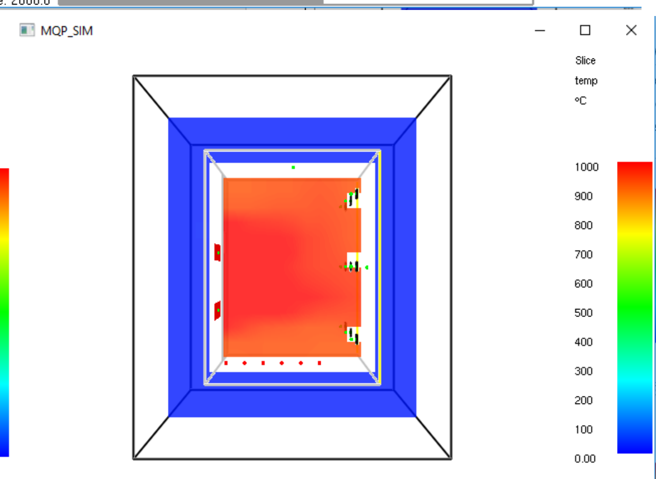




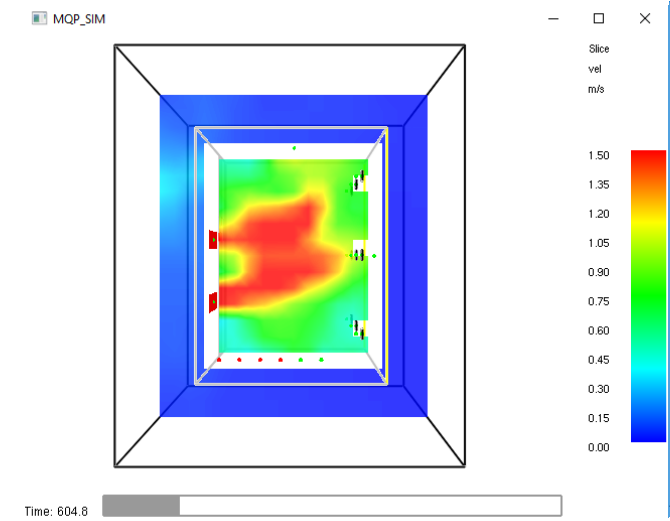


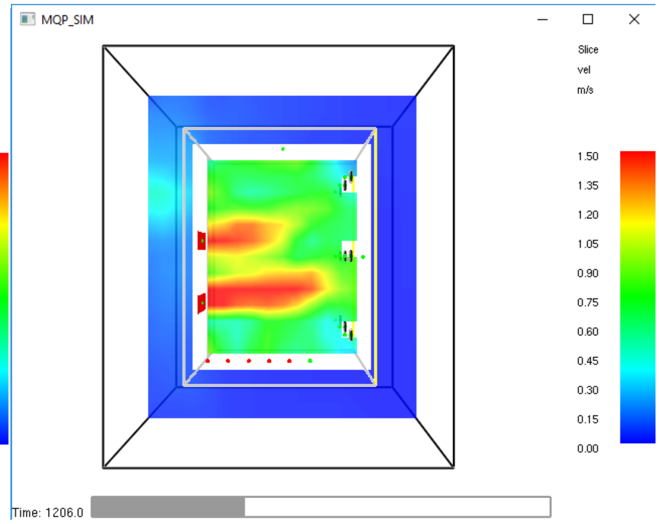


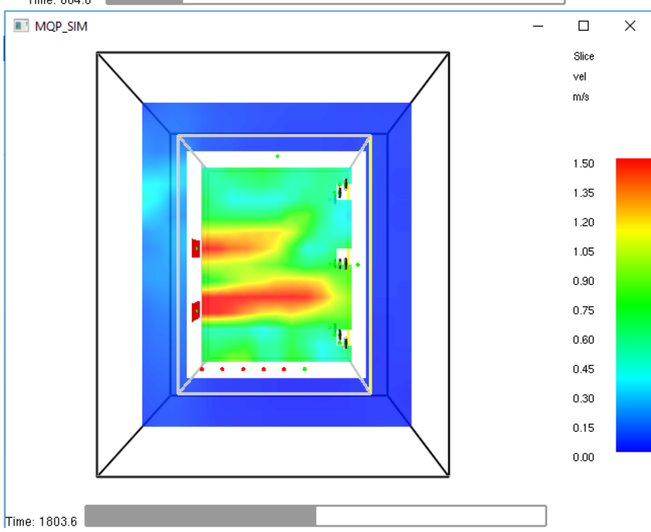


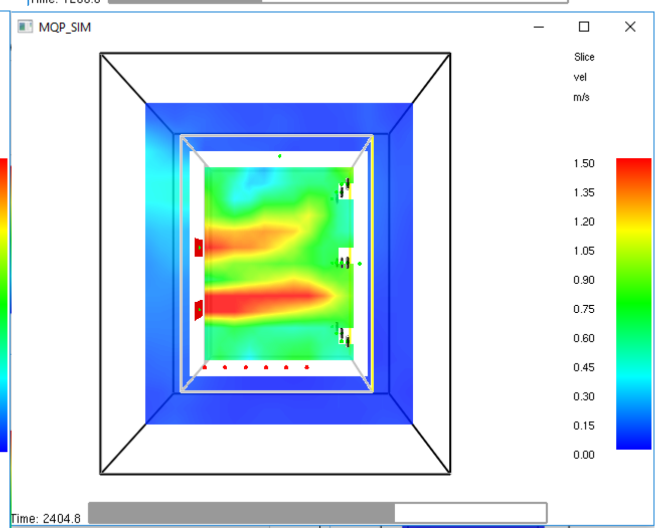


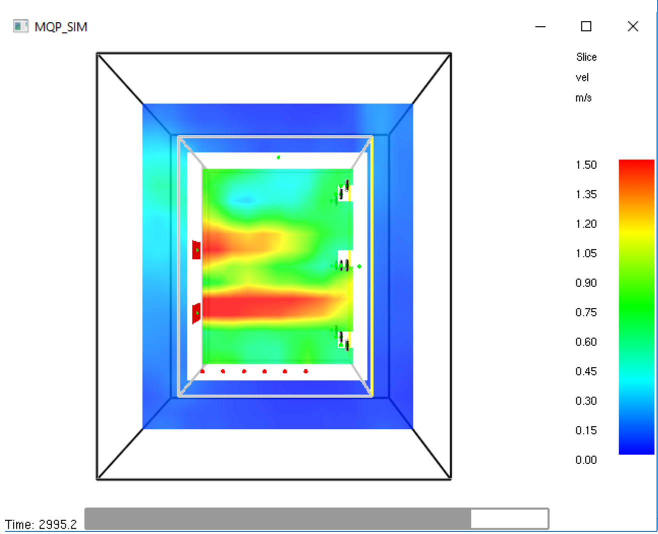
Appendix D.5.5: Simulation Velocity Slice Files

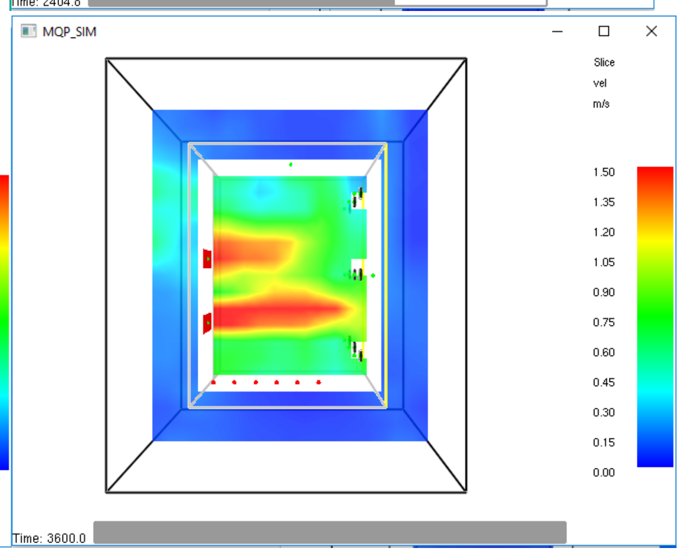


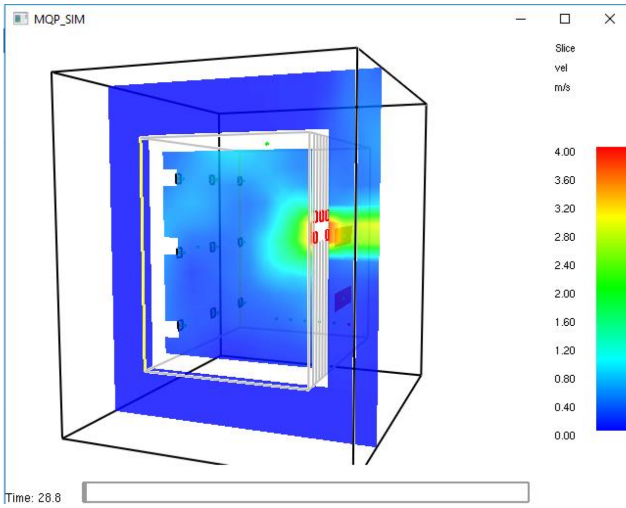


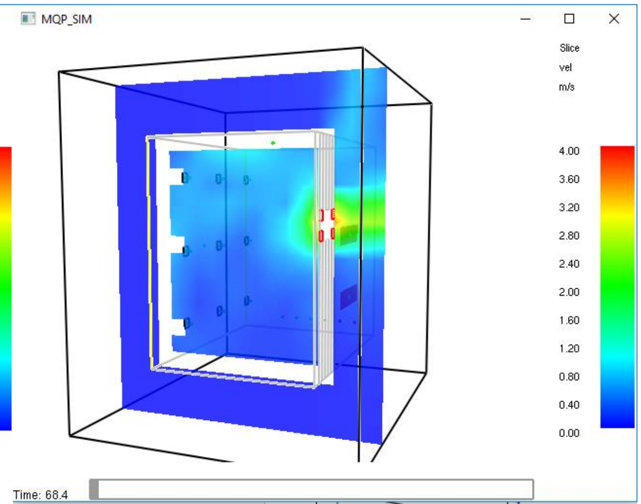


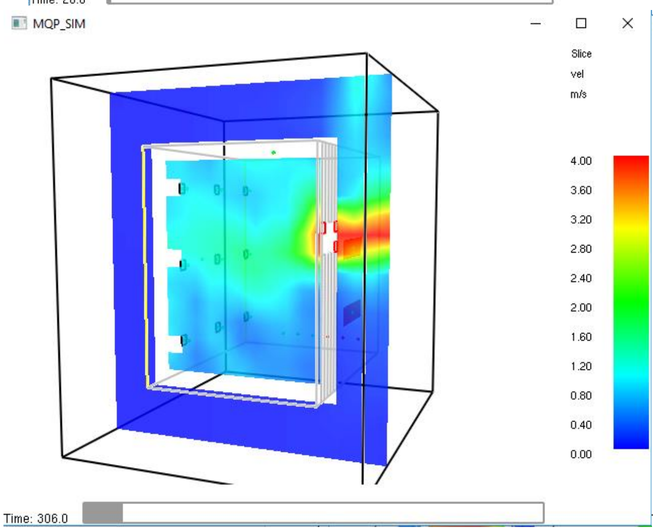


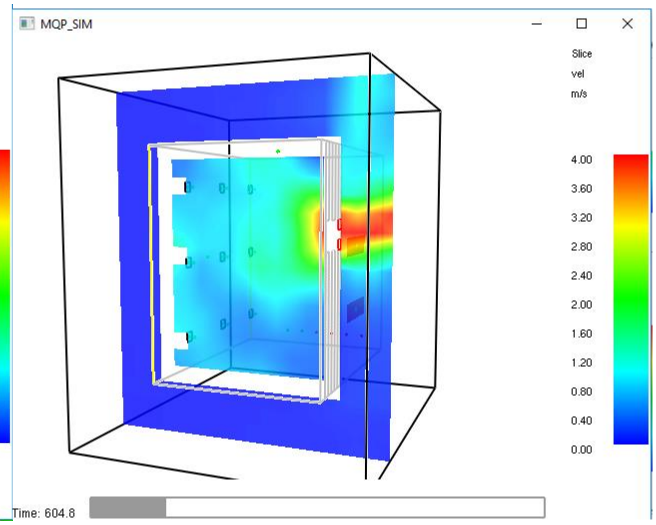


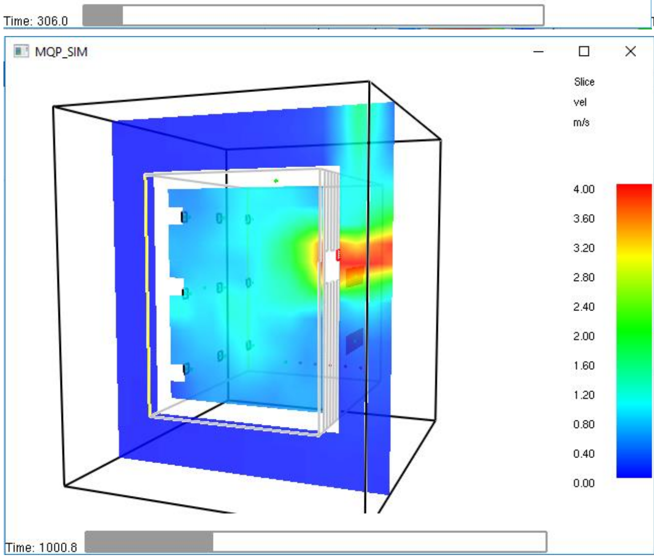


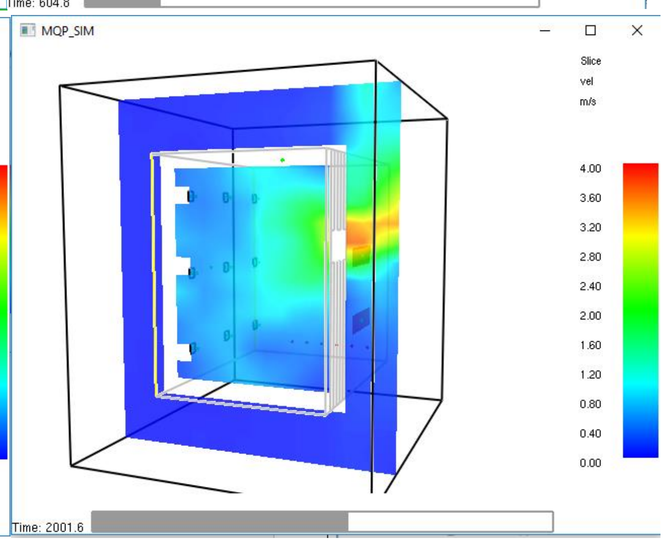

MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 28.8


MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 68.4

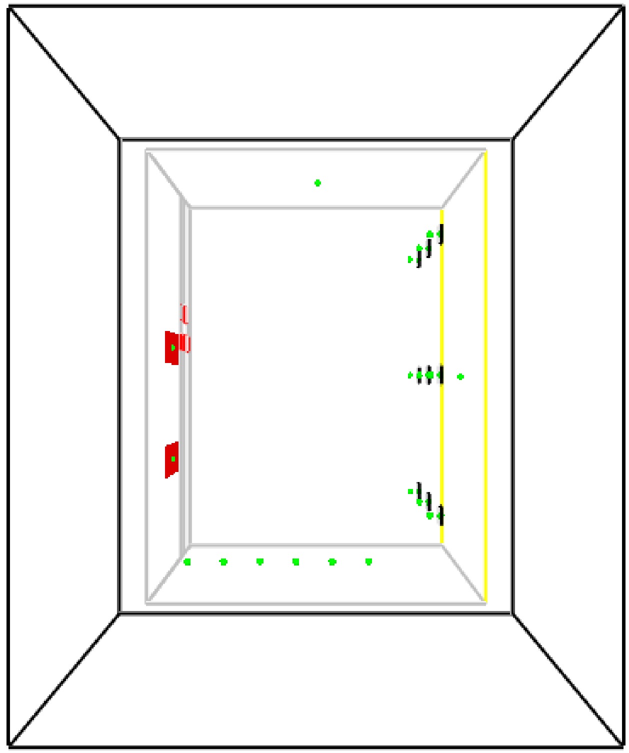

MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 306.0

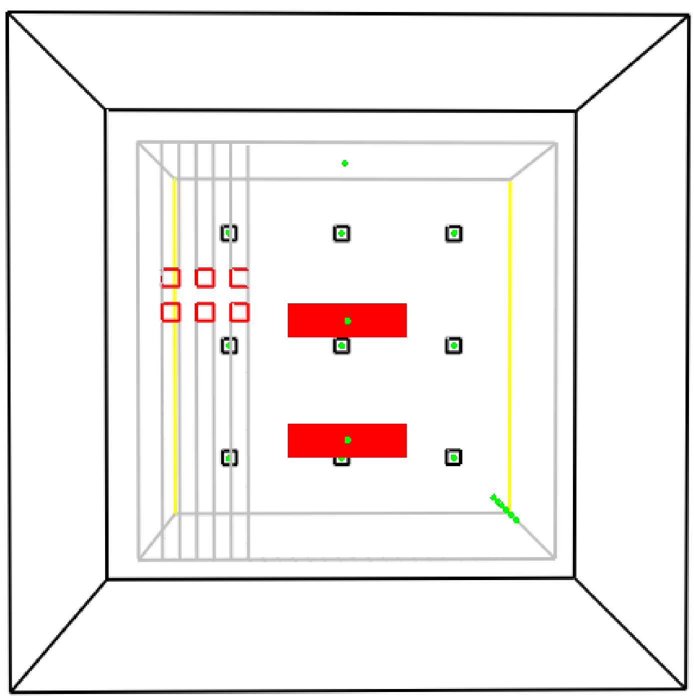

MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 604.8


MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 1000.8


MQP_SIM
Slice
vel
m/s
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Time: 2001.6

Appendix D.5.6: Computation Domain





Appendix D.5.6: FDS Input File

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&HEAD CHID='MQP_SIM', TITLE='SIMULATION_2'  /

&MESH IJK= 18, 20, 20, XB= -0.30, 1.21, -0.30, 1.52, -0.30, 1.52/
&MISC THICKEN_OBSTRUCTIONS =.TRUE., SURF_DEFAULT='FURNACE_INSULATION'/

&TIME T_END=3600/

&MATL ID                = 'CERACHEM'
      CONDUCTIVITY      = 0.34
      DENSITY           = 128
      SPECIFIC_HEAT     = 1.046 /

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

&MATL ID='CONCRETE'
      CONDUCTIVITY      =0.80
      SPECIFIC_HEAT     =0.75
      DENSITY           =2400 /

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

&SURF ID                = 'FURNACE_INSULATION'
      COLOR             = 'GRAY 75'
      MATL_ID           = 'CERACHEM','MICROPOROUS'
      THICKNESS         = 0.165,0.025
      BACKING           = 'EXPOSED'/

&SURF ID='CONCRETE WALL'
      MATL_ID           ='CONCRETE'
      COLOR             ='YELLOW'

      THICKNESS         =0.14
      BACKING           ='EXPOSED'/

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

&VENT MB=XMIN, SURF_ID='OPEN'/
&VENT MB=XMAX, SURF_ID='OPEN'/
&VENT MB=YMIN, SURF_ID='OPEN'/
&VENT MB=YMAX, SURF_ID='OPEN'/
&VENT MB=ZMIN, SURF_ID='OPEN'/
&VENT MB=ZMAX, SURF_ID='OPEN'/

&OBST XB=0.0, 0.91, 0.0, 1.22, 1.22, 1.22,  SURF_ID='FURNACE_INSULATION' /Ceiling
&OBST XB=0.0, 0.91, 0.0, 1.22, 0.0, 0.0,    SURF_ID='FURNACE_INSULATION' /Floor
&OBST XB=0.91, 0.91, 0.0, 1.22, 0.0, 1.22,  SURF_ID='CONCRETE WALL' /XMAX WALL
&OBST XB=0.0, 0.0, 0.0, 1.22, 0.0, 1.22,    SURF_ID='FURNACE_INSULATION' /XMIN WALL
&OBST XB=0.0, 0.91, 1.22, 1.22, 0.0, 1.22,  SURF_ID='FURNACE_INSULATION' /YMAX WALL
&OBST XB=0.0, 0.91, 0.0, 0.0, 0.0, 1.22,    SURF_ID='FURNACE_INSULATION' /YMIN 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, 0.59,0.64, 0.59,0.64, SURF_ID='plate' /PT5
&OBST XB=0.81,0.81, 0.19,0.24, 0.59,0.64, SURF_ID='plate' /PT6
&OBST XB=0.81,0.81, 0.99,1.04, 0.19,0.24, SURF_ID='plate' /PT7
&OBST XB=0.81,0.81, 0.59,0.64, 0.19,0.24, SURF_ID='plate' /PT8
&OBST XB=0.81,0.81, 0.19,0.24, 0.19,0.24, SURF_ID='plate' /PT9
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&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

&SURF ID='INLET',
       SPEC_ID ='PRODUCTS'
       MASS_FLUX   = 0.70,
       TMP_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/

&VENT XB= 0.0, 0.0, 0.435, 0.785,  0.30, 0.40, SURF_ID='INLET'/
&VENT XB= 0.0, 0.0, 0.435, 0.785,  0.65, 0.75, SURF_ID='INLET'/

&HOLE XB=-0.2,0.1,1.00,1.05,0.70,0.75, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 3' /
&DEVC XYZ=0.1,0.1,0.1, ID='timer 3', SETPOINT= 05.0, QUANTITY='TIME', INITIAL_STATE=.FALSE./

&HOLE XB=-0.20,0.1,1.00,1.05,0.80,0.85, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 4' /
&DEVC XYZ=0.2,0.1,0.1, ID='timer 4', SETPOINT= 50.0, QUANTITY='TIME', INITIAL_STATE=.FALSE./

&HOLE XB=-0.20,0.1,1.10,1.15,0.70,0.75, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 5' /
&DEVC XYZ=0.3,0.1,0.1, ID='timer 5', SETPOINT= 300.0, QUANTITY='TIME', INITIAL_STATE=.FALSE./
&HOLE XB=-0.20,0.1,1.10,1.15,0.80,0.85, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 6' /
&DEVC XYZ=0.4,0.1,0.1, ID='timer 6', SETPOINT= 600.0, QUANTITY='TIME', INITIAL_STATE=.FALSE./

&HOLE XB=-0.20,0.1,0.9,0.95,0.70,0.75, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 7' /
&DEVC XYZ=0.5,0.1,0.1, ID='timer 7', SETPOINT= 1000.0, QUANTITY='TIME', INITIAL_STATE=.FALSE./

&HOLE XB=-0.20,0.1,0.90,0.95,0.80,0.85, COLOR='RED',TRANSPARENCY=0.75, DEVC_ID='timer 8' /
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&DEVC ID='WALL_MID_TEMP#1',    XYZ= 0.91, 0.61, 0.61, QUANTITY='WALL TEMPERATURE',IOR=-1 /
&DEVC ID='CEILING_MID_TEMP#1',XYZ= 0.46, 0.61, 1.22, QUANTITY='WALL TEMPERATURE',IOR=-3 /

&SLCF QUANTITY='TEMPERATURE', PBY=0.61/
&SLCF QUANTITY='TEMPERATURE', PBX=0.46/
&SLCF QUANTITY='TEMPERATURE', PBX=0.81/
&SLCF QUANTITY='VELOCITY', PBY=0.61/

&SLCF QUANTITY='TEMPERATURE', PBY=1.05/
&SLCF QUANTITY='VELOCITY', PBY=1.05/

&SLCF PBY=0.61,QUANTITY='DENSITY' /
&SLCF PBY=0.61,QUANTITY='PRESSURE' /
&SLCF PBY=0.61, QUANTITY='HRRPUV' /

&DEVC ID='VOLUME FLOW', XB=0.001, 0.001, 0.435, 0.785, 0.30, 0.40, QUANTITY='VOLUME FLOW'/BURNER 1
&DEVC ID='VOLUME FLOW', XB=0.001, 0.001, 0.435, 0.785,  0.65, 0.75, QUANTITY='VOLUME FLOW'/BURNER 2

&DEVC ID='NHF_topleft',  QUANTITY='NET HEAT FLUX', XYZ=0.81,1.015,1.015, IOR=-1 /
&DEVC ID='NHF_topmid',   QUANTITY='NET HEAT FLUX', XYZ=0.81,0.615,1.015, IOR=-1 /
&DEVC ID='NHF_topright', QUANTITY='NET HEAT FLUX', XYZ=0.81,0.215,1.015, IOR=-1 /
&DEVC ID='NHF_midleft',  QUANTITY='NET HEAT FLUX', XYZ=0.81,1.015,0.615, IOR=-1 /
&DEVC ID='NHF_midmid',   QUANTITY='NET HEAT FLUX', XYZ=0.81,0.615,0.615, IOR=-1 /
&DEVC ID='NHF_midright', QUANTITY='NET HEAT FLUX', XYZ=0.81,0.215,0.615, IOR=-1 /
&DEVC ID='NHF_botleft',  QUANTITY='NET HEAT FLUX', XYZ=0.81,1.015,0.215, IOR=-1 /
```

```
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&DEVC ID='IHF_topmid',   QUANTITY='INCIDENT HEAT FLUX', XYZ=0.81,0.615,1.015, IOR=-1 /
&DEVC ID='IHF_topright', QUANTITY='INCIDENT HEAT FLUX', XYZ=0.81,0.215,1.015, IOR=-1 /
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&DEVC ID='IHF_botleft',  QUANTITY='INCIDENT HEAT FLUX', XYZ=0.81,1.015,0.215, IOR=-1 /
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&DEVC ID='AST_topleft',  QUANTITY='ADIABATIC SURFACE TEMPERATURE', XYZ=0.81,1.015,1.015, IOR=-1 /
&DEVC ID='AST_topmid',   QUANTITY='ADIABATIC SURFACE TEMPERATURE', XYZ=0.81,0.615,1.015, IOR=-1 /
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&DEVC ID='AST_botright', QUANTITY='ADIABATIC SURFACE TEMPERATURE', XYZ=0.81,0.215,0.215, IOR=-1 /

&DEVC ID='TC', XYZ=0.78,1.015,1.015, QUANTITY='TEMPERATURE'/
&DEVC ID='TC', XYZ=0.78,0.615,1.015, QUANTITY='TEMPERATURE'/
&DEVC ID='TC', XYZ=0.78,0.215,1.015, QUANTITY='TEMPERATURE'/
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&DEVC ID='TC', XYZ=0.78,0.215,0.615, QUANTITY='TEMPERATURE'/
&DEVC ID='TC', XYZ=0.78,1.015,0.215, QUANTITY='TEMPERATURE'/
&DEVC ID='TC', XYZ=0.78,0.615,0.215, QUANTITY='TEMPERATURE'/
&DEVC ID='TC', XYZ=0.78,0.215,0.215, QUANTITY='TEMPERATURE'/

&BNDF QUANTITY='WALL TEMPERATURE'/

&TAIL /
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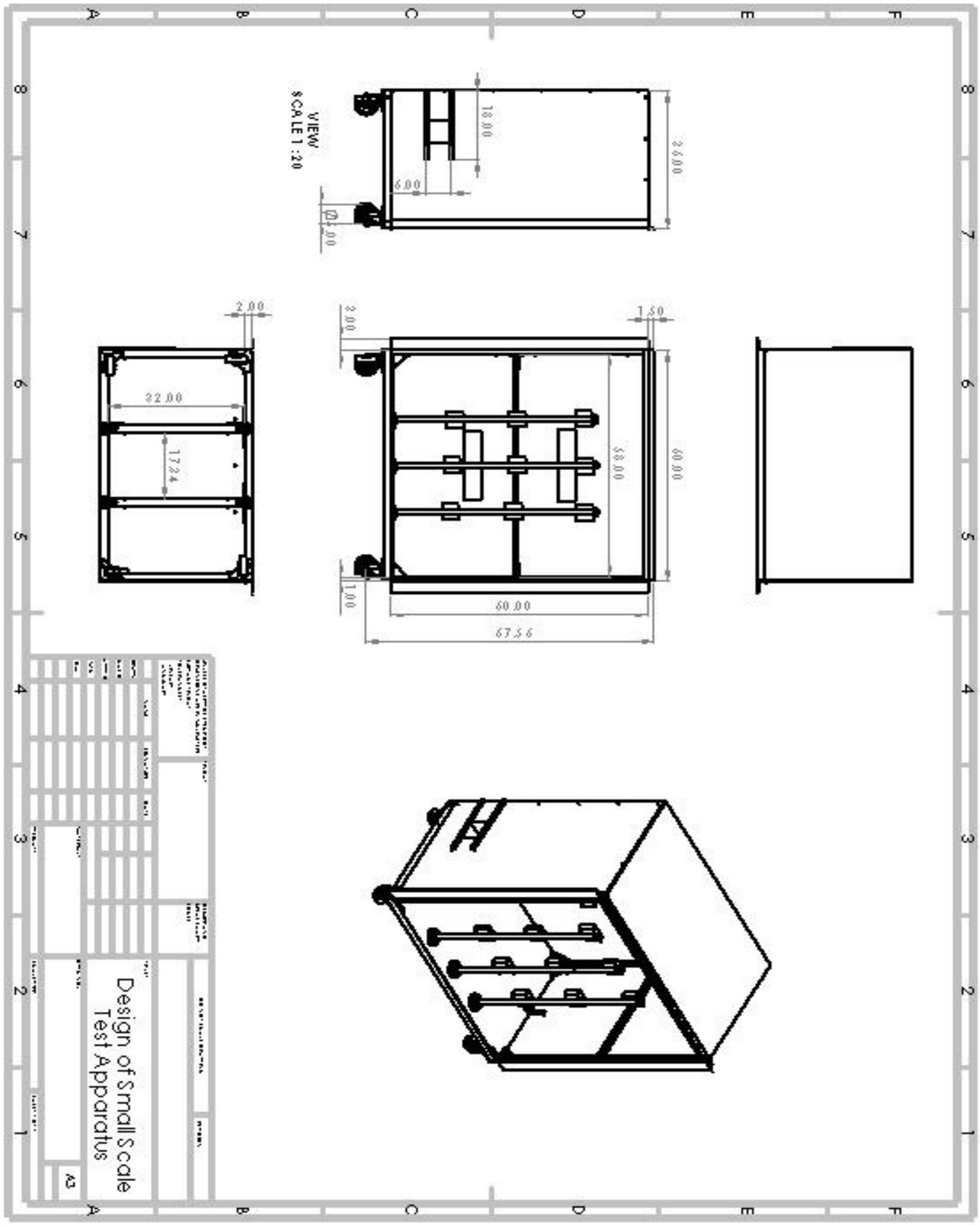
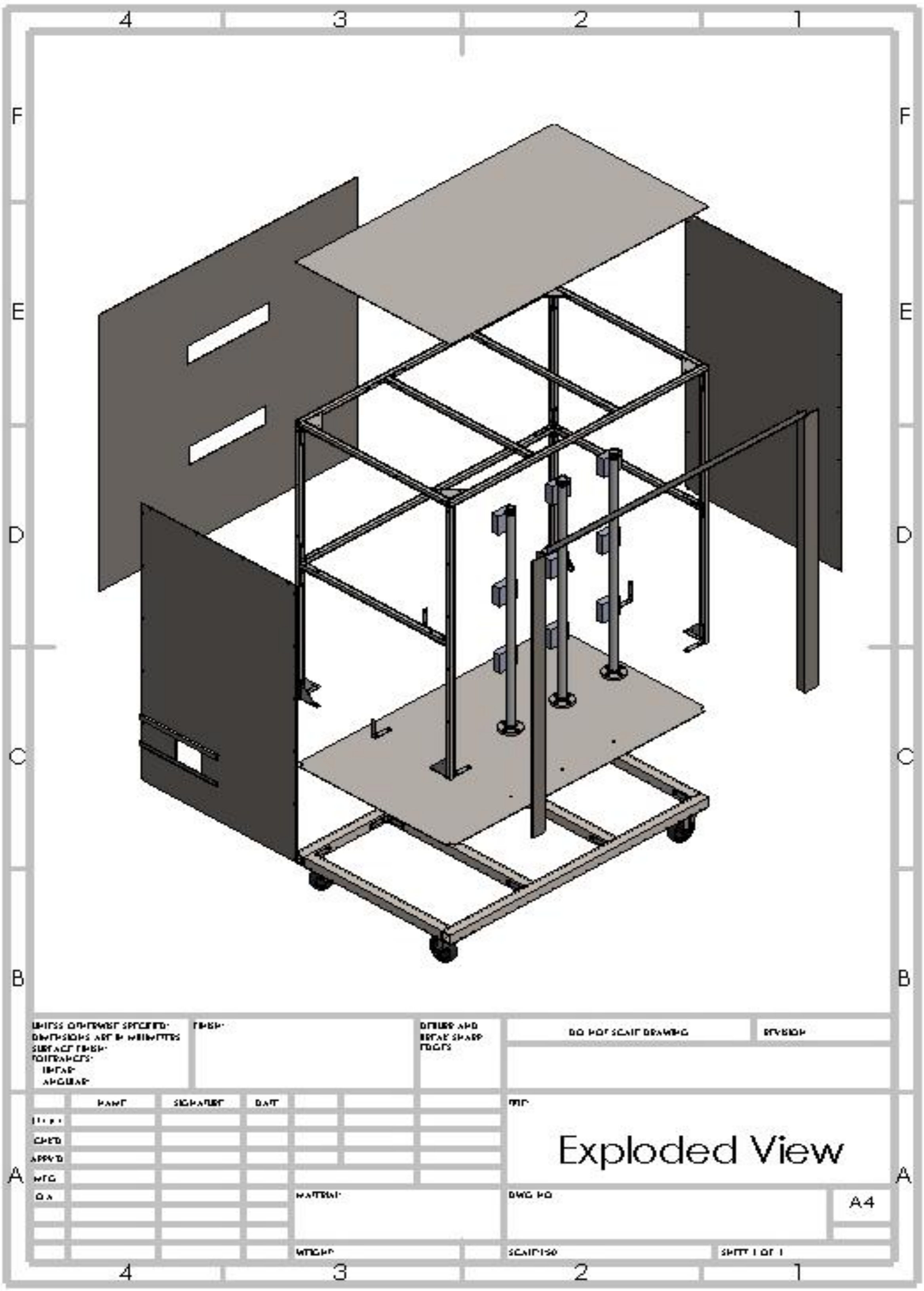
Appendix E: System Design

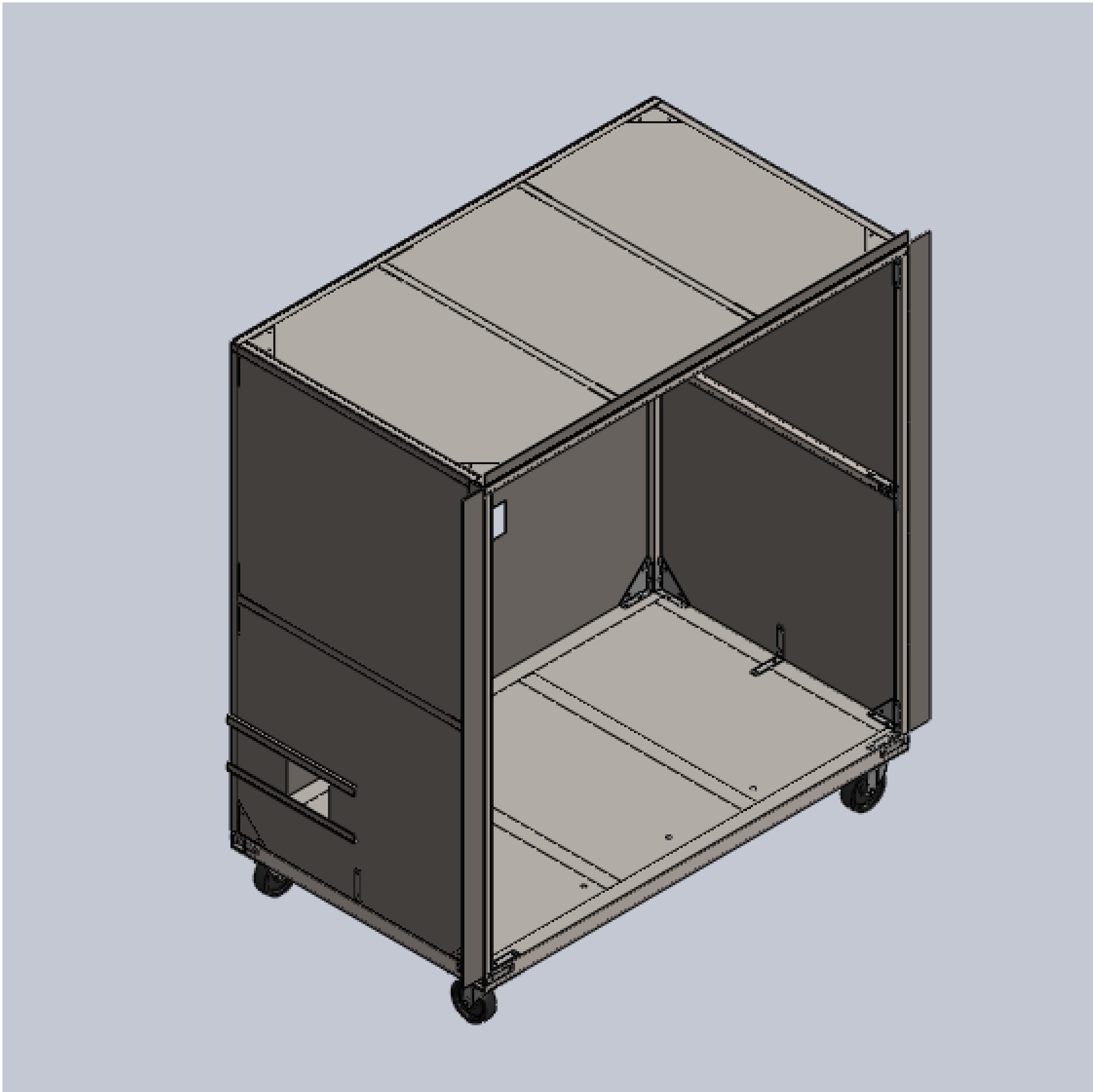
Appendix E.1: Furnace Design

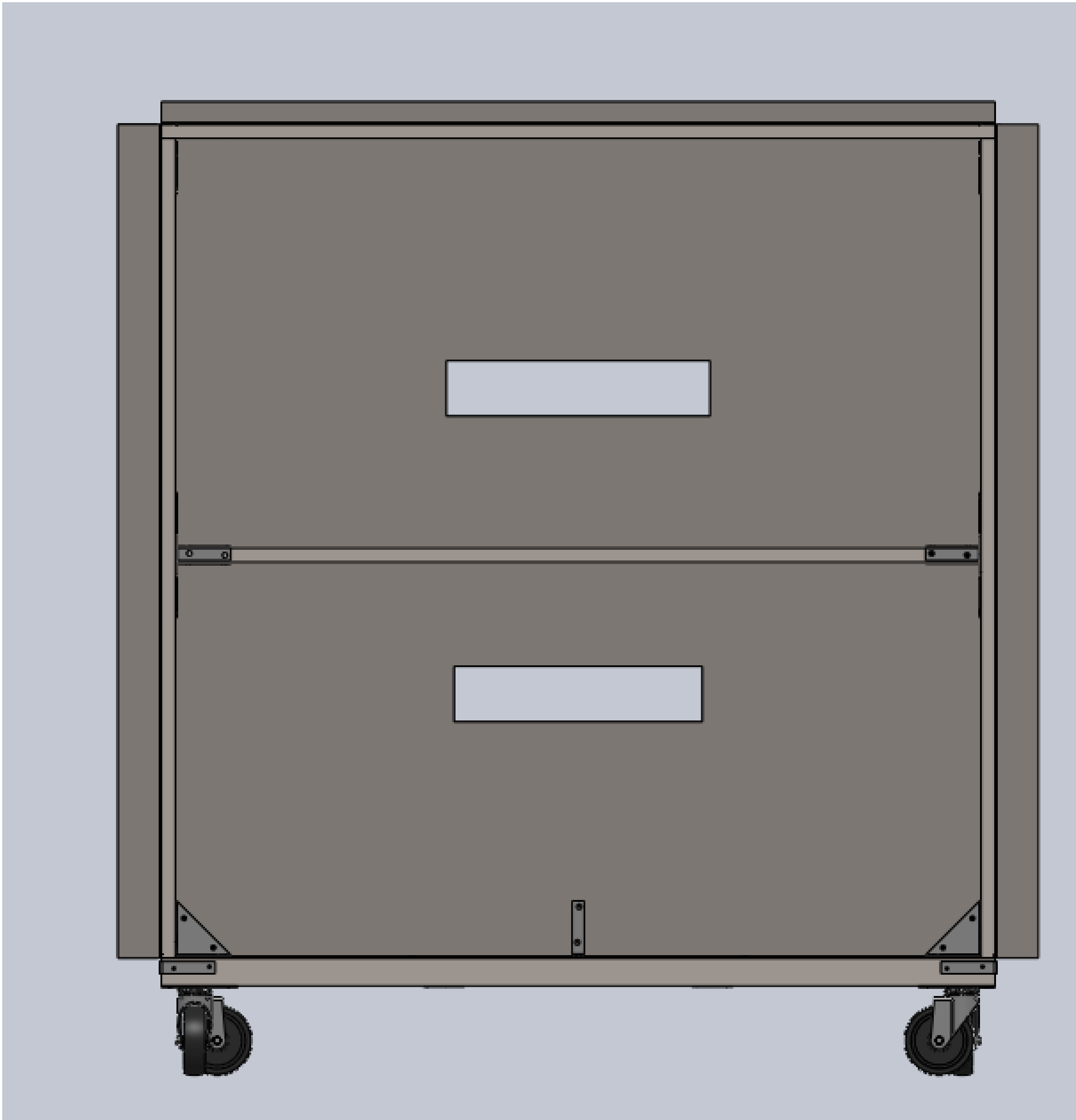


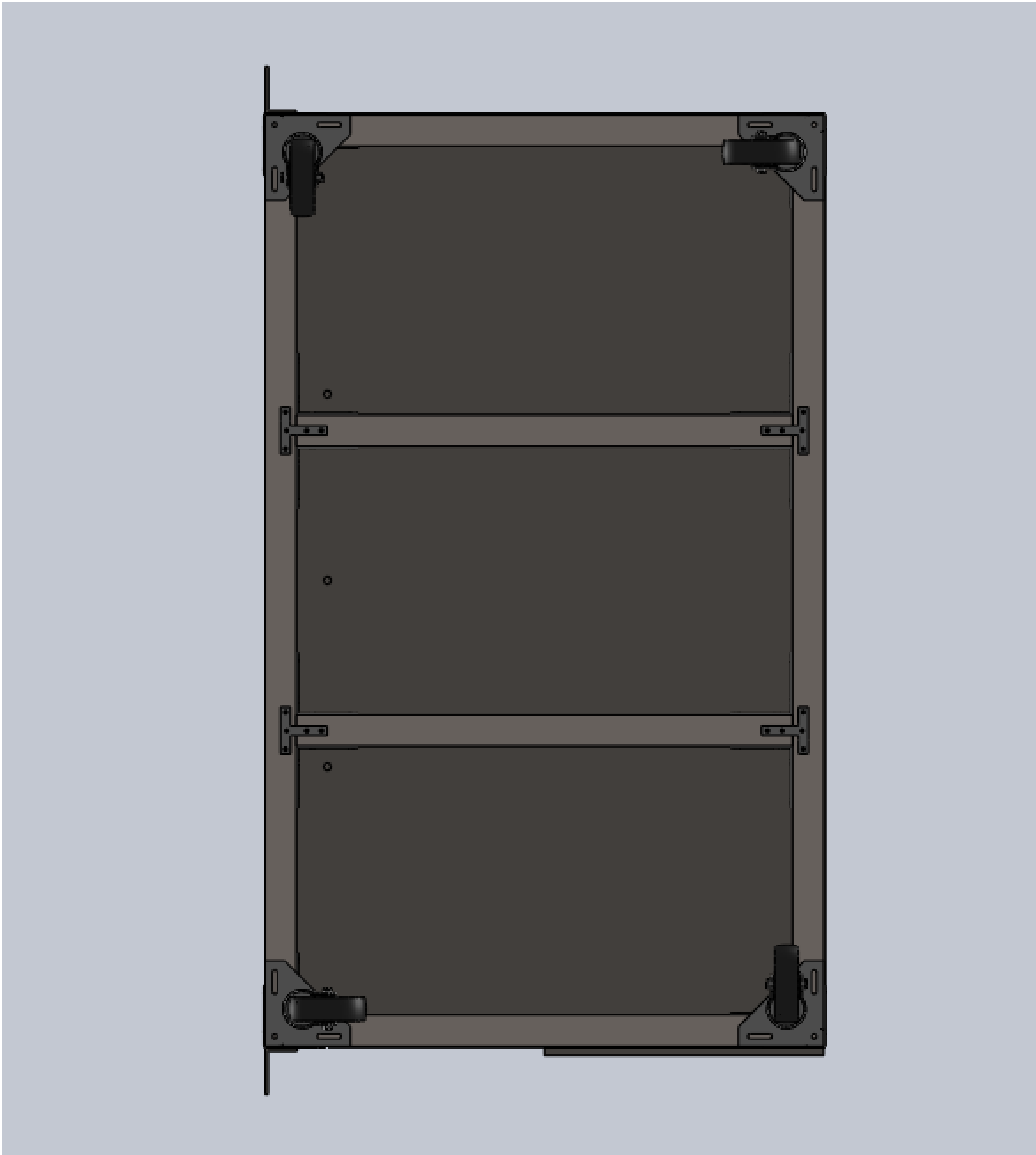

Exploded View
A4

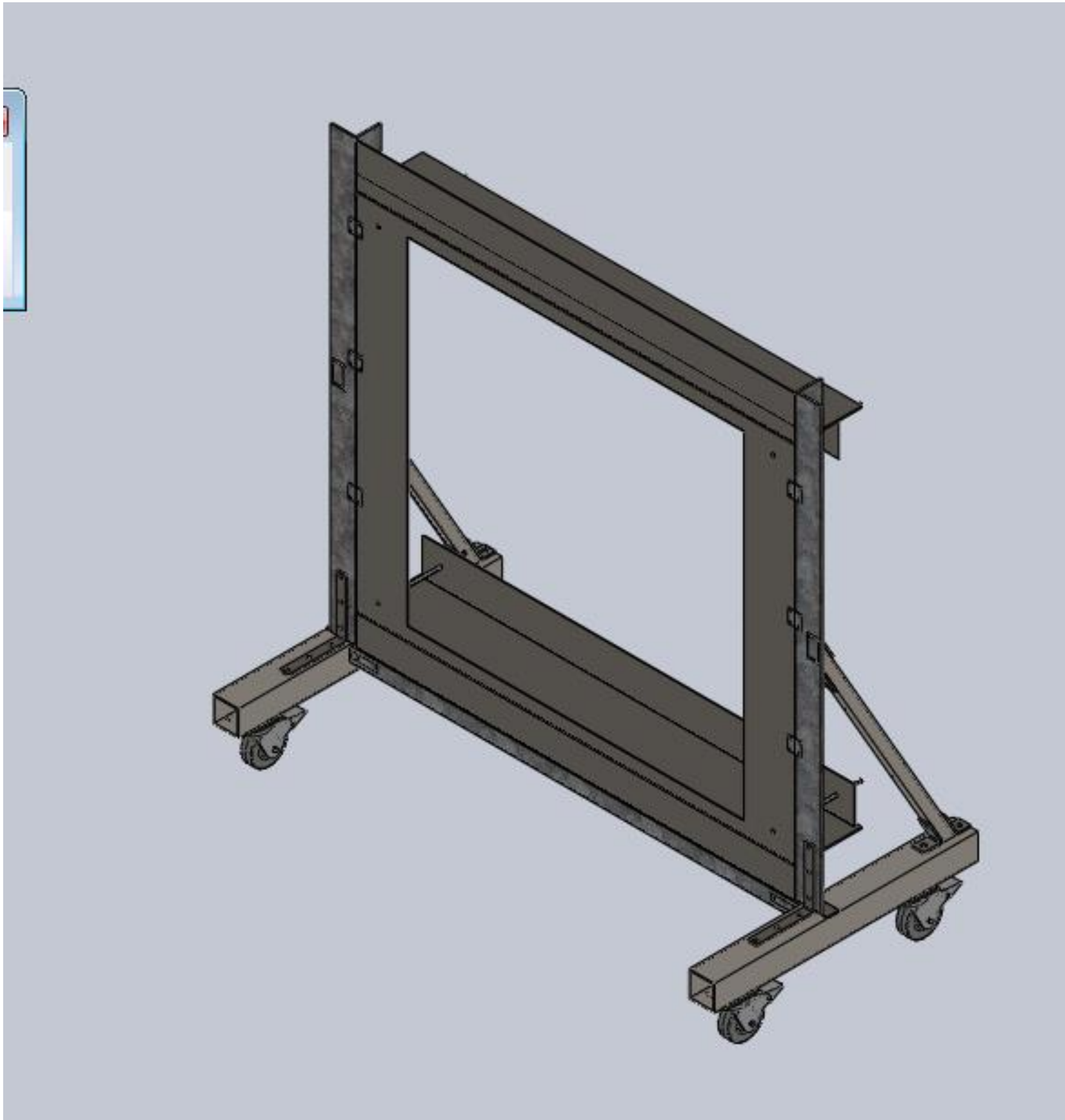

FRONT
FRONT

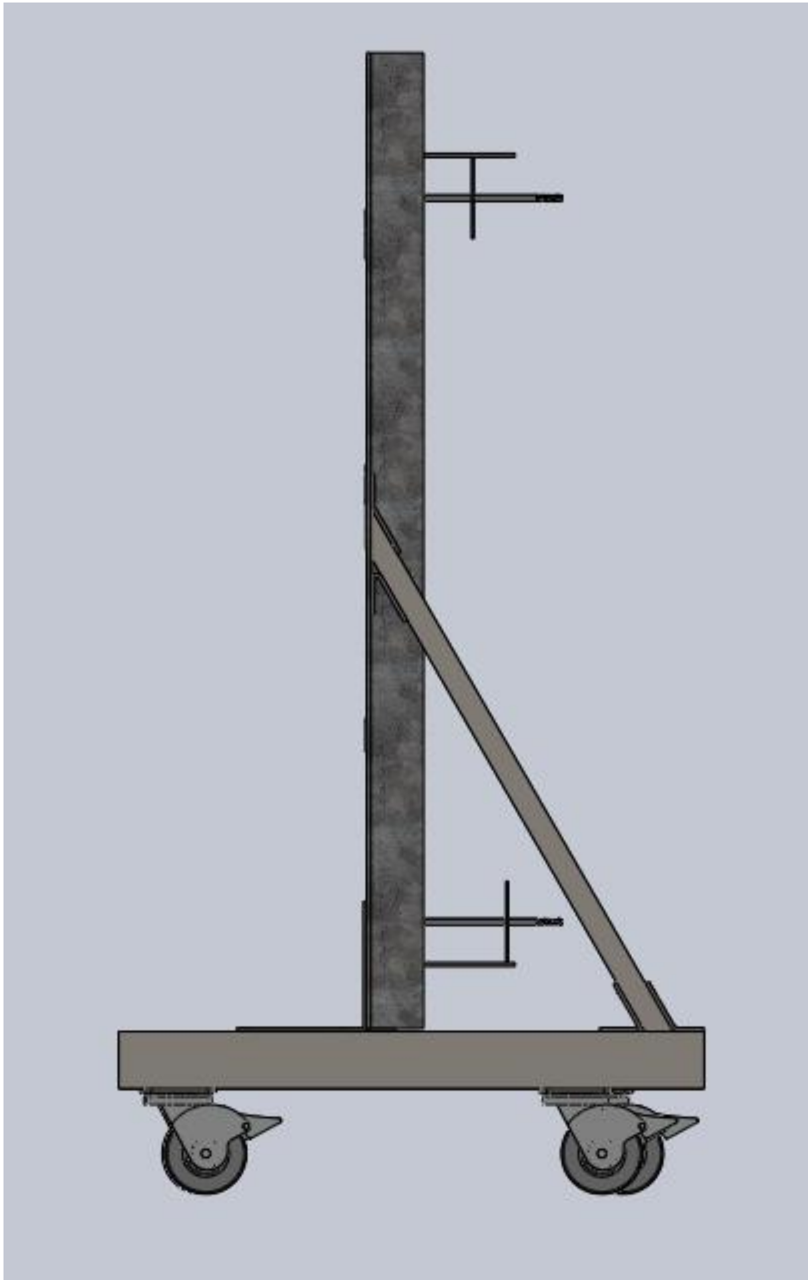

FRONT



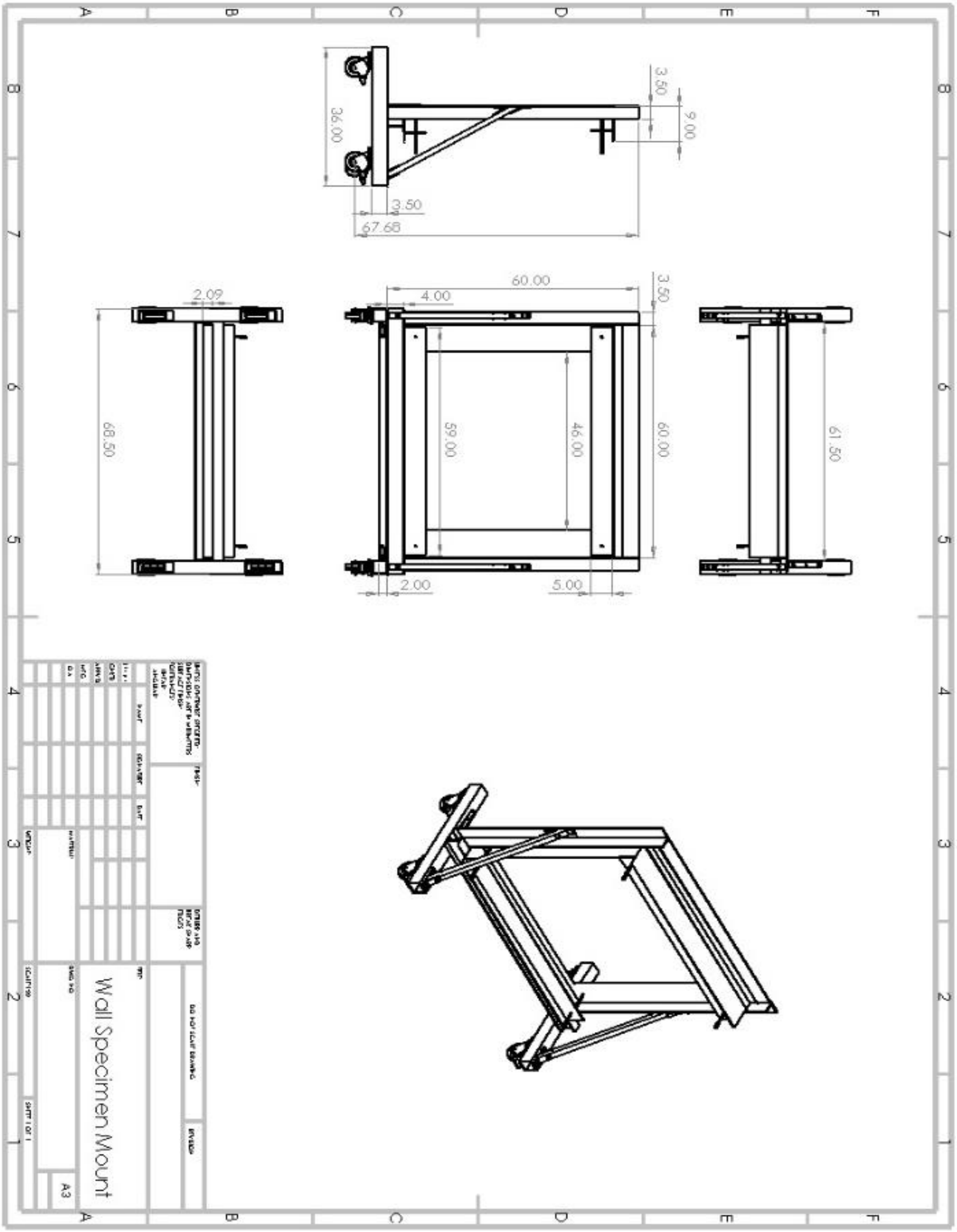


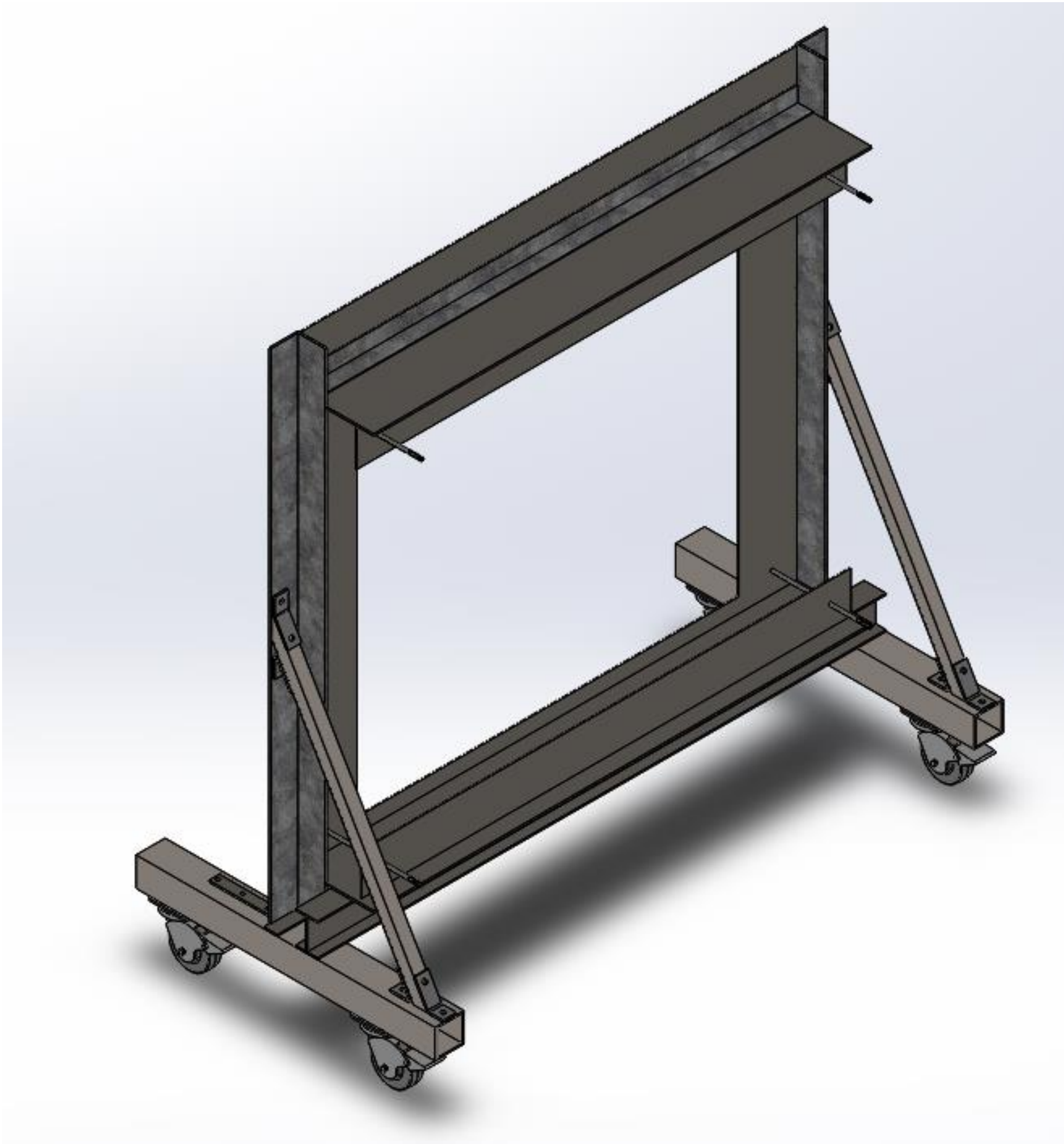


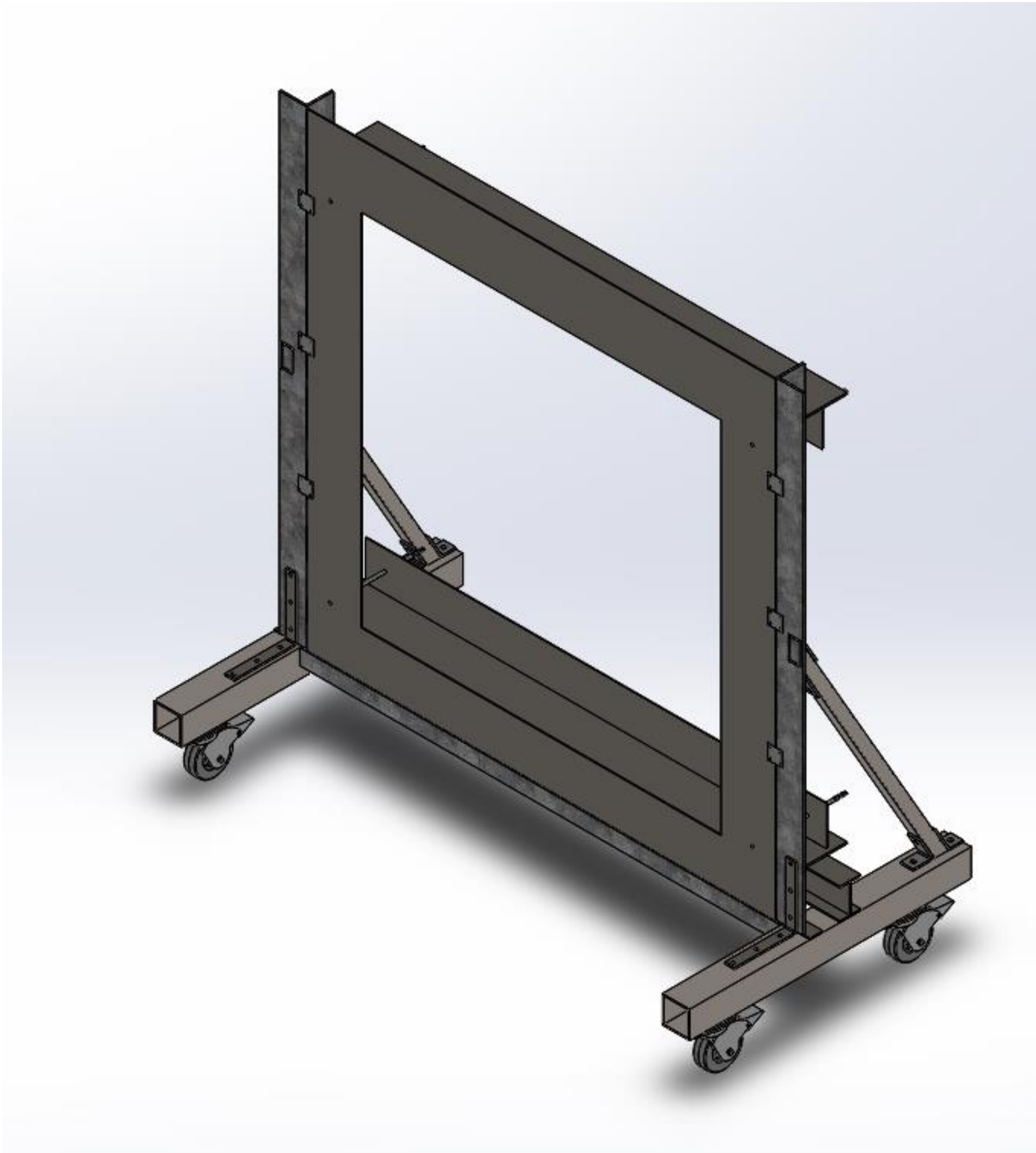


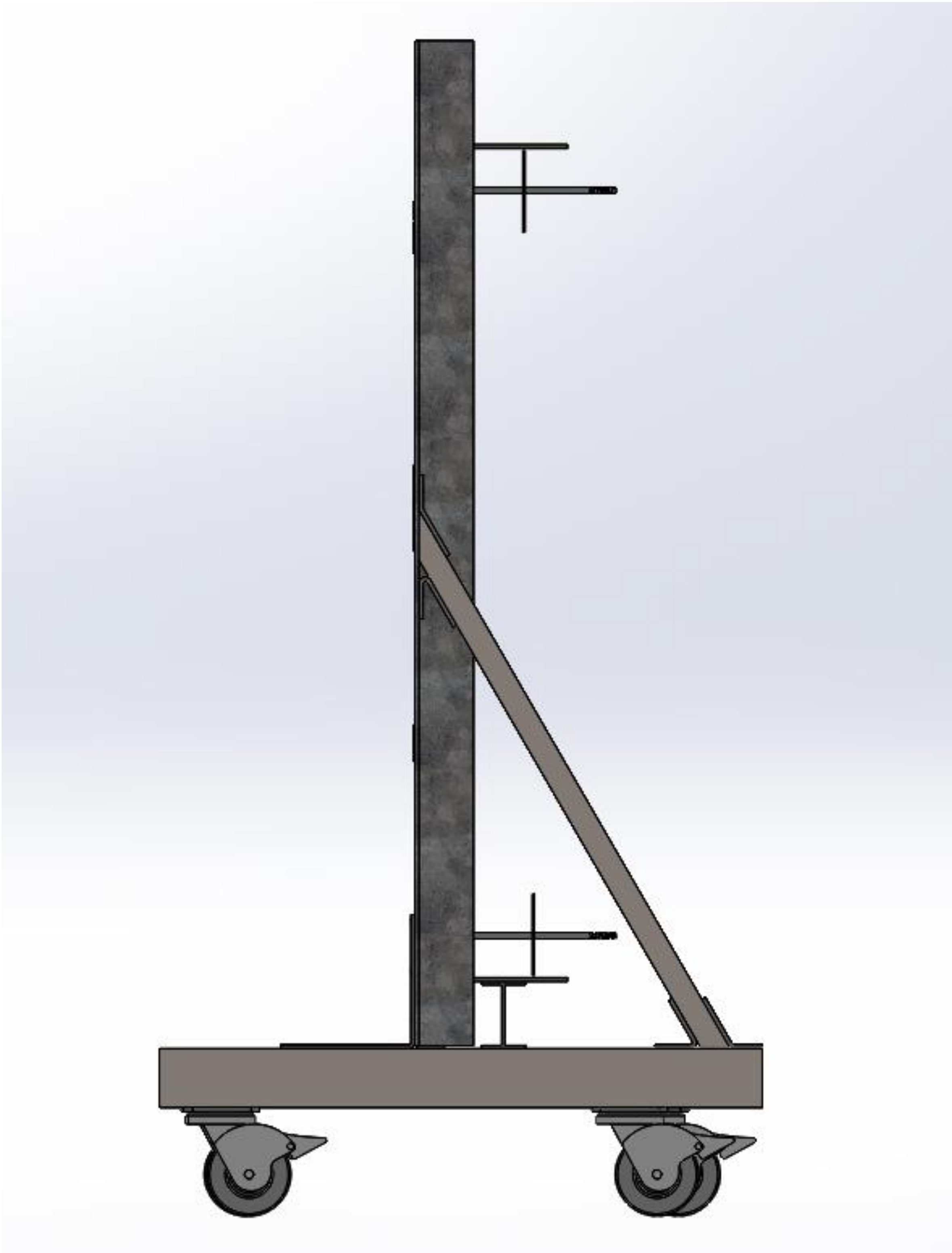


Appendix E.2: Specimen Mount Design







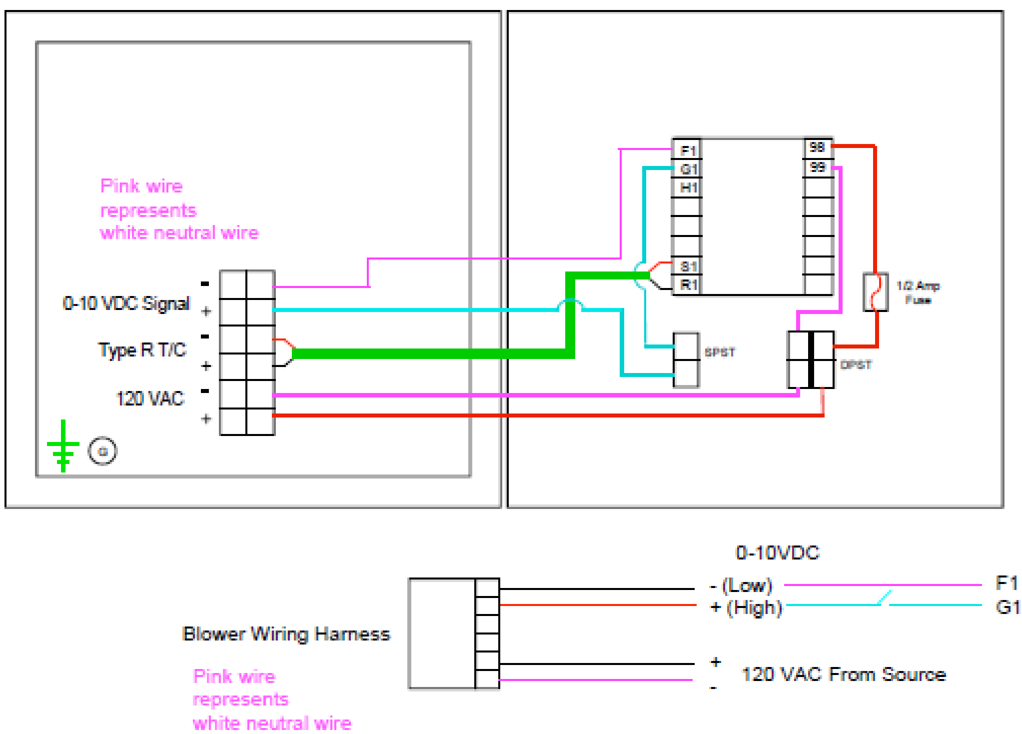


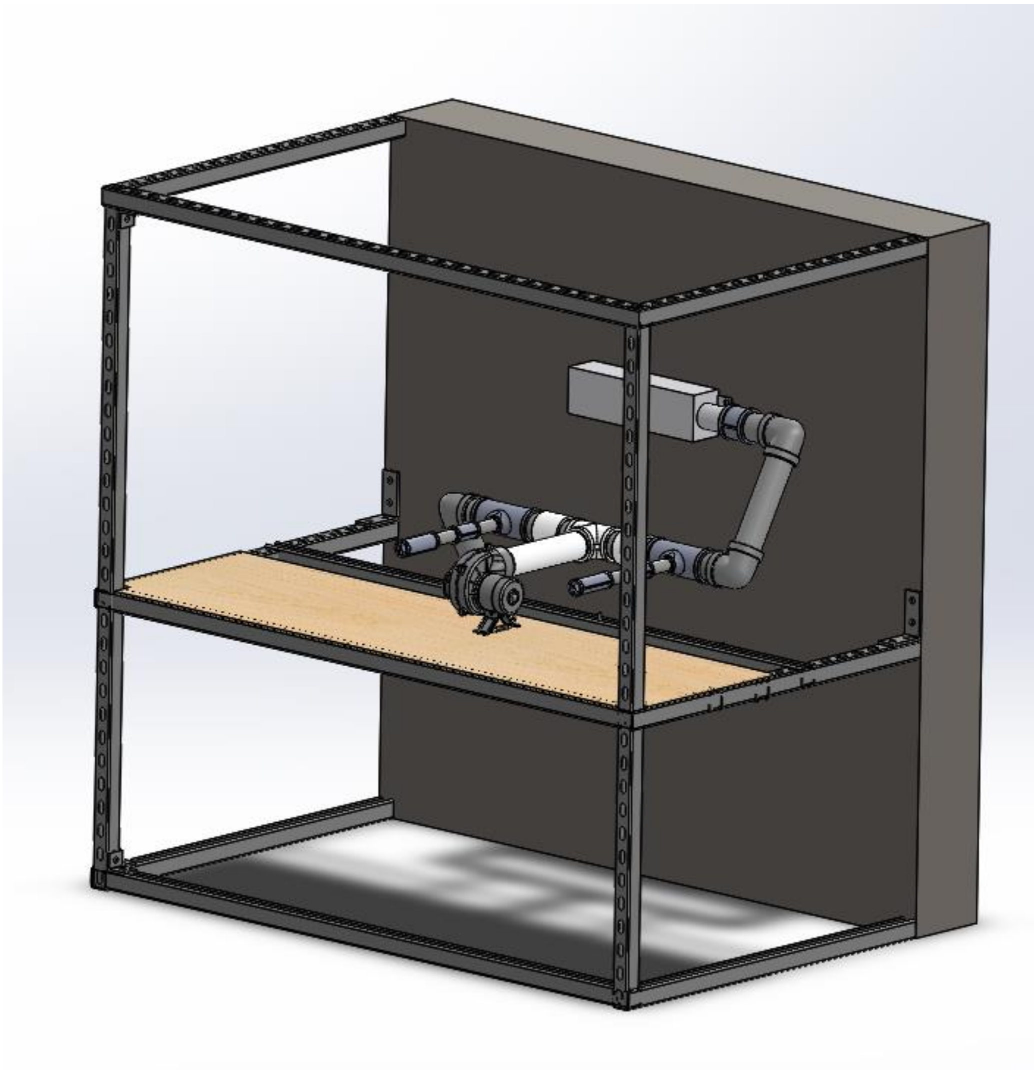
Appendix E.3: Burner System Design

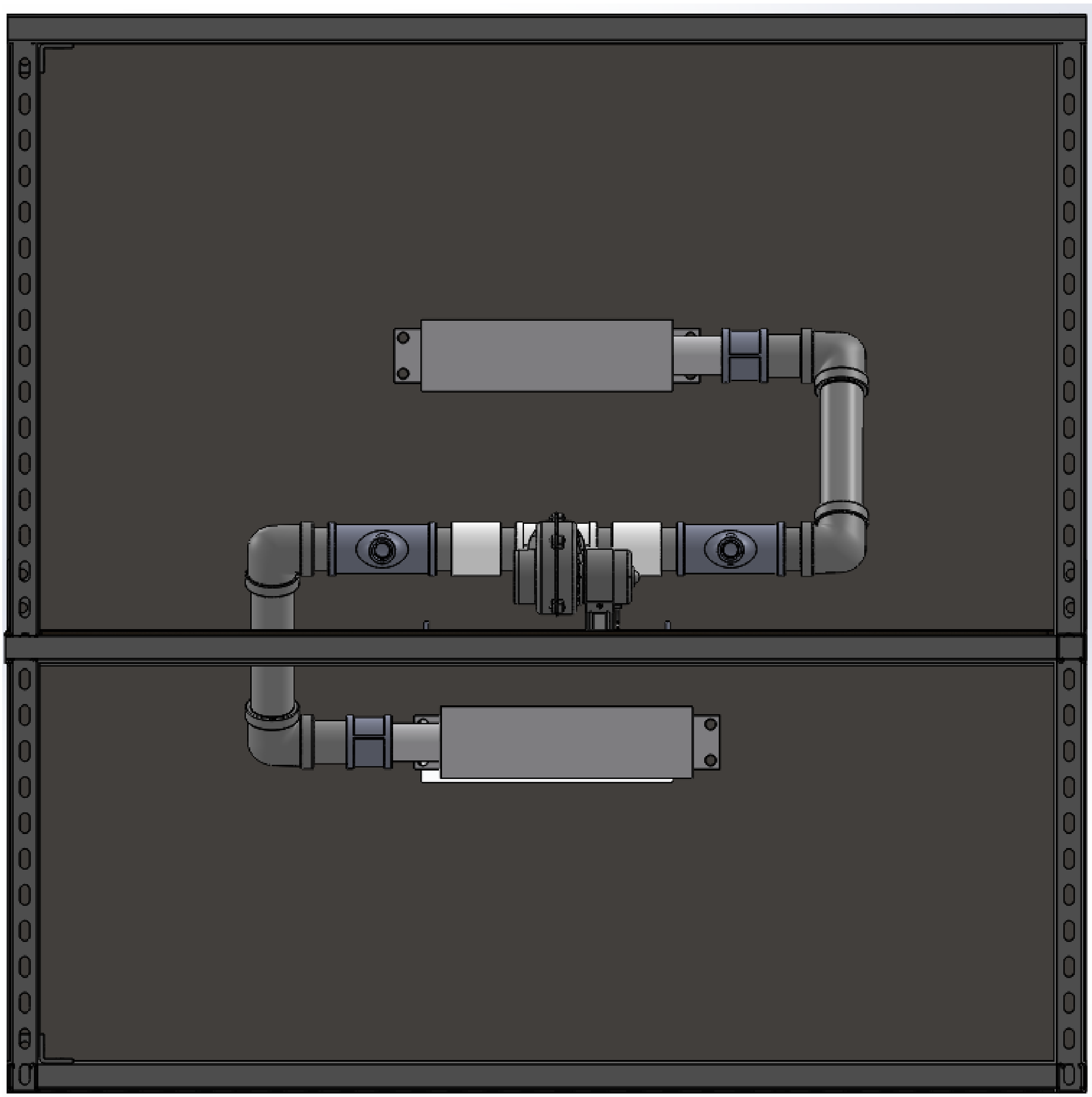
Pipe sizing needed to be estimated in order to complete the system. It was recommended by the manufacturer to design the manifold so that it is symmetric with as minimal piping. The concept here is to have an even distribution of an air and gas mixture with as little resistance to flow as possible. A 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:

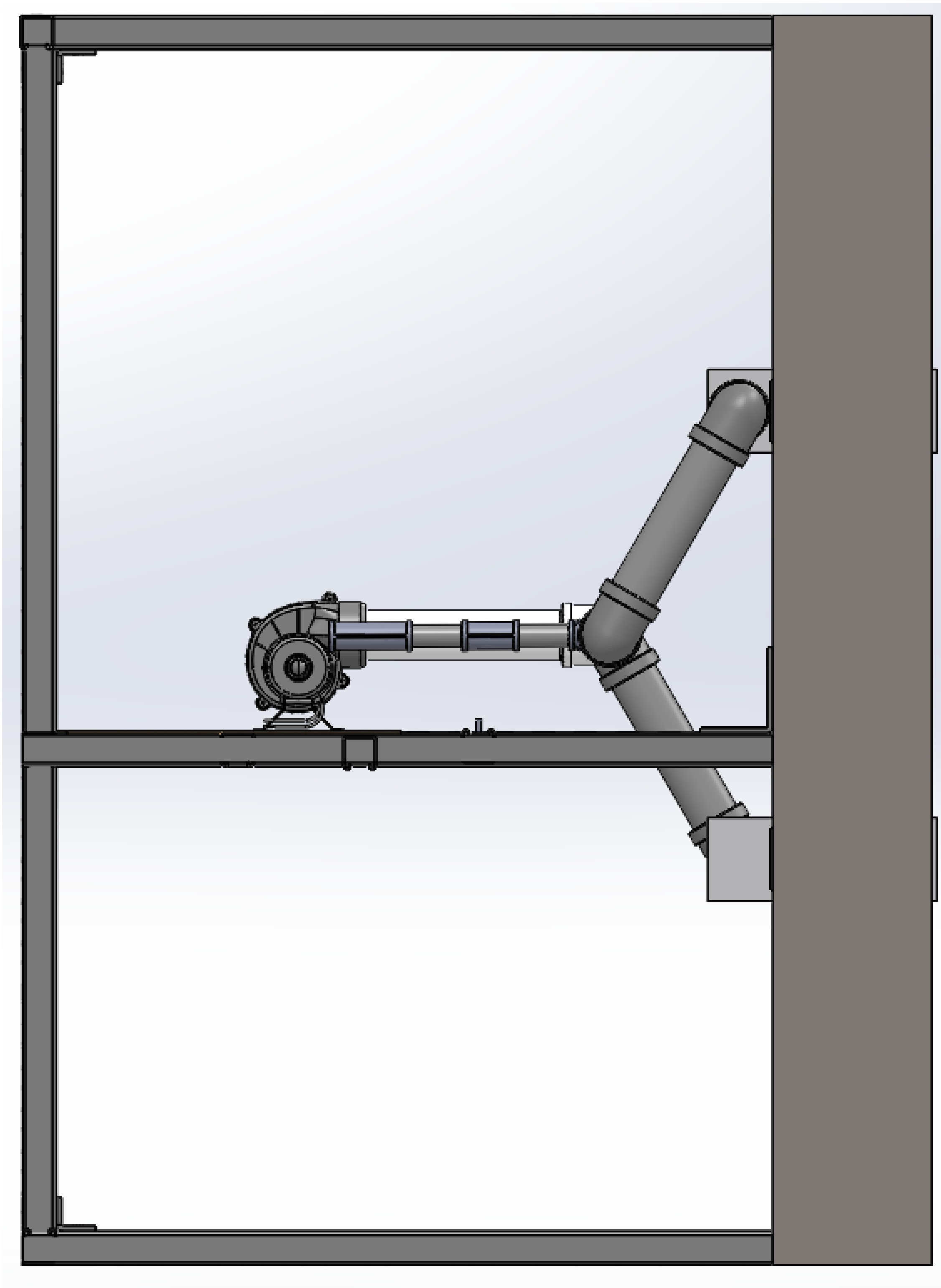
- 2” Diameter - 3” Length Black Malleable Pipe (4)
- 2” Diameter - 4” Length Black Malleable Pipe (2)
- 2” Diameter - 3” Length PVC Pipe (4)
- 2” Diameter - 12” Length PVC Pipe(1)
- 2” Diameter - 10” Length Black Malleable Pipe (2)
- ¾” Diameter - 4” Length Black Malleable Pipe (4)
- 2” Diameter - 2.5” 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 2in 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.

Figure 31:Plate Thermometer Visual

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.


Figure 32: Constructed Final Plate Thermometer

The plate thermometers where 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

ε = emissivity

σ = Stefan-Boltzmann constant

ρ = density of steel plate

δ = thickness of steel plate

C_p = specific heat of steel plate

h = convective heat transfer coefficient

T_s = surface temperature of plate

T_g = ambient gas temperature

$T_{insulated}$ = temperature of thermocouple in insulation

h_c = conductive resistance of insulation

L = thickness of insulation

k = thermal conductivity of insulation

$$\dot{q}''_{net} = \varepsilon \dot{q}''_{incident} + \dot{q}''_{conv} + \dot{q}''_{rad} + \dot{q}''_{cond}$$

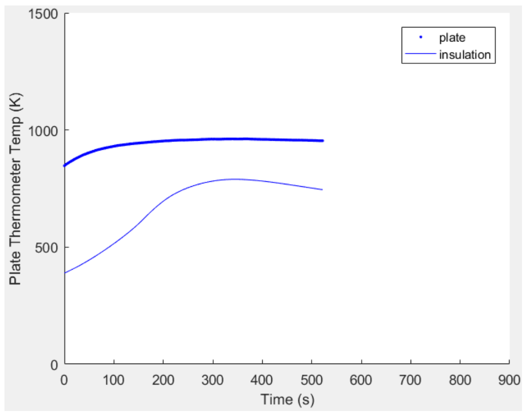
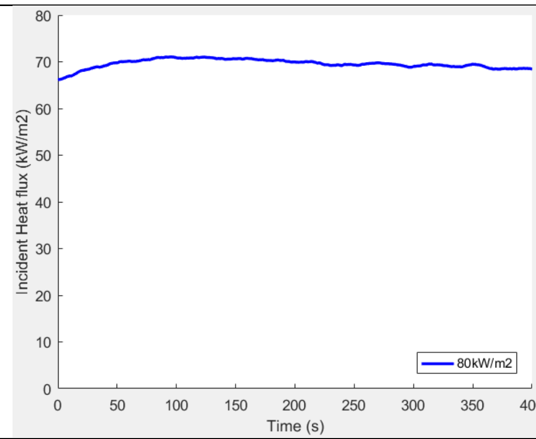
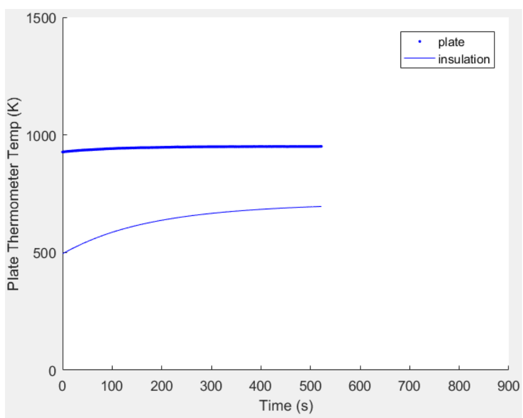
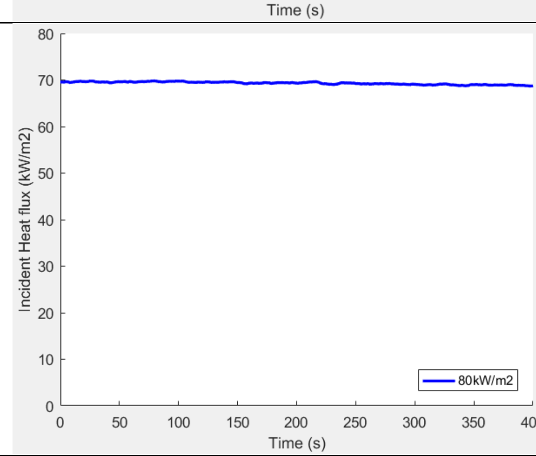
$$\dot{q}''_{incident} = \frac{\dot{q}''_{net} + \dot{q}''_{conv} + \dot{q}''_{rad} + \dot{q}''_{cond}}{\varepsilon}$$

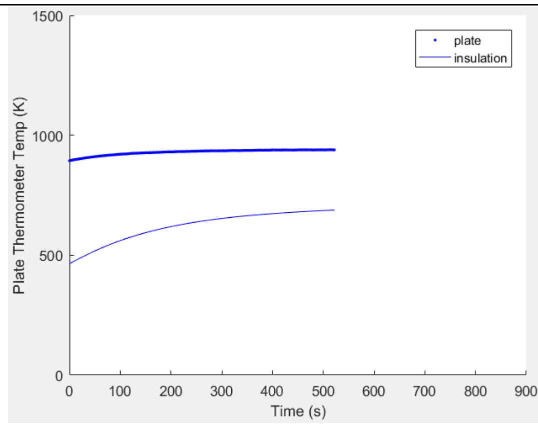
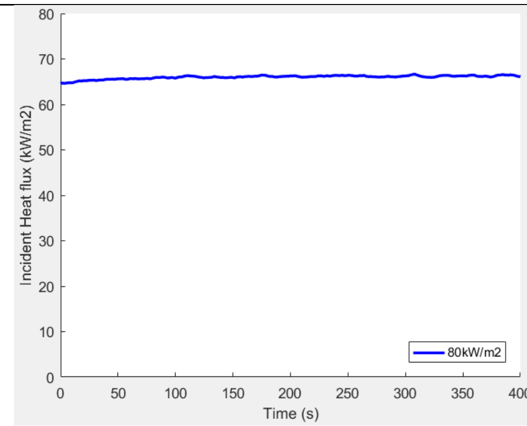
$$\dot{q}''_{net} = \rho c_p \delta \frac{dT}{dt} \qquad \dot{q}''_{conv} = h\left(T_s + T_g\right) \qquad \dot{q}''_{rad} = \varepsilon \sigma T_s^4 \qquad \dot{q}''_{cond} = \frac{(T_s - T_{insulated})}{\frac{1}{h_c} + \frac{L}{k}}$$

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.

<u>Cone and Heat Flux Calculation Results for Initial Test Plate Thermometers</u>

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

Plate Thermometer	Test	Temperature vs Time	Incident Heat Flux vs Time
1	1		
	2		

<table>
<tr><td></td><td>3</td><td>
</td><td>
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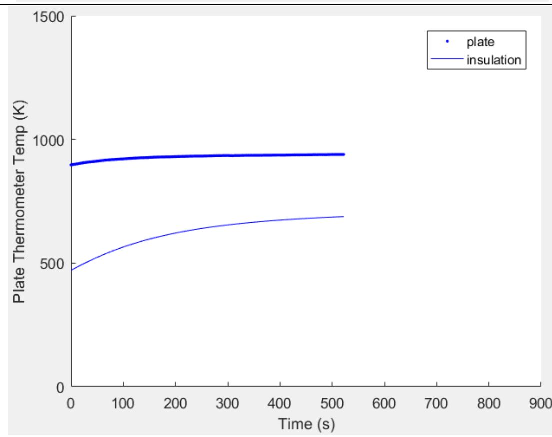
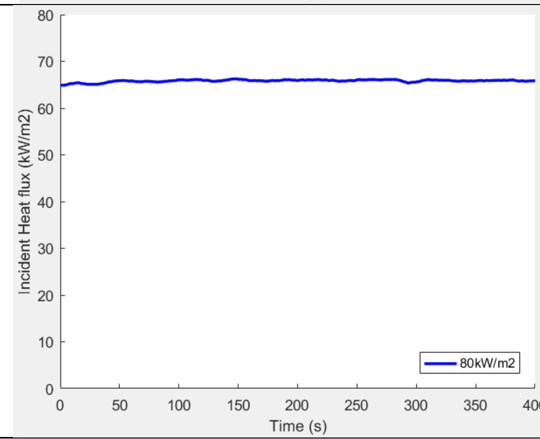
<tr><td></td><td>4</td><td>
</td><td>
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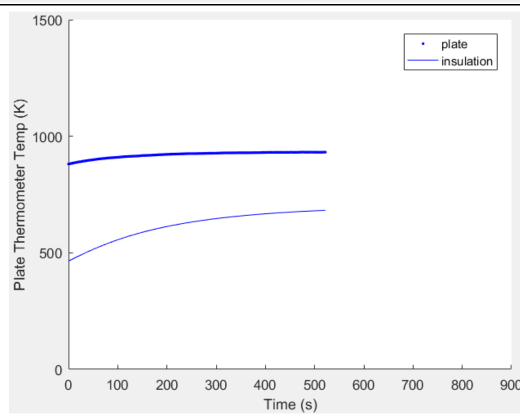
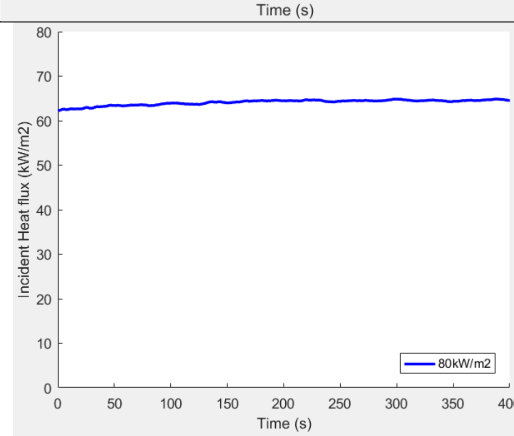
<tr><td></td><td>5</td><td>
</td><td>
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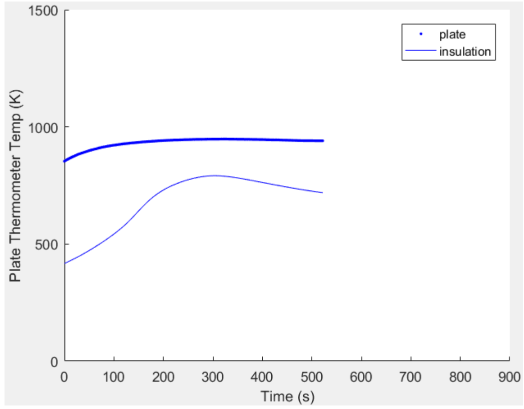
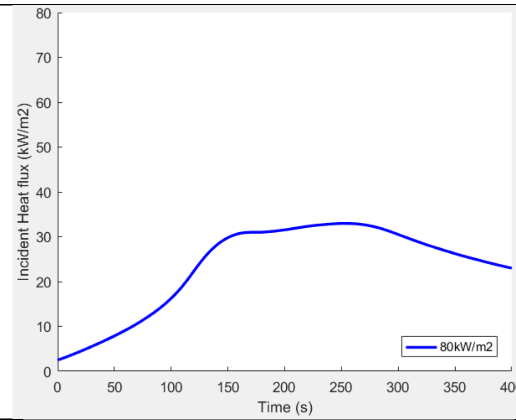
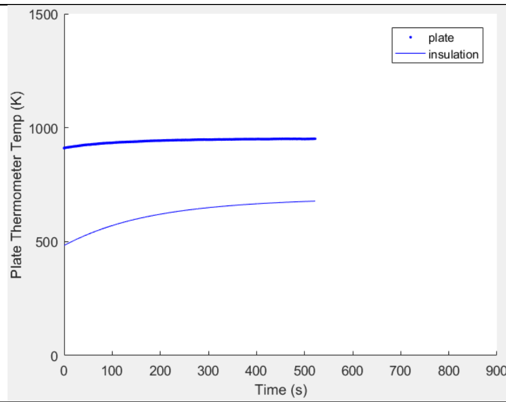
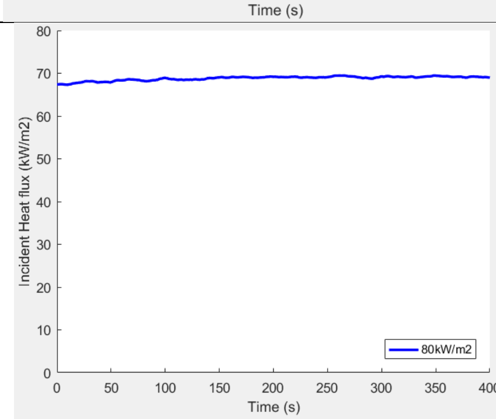
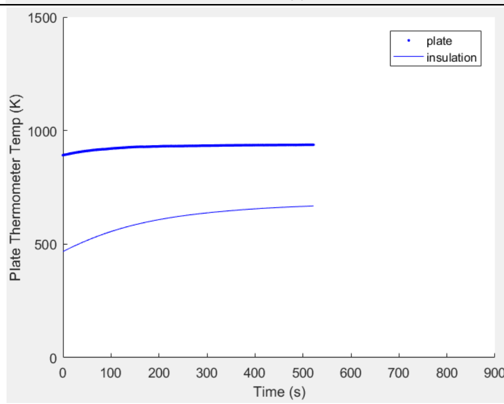
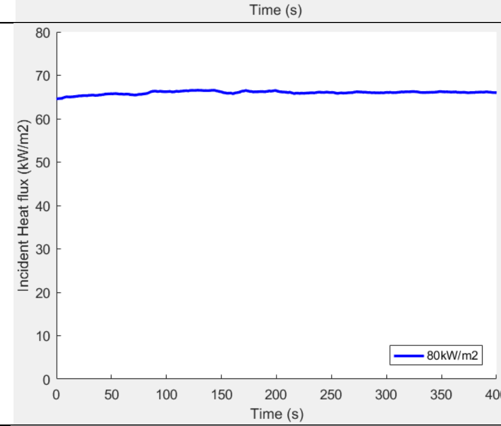
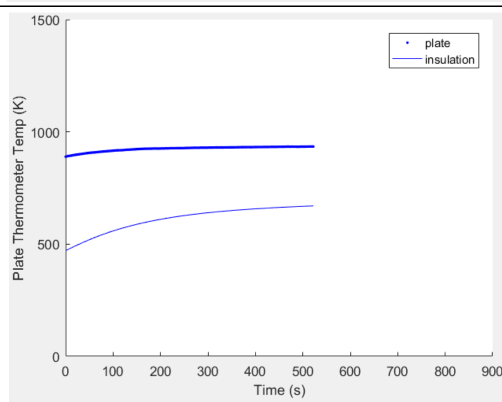
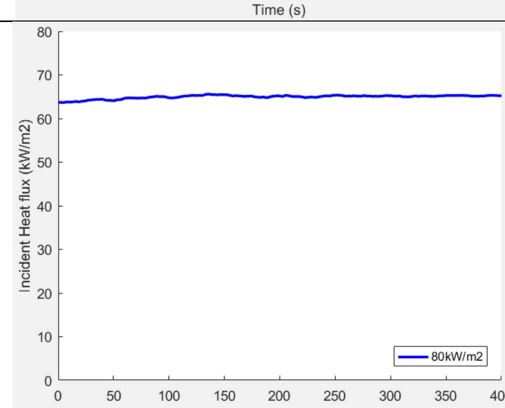
2	1	plate insulation Plate Thermometer Temp (K) Time (s)	Incident Heat flux (kW/m2) 80kW/m2 Time (s)
	2	plate insulation Plate Thermometer Temp (K) Time (s)	Incident Heat flux (kW/m2) 80kW/m2 Time (s)
	3	plate insulation Plate Thermometer Temp (K) Time (s)	Incident Heat flux (kW/m2) 80kW/m2 Time (s)
	4	plate insulation Plate Thermometer Temp (K) Time (s)	Incident Heat flux (kW/m2) 80kW/m2 Time (s)

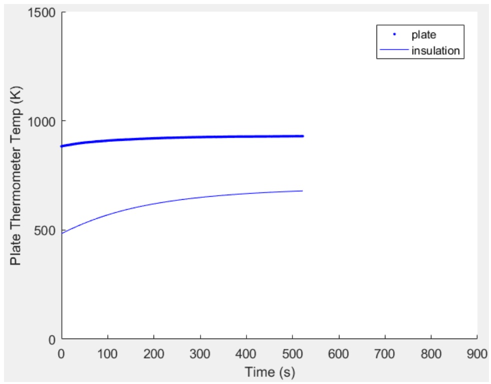
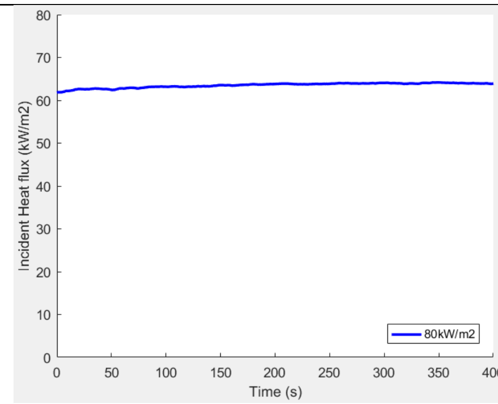
	5		

Table 19: Measured Temperature and Calculated Heat Flux of Test Plate Thermometers

Plate Thermometer	Test	Measured Temperature [°C (K)]	Calculated Heat Flux [kW/m^2]
1	1	690 (963)	70
	2	680 (953)	69
	3	670 (943)	66
	4	670 (943)	66
	5	660 (933)	63
2	1	675 (948)	67
	2	680 (953)	68
	3	670 (643)	65
	4	665 (938)	64
	5	665 (938)	63

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
clc

sigma= 5.67e-8; %[W/m2K4)]
epsilon= 0.8; %[]
h= 20; %[W/(m2 K)]
rho= 7600; %[kg/m3] density of stainless steel
c_p= 510; %[J/(kg K)] specific heat of stainless steel
delta= 0.00158; %[m]  thickness of stainless steel 1/16inch
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\Cone Results\TC25T&~1.XLS') ;
%%
time1= data(:,1);
TSC_tempp = 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_tempp(time_start(count):time_stop(count)) ; % Thin skin calorimeter temperature
temp(1:(time_stop(count)-(time_start(count)-1)),count) = tempp(time_start(count):time_stop(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(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]


k = 0.135 ; %[W/(m K)] insulation
L = 0.00635 ; %[m] length of substrate
h_c = 150 ;
q_cond_k = (T_s - T_ins)/(1/h_c + 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

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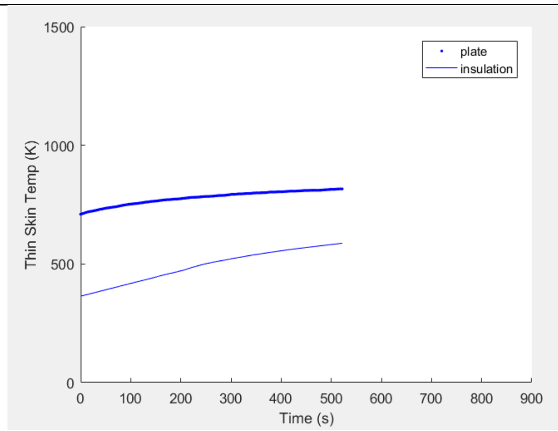
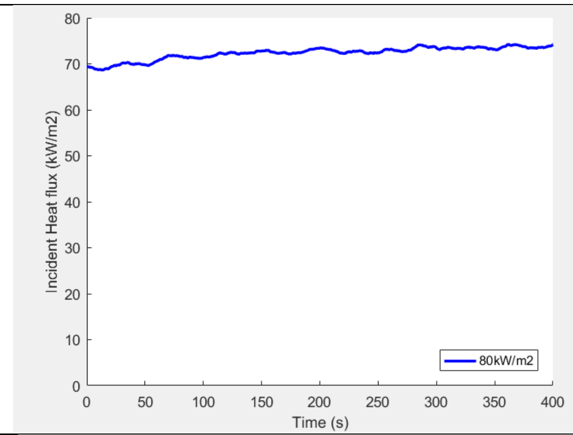
<tr><td>1</td><td>
</td><td>
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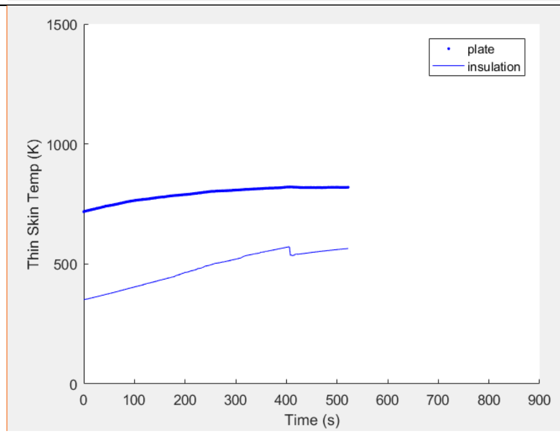
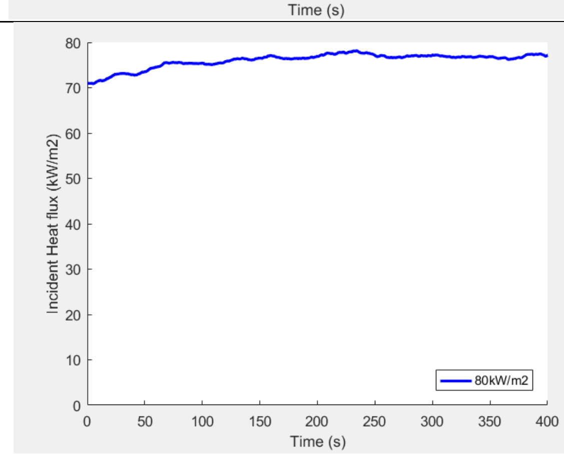
<tr><td>2</td><td>
</td><td>
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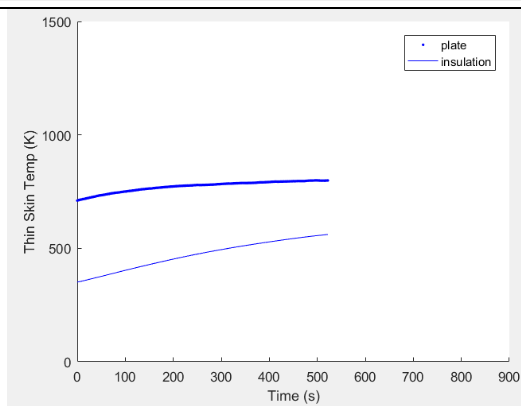
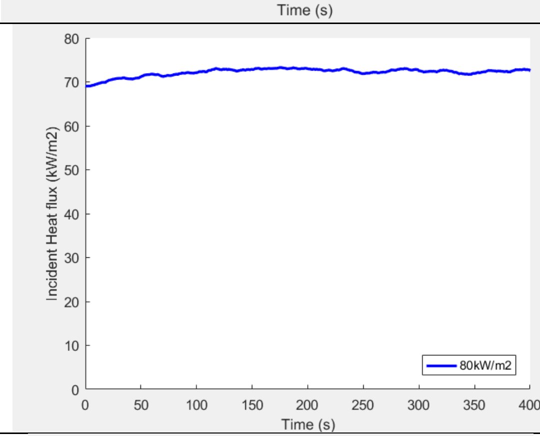
<tr><td>3</td><td>
</td><td>
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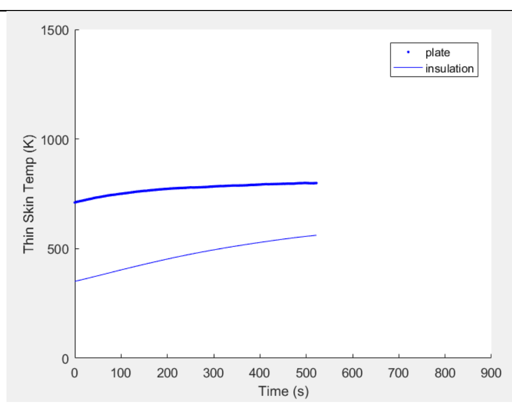
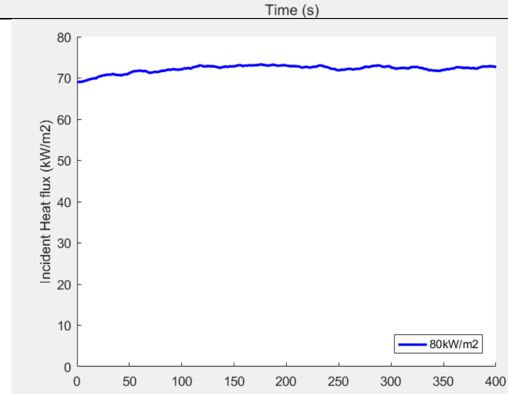
<tr><td>4</td><td>
</td><td>
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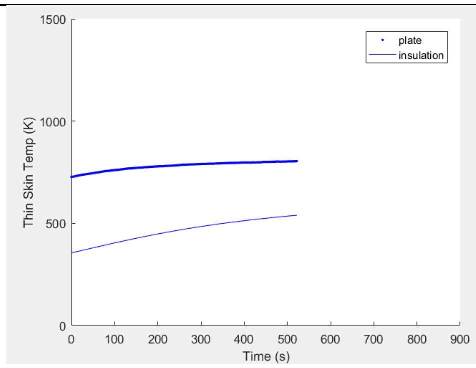
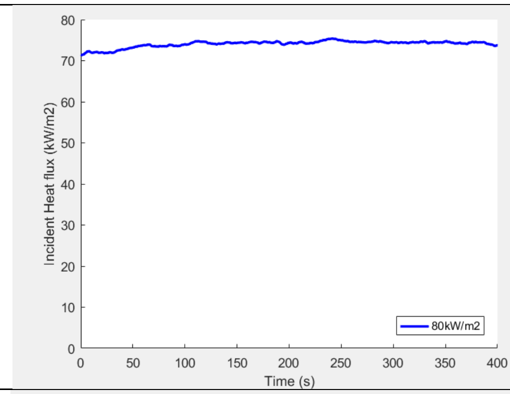
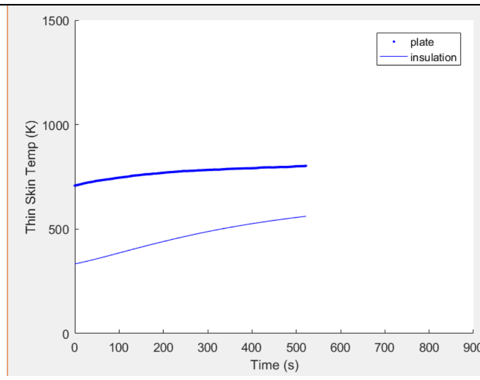
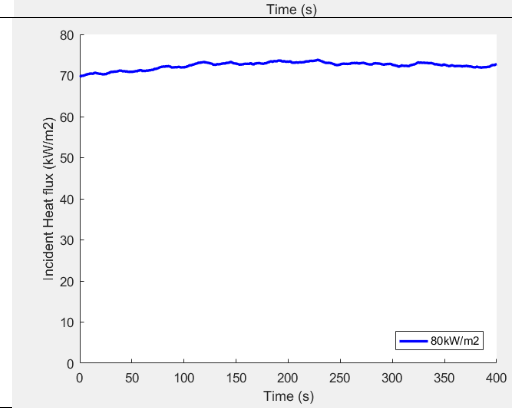
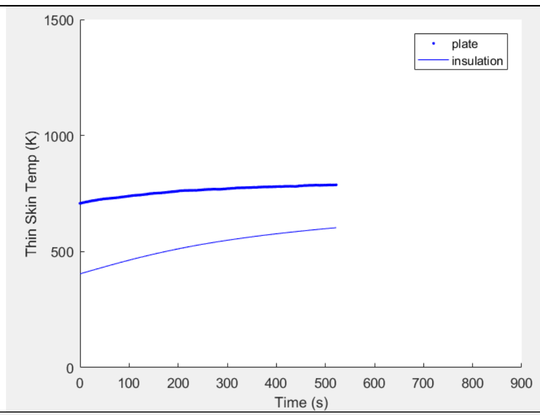
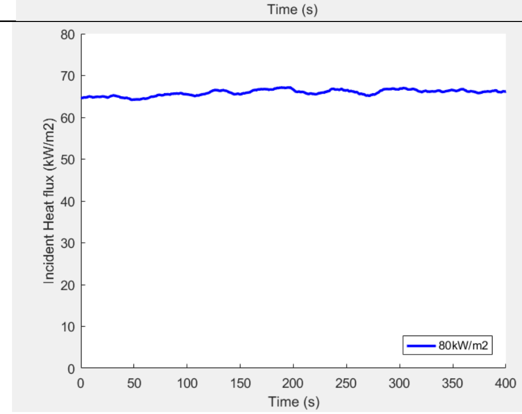
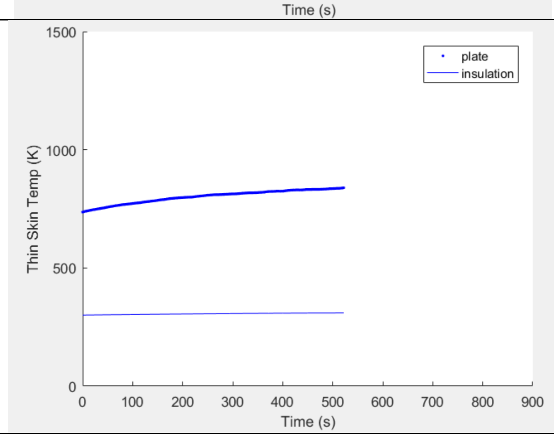
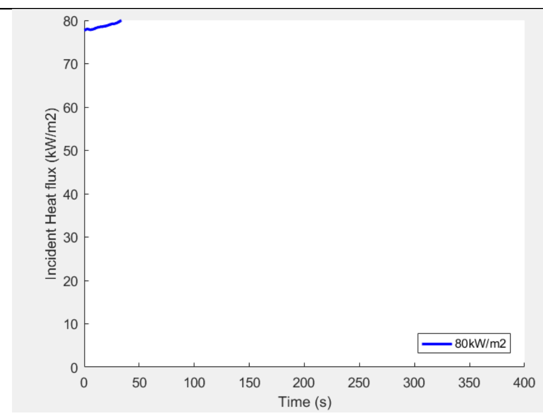
<tr><td>5</td><td></td><td></td></tr>
<tr><td>6</td><td></td><td></td></tr>
<tr><td>7</td><td></td><td></td></tr>
<tr><td>8</td><td></td><td></td></tr>
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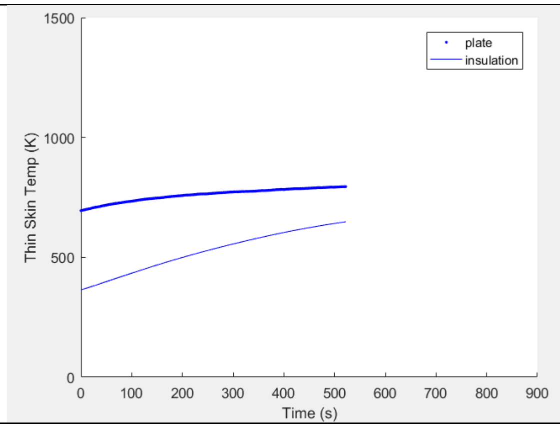
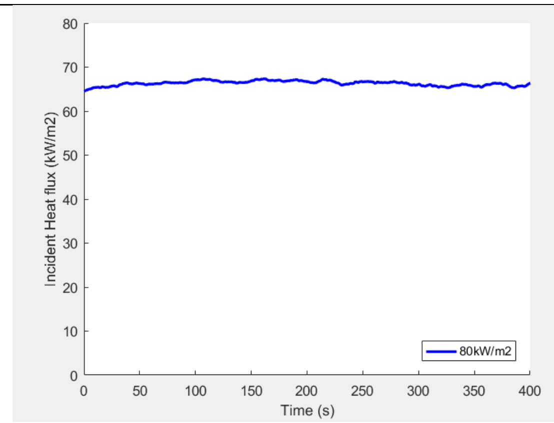
9





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.

```
clear all
close all
clc

sigma= 5.67e-8; %[W/m2K4)]
epsilon= 0.3; %[]
h= 20; %[W/(m2 K)]
rho= 8440; %[kg/m3] density of Inconel 625
c_p= 410; %[J/(kg K)] specific heat of Inconel 625
delta= 0.0007112; %[m]  thickness of Inconel 625 1/16inch
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') ;
%%
time1= data(:,1);
TSC_tempp = 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_tempp(time_start(count):time_stop(count)) ; % Thin skin calorimeter temperature
temp(1:(time_stop(count)-(time_start(count)-1)),count) = tempp(time_start(count):time_stop(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(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]


k = 0.135 ; %[W/(m K)] insulation
L = 0.00635 ; %[m] length of substrate
h_c = 150 ;
q_cond_k = (T_s - T_ins)/(1/h_c + 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
```