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LAWRENCE LIVERMORE NATIONAL LABORATORY

Cal Poly student report and presentation on the High Temperature Test Unit (HTTU) for the LLNL Ceramic HEPA Filter Program, "High Temperature HEPA Filter Test Unit Final Design Report" and "High Temperature HEPA Filter Test Unit"

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HEPA Filter High Temperature Test Unit (HTTU)

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Sponsored by:

Lawrence Livermore National Laboratory

Prepared by LLNL under Contract DE-AC52-07NA27344

Purpose and Background

- LLNL needs a way to test next generation high temperature HEPA filter prototypes

- Currently no test apparatus designed to test HEPA filters at over 540°F (several are under development)

- Apparatus to simulate fire conditions in a building

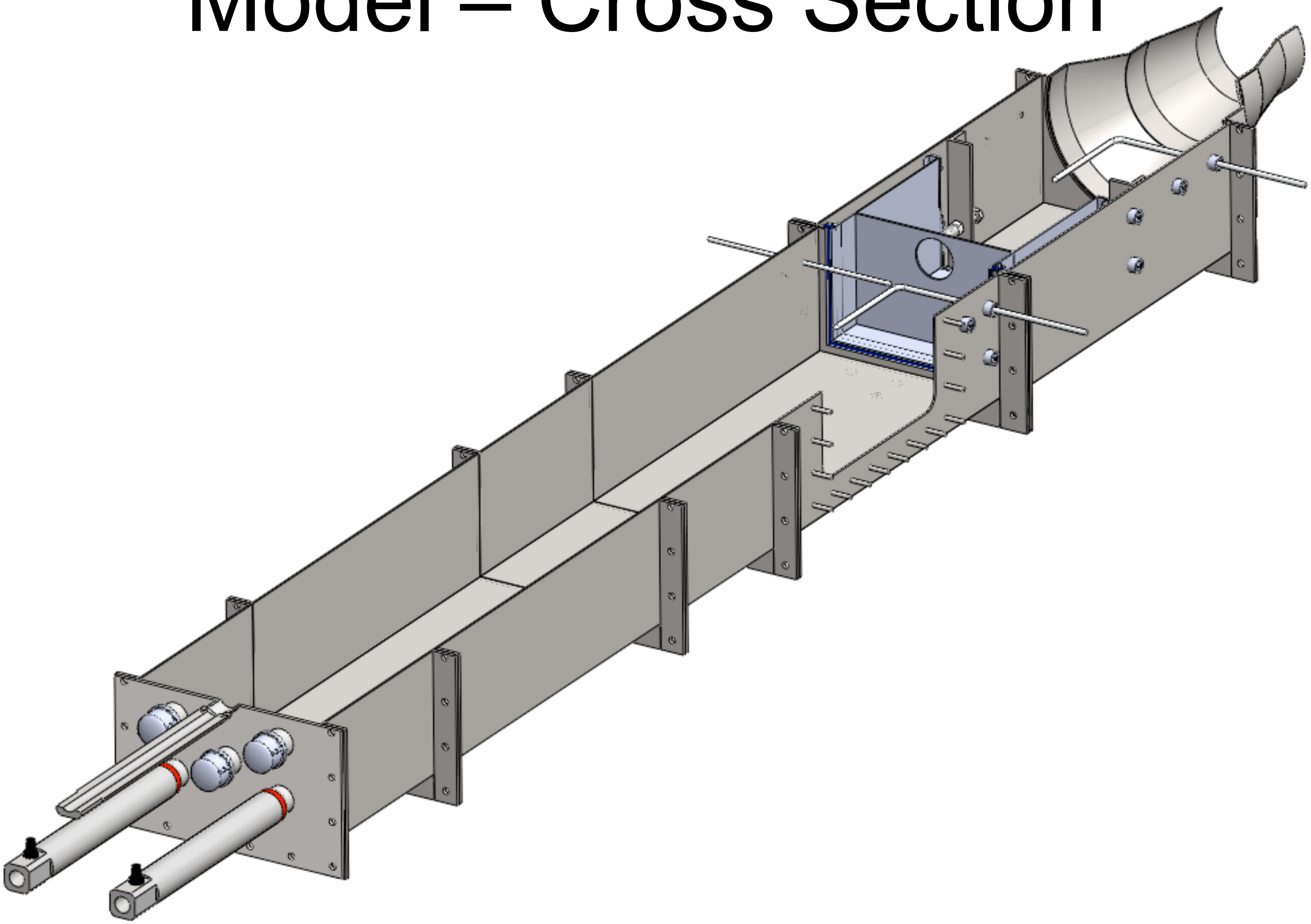
Project Objectives

- Achieve at least 1000°F temperature
- Variable pressure drop across the filter from 1-6” H_20
- Inlet flow rate variable between 5 and 250 SCFM
- Measure temperature, airflow, and pressure
- Able to accommodate future improvements
- Complete requirements with $15,600 budget

HTTU Overview

HTTU Overview

Model – Cross Section



Previous Design Considerations

- Once Through Electrical System 1800°F
  - Required 180 kW of power
- Recirculating gas system at 1800°F
  - Blower is cost and temperature prohibitive
- Once through gas system at 1000°F
  - Back pressure too great for traditional burners
- Once through electrical system with heat exchanger
  - Temperature rated heat exchangers too costly

Gas or Electric Heating?

	Pros	Cons
Gas	•High Heat output can achieve required temp •Cheaper equipment	•Cannot operate with the high backpressure required •Fuel source safety •Cost of facility modifications
Electric	•Simple to install and operate •Can achieve flow rate at temp and backpressure •Greater temperature resolution	•Does not get as hot •Requires modifications to test facility

Compressed Air Supply

- Compressor: 330 SCFM at 120 PSIG

- Tanks alone will provide 250 SCFM for 45 minutes

Flow Rate Control and Measurement

- A Ball valve in series with a needle valve control flowrate
- Flowrate is monitored using a rotameter

Heat Source

- 3 (expandable to 8) Tutco Heat Torch 200 at 12.5 kW each
- Maximum Theoretical Temperature of 1250°F at 240* ACFM
- 1000°F at 270* ACFM
- 1200°F @ 250 SCFM With 8 heat torches

*20% Factor of Safety on Flow Rate

Duct Material

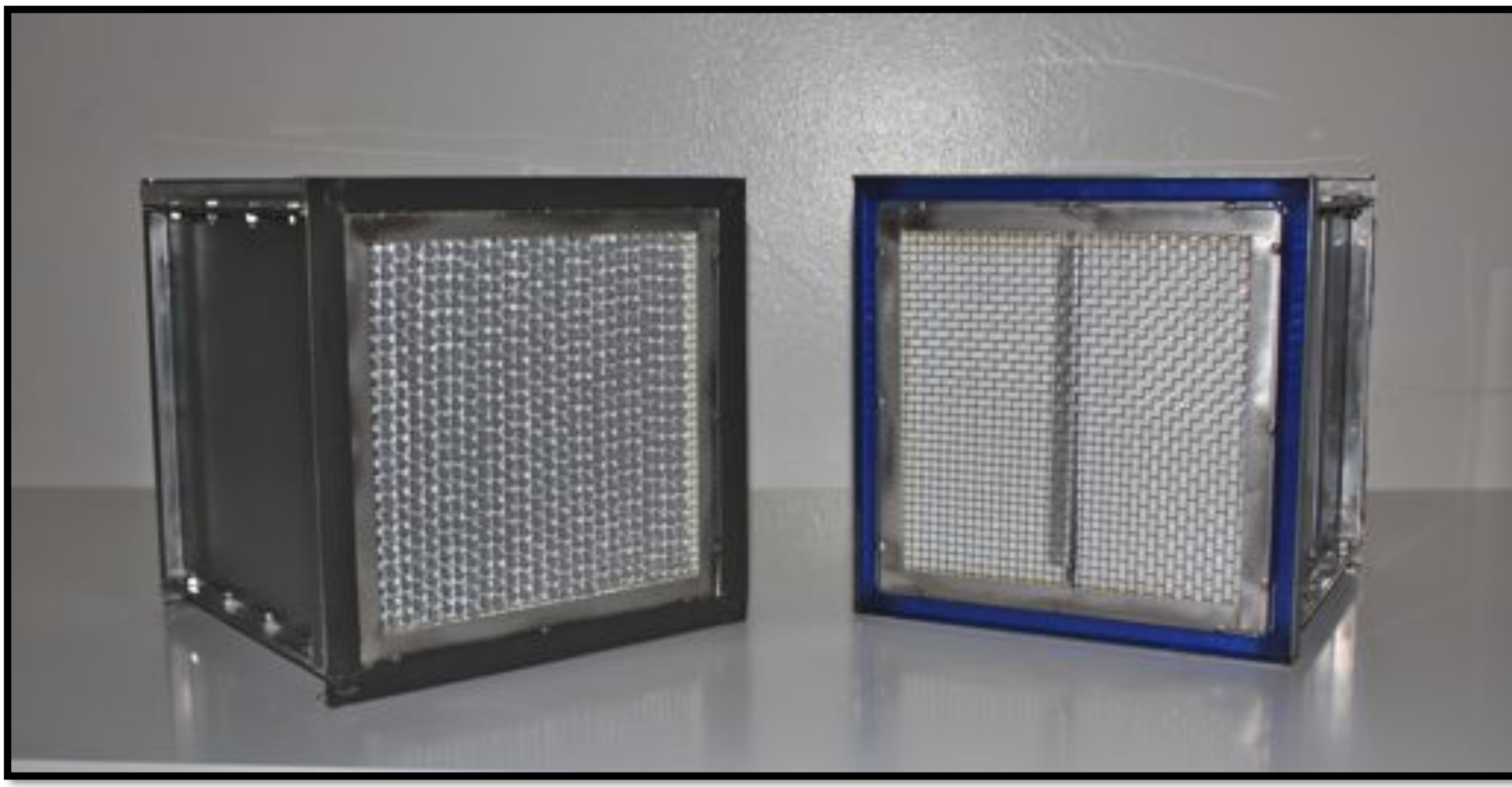
- 12 Gauge Stainless Steel Ducting
- 3/8” Bolts 2 ¾” on center Through ¼” thick Flanges
- High Temperature Grafoil^tm^ Gasket between sections

Insulation

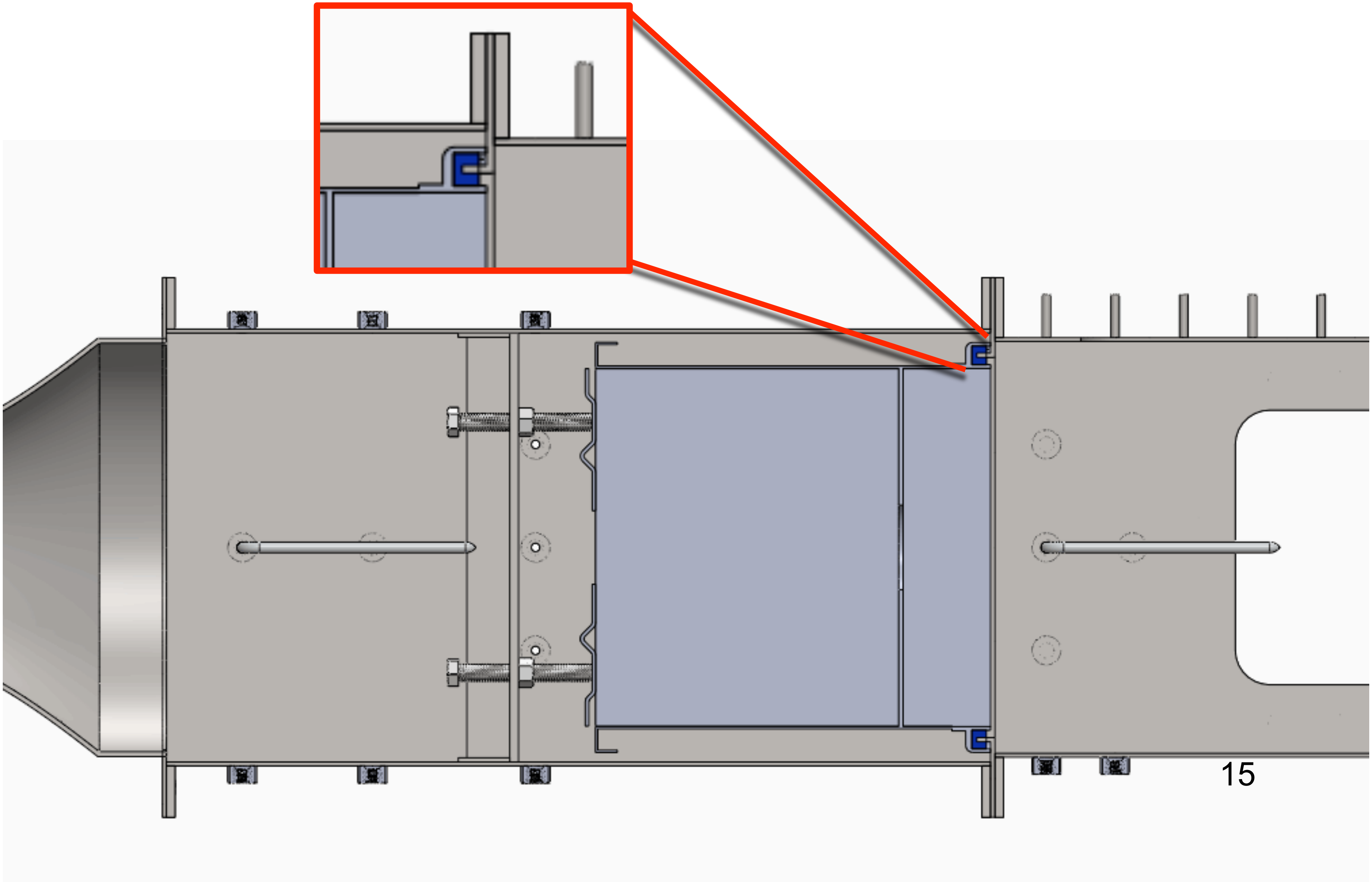
- Gemcowool Mineral Wool Insulation
- Rated to 2100°F

Filters

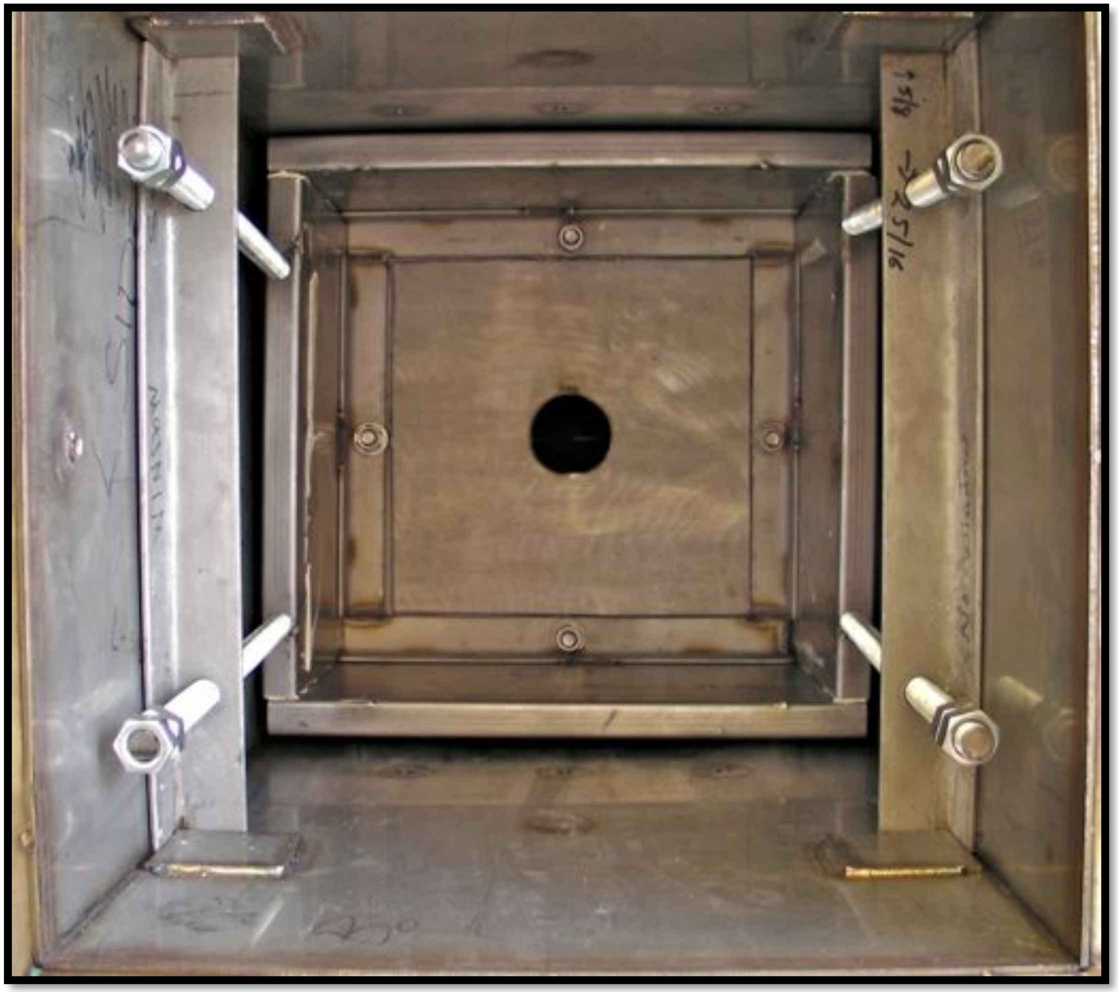
- HTTU interfaces with both Gasket Seal and Gel Seal filters



Filter Interface



Orifice Plate and Filter Retaining System

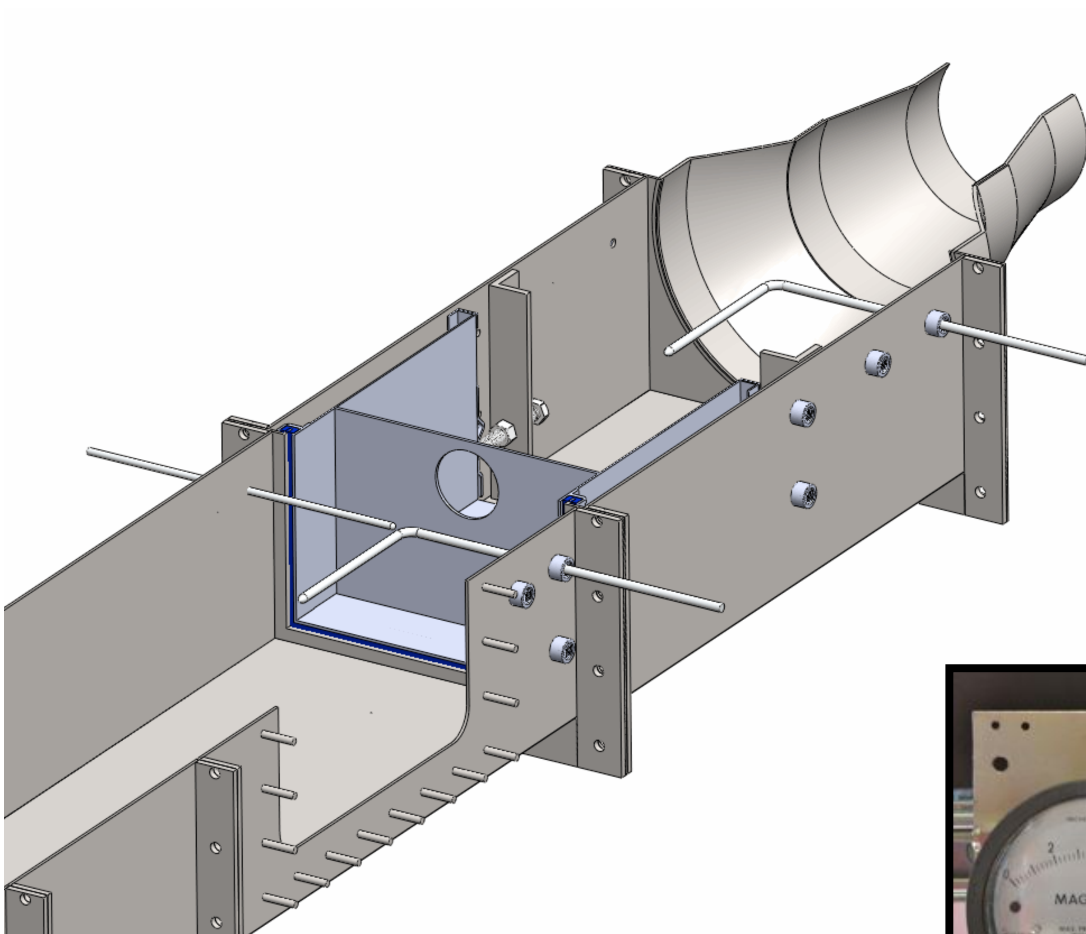


- Use of orifice plates to simulate clogged filters
- Filter retainer design puts no holes in ducting

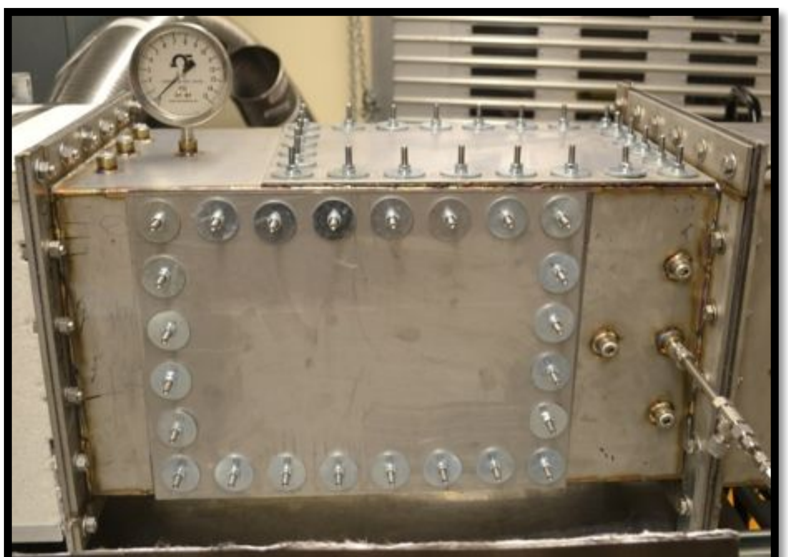
Exhaust

- 6 inch stainless steel flexible tubing
- 1900 CFM roof mounted exhaust fan

Instrumentation



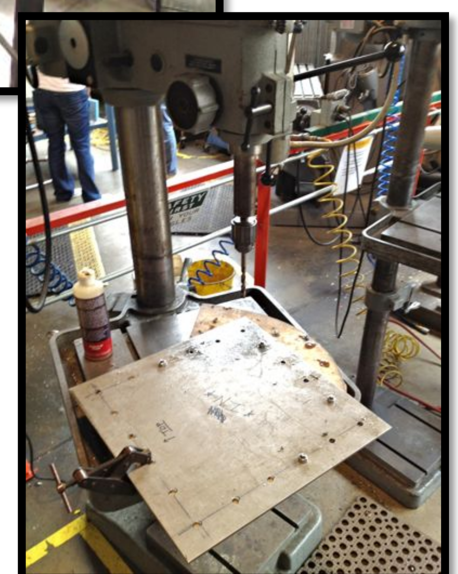
Key Design Features



- Modular design
  - Expandable
    - Additional heaters & sensors via extra receptacles
  - Easily modified
    - Specialized duct sections
  - Accommodates future systems
    - Blanks for viewing windows

Manufacturing

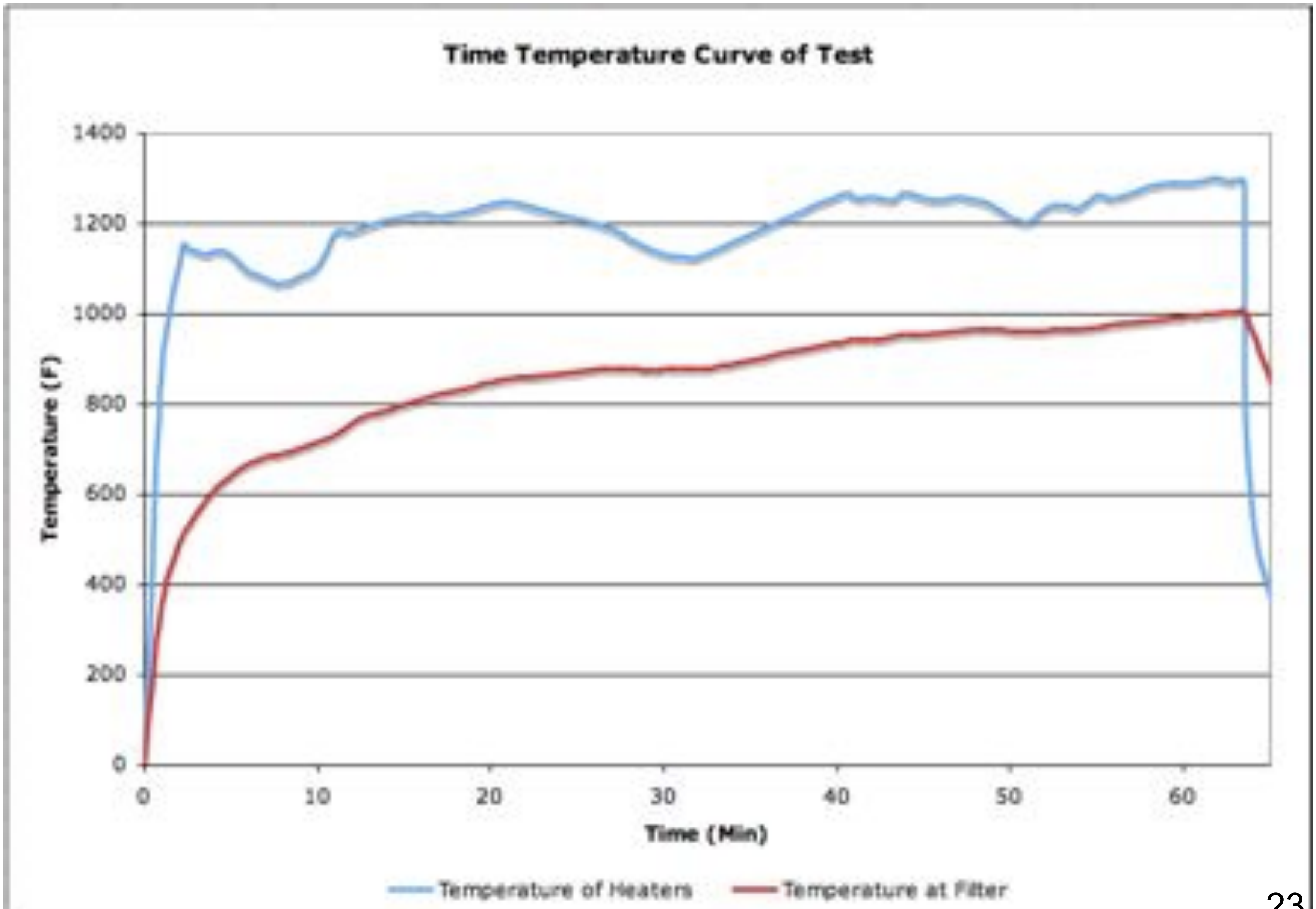
- Over 90’ of welds
- Over 380 Holes drilled
- Total Length of holes drilled through stainless steel: 6’-3”



Testing

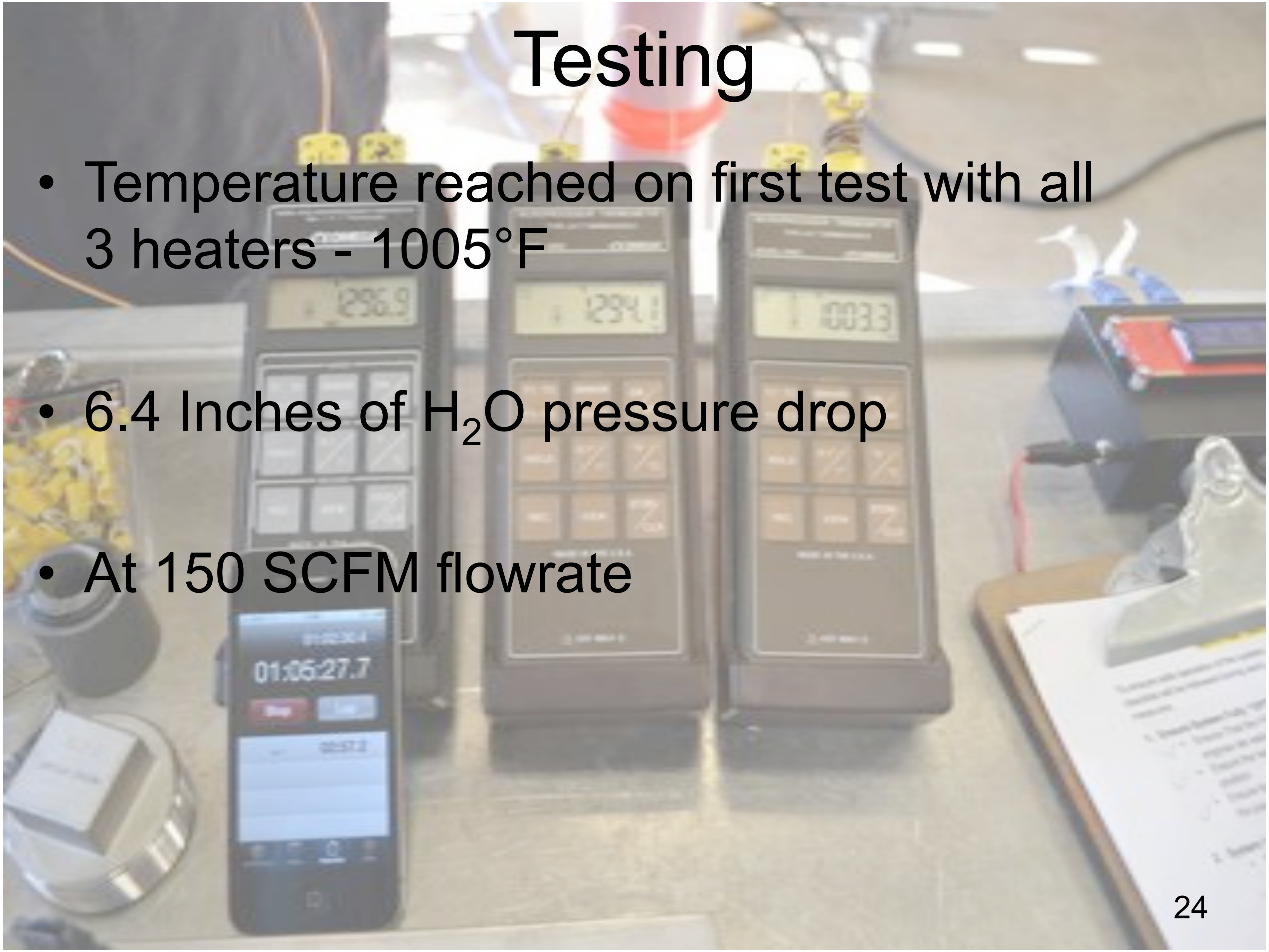
Testing

Testing



Time Temperature Curve of Test
Temperature (F)
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
Time (Min)
Temperature of Heaters
Temperature at Filter

Testing

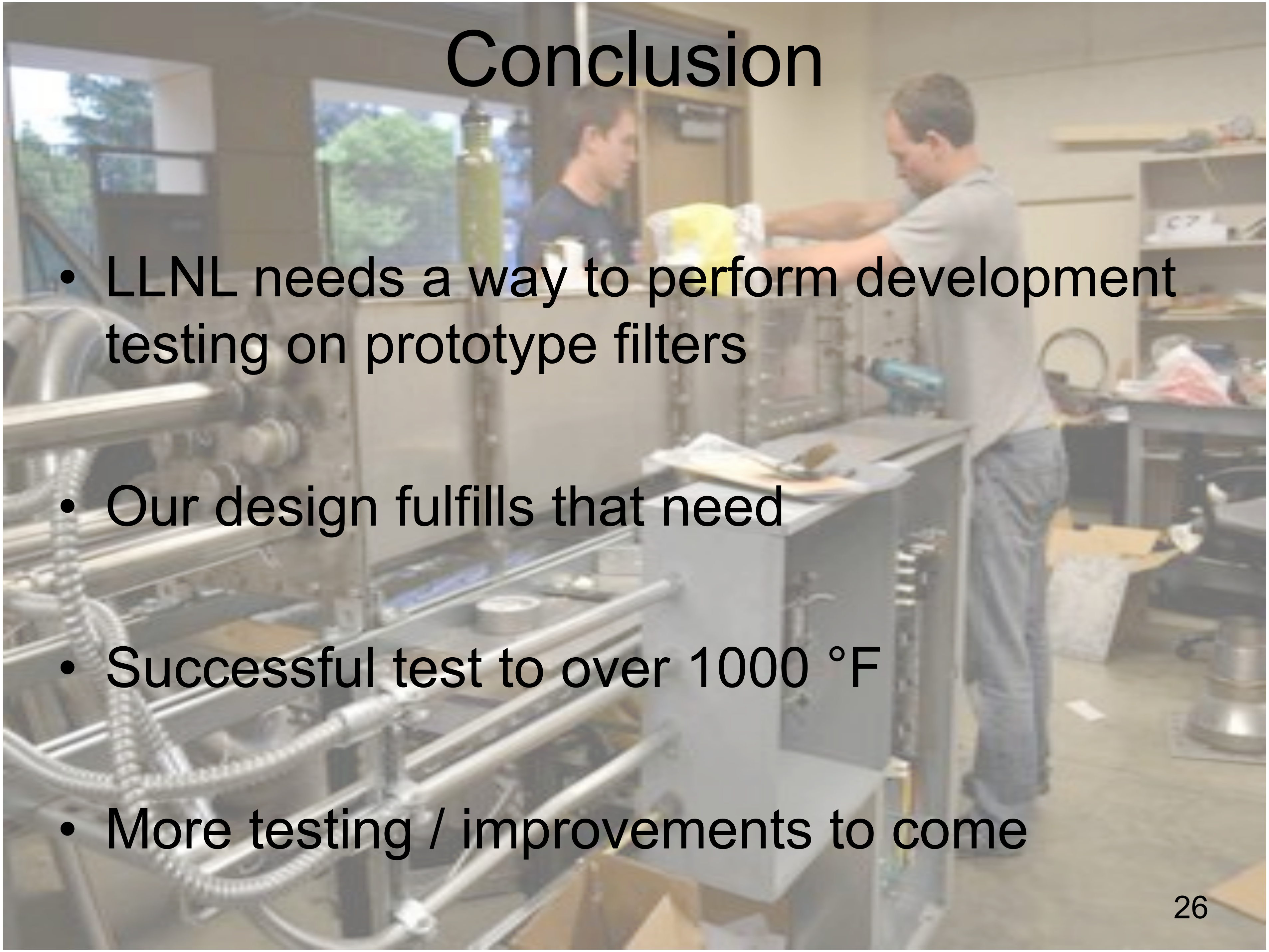


- Temperature reached on first test with all 3 heaters - 1005°F
- 6.4 Inches of H_2O pressure drop
- At 150 SCFM flowrate

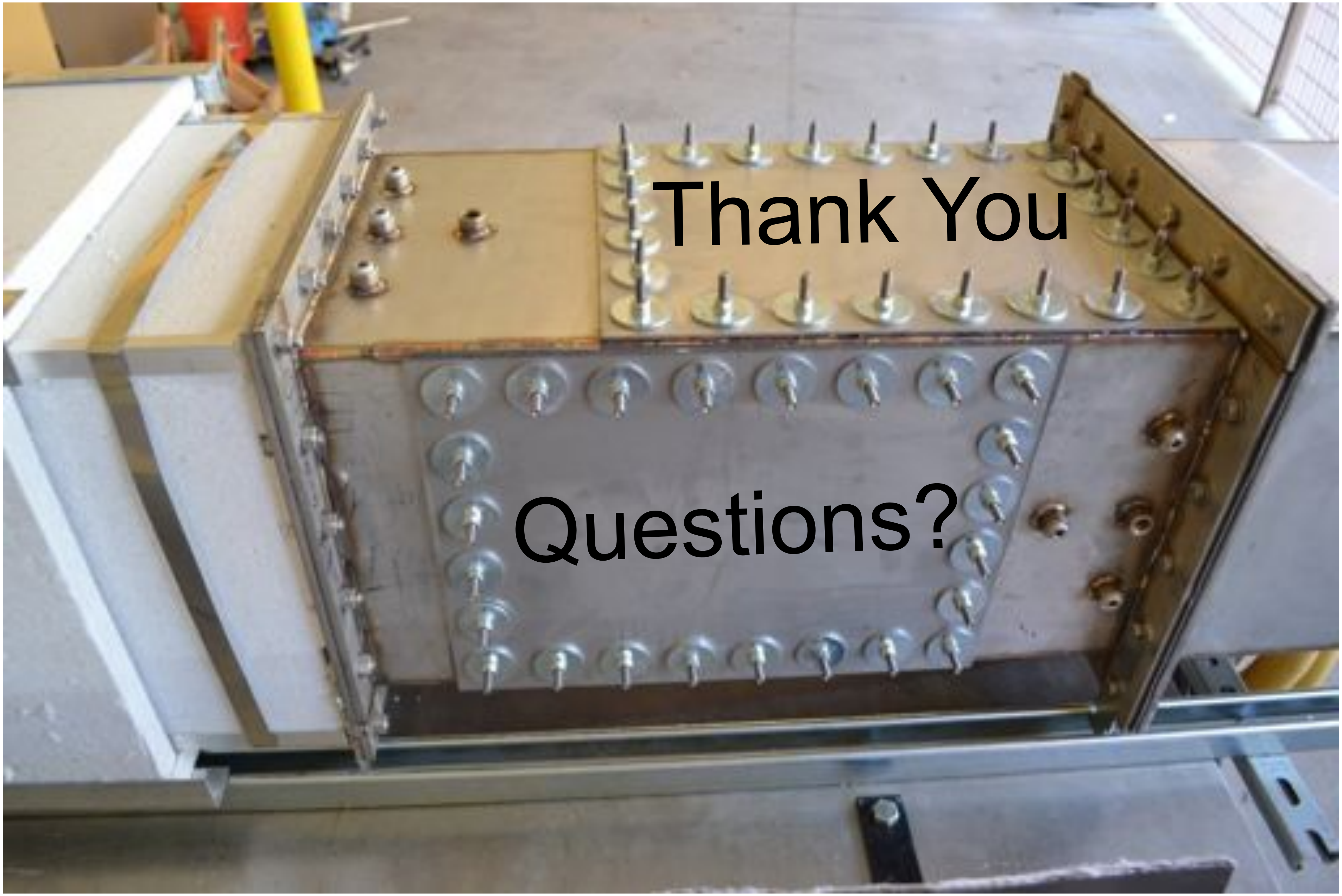
Future Expansion on Project

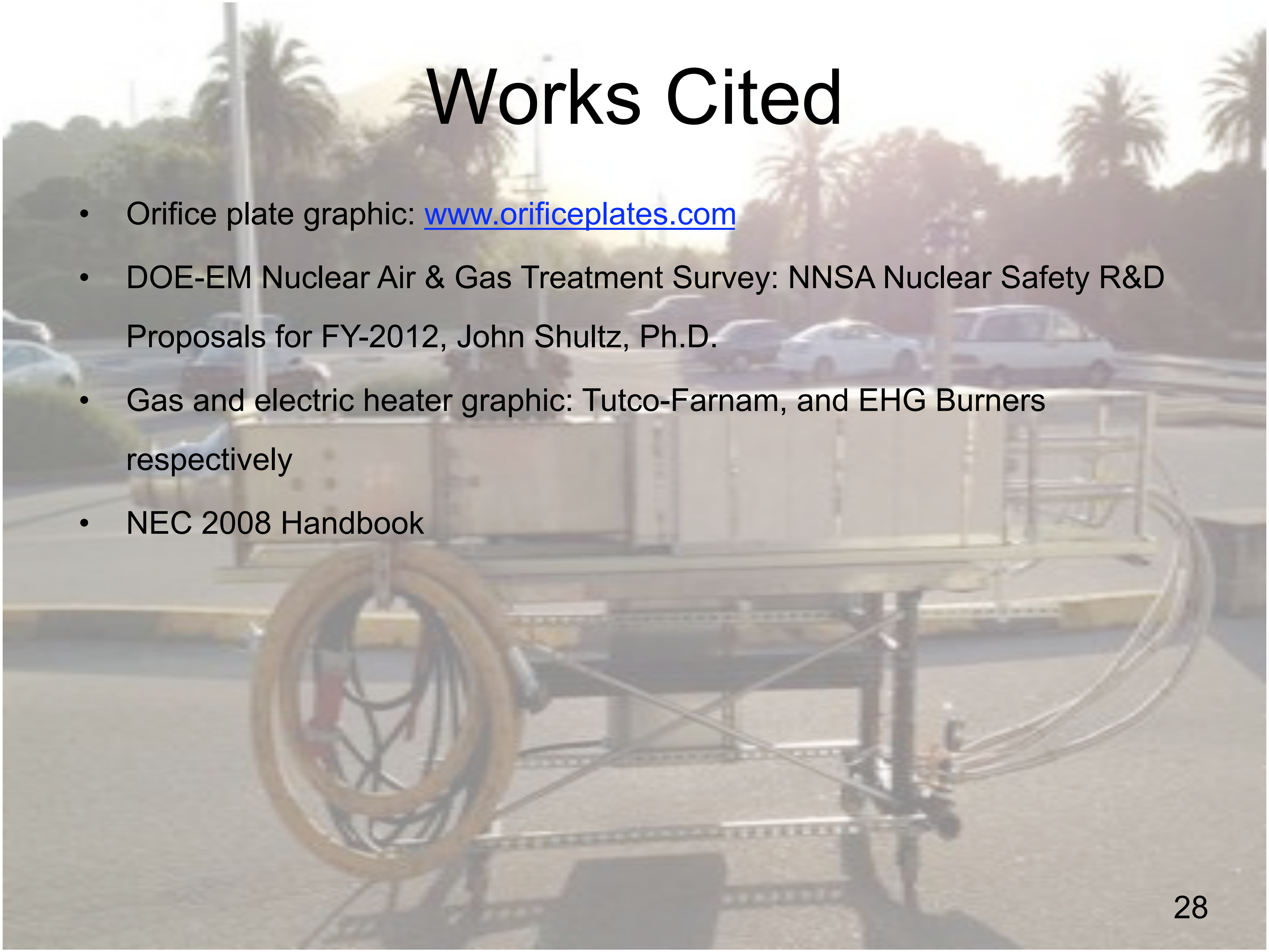
- Completely automated test procedure
  - In progress with 2nd senior project team
- Higher flow rates from additional heaters
- Direct flame impingement
- Soot loading test
- Additional data acquisition
  - Strain on filter frame
  - Leak Detection
  - CCTV recording of test through viewing windows

Conclusion



- LLNL needs a way to perform development testing on prototype filters
- Our design fulfills that need
- Successful test to over 1000 °F
- More testing / improvements to come


Thank You
Questions?



Works Cited

- Orifice plate graphic: www.orificeplates.com
- DOE-EM Nuclear Air & Gas Treatment Survey: NNSA Nuclear Safety R&D Proposals for FY-2012, John Shultz, Ph.D.
- Gas and electric heater graphic: Tutco-Farnam, and EHG Burners respectively
- NEC 2008 Handbook

High Temperature HEPA Filter Test Unit
Final Design Report

Prepared For: Erik Brown
(Lawrence Livermore National Laboratory)

Prepared By:
Garrett Brown
Garrett Dong
Joe Marino

March 1, 2012

The Critical Design Report created by Team Icarus is

Approved and Accepted By

Garrett Brown: ___________________(date)_____

Garrett Dong: ___________________(date)_____

Joe Marino: ___________________(date)_____

Erik Brown (LLNL): __________________(date)_____

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Abstract

Being able to filter exhaust air is critical for many industrial applications to operate in a capacity that is friendly with the environment; HEPA filters frequently fulfill this need. In the event of fire however, the current HEPA filters fail through various modes and release filtered particulate, and potentially hazardous gases from the fire to the atmosphere. Lawrence Livermore National Laboratory (LLNL) is developing a new type of filter, designed to withstand significantly greater heat than filters currently available.

A requirement when developing new technology is the ability to test at expected conditions. Additionally, this testing will determine if the new design is superior the current standard. LLNL is funding this group of Cal Poly students to develop a high temperature test unit (HTTU) in which to test these new prototype filters, helping facilitate the development of this new technology.

Simulating a building fire is not trivial, and several ideal capabilities have been iterated to a level that is both achievable by students at Cal Poly with the resources and funding available, and meets or exceeds the testing parameters specified by LLNL. This project will occur in multiple stages, this first stage involves building a device capable of producing air at a variable temperature from ambient to a minimum 1000℉, flowing at 250 ACFM and producing a 6 inch of water column pressure drop across the filter.

The design chosen meets the requirements set by LLNL and is capable of a maximum temperature of 1300℉. Electrical resistance heaters connected to a compressed air supply are used to achieve these results.

Chapter 1 Introduction

This project has been contracted through LLNL, a Department of Energy (DOE) facility. Part of the LLNL mission is energy and the environment security, defined as "… advancing science to better understand climate change and its impacts and develop technologies supportive of a carbon-free energy future." Part of said scientific and environmental advancement is the development and testing of next-generation temperature resistant HEPA Filters. These filters will be used in nuclear facilities and other buildings with high environmental risk in the event of fire. The apparatus to be constructed by Team Icarus continues this mission for LLNL.

This Final Design Report is intended to convey the details of the design that will be built, as well as discuss other designs that were considered and the rationale behind design decisions.

Objectives

Team Icarus utilized a QFD Table (see Table 5 in the Appendix) to aid in defining the project requirements. The QFD Table provides a visual way to quantify and relate customer requirements to engineering requirements. The testing apparatus built for this project should be able to achieve the following requirements in a safe manner, and by so doing constitute a fully successful project. The following is a list of these specifications and requirements:

Specifications

- The system operating at maximum power is to achieve a temperature of at least 1000 °F at the HEPA filter face
- The inlet flow rate variable between 5 and 250 SCFM
- Variable pressure across the filter from 1-6 inches water column
- The testing apparatus is to have an airtight fixture to accommodate 1 ft^3 HEPA Filter with either a gasket or gel seal
- The heater is to use no more than 50kW of power, calculated in Appendix C including an additional 30% factor of safety
- Measure the temperature and air flow rate of the system at the inlet of the filter
- Measure the change in pressure across the filter
- Device is to have user protection to prevent contact with extremely hot surfaces
- System is to be able to connect to building exhaust system

Standard Cubic Feet per Minute (SCFM) is a measure of the mass flow of air at ambient conditions, i.e. 60 °F, 1 atm. Actual Cubic Feet per Minutes (ACFM) is a measure of the volumetric flow rate of air that takes into account the differences in temperature and pressure. For the purpose of this project, pressure and humidity are negligible relative to the effects of temperature. Therefore, the conversions between ACFM and SCFM only take into account the change in temperature as shown in Figure 38. The plot shows how much less power is required to flow air when at a higher temperature (ACFM) than when under ambient conditions (SCFM). There is debate in the industry about which standard to use (SCFM or ACFM) for the testing of HEPA filters, with filter manufacturers backing ACFM and safety and testing personnel requesting SCFM be used. Because of the limited resources, and the fact that a standard has yet to be picked, the design will be based on meeting the ACFM requirement, with design features that enable the HTTU to be upgraded to test at 250 SCFM in the future.

Additional Requirements

- The apparatus must be NEC and UL508A compliant
- If the device exceeds 90dB of noise, ear protection is required per OSHA standards
- The project is budgeted at $15,500
- Must be portable for transport from the building facility to testing facility. Height and width are constrained to 10 feet each
- Incorporate safety systems to prevent damage to from improper operation
- At a minimum a manual control system is needed to operate the apparatus
- The apparatus is to be able to accommodate future improvements/modifications
    - Cameras
    - Fully automated controls system
    - Direct flame impingement
    - Viewing windows
    - Soot loading test
    - Stress and strain measurements between the filter element and housing

Chapter 2 Project Background

Background

This project began over ten years ago as an initiative to employ Russian nuclear scientists to work on nuclear non-proliferation. They were paid by the United States Government to start the research and development of a new type of HEPA filter for use in nuclear, biomedical, and semiconductor facilities that would be in essence “fire proof”. Earlier this year the prototype filters were shipped to LLNL for further study.

The Russian effort was focused on developing the filter media. However, two other components of HEPA filters (filter media to frame and frame to duct sealing) need to be upgraded to create a functional fireproof filter. LLNL needs a way of testing the seal performance of the prototypes at extreme fire-like conditions. This includes the seal performance of the interface between the filter media and the frame, and the interface between the frame and the duct itself. The scope of this project is to build a High Temperature Testing Unit (HTTU) that can achieve the agreed upon initial temperature goal of at least 1000℉.

Existing Information

The existing information on the high temperature testing of HEPA Filters is very limited. There is a testing facility in the United Kingdom, which can test filters at high temperatures, as well as a facility In Mississippi that is trying to add similar capabilities. Background research was unable to locate a commercially available high temperature testing apparatus for HEPA Filters. It is currently believed there is no testing apparatus in the world that can test HEPA Filters at temperatures greater than 550℉.

ICET at Mississippi State University

The Institute for Clean Energy Technology (ICET) asked in their 2012 National Nuclear Security Administration proposal (NNSA) for over $450,000 to retrofit existing facility for high temperature testing. (They will be testing at 1000℉ and 1000 CFM.) In contrast to the testing unit—which is for testing the prototype filters and their sealing performance; ICET would be used for certification testing of the production ready filters if they get funded.

Figure 1. ICET HEPA Test Facility.

UK Dynamic System

The UK Dynamic System[1] is the only test facility known that tests HEPA filters at high temperatures, in their case 572°F. They perform certification testing on filters in the UK. Their test procedure differs from ours as they first put the filters into an oven to heat them up to temperature, and then put them into a cold flow test apparatus. Because the HTTU system will be able to test with hot flow, it better simulates the conditions a filter would encounter in the event of a fire. The system will achieve over 1200°F which puts the apparatus in the situation of being one of the first of its kind.

Applicable Codes and Standards

The following codes and standards are applicable to this project. Other codes may also apply depending on the final design.

- NFPA72 *National Electrical Code*
- UL508A *Industrial Control Equipment* — equipment electrical code.
- DOE-STD-1066-97 *DOE Fire Protection Standard*
- MIL-STD 282 *Provides Filtration Standards for Nuclear Grade Filters*
- ASME N509 *Nuclear Power Plant Air-Cleaning Units and Components*
- ASME N510 *Testing of Nuclear Air Treatment Systems*
- ASME AG-1 *Code on Nuclear Air and Gas Treatment*

Facilities Research

Another component in the background research was to determine the capabilities of the facilities uses for testing. This included ascertaining the Cal Poly Engine Lab's electrical, compressed air, and high temperature gas evacuation capacity. While working closely with Cal Poly Facilities and their electrical and gas specialists, the following breakdown of facility capabilities and potential modifications required/pending were determined:

- The engines lab has a 480v 3-phase 100A circuit, with only a 20A exhaust fan currently drawing from it. A quote was acquired from the facility electrician to install a new 60A plug and a conduit down to a pin and sleeve disconnect on the wall, as well as a 40-foot power cable that would interface with the test unit. The new 60A plug for use on the project gives us a theoretical max power of almost 50kw. This was in the target budget range and permission was received to purchase the facility modifications.
- The air compressor system to be utilized for the design was designed for use as an air supply for a small-scale wind tunnel, it has two massive storage tanks- which have enough capacity to run at 250 SCFM for 45 min, and the compressor itself is capable of 330 CFM at 120 psig continuous.
- The exhaust extraction system in the lab are designed for exhaust from large diesel engines, gas turbines and AeroSpike rocket engine project which generate temperatures in excess of 3000°F The roof mounted exhaust fan has a capacity of 1900CFM and a fresh air supply fan replaces that air at a rate of 2100 CFM.

This existing system can easily accommodate both the high temperature exhaust gasses, and the flow rate that will be generated.

- The natural gas line to the Engines Lab is very small and the system would require a new 5lb gas line to be added. This would be cost prohibitive, and for gas designs a stand-alone tank based system would be the only option.

Chapter 3 Final Design

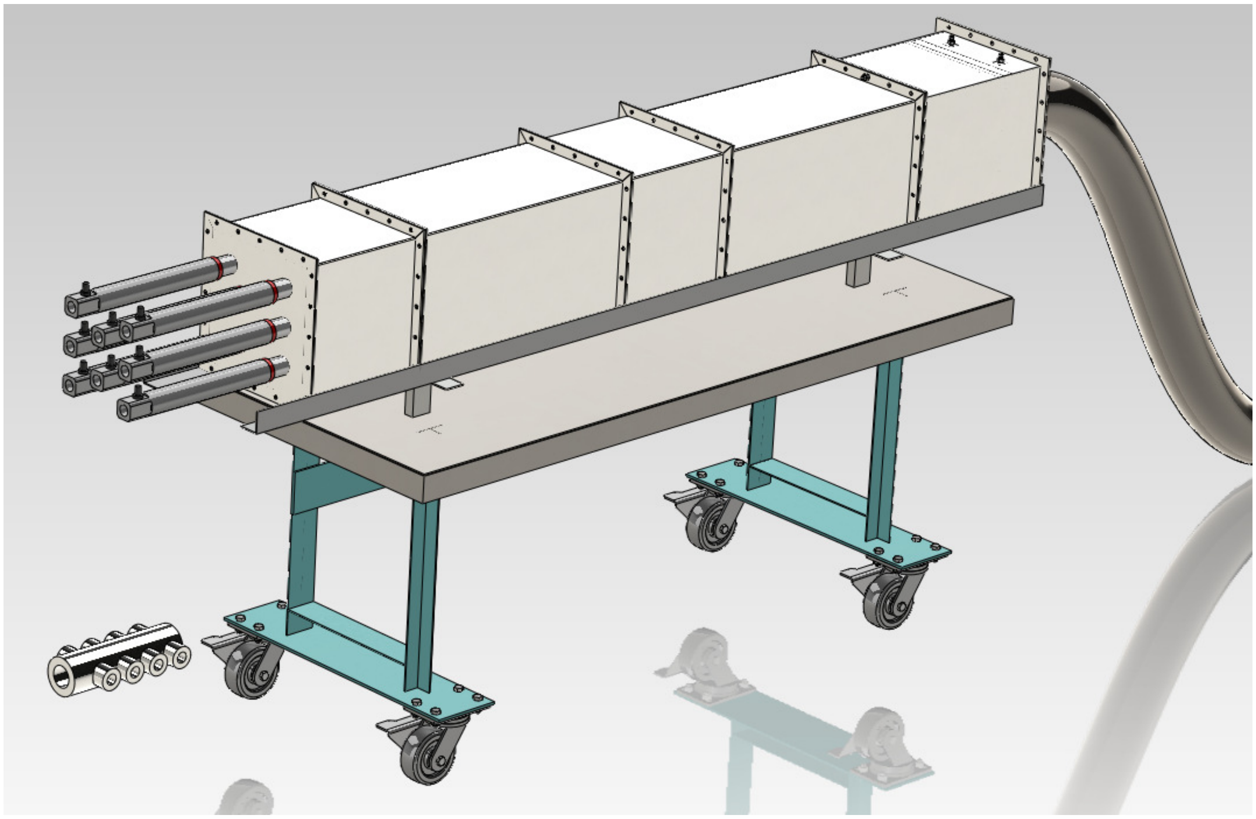


Figure 2. SolidWorks Model of HTTU Design.

The figure above is a solid model of the HTTU to be built. The model primarily shows the components that will have to be custom built. Primary components that are not shown include: compressed air source, flow meter, flow control valve, burst disk and compressed air lines. What is shown, from left to right, are: eight electric resistance heaters that are mounted to a 7 foot long stainless steel square duct mounted on a cart. At the far right is a flexible stainless steel tube leading to a powered exhaust system to vent the hot air from the test area. The ducting is designed to be modular, enabling future teams to add or remove sections as needed. The filter is located inside the last section of duct. A window, not shown, will also be included in the duct section immediately prior the filter, allowing a CCTV to monitor the filter during testing. While most of the components will be purchases from suppliers, the ductwork will be one of the few components custom built for this stage of the project. For dimensioned drawings of the apparatus see Appendix D

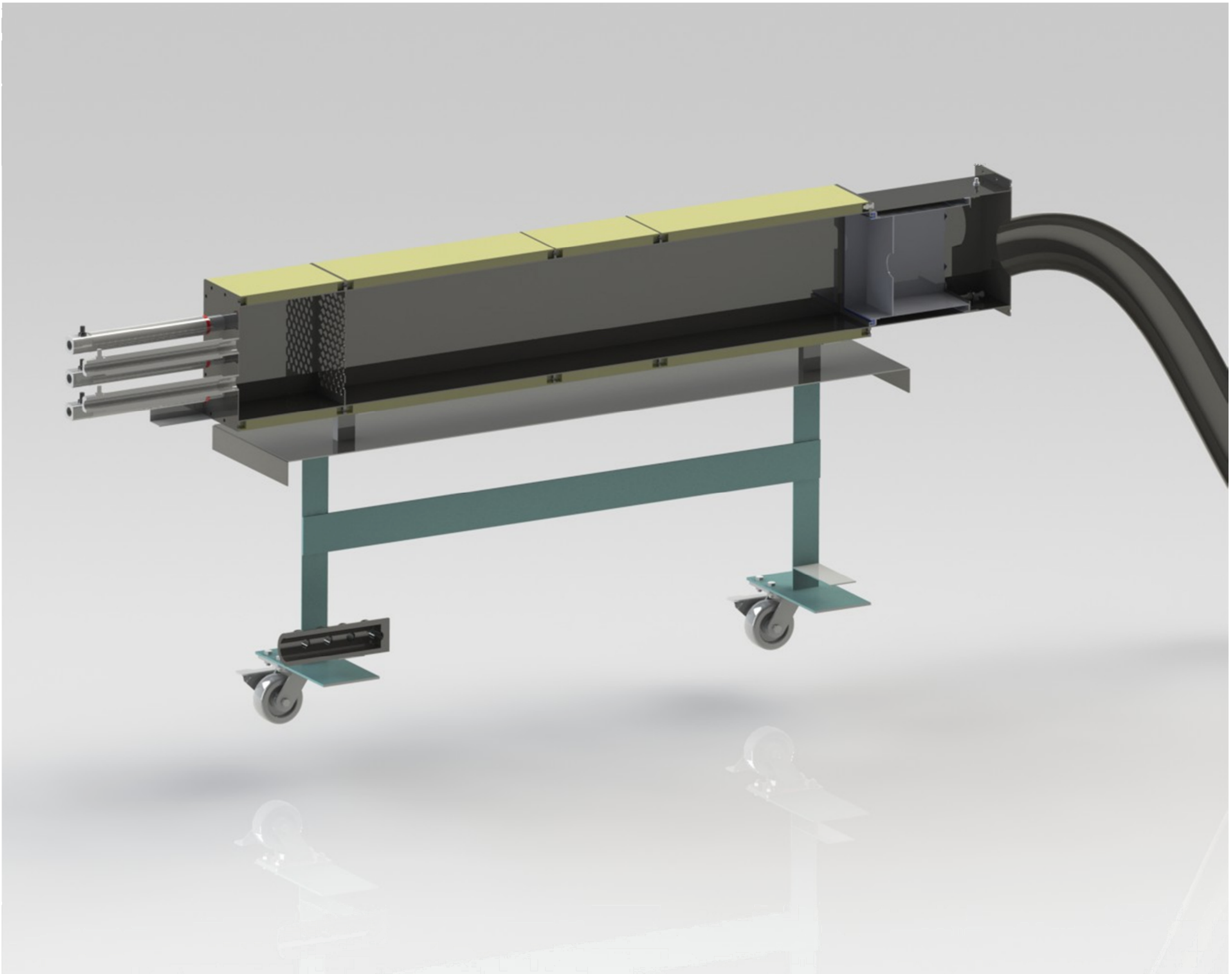


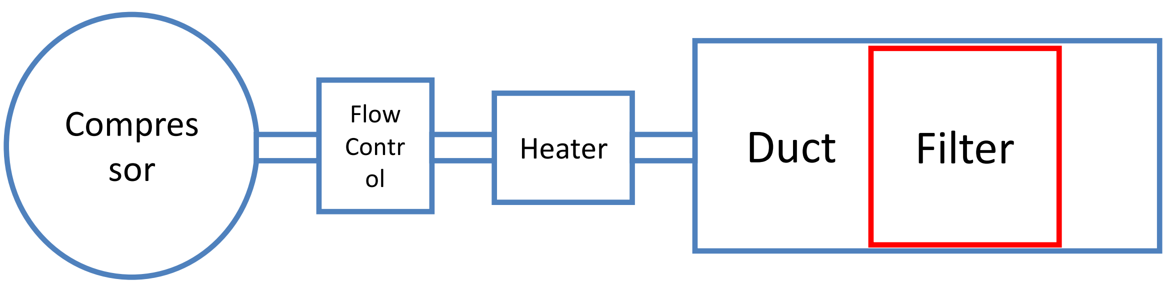
Figure 3 Cross Section of Final Design

This is a cross-section of the current design showing the perforated plates at the first duct joint. The far right section shows a filter in the apparatus with an orifice plate installed to simulate back-pressure. This illustration shows the duct with only one inch of insulation to more clearly see details in the drawing. Two inches of insulation will be used in our final design.

Components

There were many different ways to achieve the project requirements using various component combinations. This section details the process and rational behind the component choices made, and explain how they are integrated into the unit as a whole. The main components needed to create the unit fell into the following categories:

- Airflow
- Heat Source
- Controllers / Electrical
- Ducting
- Insulation
- Pressure Drop
- Burst Disk
- Exhaust



Air Flow

Our contemplation of ways to achieve the 250 SCFM of airflow included consideration of using fans or blowers to create the airflow as well as looking at using an air compressor to provide the flow. The design will utilize the on-site air compressor for airflow and the accompanying infrastructure that is preexisting in the engines lab.

Figure 4. Air Compressor at Test Facility.

Figure 5. V Seated Ball Valve and Orifice Plate.

Flow Rate Measurement and Control

The airflow will be controlled using a characterized V-seated ball valve that is electronically controlled. This in conjunction with an interchangeable orifice plate upstream of the valve will give us flow rate control of the system.

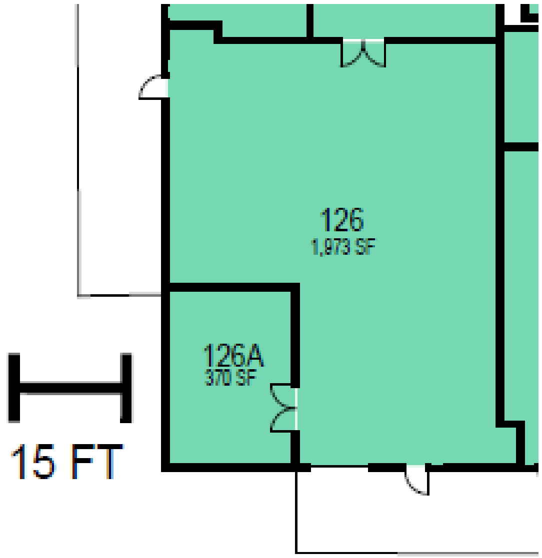


Figure 6. Compressed Air Supply Location.

Compressed Air Location

The compressed air line is located in 126A the testing will be conducted in 126, a flexible compressed air line will connect the test unit to the compressed air supply in 126A.

Manifold

A manifold with 3 individual valves for each of the 3 heaters (expandable to 8) will be used at the end of the main flexible compressed air line. Each of the valves will have 1" NPT fittings for stainless steel compressed air lines that will go to each respective heater. To save on cost, the manifold will be built from pip-fittings, and extra valves can be added when more heaters are added.

Figure 7. Example of a Manifold for Air Distribution.

Pressure Drop Calculation Summary

Node	Pressure Drop [psi]	Node	Pressure Drop [psi]
5	4.2E+00	19	1.5E-01
6	3.8E-03	20	1.1E-05
7	1.5E-01	21	6.3E-05
8	9.7E-02	22	2.4E-04
9	1.5E-01	23	1.5E-04
10	7.3E-02	24	4.9E-05
11	1.1E-01	25	2.0E-01
12	1.2E-02	26	2.8E-05
13	5.6E+00	27	1.7E-04
14	7.4E-03	28	1.5E-05
15	1.0E-01	29	6.3E-03
16	1.1E-05	30	1.7E-02
17	1.5E-01	31	1.3E-02
18	4.1E-06	Total	1.1E+01

Pressure drop calculations were performed for the system at 31 different locations to determine both the total pressure drop through the entire system and the drop in pressure due to each of the individual system components. The total pressure loss through the system is much less than the pressure the compressed air system can provide, validating the design. The model shown is an analysis for an earlier design, but the results still play to the final design.

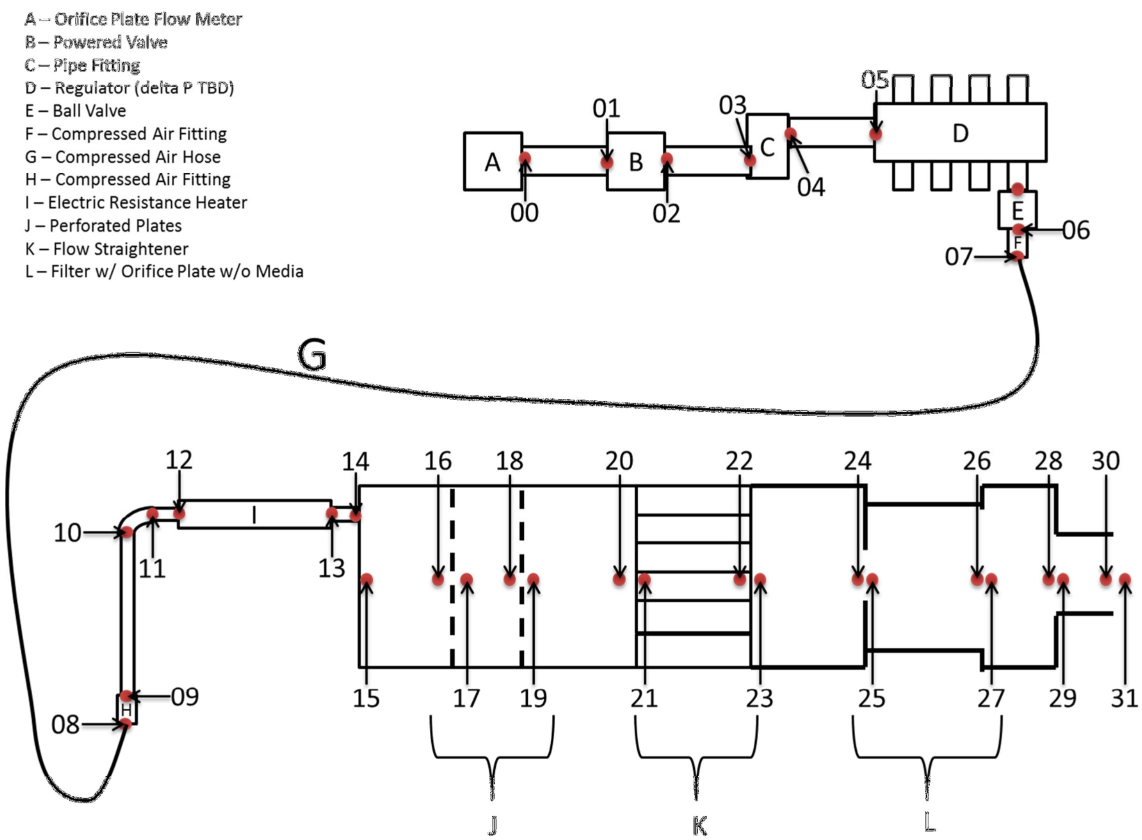


Figure 8. Pressure Drops

Heat Source

The Heat source chosen to use is the Tutco Farnam Heat Torch 200. The design will use 3 heaters at the outset of testing, but the apparatus will have the ability to mount a total of 8 heaters when more funding is available to achieve 250 SCFM at over 1200 F at the filter face.

Figure 9. Tutco Heat Torch 200.

- 3 Tutco Heat Torch 200 at 12.5 kW each
- Maximum Temperature of 1300℉ at 240* ACFM
- 1000℉ at 270* ACFM
- 1200℉ with 250 SCFM With 8 heat torches

Controller

Figure 10. Tutco Process Controller

The Tutco 7550 Series Process Controller will be used to controll the output temperature of a single heater. The controllers are expensive and there is not enough funding to purchase a controller for each heater. Each heater does not need a controller to function, only to control the power to achieve a specificied air temperature. Without a controller, the air temperature is dependent upon the aif flow. Using one controller, the system will be able to prove it can achieve variable temperatures from ambient to greater than 1000℉ and also send full power to all heaters to achieve 250 ACFM at over 1200℉. To achieve greater control in the future while still achieving low cost, a second senior project group is developing a comperable controller for the other heaters.

Electrical Design

The electrical design of the HTTU will be NEC 2008 compliant. Care was taken to ensure that all specifications such as wire and conduit sizing, circuit breaker sizing and conduit fill were within code. For a full list of calculations and their NEC code reference see Appendix A. Before the system is ever connected to power, the electrical system will be scrutinized by and electrical AHJ at both LLNL and Cal Poly.

The following is a rendering of the basic electrical layout of the system; this layout excludes instrumentation wiring and modules that will be added by the controls team (CP HEPA).

- 480V 3- Phase at 60A enters the main breaker box on the right by a flexible cable that will be plugged into a wall receptacle via pin and sleeve safety disconnect
- Conduit shall be ¾" EMT which will be common grounded with a minimum bend radius of 5"
- Main breaker box and the three heater controllers are mounted to the cart using strut in a modular design with space for an additional heater controller and corresponding breaker in the breaker box
- Controller arrangement can be mirrored on the other side of the cart to give us a maximum of 8 heater controllers into a single breaker panel; for future expansion of test capabilities and the ability to achieve 250 SCFM

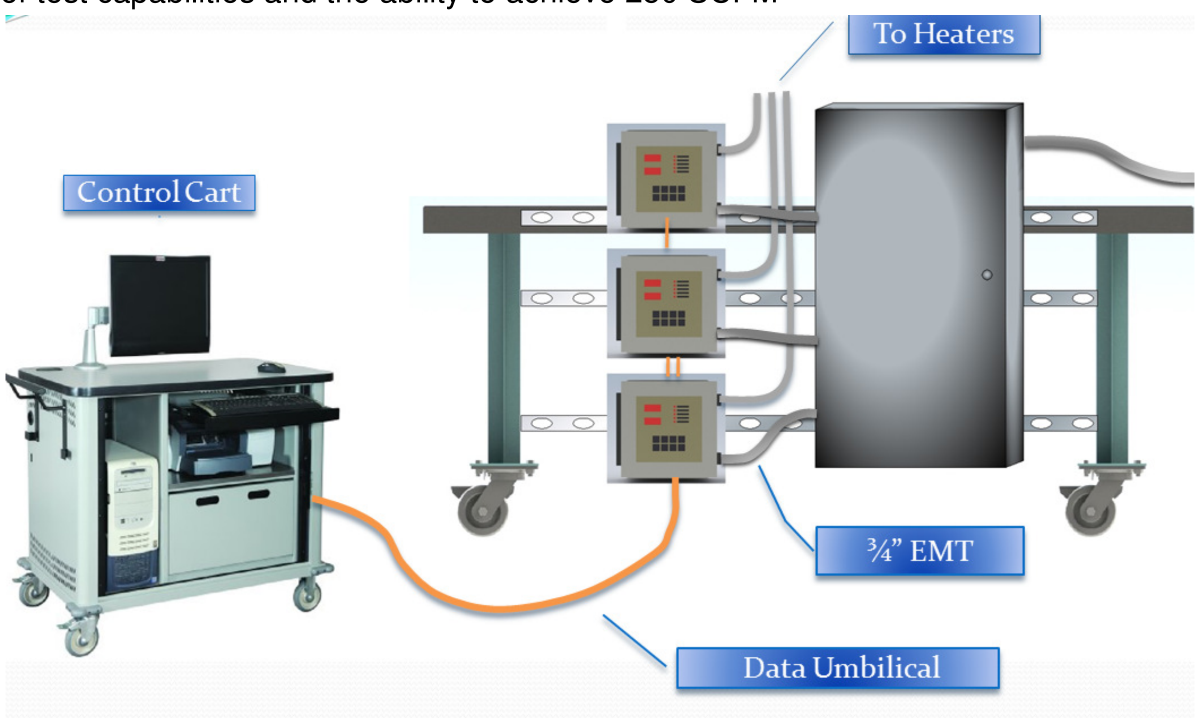


Figure 11. Electrical Layout

Preliminary 480 V 3-Phases Wiring Diagram

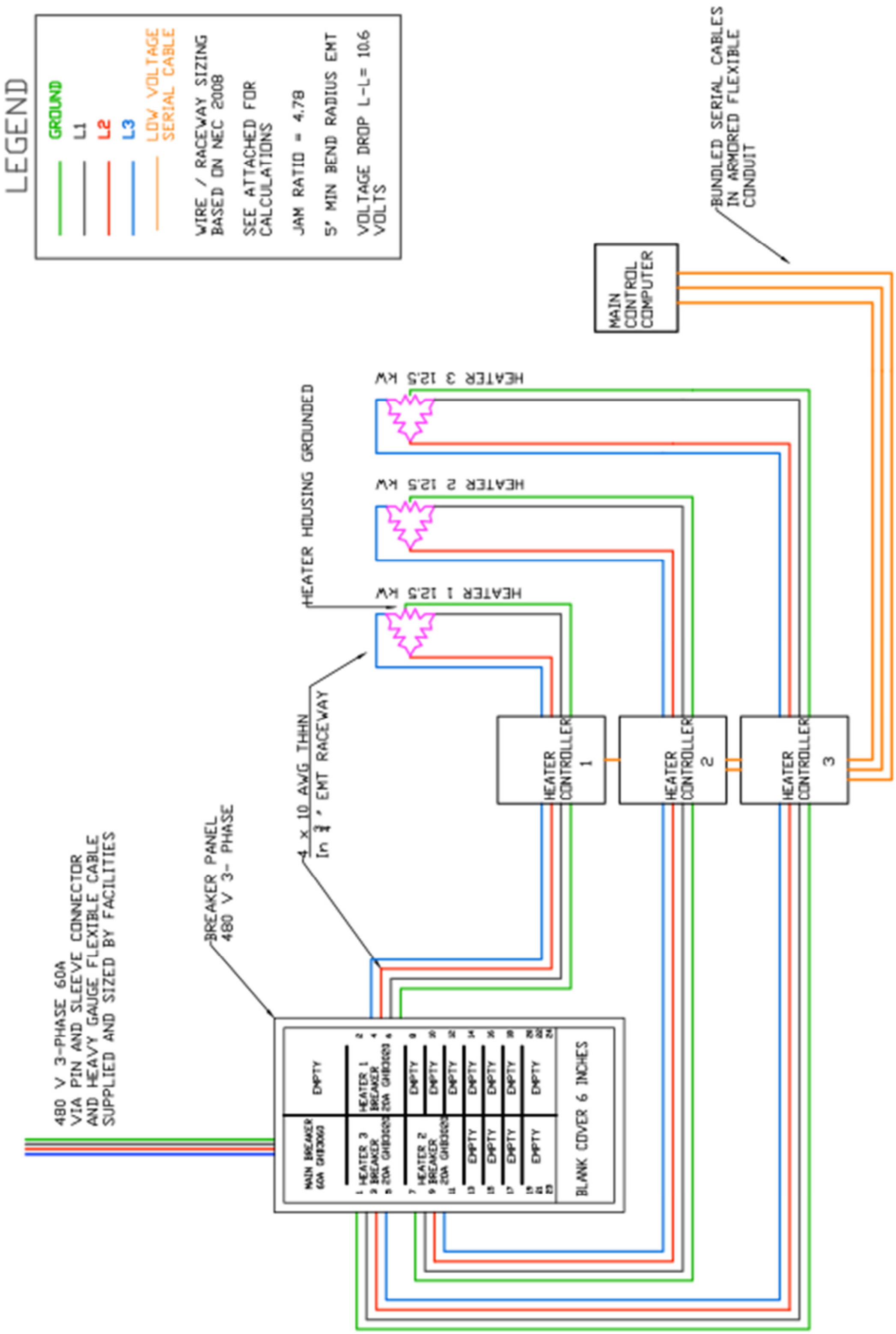


Figure 12 Wiring Diagram

Ducting and Insulation

Figure 13. Gemcolite Ceramic Insulation

Different ducting options were considered for the design. One option was to use heavy gauge stainless steel for the ducting and have no insulation, however when the heat transfer calculations were completed it was actually cheaper (and safer) to use a thinner gauge stainless steel (12 Gauge) for the duct and have a ceramic fiber board insulation such as Gemcolite (see appendix B for data sheet) on the outside of the duct at a thickness of 2”. Using insulation also slows the loss of heat to the environment, which increases the efficiency of the design. During a 20 min test at full 1300℉ temperature the expected outer skin temperature of the duct with the insulation to reach approx. 390℉ (See appendix A for calculations)

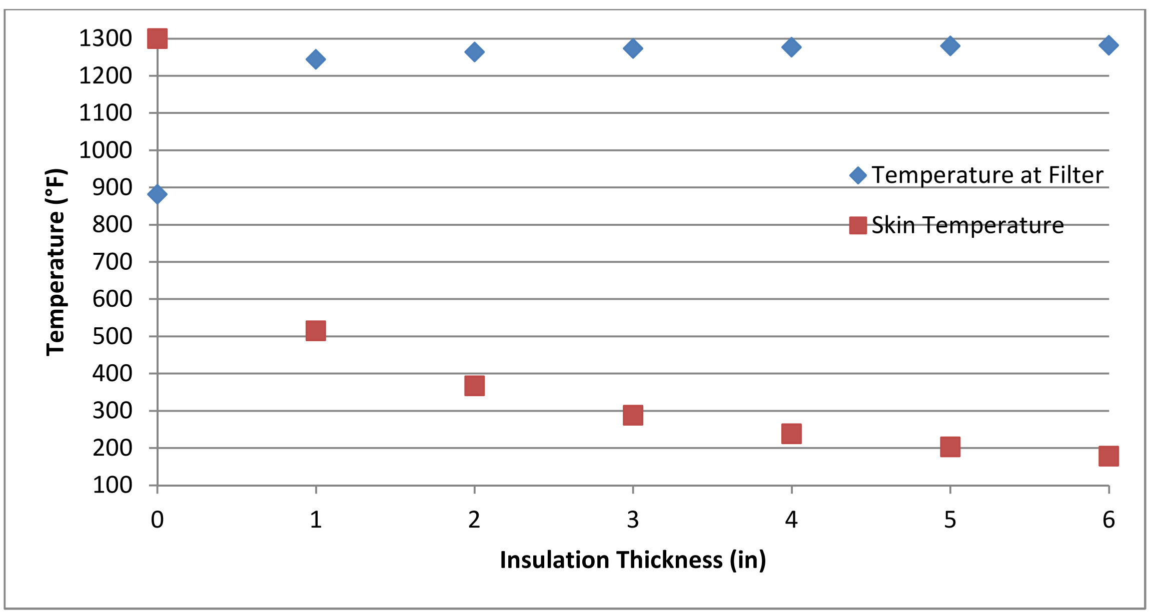


Figure 14. Skin Temperature of Ducting for Various Insulation Thicknesses.

Inlet Manifold

Each heater has a 1 ¼" NPT female threaded fitting on the exit. To attach the heaters to the ducting, a custom manifold will be made for the entrance. The manifold will be made of ¼" stainless steel plate. Holes will be drilled into the plate and NPT pipe fittings will be welded to the holes. Initially, only 3 pipe fittings will be welded to the plate but in a configuration that provides enough room for up to 8 pipes fitting for future use.

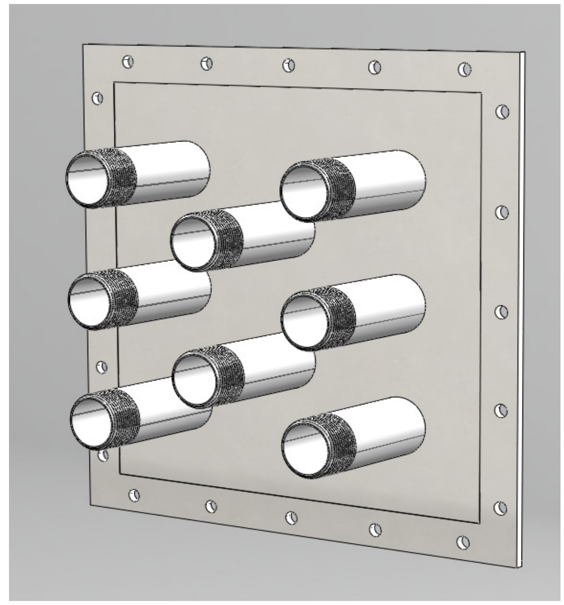


Figure 15. Inlet Manifold

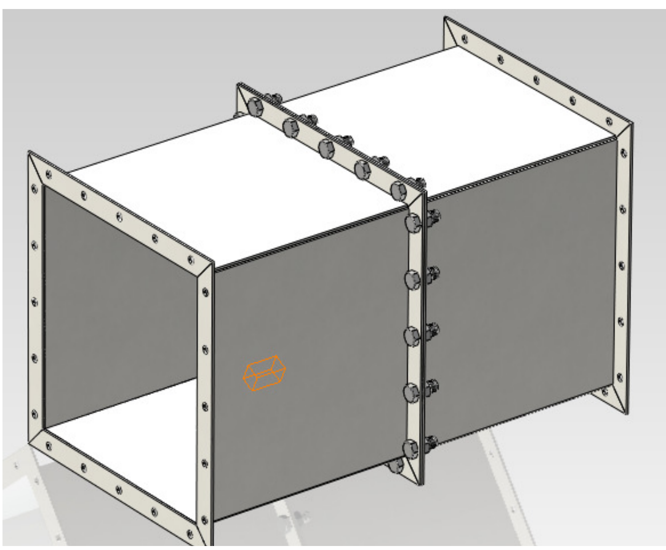


Figure 16. Solid Modeling Ducting

Ducting

The ducting will be custom fabricated from 12-gauge stainless steel. The interior of the duct will be square and have a side length of 12 inches. Each duct section will be a different length depending upon its purpose in the system. However, every flange interface will be identical, such that the duct sections can be moved if desired. Duct section will be held together by bolts, with a high temperature gasket seal between each section to ensure an airtight seal.

Ducting Deflection Calculation

Duct Deflection was calculated using an excel program that related the pressure in the duct, the self-weight of the duct, and the reduction in strength of the steel with respect to temperature. Deflection is a concern because excess deflection may crack the rigid insulation on the outside of the duct. This analysis neglects the stiffening effect the flanges have on the duct and so values are higher than should be seen in testing. Stress in the duct at the max-expected pressure of 3psi is well within tolerable levels of the steel.

INPUT			Output			
Temperature of steel(F)	1300		Self Weight (lbs/ft^2)	4.5063		
Steel Thickness (Ga)	12	0.1094	I_y	16464	0.00152756	I_x
Steel Type	Stainless Steel		w (pounds/Ft)	36.025	8.006	w_x
Duct Length (in)	72		Adjusted E (psi)	10588235.29		
Duct Width (in)	14		Surface Area Sq Ft	28		
Pressure (psi)	3		Dead Load (Lb/Ft)	18.0252	4.5063	DL_x
			Deflection Strong Axis (Inches)	7.2313E-05		
			Deflection Weak Axis (Inches)	0.2476		
			Thermal Expansion (Inches/Linear Foot)	0.165312	0.0000096	α

Figure 17 Ducting Deflection Calculations With Respect to Pressure, Temperature, and Self Weight

Flow Conditioning

At this stage in the development of the HTTU, the quality of the flow profile is not of the utmost importance, however, methods to improve the flow profile implemented. Shortly after the duct entrance there is a location to mount perforated plates. If needed, multiple plates can be added to help produce a uniform velocity profile. These perforated plates will have the greatest effect at low flow rates, when only one of the heaters is being used

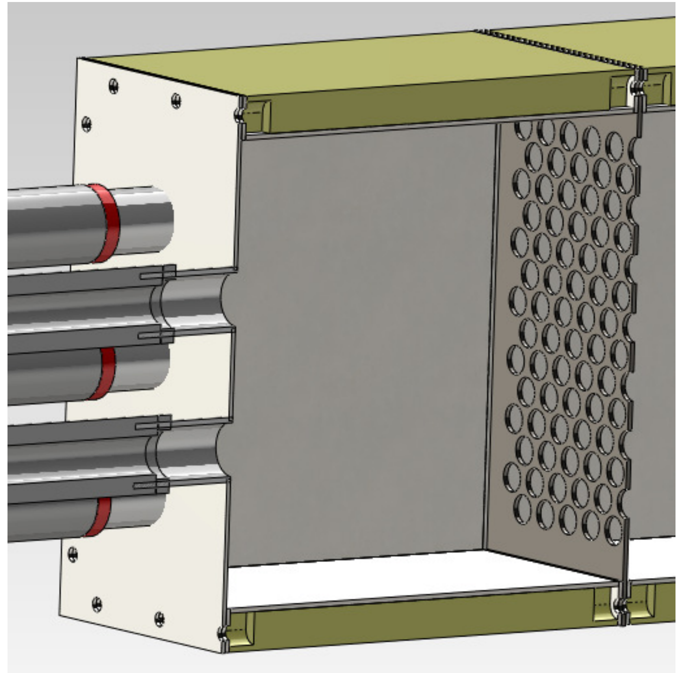


Figure 18. Perforated Plate for Flow Conditioning

Over Pressure Protection

Figure 19. Example of a Burst Disk

The HTTU is not designed to be a pressure vessel, since it is open to exhaust is always open to the atmosphere. In the event of a blockage, which prevents the air from exiting the system, the pressure of the system would increase. To prevent this from occurring, a burst disk will be installed in the system. Bust disks are designed to break once a specified temperature is reached. The system will be designed such that if the disk does burst, any exhaust gas will be vented away from any operators.

Filter Interface

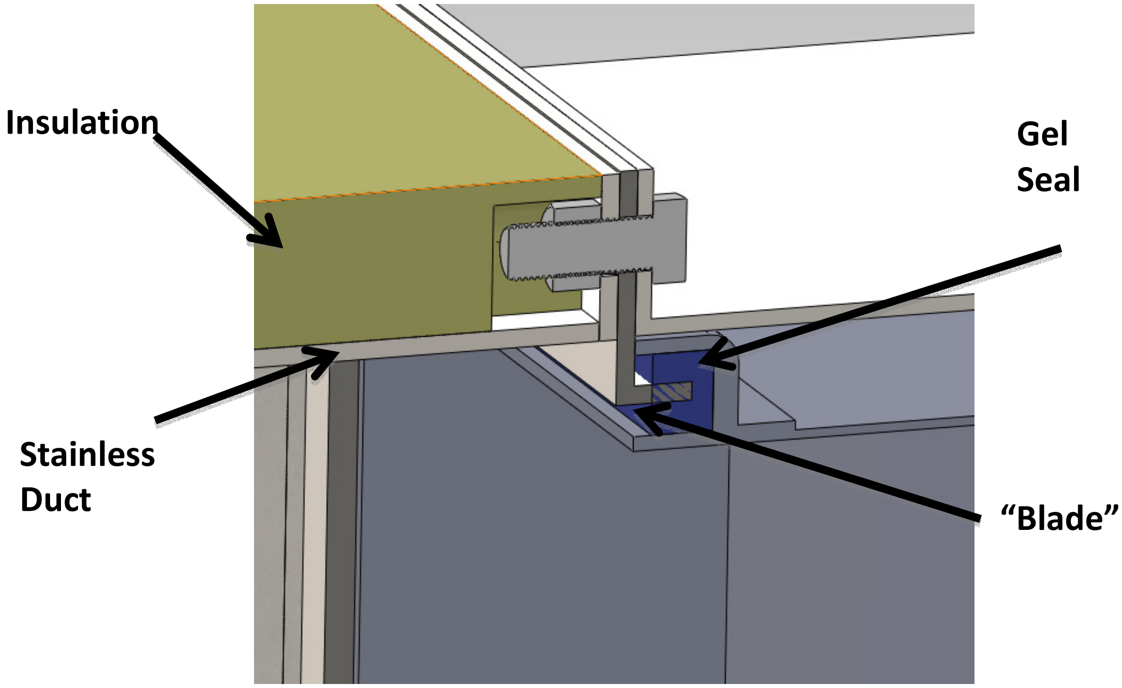


Figure 20. Gel Seal Filter Interface

It is necessary to create and airtight seal between the entrance of the filter and the duct walls. This seal will be achieved by inserting a stainless steel plate between two duct sections. Two different types of filter interfaces need to be accommodated, a gel seal (as seen above) and a flat seal. For the gel seal, the steel plate will have a 90° bend, known as a blade (as seen above). The gasket seal requires a plate with a flat interface

Filter Retainment System

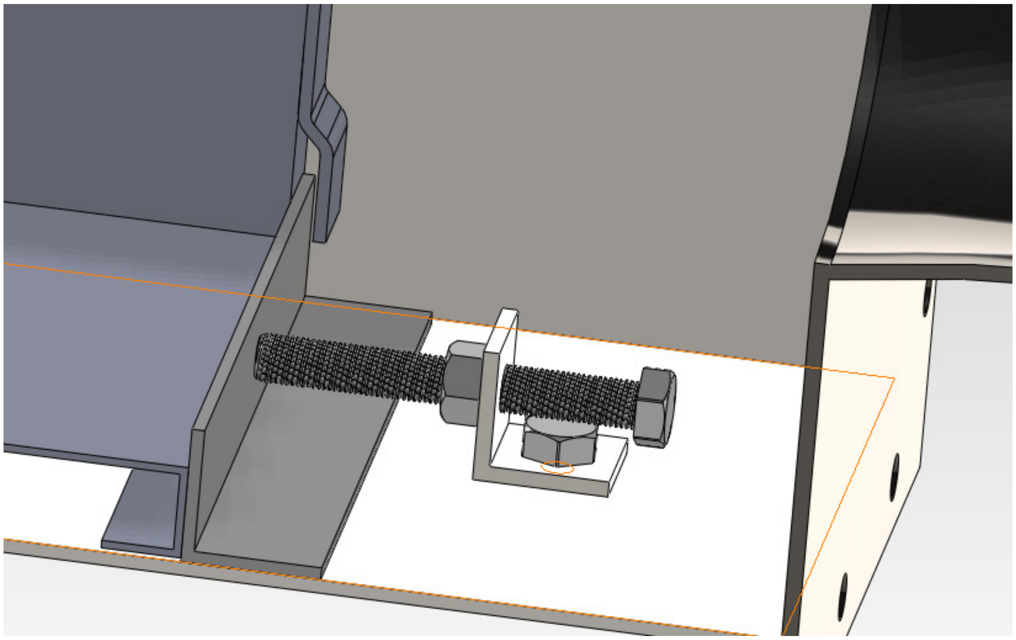


Figure 21. Filter Tensioner, One of Four

At the exit of the filter will be four sets of bolts used to create pressure at the filter interface. The system used is similar to what is used in industry and will be fastened with a torque wrench to ensure adequate pressure is applied. The system is also designed to be completely removed, allowing the operator to switch out filters while only having to remove the exhaust plate of the duct.

Orifice Plates

An orifice plate will be used to simulate a clogged filter and apply a force to the filter frame that will oppose the retainment system and effectively try to “unseat” the seal of the filter to the housing. There will be a variety of orifice sizes depending on the pressure drop wanted for the specific test.

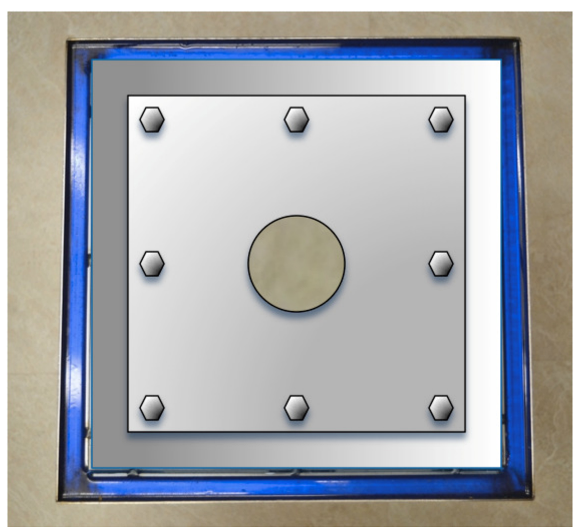


Figure 22 Orafice Plate Diagram

Gaskets

Gaskets will seal the junctions between duct sections, due to the high temperatures involved, flexible graphite will be used as the gasket material due to its excellent high temperature performance. The material comes in sheets measuring 39.4 in x 39.4 in. one sheet will contain enough material for us to make 2 sets of gaskets. The following is a drawing illustrating the size of the material sheet and the overall size of an assembled gasket. The next figure illustrates the pattern for maximizing the number of gaskets that can be made from one sheet.

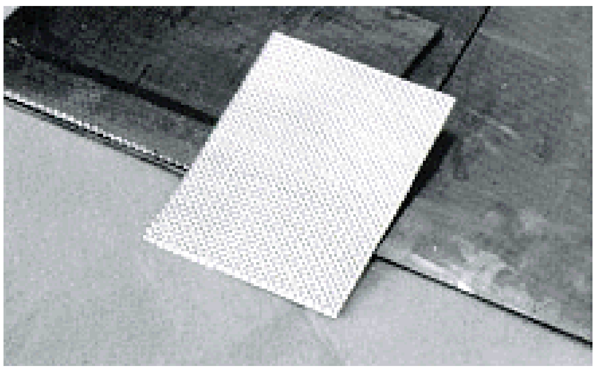


Figure 23 Grafoil Gasket Material

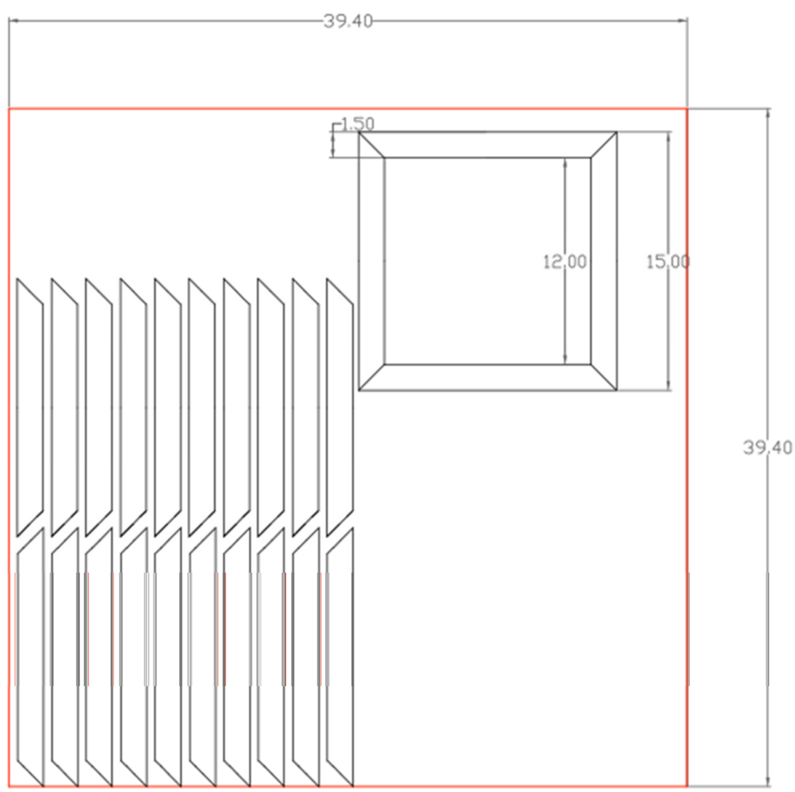


Figure 24 Gasket Layout

Exhaust

Figure 25. Flexible Exhaust Tubing

Figure 26. Inlet to Buidling Exhaust System

The hot exhaust air exiting the HTTU needs to be vented away from the operator. The engines lab has a building exhaust system capable of evacuating 2300 SCFM of air. To connect the HTTU to the exhaust system 6-inch diameter flexible stainless steel tubing will be used. The inlet to the building exhaust is located near the compressed air source; therefore, approximately 25 feet of flexible tubing will be purchased. The exhaust system is already used for high temperature and much higher flow applications than the HTTU and can easily accommodate our exhaust.

Chapter 4 Design Development

Research on this project included consideration of different design approaches to meet the stated objectives. The following is a summary of some of the preliminary design ideas. The most promising design ideas have been analyzed to determine the best overall design concept for the budget and facility constraints, this analysis and the final design choice can be found in the Concepts section of this report.

- (Design A) was based on an approach to reach the highly ambitious goal of an 1800°F test apparatus (we have since agreed upon a more achievable goal of 1000°F for this project with provisions for future improvement). This design utilized a blower or fan to force 250 SCFM of air through an electric heater and then directly through the filter element itself, finally being evacuated through an exhaust hood system. It was quickly realized with some energy calculations that a once through electrically heated system like this would be infeasible because of the massive 150 KW power requirements (see appendix A), and the fact that were not able to find any commercially available electric duct heaters that could achieve an 1800°F temperature.

- (Design B) was to use a recirculating air system to build up heat as the air was passed through the duct heater multiple times. This lowered the power requirements but was not a viable option because in such a system all the components (such as the blower or fan) would have to be constructed to withstand the 1800°F temperatures. Making all the components resistant to the extreme temperature was cost prohibitive.

- (Design C) would heat air using a propane or natural gas powered heater (see appendix B.) in a once through system using the blower built into the gas burner and makeup air duct to achieve correct flow rates. This system should also be able to meet the temperature requirements. The benefits of gas heaters are the ease to acquire the fuel in contrast to the cost and difficulty of obtaining and implementing the amount of electrical power necessary. However controlling temperature is more difficult.

- (Design D) For Design D, circling back around to a once through design after the requirements was reduced from 250 SCFM to 250 ACFM. This design would utilize the compressed air resources in the Engine Lab (330 CFM) as the air source. This compressed air would then be fed into a once through heating system consisting of 3 Tutco-Farnam HT200 “Heat Torch” electric heaters (see Figure 39) With this combination, the system will be capable of reaching and exceeding the minimum temperature goal of 1000°F, (max of 1300°F) as well as the flow rate and pressure goals. (The ACFM SCFM requirement and explanation is detailed in the Objectives section)

Extensive research was conducted on possible components for use in the various design approaches. Price proved to be the main factor in the decision making process.

Final Design Development

Several design approaches for the apparatus itself were considered after we chose the once-through electrical design (Design D). The following shows illustrations of some of the early designs and point our various components that were added/changed on the way to our final design.

This design utilized a series of needle valves to control the flow with a bleed off line, and a diffuser to expand the flow smoothly. It was later determined that a bleed of valve was not needed and the design was changed.

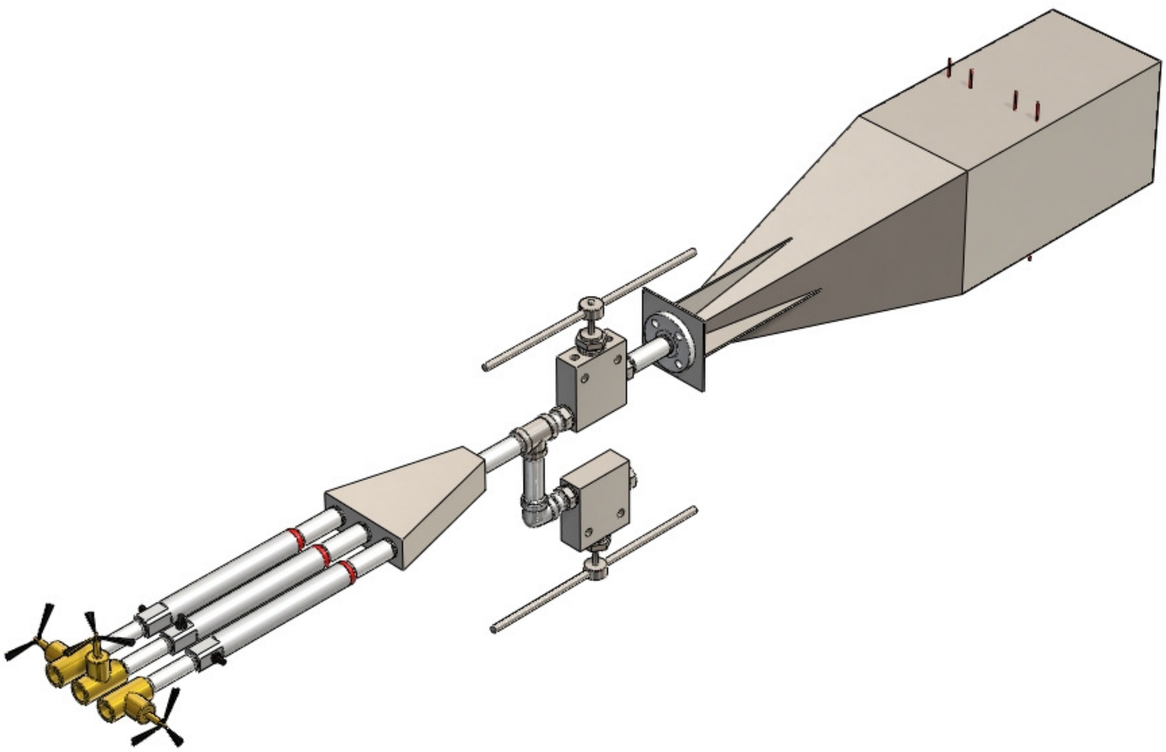


Figure 27 Preliminary Design Drawing 1

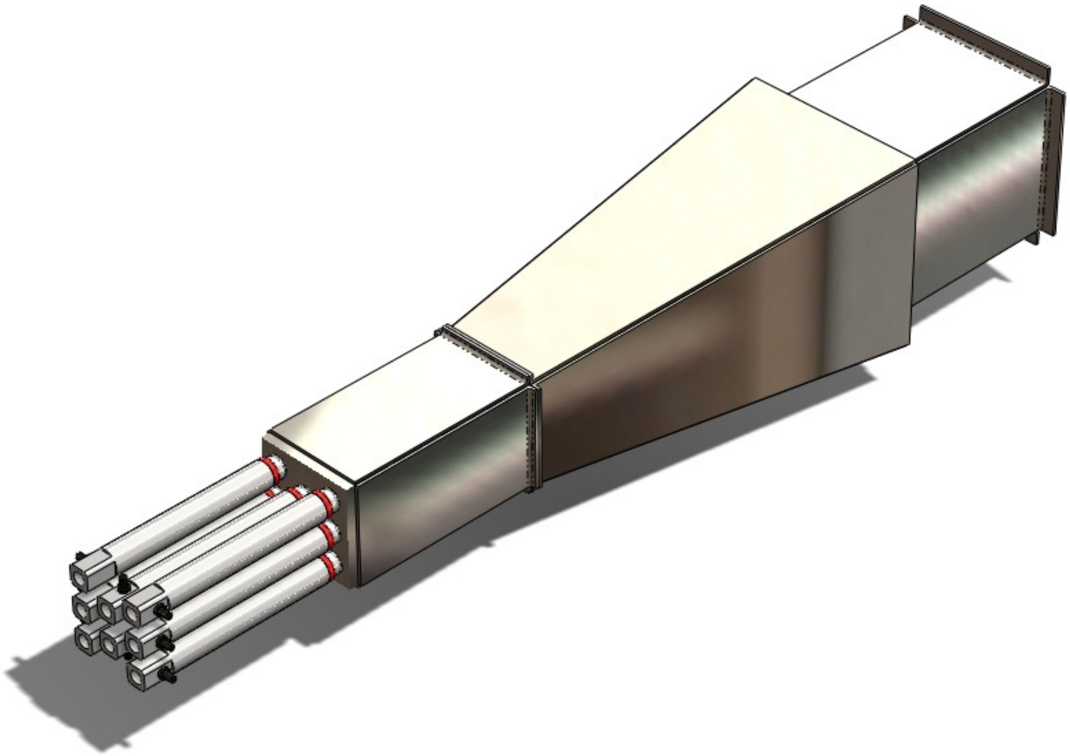


Figure 28 Preliminary Design Drawing 2

In this design the air from the torches was dumped directly into a square section of duct, removing the complicated piping system of the previous design and reducing pressure losses, this design also utilized a diffuser, and this drawing shows the insulation on the diffuser section.

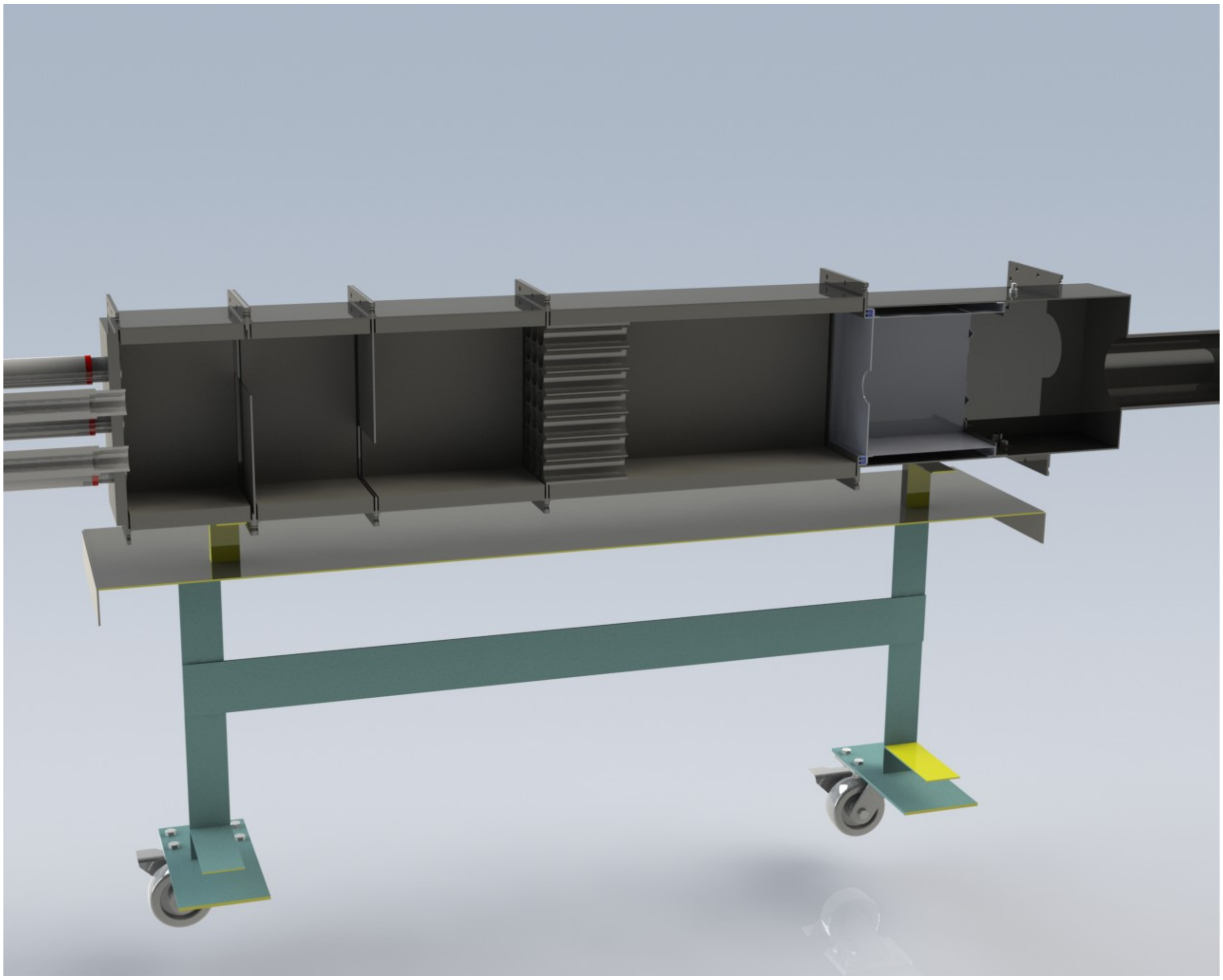


Figure 29 Preliminary Design Drawing 3

The third design is very similar to our final design, it features a simple square duct and uses baffles and a flow straightener to mix and condition the flow respectively. After consulting some of the fluid dynamics professors, it was determined that the baffles would be ineffective and that perforated plates should be used in their place to mix the airflow from the heaters. The perforated plates have the additional benefit of straitening the flow to some extent. Because LLNL did not require perfectly developed flow, the flow straightener is absent in our final design, preliminary flow testing will determine whether one is needed and it can be easily added to the HTTU due to its modular design.

Airflow

Many fan and blower companies were contacted regarding a fan/blower that would be able to move 250 SCFM of air from temperature ranges of 1000 to 1800 °F and produce a pressure of 6 inches of water column. Of the companies that were contacted, three were able to meet the requirements and are listed as such.

Cincinnati Fan

Option 1

Price: $37,000

Specifications

- Up to 1800°F
- Minimum air flow 300 SCFM
- Direct drive with high temperature coupling

Conclusion: Too expensive cannot be ordered with current budget.

Option 2

Price: $25,000

Specifications

- Up to 1800°F
- Minimum air flow 300 SCFM
- Belt drive with radial bladed fan

Conclusion: Too expensive cannot be ordered with current budget

Option 3

Price: $6,600

Specifications

- Up to 900°F
- Minimum air flow 300 SCFM
- Belt drive with radial bladed fan

Conclusion: A bit low on the temperature side-will not meet project requirements.

AirPro

Price: $8,159

Specifications

- Up to 1200°F
- 42% static efficiency
- 6 inches water
- Weight 300 lbs

Conclusion: high on the price side, will not be able to fulfill other project requirements if item is purchased.

Fan Equipment Co.

Price: $6,320

Specifications

- Up to 1000°F
- 316 Stainless steel construction
- Flexible coupling
- 250 ACFM

Conclusion: Price is better than AirPro, but still expensive.

The additional cost of using a fan over the free air supply of the on-site combined with the fact that the compressor air source has the needed electronically controlled flow valves already installed made it the most attractive option to use as an air source.

Heat Source

How to heat the air was the design consideration that loomed over all the rest, driving the entire design direction. Both gas and electric air heating have their own merits and pitfalls; however when all the options were measured the gas heating option had a deal-breaking attribute. The following table summarizes the pros and cons of each type of heating.

	PROS	CONS
Gas	High heat output No facility modification Cheaper Additional heating capacity optional	Off-the-shelf burners cannot operate with high backpressure Cannot achieve flow rates required with built in blower Difficult to control University safety concerns
Electric	Simple to install and operate Can achieve flow rate at temp and pressure Greater temperature accuracy	Expensive Requires modification to facility Additional power requires additional facility modification

Table 1. Pros and Cons list for Gas and Electric Heating Options.

Team Icarus acknowledges that other test facilities use gas burners for the air heating, however with the limited time and budget constraints the gas option is currently infeasible for Team Icarus to implement because all the off-the-shelf gas burners researched could not operate in the high back pressure environment that is a requirement of this project. For these reasons pursuing a gas heating option would entail building or ordering a custom gas burner that could operate in a high-pressure environment, where the fuel/air mixture is constantly changing (5-250 ACFM). Team Icarus does not have the capacity to build and implement such a system with the current resources. The following is a comment and decision breakdown of a selection of the burners researched; data sheets on those discussed are included in appendix B.

Gas Burners

Wayne Combustion Model EHG

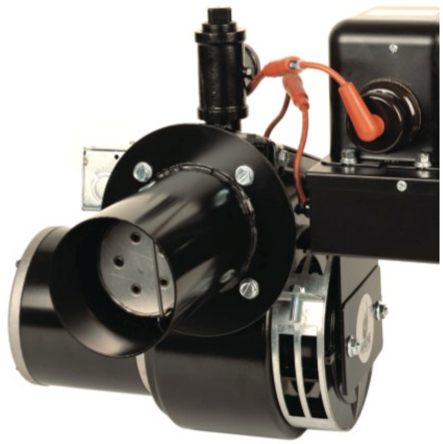


Figure 30. Wayne Combustion Gas Burner Model EHG

Specifications

- LP or Natural Gas
- Built in Blower
- Burner range from 425-700 M Btu/hr.
- Price $2,621 burner only

Pros:

- Can achieve heat output required for the project
- Integrated fan unit for airflow

Cons:

- Fan cannot achieve the 250cfm flow rate required for the project
- The burner cannot operate in the high backpressure environment of the test chamber → 6” H_2O

The Wayne Combustion Model EHG Burner showed promise in that it incorporated both a heat source and an air supply in one distinct unit. The unit ultimately failed to meet the requirements needed to work with the system because of the following shortcomings: The burner could not operate at a static pressure of 6” of water column which is a design requirement of the test apparatus, and the blower that is integral with it cannot provide the amount of airflow that is required under the project requirements. In addition the flame could not be adjusted on the fly, making precise temperature control using this device difficult.

Figure 31. Ward MBR 700 Gas Burner

Ward Power Burners MB700

Specifications:

- 140 CFM Blower
- 750,000 BTU/HR
- Built in Blower
- $919

Pros:

- Can Achieve Heat Output required
- Integrated fan unit for airflow
- Inexpensive

Cons:

- Would need two of them to give us adequate airflow
- The burner cannot operate in the high backpressure environment required for the test apparatus.

The Ward Burner Systems power burners were very promising at first. They offered both high heat output and a decent airflow from their built in blower at a very low price. Unfortunately none of Wards Power Burners can operate in the high backpressure environment that a requirement for this project. Because using this burner system would not achieve the project requirements, it was also rejected.

Johnson Gas Adjustable Power Burner

Specifications

- Available with 200,000-800,000 BTU/HR Versions
- 1/3 HP Integrated Blower

Pros:

- Can achieve required heat output
- Integrated blower (flow rate unknown)
- Integrated safety systems

Cons:

- Cannot operate in the high backpressure environment required for the test apparatus.
- Would need a number of them to achieve required flow rate, or add makeup air from compressor.

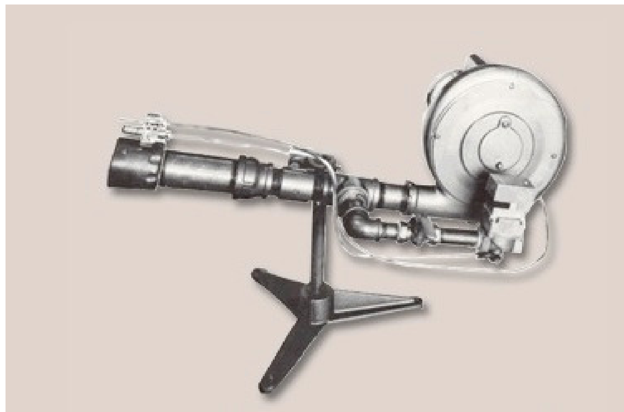


Figure 32. Johnson Adjustable Power Burner

The Johnson Gas Power Burners failed in the same capacity as the others, the fact that they cannot operate with high backpressure is an instant deal-breaker. As with the others, the flow rate of the integrated blowers is likely insufficient to meet the requirements and would either have to be supplemented by an additional burner, or by the air compressor.

Electric Air Heating

Many types of electric air heaters were also considered for this project, in the research only two traditional duct heaters were found that could reach temperatures greater than 1000°F and they were both extremely large and extremely expensive (on the order of 15-35K) for this reason the Tutco-Farnam Heat Torch 200 is the most promising of the electric heaters. This electric air heater is capable of heating 100 SCFM of air to 1200°F. A number of these small and powerful heaters would be used in the design. *A summary of the specifications for this heater and controller is included in Appendix B of this document*

Flow Control

Wermec.org has listed off the advantages and disadvantages of butterfly and globe valves and are as follows:

Butterfly Valves

Advantages
- Compact design requires considerably less space, compared to other valves
- Light in weight
- Quick operation requires less time to open or close
- Available in very large sizes
- Low-pressure drop and high-pressure recovery

Disadvantages

- Throttling service is limited to low differential pressure
- Cavitation and choked flow are two potential concerns
- Disc movement is unguided and affected by flow turbulence

Globe Valves

Advantages
- Good shutoff capability
- Reasonably good throttling capability

Disadvantages

- Higher pressure drop compared to a gate valve
- Large valve sizes require considerable power or a larger actuator to operate

Needle valves are a special type of globe valves and have a high precision of airflow. Airflow through needle valves is a linear relationship with respect to the amount the valve is open. On McMaster, a one-inch diameter stainless steel easy-set needle valve is about $177.

Chapter 5 Testing Verification

To ensure safety of participants and integrity of the system, incremental component building / testing will be completed first before a full system test is conducted.

1. Pressure and Flow Calibration

Connect the computer system to the valve control system. Test the control of flow and pressure. Use an external flow meter and pressure transducer to calibrate the system and ensure the readings are correct.

2. Manifold

Second in the incremental testing is the manifold. The manifold will have separate valves for each compressed air line to the heater. Close all of the valves on the manifold and attach the manifold to the compressed air system. Pressurize the system and look for air leaks. Once it is determined the system is performing with no leaks, open each valve one at a time to check the air flow and pressure. Then start opening in different combinations to ensure the flow is expected. Use the flow meter and pressure transducer. Always point the manifold lines away from people and never at oneself.

3. Individual Heater without Heat

Each individual heater is to be tested with a flow rate of 50 CFM with no power. DO NOT test any heater with more than 100 CFM it can damage the heaters. This test is used to check the airflow coming out of the heaters and to verify the theoretical pressure loss through them.

4. Individual Heater with Heat

As with the heater test without heat, set the flow rate to 50 SCFM. Attach thermocouples to the heater at the beginning and end of the heaters. Establish a test zone of no less than 5 ft. Electricians will be required to connect the power to the system. Verify with the theoretical model the amount of power being supplied to the system is outputting the expected temperature of air. Vary the amount of airflow and electrical power to compare with theoretical models.

5. Full System without Heat

A system test with air passing through the heaters is needed to verify the ducting is airtight except at the end. The airtight ducting is needed for safety and to ensure when hot air is flowing through the system, it will not be exiting though the sides which could potentially burn individuals. This test will also serve as a pretest of the cool down of the system with low airflow passing over the heaters.

6. Full System with Heat

For the full system test, a 10 FT barrier, using delineators and tape, will need to be implemented before the heaters are powered. Electricians will be required to connect the system for use. Ensure everything is connected correctly, set the flow rate with the computer, open the valve(s), and power on the heaters. Heaters are to be controlled via a computer.

7. Cool Down

The cool down is needed to figure out the best amount of airflow over the heaters after they have been on. Air at full blast over the heaters is not recommended due to the possibility of shocking the system. With some airflow it will allow the system to cool faster and allow

8. Other Tests

Differential Pressure Test orifice plates will be inserted and tested to see if a differential pressure of 6 inches water can be achieved.

Following all these tests, a test with the filter media installed will be conducted with the system running for 20 to 30 minutes.

Chapter 6 Management Plan

Key Milestones

Project Update Memo – March 30, 2012
Senior Design EXPO – May 31, 2012
Final Project Report – June 4, 2012

Roles and Responsibilities

Garrett Brown	- Primary coordinator between the sponsor and the team - Design and structural analysis of the test apparatus - Ensure electrical and control components are installed per NEC and UL508A Standards
Garrett Dong*	- Primary coordinator between the team and suppliers/university administration - Background research of existing systems - Procedures for safe testing to be used in the third quarter
Joe Marino	- Component selection and lead in manufacturing - Thermal, fluids, and heat transfer analysis of test apparatus - Power and design requirements for analysis of test apparatus

Tasks will be distributed amongst the group members, as shown below:
*Garrett Dong will be a working on this project for only the first two quarters

Logbooks

Each team member keeps a logbook in order to document the design process. The logbooks will serve as a record of ideas, meeting notes, design considerations, testing, analysis, evaluations, and any other information pertaining to the project. Each member is expected to make frequent entries in a professional and legible fashion.

Communication

The primary means of communication between the team and the sponsor will be biweekly conference calls. These conference calls allow the team to ask the sponsor any clarifying questions, in addition to keeping the sponsor apprised of all the progress being made on the project. Prior to each call, an agenda will be emailed to the sponsor, and minutes will be emailed after the meeting. Any communication required between conference calls will be conducted via emails or one-on-one phone calls

Budget

Table 2. Budget

Budget		
Duct work, test chamber	**$3,150.00**	
Sheet Stainless Steel and Labor	$1,300.00	
Plate Stainless Steel		$0.00
SS Flange Material	$200.00	
Pipe Fittings	$200.00	
Valves	$200.00	
Fasteners/Hardware	$200.00	
Compressed Air lines (4)	$550.00	
Flexible Exhaust Tube	$500.00	
Support frame	**$350.00**	
Unistrut	$250.00	
Misc. Hardware	$100.00	
Carts		$0.00
Heat Shield / Safety cage	$100.00	
Heat and Insulation	**$5,700.00**	
Heat Torches and Control Panel		$5,000.00
Gemcolite Insulation	$500.00	
Blanket Insulation	$200.00	
Instrumentation	**$100.00**	
Temperature (Thermocouple)	$50.00	
Pressure Sensor	$50.00	
Controls	**$750.00**	
Computer	$0.00	
Manual controls e.g. emergency stop	$300.00	
Control & Relay panels	$200.00	
Misc.	$250.00	
Electrical	**$4,300.00**	
Electrical Panels		$500.00
Breakers		$0.00
Conduit	$150.00	
Conductors (Wire)	$150.00	$0.00
Facilities Building Modification	$3,700.00	
Misc. / Contingencies	$1,250.00	$0.00
Cal Poly Total	**$10,100.00**	
LLNL Total		**$5,500.00**
Grand Total	**$15,600.00**	

Schedule

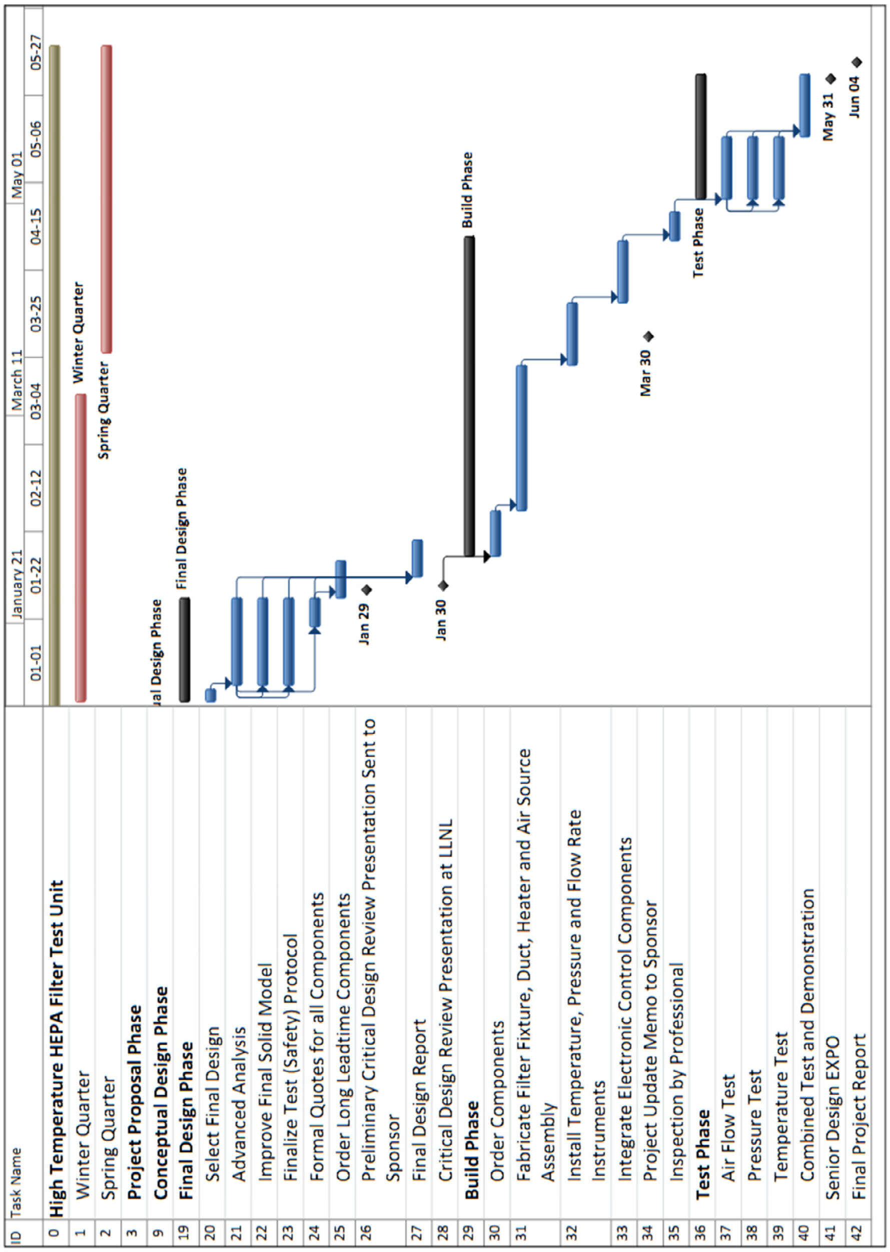


Figure 33 Gantt Chart Project Schedule

Chapter 7 Conclusions and Recommendations

Team Icarus is charged with designing a test unit that can heat 250 SCFM inlet air to at least 1000°F in a safe manner to test HEPA filters. Several preliminary design ideas were considered and analysis on them proved that they were unviable. Progressing forward Icarus will continue to refine its electrical concept until it is production ready. A final design will be presented at the Critical Design Review in Jan 2012.

Pending Design and Safety Considerations

Pending design considerations are issues that do not undermine the basic concept but need to be address in the future; the following is a list of these considerations to date:

- Uniform temperature distribution (no hot spots)
- Uniform flow and velocity profile
- Hearing protection may be required.

Appendix A Analysis

Electrical Power Requirements at Maximum Flow Rate
Ducting deflection due to pressure
Thermal expansion in ducting
Heat transfer through duct with 1” insulation
Heating Humid Air
ACFM vs. SCFM Plot Generation

First determine Mass Flow Rate at 250 SCFM, 70°F, 6 in H_2O

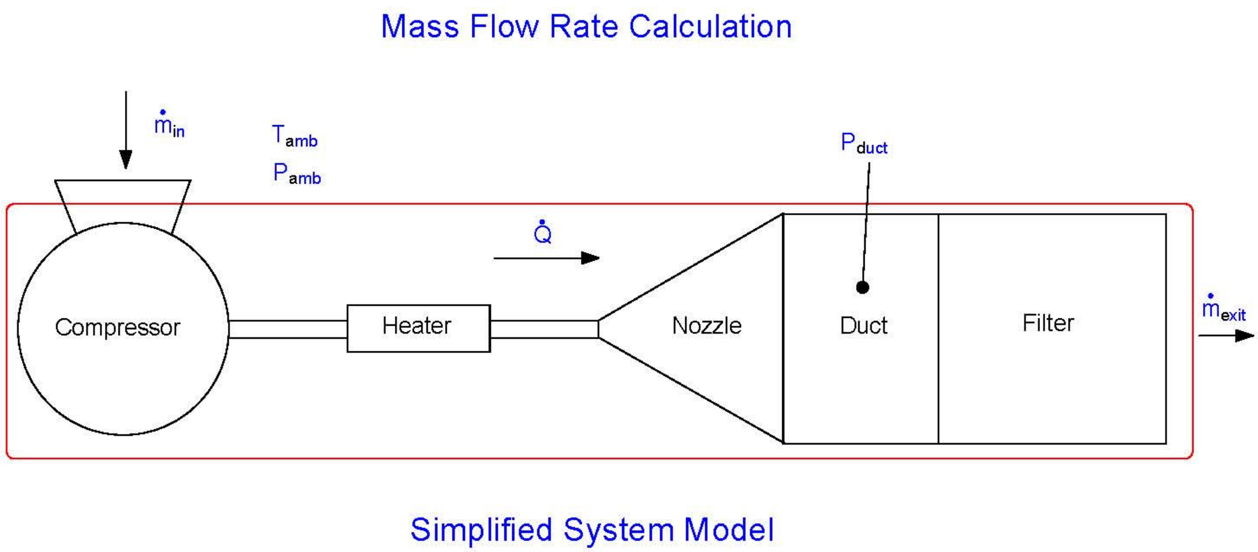


Figure 34. Diagram of Conceptual Design.

SOLUTION

Unit Settings: Eng R psia mass rad

$\dot{m}$ = 19 [lb_m/min]

$\dot{Q}$ = 250 [ft^3/min]

T_{amb} = 70 [F]

P_{duct} = 14.92 [psia]

R_{dryair} = 53.35 [ft*lb_f/lb_m*R]

~~~~~~~~~~~~~~~~~Mass Flowrate Calculation~~~~~~~~~~~~~~~~~

Updated October 21, 2011

The system must be capable of producing at least 250 SCFM of air at the filter.
To determine how much air is required the Maximum Mass Flow will be calculated
at Ambient Temperature and Highest Pressure

~~~Assumptions~~~
- *Steady State*
- *Inviscid Flow*
- *Dry Air*
- *Ideal Gas*
- *Air is passing through filter at ambient temperature*
- *No change in Kinetic or Potential Energy*
- *Cross Sectional Area of filter is 1 ft^2*

~~~Given~~~

$$T_{amb} = 70 \quad [F]$$

$$P_{duct} = 6 \quad [inH2O] \cdot \left| 0.036127157 \cdot \frac{psia}{inH2O} \right| + 14.7 \quad [psia]$$

$$\dot{Q} = 250 \quad [ft^3/min]$$

~~~Find~~~

$\dot{m}$ - Mass Flow Rate

~~~Analysis~~~

Continuity

$\dot{m} = \dot{m}_{in} = \dot{m}_{exit}$

Specific Gas Constant

$$R_{dryair} = \frac{1.986 \quad [Btu/lbmol\text{-}R]}{\mathbf{MolarMass}\,[\text{'Air'}]} \cdot \left| 778.2 \cdot \frac{ft*lb_f}{BTU} \right|$$

Ideal Gas Law
$P * \dot{Q} = \dot{m} * R_{specific} * T$

$$P_{duct} \cdot \left| 144 \cdot \frac{lb_f/ft^2}{psia} \right| \cdot \dot{Q} = \dot{m} \cdot R_{dryair} \cdot \mathbf{ConvertTemp}\,[F, R, T_{amb}]$$
~~~~~~~~~~~~~~~~~

ERROR: stackunderflow
OFFENDING COMMAND: ~

STACK:

High Temperature HEPA Filter Test Unit

Icarus

Presented by:
Garrett Brown
Garrett Dong
Joe Marino

Sponsored by:
Lawrence Livermore National Laboratory

Introduction

What is a HEPA Filter?

- High Efficiency Particulate Air filter
- DOE standard: 99.7% efficient at removing particles greater than .3 microns in diameter
- Media currently used is low strength glass fiber

What is the need?

- Need for High temperature and strength HEPA Filters for Nuclear, semiconductor, and biomedical facilities
- 92% of ASME AG-1 said that it is either very, or extremely, important to develop alternatives to current, conventional, glass-fiber HEPA filter media

Purpose / Background

- LLNL needs a way to test next generation temperature resistant HEPA filters
- Apparatus Simulates fire conditions in building.
- Currently no test apparatus designed to test HEPA filters at over 540°F

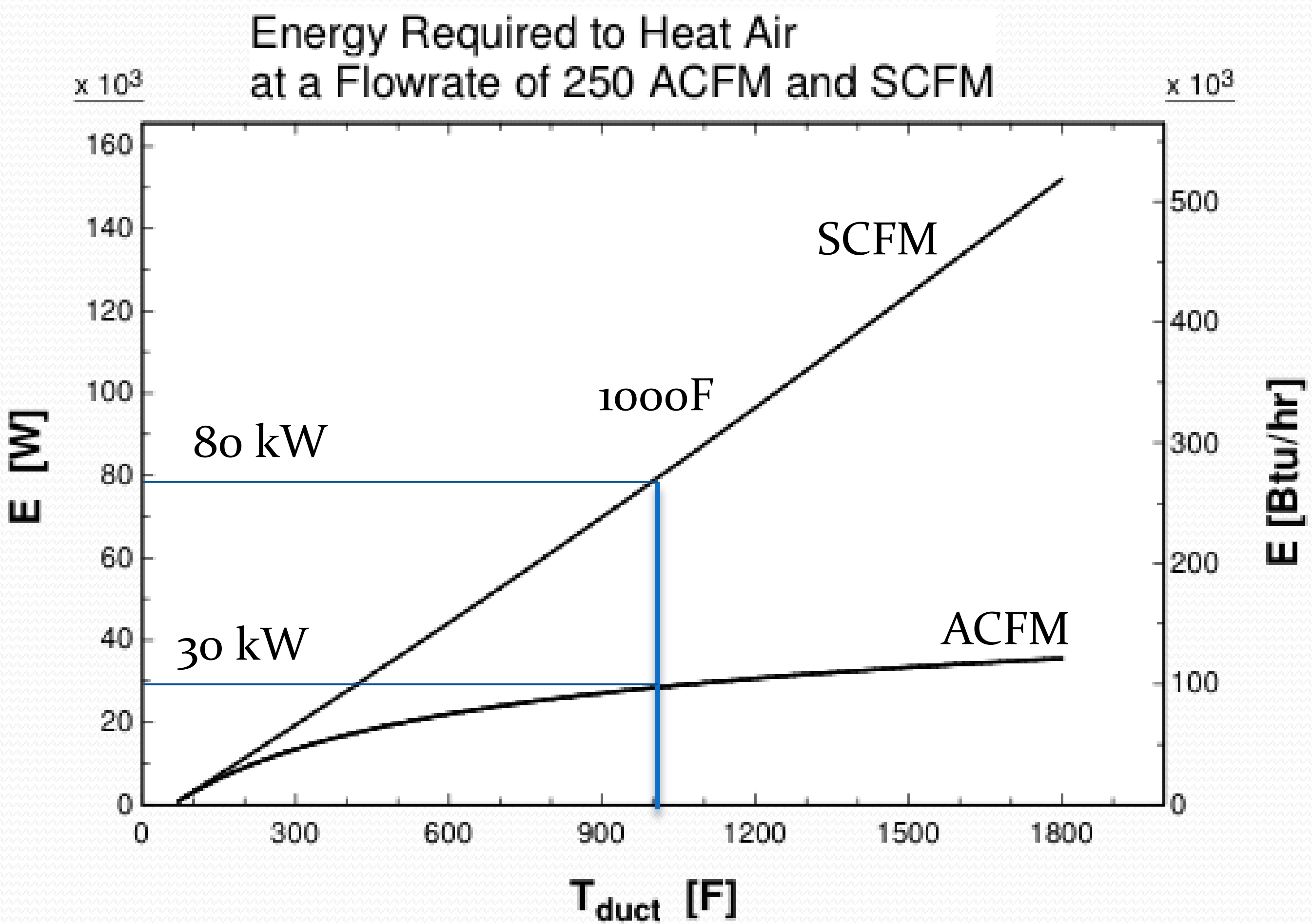
Similar Concepts

- Wind tunnel
- The UK dynamic system HEPA Test unit, 540°F
- ICET at the MSU

Project Requirements

- Achieve at least 1000°F temperature; 1800°F desired
- Variable pressure drop across the filter from 1-6" H_2o.
- Inlet flow rate variable between 5 and 250 SCFM
- Measure temperature and airflow rate at filter
- Measure change in pressure across filter
- Portable
- Able to accommodate future improvements.
- Complete requirements with $10,500 budget

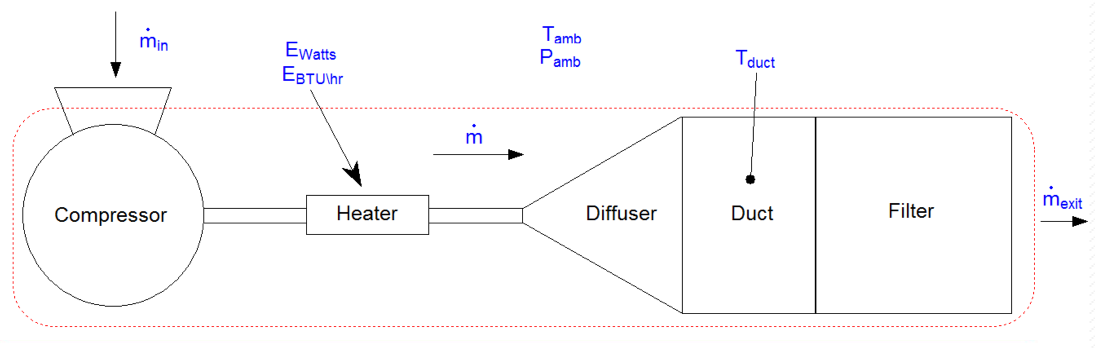
ACFM vs. SCFM and Power Requirements



Components

Many different ways to achieve our project requirements

- Air flow
  - Blower/Fan
  - Air compressor
- Heat
  - Gas or Electric
- Ducting
  - Thick stainless
  - Thinner with insulation
- Pressure Drop
  - Orifice Plates
- Data Acquisition



Critical Design Consideration

The Big Question

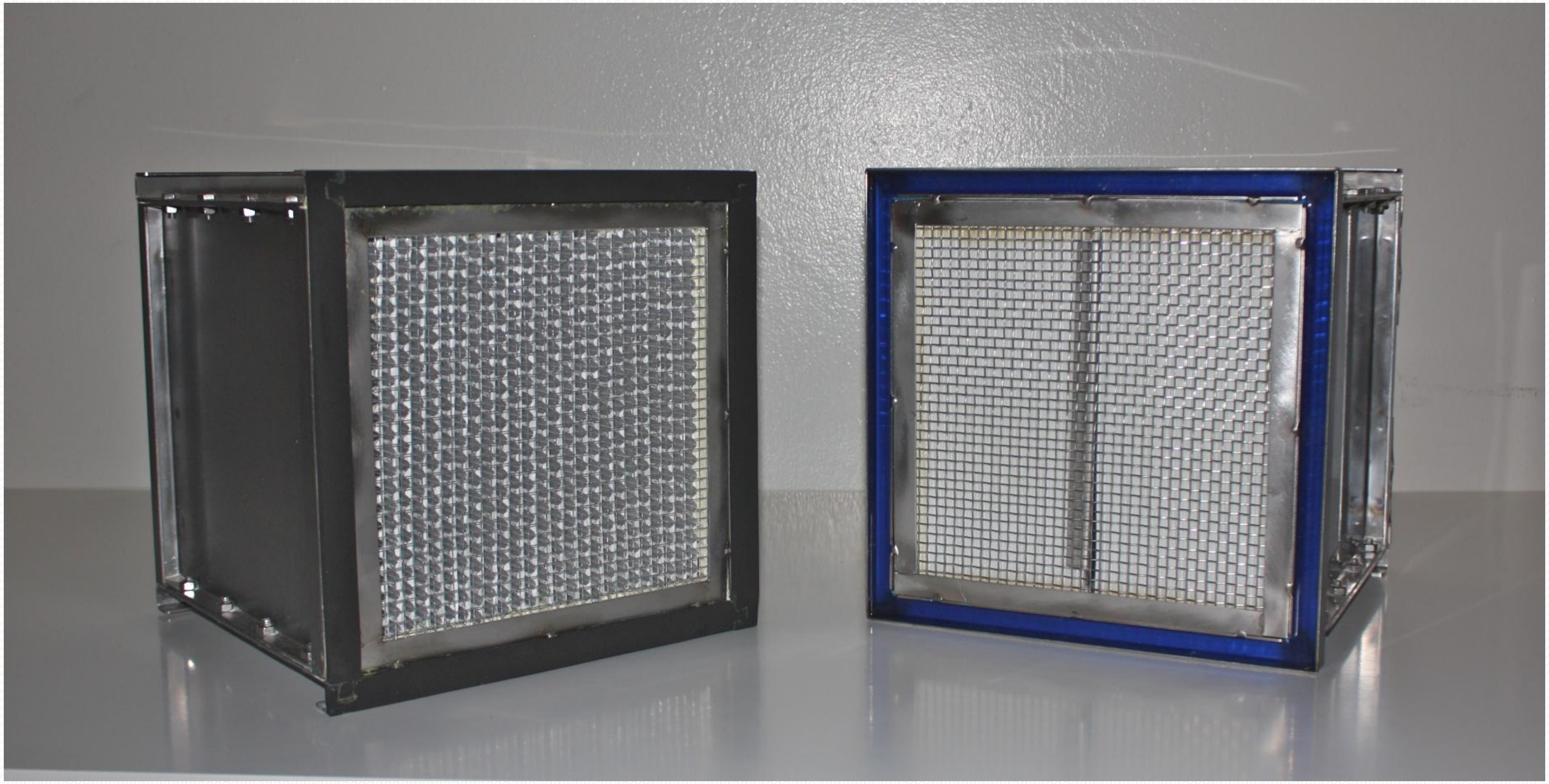
- Gas or Electric?

Gas or Electric Heating?

	Pros	Cons
Gas	•High Heat output can achieve required temp •No facility modifications •Cheaper	•Cannot operate with the high backpressure required •Cannot achieve flow rates required with built in blower •Controlling them is difficult
Electric	•Simple to install and operate •Can achieve flow rate at temp and backpressure •Greater temperature resolution	•Expensive •Requires modifications to test facility

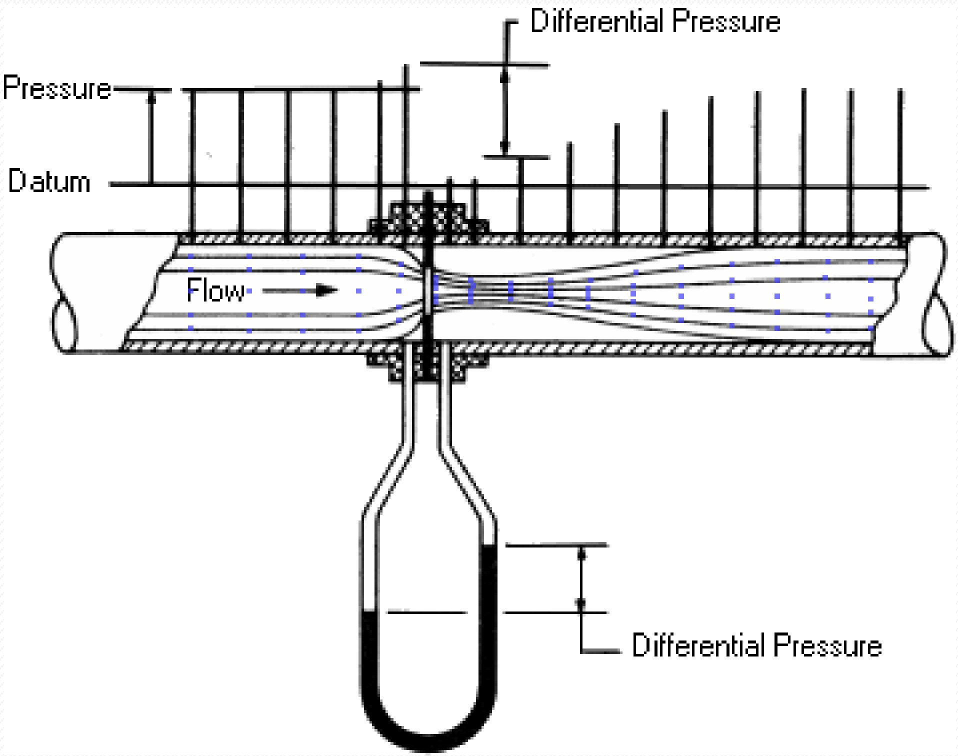
Filters

- Gasket Seal and Gel Seal

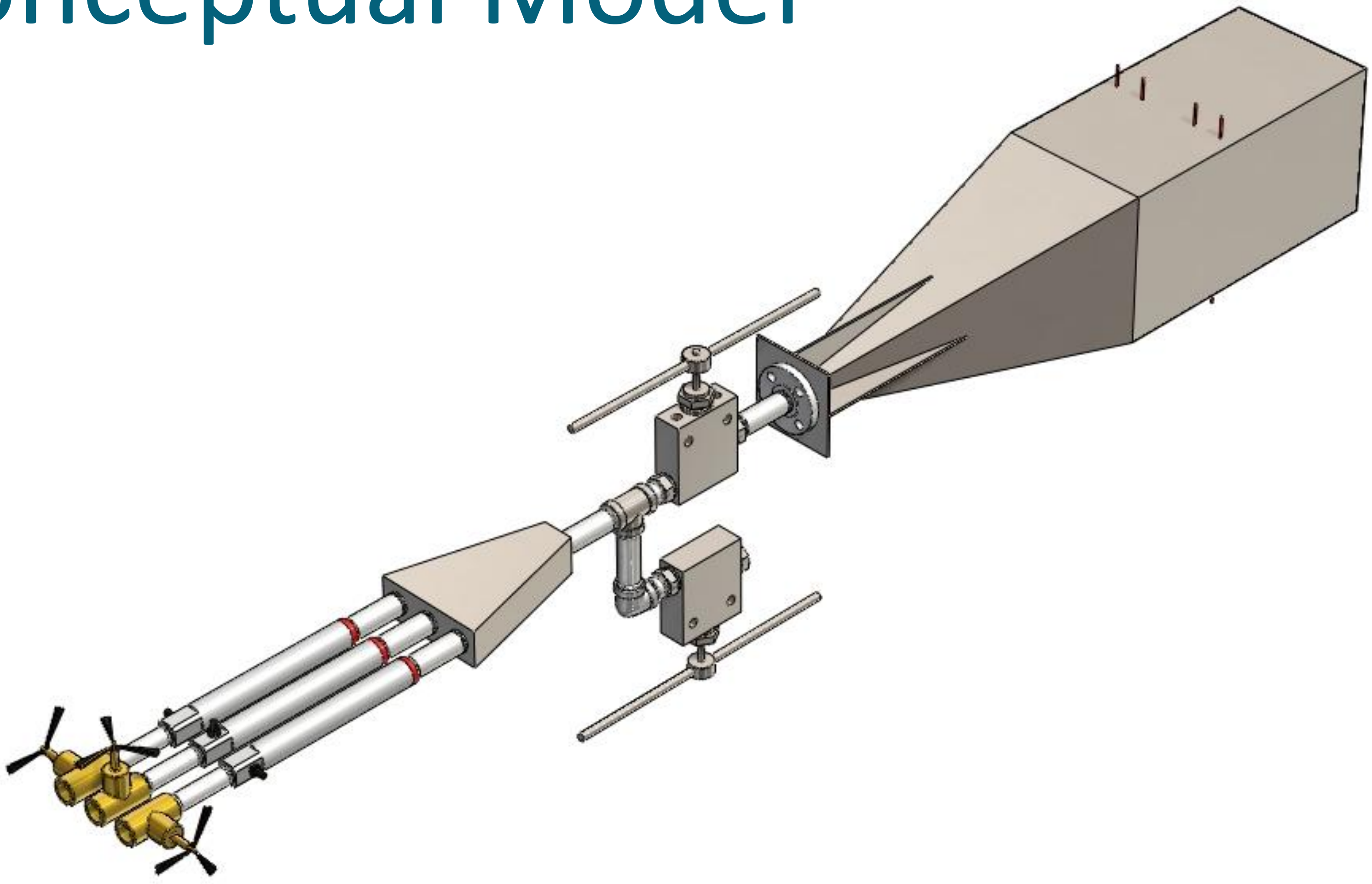


Requirement: Pressure Drop

- Use of orifice plates to control back pressure

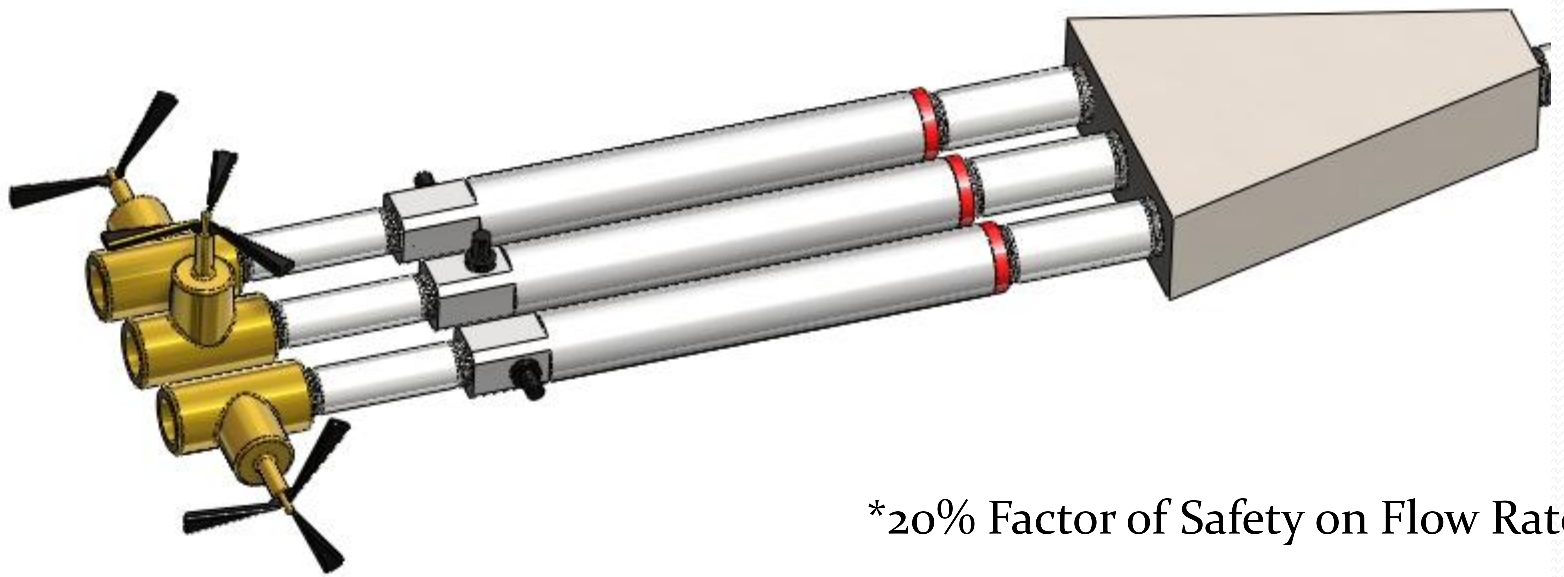


Conceptual Model



Heat Source

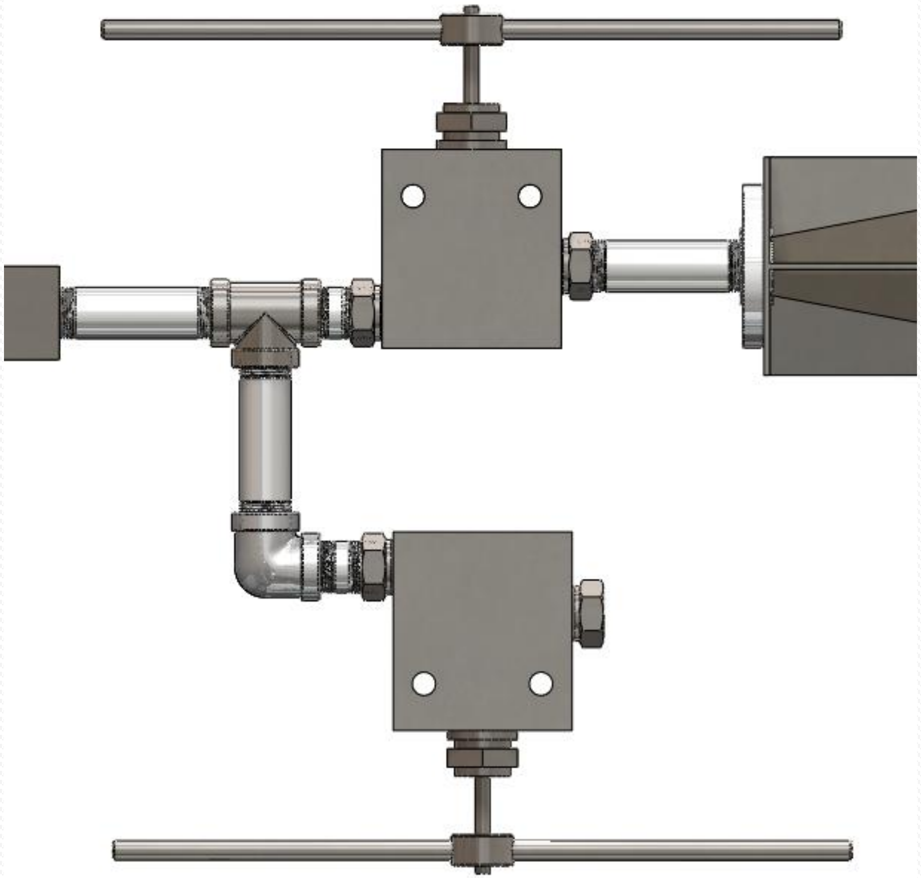
- 3 Tutco Heat Torch 200 at 12.5 kW each
- Maximum Temperature of 1300°F with 240* ACFM
- 1000°F at 270* ACFM



*20% Factor of Safety on Flow Rate

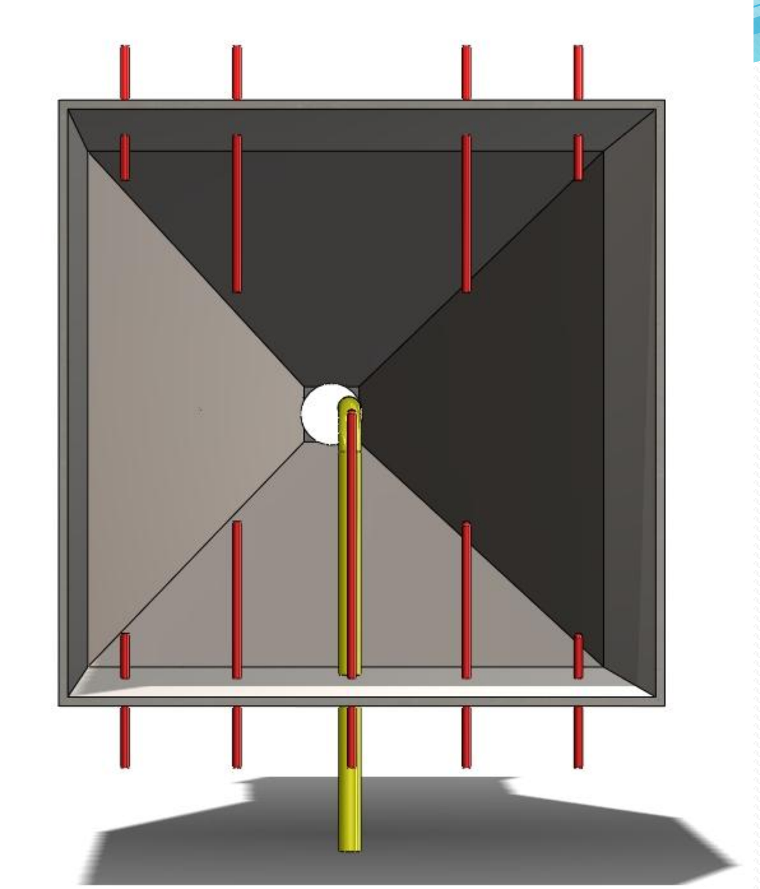
Flow Control

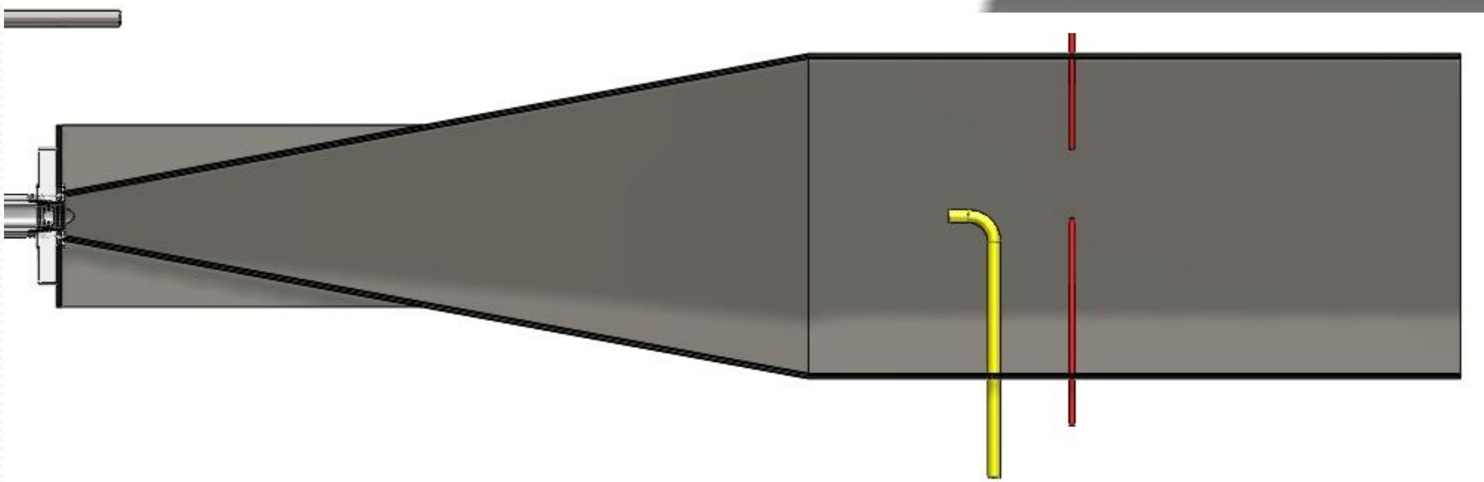
- Stainless Steel Needle Valves
- Maximum Operating Temperature of 1200°F



Data Acquisition

- Temperature Profile from Thermocouple Mesh
- Pressure and Flow Rate from Pitot-Static Tube





Additional Analysis

Analysis Completed	Value(s)
Heat Transfer Through Ducting (at 1200°F)	394 BTU/(hr*ft^2)
Outside Surface Temperature of Duct (at steady state at 1200°F)	416 °F
Duct Deflection Due to Pressure (at 6" H_2O)	9.93×10^6 in
Thermal Expansion Calculations (at 1200°F)	.1307 in / linear ft
Additional Power Required for Humid Air	Adds 1.6kW

Pending Design Considerations

- Total heat (power) loss to the environment
- Uniform temperature distribution
- Uniform flow and velocity profile
- Pressure drops through fittings/heaters
- Airtight seal between filter and duct
- Hearing protection may be required

Future expansion on project

- Higher test temperatures and flow rates from additional heaters
- Direct flame impingement
- Soot loading test
- Additional data acquisition
  - Strain on filter frame
  - CCTV recording of test
- Completely automated test procedure
  - Follows time temperature curve

Conclusion

- After consideration of both designs, electric is most viable
- Complete detailed analysis and design of concept for critical design review in Jan, 2012

Thank you

Questions?

Bibliography

- Orifice plate graphic: www.orificeplates.com
- DOE-EM Nuclear Air & Gas Treatment Survey: NNSA Nuclear Safety R&D Proposals for FY-2012, John Shultz, Ph.D.
- Gas and electric heater graphic: Tutco-Farnam, and EHG Burners respectively