HIGH TEMPERATURE HEPA FILTER TEST UNIT UPGRADES

Final Design Report

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TEAM FLASHPOINT
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Chapter 1 – Introduction

Sponsor background and needs

The Ceramic HEPA Filter Program has been in continual progress for over 10 years at Lawrence Livermore National Laboratory. The goal is to develop a fire resistant filter with better performance (e.g., heat, flame, moisture, corrosion, loading). These ceramic HEPA filters should survive higher temperatures and fires better than existing technology [1]. Concurrent with the development of better filter media, testing must also be undertaken in order to verify predictions about performance with empirical data.

The necessity of such a fire and fire suppressant resistant filter media was made apparent during a fire in a plutonium glove box at the Rocky Flats Plant in 1957. The fire burned 400 out of 700 cellulose based HEPA filters, resulting in Building 71 being contaminated with radiation. The advent of glass- fiber filters proved insufficient as a second fire in 1969 also damaged the filter bank. Figure 1 shows the damage caused.

Figure 1. Pictures of Rocky Flats Fire Aftermath [2]

This led to water spray nozzles in the filter columns to reduce the temperature of incoming gases in the filter. Yearly tests of the fire suppression system breaks down the filter media and limits the lifespan of a HEPA filters to less than 10 years. Due to the hazardous nature of the particulate matter, replacement of HEPA filters is an expensive undertaking.

Previous Development of the HTTU

As it was necessary to have a means to test new filters, the senior project team Icarus was tasked with designing and building a test unit. The test unit had to be capable of simulating fire like conditions to test filter durability and heat resistance. Icarus then designed and fabricated the HTTU. They were successful in manually controlling the HTTU and bringing it up to a temperature of 1005°F with a pressure drop of 6.4 inH_2O across an orifice plate to simulate a filter. Figure 2 shows the test setup of this original unit. [2]

A second team, CPHEPA, implemented a control system for the HTTU. [3] The added control system also implemented a data acquisition system to help facilitate recording test data. Using an ATMega 2650 development board they built a fully automated control system able to operate the HTTU automatically with integrated data acquisition capabilities. They were not completely successful in final development of a user interface, multi-torch control and gating control.

The third team, Team Hi-Top, added the capacity to perform additional tests, a flame impingement test and a leak detection test as well as adding clear view ports and a camera system onto the existing HTTU. [4] Testing verified all the upgrades, although further refinement was advised.

Figure 2. Cal Poly High Temperature HEPA Filter Test Unit [2]

Current State of the HTTU

As the system currently stands, it is a cumbersome system with long run times approaching 4 hours for a full cycle from heat up to cool down. The Gemcowool Mineral Wool insulation used on the exterior of the HTTU is difficult to remove and reattach to the system and many of the smaller pieces have begun to break.

The control system for the HTTU is still under work as part of a graduate student’s master’s thesis. Currently, the graduate student’s laptop is the only device that can control the HTTU. The control system is under retrofit to work on a Raspberry Pi. Control system progress will be updated as the information comes available

Part of the original design considerations of the HTTU was the availability of power at the facilities on campus to power it. The Cal Poly Engines Lab was chosen as the location for testing as it had access to a compressed air supply capable of providing a continuous 330 SCFM at 120 psig, and has an exhaust extraction system capable of removing air at a rate of 1900 SCFM. Finally, the Lab has a 480V 3φ 100A circuit installed in it. As only 20A was being drawn off the circuit to run the exhaust fan, Cal Poly Facilities installed a 480V 3φ 60A drop line. The HTTU and its electrical systems were all inspected by Cal Poly Facilities and are NEC compliant [2].

The HTTU takes almost an hour to come up to an operating temperature of 1000°F. The HTTU can produce airflow in excess of 1300° F; however, the airflow loses over 300°F by the time it reaches the filter [2]. It is possible if allowed to run longer the HTTU would come to a higher steady state temperature, but having to wait longer than an hour for system heat up is impractical.

Formal Problem Definition

The High Temperature Test Unit (HTTU) was commissioned by Erik Brown of Lawrence Livermore National Laboratory (LLNL) to test High-efficiency particulate air (HEPA) filters in conditions up to 1225°F, thereby simulating fire like conditions. The HTTU was originally built by Team Icarus as their Cal Poly senior project in 2011-2012. A second senior project team, CPHEPA, was tasked with developing a control system and fully automatic testing procedures. Finally, Team Hi-Top, was enlisted to add to the capacity of the original HTTU by adding flame impingement testing, transparent view ports, video capability and leak detection.

Tasked with retrofitting the HTTU, a Quality Function Deployment (QFD) diagram was employed to help identify the major areas of concern where efforts would need to be focused. The QFD is presented in Figure 20. QFD and only the results are discussed here. Two main areas of concern identified through the QFD. First, decreasing the temperature losses of the system, and second decreasing the heat up time of the system. Both areas of concern are strongly related. The less thermal energy the HTTU retains, the longer the heat up time and the cooler the steady state temperature of the system. Conversely, the more thermal energy the system can retain, the quicker the heat up and the hotter the steady state of the system.

The specifications from the QFD are presented in Table 1. The items are presented with design target and a tolerance. Tolerances are presented as Min or Max indicating the parameter needs either to be minimized or maximized. All items are quantified by the risk they entail: high (H), medium (M) or low (L). This risk is not in reference to the specific danger of the specification, but rather the difficulty of achieving the parameter. Compliance indicates how the parameter will be verified. Testing (T), analysis (A), and inspection (I) being the three compliance methods used in the table below. The current state of the HTTU does not meet all the necessary specifications outlined in Table 1.

Table 1. List of objectives and specifications

Table 1: List of Design Parameters

Spec #	Parameter	Requirement or Target	Tolerance	Risk	Compliance
1	Maximum Temperature	1225°F at high flow 1150°F at 25 SCFM	Min	H	A,T
2	Heat up time	40 min	Min	M	A,T
3	Low Flow Rate	25 SCFM	Min	H	A,T

The objective of this senior project is to bring the HTTU into line with requirements.

Chapter 2 – Background

Comparable Systems

There are several systems in existence, which provide comparable capabilities to what is needed to simulate fire conditions for testing a HEPA filter. In addition to heating, these systems also provide airflow. Under fire conditions the HEPA filters need to maintain their structural integrity and filtration qualities. A patent search did not reveal any relevant technologies to the testing of HEPA filters at high temperature, but several analogous systems were found.

Institute for Clean Energy Technology (ICET)

The University of Mississippi has designed a high temperature and high flow system (Figure 3) for the Institute of Clean Energy Technology. The system operates at 1000°F and 1000 SCFM. It is currently undergoing a retrofit procedure with a budget of $450,000. The purpose of the system is certification of HEPA Filters.

Figure 3. ICET at Mississippi [2]

Advanced Thermal Systems CLWT-115

The Advanced Thermal Systems CLWT-115 (Figure 4) is a closed loop system designed to test PCB heat sinks at elevated temperatures. It operates at 185°F and 1000 SCFM. While an excellent example of a recirculating design, it has far too small a test chamber to be useful for testing full sized HEPA filters.

Figure 4. Advanced Thermal Systems CLWT-115 [2]

NASA Langley High Temperature Tunnel

NASA Langley designed a high temperature wind tunnel for modelling hypersonic flows (Figure 5). The air speeds go up to Mach 7. It is a good example of a high flow high temperature set up. It is far beyond the scope of a senior project and far too powerful a test apparatus to use with the delicate HEPA filters.

Figure 5. NASA Langley High Temperature Tunnel [2]

Chapter 3 – Design Development

Discussion of Conceptual Designs

The focus of conceptual designs revolved around upgrading the components of the HTTU, mainly the source of heat input to the air and the insulation of the duct section. Due to having to keep the previous groups work in place, the only upgrades that can be made to the HTTU are to the entrance section and exterior insulation of the window section.

Heaters

In deciding which path to take for upgrading the heat input system, multiple types of heating elements designed for industrial air process heating were considered. The system currently has three Tutco 200 heat torches providing heat for the HTTU. Each torch is capable of outputting a maximum of 12.5KW. The torches have a minimum flow rate of 27.8 SCFM to prevent damage to the torches. Because of this, the minimum flow rate for the HTTU will be 27.8 SCFM with one heater running, and 55.6 SCFM with two heaters running. The heaters have a maximum outlet temperature of 1300◦F.

Previous groups considered natural gas burners. The backpressure of the HTTU is relatively low at 6.4in of H_2O, but still too high to operate standard gas burners. Unless there was a large enough budget to commission a custom made gas burner, electric heaters are the only option.

Inline Heaters

A straightforward solution to heating up the system faster and achieving a higher temperature would be a higher capacity inline heater. Sylvania Osram provided several custom designed inline heater choices, however only one of which could achieve higher temperatures. This fact, along with the price point, removed them from consideration. They could be a viable option for a redesign of the system with a larger budget. The capabilities match what would be required to achieve high temperatures at high flow rates. Table 2 shows a price matrix for Sylvania Osram heaters.

Table 2. Sylvania Osram Heaters

Heater	Air Temperature	Voltage	Amperage	Power	Price
Custom	1300◦F	480V	200A	120kW	$35,000
Custom	1300◦F	480V	80A	50kW	$25,000
Custom	1300◦F	480V	60A	30kW	$19,000
SureHeat Max	1400◦F	480V	60A	36kW	$8,000

Blanket Heaters

Blanket heaters were proposed as a means to preheat the steel of the HTTU duct to reduce heat up time and thermal losses of the system. Most commercially available blanket heaters were unable to meet the temperature requirements needed. While heating the steel would improve the performance of the HTTU

and the response time. In an effort to add more insulation and heat the airflow more, blanket heaters were ultimately removed from consideration

Ceramic Rod Heaters

Another heater investigated was a ceramic rod heater, similar to an immersion heater. A ceramic rod heater is essentially a resistance heater within a ceramic housing. They are able to reach temperatures above 2200°F with high watt densities. Several ceramic rod heaters could be inserted through the outer shell of the HTTU in front of the filter face. Not only could they provide high temperatures near the filter face, but also could act as baffles, disturbing the flow and helping keep the airflow thoroughly mixed. It is necessary to take into account the watt density when selecting a ceramic heater, and watt densities over $23W/in^2$ are at risk of overheating in air. Ceramic heaters were not pursued, because their performance at high flow rates will not be able to meet the requirements.

Immersion Heaters

Immersion heaters are similar to ceramic rod heaters, and are designed for low to mid flow rates and higher temperatures. Unlike ceramic rod heaters, immersion heaters use a metallic coil or rod to heat up a fluid, and are designed in a wide variety of configurations, such as flanged, over the side and inline. Most of these designs are also available in a wide variety of watt densities, but the maximum temperature is limited to about 1600 °F at low watt densities.

Duct Heaters

Duct heaters are a variant of immersion heaters designed to sit inside an air duct. Designed for high flow applications they are unable to heat air effectively over a range of more than several hundred degrees. The inability to raise airflow to the needed operational temperatures removed them from consideration.

Insulations

Aerogel

Aerogel is a synthetic porous insulating material. Formed by supercritical drying of a silica gel, Aerogel is nearly 99% air. Coupled with excellent thermal resistance to all modes of heat transfer it also has a very low density of approximately 1 kg/m^3. The very low thermal conductivity coupled with the extremely low thermal mass of Aerogel makes it a very effective and efficient insulator. The main problems concerning Aerogel are the cost and means of application.

Most industrial applications of Aerogel are external where banding or an adhesive overlay is used to secure the Aerogel sheets. Any methods to attach the Aerogel on the inside of the HTTU would need to be mechanical in nature as adhesives to attach the Aerogel to the steel are either non-existent, or extremely proprietary.

Refractory Cements

Precast cement blocks and coatings are standard practice for situations that combine storing or transferring fluids at high temperatures. They are readily available in a number of precast forms and have the ability to be custom cast to specific needs. While the needed amount of cement would have a much higher mass than Aerogel would, the insulation properties of the two are nearly identical. Casting refractory cements involve a long and delicate curing procedure to ensure all water content has been baked out. Failure to cure the cement correctly can lead to cracking in the cement, and the possibility of shattering and exploding of the cement. As such, refractory cements are a viable option for insulation, but the curing process and risks make them an alternate choice.

Composites

The use of composites, either as an insulation or a replacement for the steel ducting of the HTTU was highly attractive because of their ability to form complex geometries easily, and their lightweight. Unfortunately, outside of highly involved and costly manufacturing techniques, almost no composite resins are designed for the extremely elevated temperatures that are going to be experienced in the inlet section. It is possible to integrate composites into a structural purpose as long as they are properly insulated; however, ensuring that the composites are thermally protected outweighs the benefits of using them as structural elements when metals are both easier to fabricate and cheaper to obtain.

Ceramic Blanket

Similar in design to mineral wool, ceramic blankets are flexible. Ideal for wrapping ductwork and high temperature pipes, many ceramic blankets have continuous operating temperatures greater than 2000°F. Low thermal conductivities provide excellent insulation properties, especially when secured with aircraft grade stainless wire ties.

Promat Microtherm Panel

Promat Microtherm panels are a high silica content particulate board covered in a glass fiber coating. For temperatures above 1000°F, a quartz cloth coating is recommended. The rigid panels are manufactured by compressing silica particulate. If the cloth coating breaks or tears the particulate can be released; however, Promat panels have an extremely low thermal conductivity and can be shaped and sealed with relative ease. See Appendix D for component datasheets, and information on cutting and sealing Promat panels.

Other Concerns

Exhaust System

The original HTTU uses a 6 inch diameter stainless steel ducting tube for exhaust tubing. This tube interfaces with the exhaust fan system in the Cal Poly engines lab. Using the tubing is a difficult undertaking as it is heavy and unwieldy. Modifications to the system will be looked into given the amount of funding left over from the necessary modifications. While testing the HTTU it was observed that after 5' of ducting, the exhaust was cooled sufficiently to no longer affect the metal color. With the HTTU being redesigned for higher thermal efficiencies, the length of exhaust hose that is required to cool the exhaust sufficiently could increase. Until testing can verify the amount of tubing needed to cool the

exhaust sufficiently to change to a smaller hose, different material or both, the hose will be left, as it is to ensure no personnel are exposed to a potentially dangerous situation.

Data Acquisition

While the main goal of this project is the redesign of the HTTU to be more thermally efficient and heat up quicker, also requested by LLNL was acquiring data about the flow characteristics. Previous teams had only taken data from the center of the duct. Also with only several runs of the system, there is very little data about the flow inside the HTTU. Taking temperature readings and differential pressure readings with a pitot tube will help to provide this information.

Concept Selection

Due to initial budgetary constraints, the design path pursued was making the HTTU much more thermally efficient through upgraded insulation sections. The research into different styles of insulation led to two distinct styles of modification. The first design kept the stainless steel sections of the existing HTTU and involved changing out the mineral wool with Aerogel wrapping. The second design utilized removing the stainless steel sections of the HTTU and replacing them with cast concrete sections. Both options have multiple variations, which have been analyzed with research and weighted decision matrices.

By use of Pugh Matrices Table 4: Pugh Matrices and weighted decision matrices Table 5. Decision Matrix several concepts were developed. The Pugh matrix easily identified several major improvements, which could be made. Changing the entrance geometry, adding interior insulation and changing a heater were all identified as very promising. After the ideas were generated, which are outlined in more detail below, the weighted decision matrix was utilized to select the final design.

Concept Design 1

Design 1 is to insulate the entrance region on the HTTU with Aerogel on the inside and outside. Aerogel is the best insulator on the market and can be cut and fastened to the HTTU with relative ease on the exterior of the system. Unfortunately, there are relatively few manufactures of Aerogel and those contacted have not responded to any form of correspondence.

- Benefits of using Aerogel
    - Extremely low thermal conductivity
    - Easy to shape
    - Thin, compatible with current entry region setup
- Drawbacks of using Aerogel
    - Expensive
    - Hard to find a reputable distributor
    - Unknown if adhesives are compatible
    - Problems supporting operation above 1200°F

Because this design is compatible with the HTTUs existing stainless steel sections, the bolted flanges should be changed to a quick-release style system with reusable gaskets. To do this, the current flanges

would need be removed, and a groove would be welded to one side of each entrance region section (GTAW welding process). This would be lined with a braided ceramic or aerogel gasket that would seal upon the pressure from the tongue of the next section. A diagram can be seen in Figure 6.

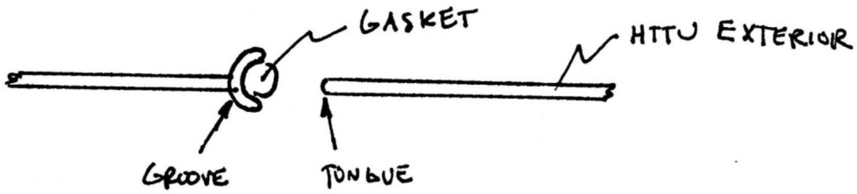

Figure 6. Tongue and Groove Design

Concept Design 2

Precast cement blocks and coatings are standard practice for situations that combine, store or transfer fluids at high temperatures. Because of this, we were able to find a number of highly engineered materials from reputable suppliers and manufacturers. Concept design 2, as shown in Figure 7, incorporates the use of precast cement sections of Plicast Airlite refractory cement. Because cement needs to go through an intensive heat up schedule, modular sections are to be pre-cast with Plicast Airlite, small enough to be fired in the kiln at Cal Poly. Both of these materials have properties desirable for this application, with thermal conductivities between 0.18 and 0.3 W/m-K. Data sheets for these materials can be found in Appendix C.

Some of the benefits of using a refractory cement as insulation include low thermal conductivity, high durability and low cost. Despite these advantages, cement still has a large thermal mass leading to longer heat up times. The larger concern; however, is the intensive curing process. A long, controlled bake out is required to cure the cement and drive out any residual water packets. Failure to do so can lead to cracking in the cement, and even catastrophic failure. If such a failure were to occur, it would be extremely hazardous and potentially destroy the HTTU.

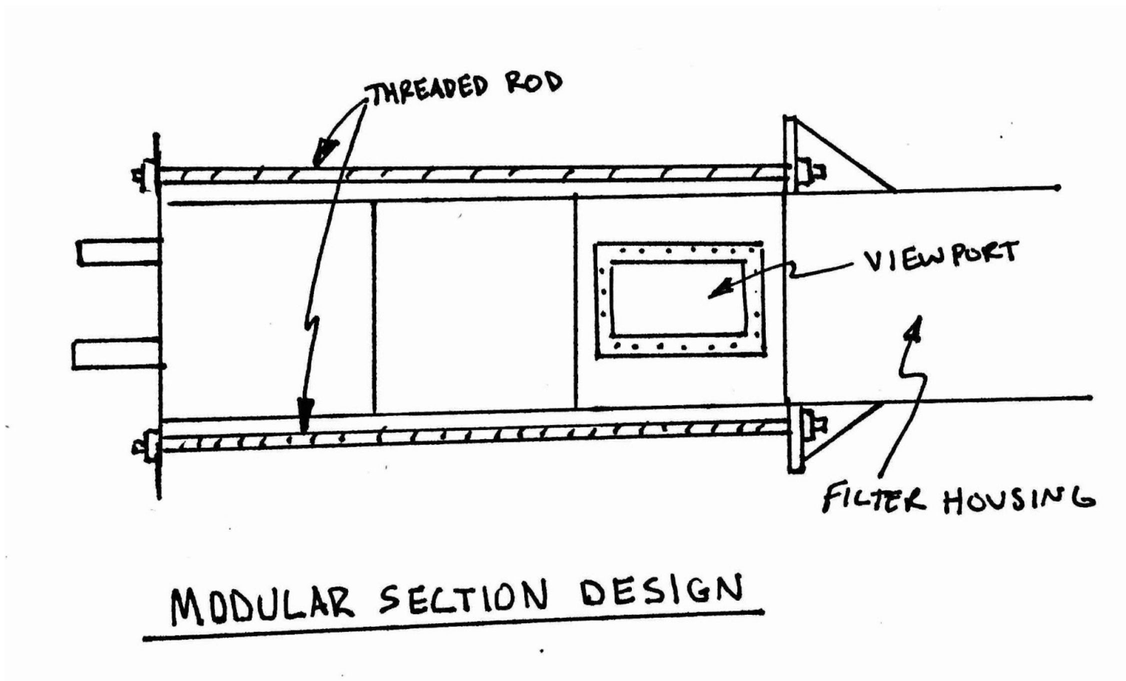

Figure 7. Modular Design Section

Supporting Preliminary Analysis

Analysis of the preliminary concepts showed much promise, while also bringing up a few concerns about how feasible the actual results would be. The new designs were analyzed using convective heat transfer and one-dimensional conduction through a flat plate to determine the improvement over the initial design. The base line was the no cement, mineral wool insulation. Calculations performed in EES showed an improvement of 40°F at the filter face for 2 inch of cement with a mineral wool wrap as shown in Figure 8. This improvement was not as drastic as anticipated. Detailed descriptions of the analysis process is found in Appendix E.

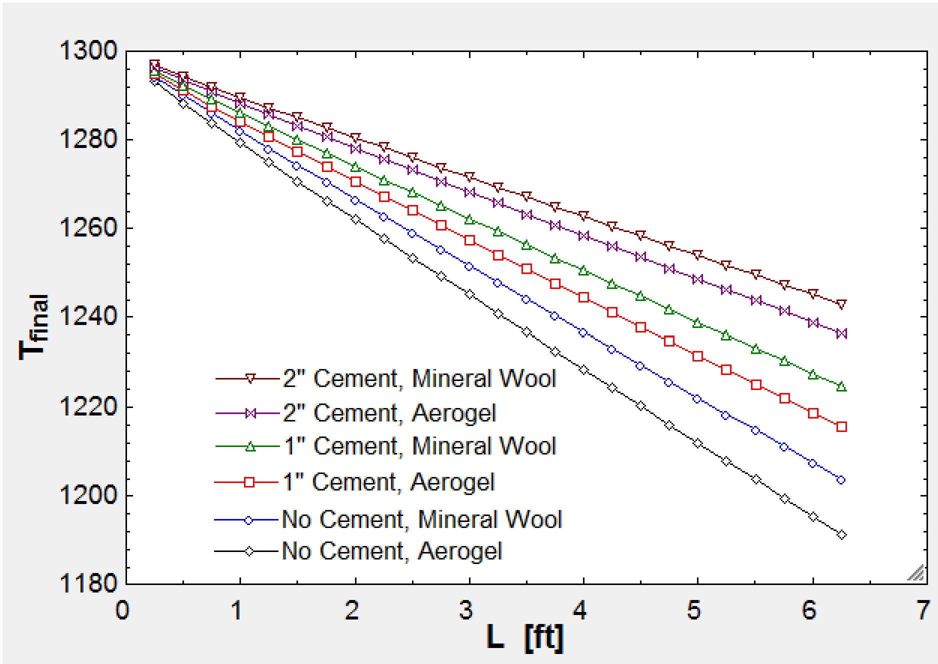

Figure 8. Comparison of different insulations for use on the HTTU

A failure mode analysis, as detailed in Appendix E, showed that the use of cement was risky. From a fabrication standpoint, the cement has such an intensive curing schedule to ensure structural integrity and this curing time would become a very high-risk issue if done incorrectly, as the cement has the capability of fracturing in an explosive manner if not cured properly. Another issue was with the use of Aerogel as an insulator. In the thicknesses that it is sold in, it would take multiple wrappings just to be on the same level of insulation as the existing mineral wool. This, along with its lack of high temperature rating, led the designs in the direction of changing the heating system and not just upgrading the insulation.

Chapter 4 – Final Design Statement
Overall Description/Layout with labeled solid model

Most of the preliminary design was changed due to feedback from the sponsor, further communication with insulation suppliers, lessons learned from previous research, supplementary calculations, and incubation. Major changes from the previously considered designs include the addition of an immersion heater, removal of one of the torch heaters, and an insulation overhaul. The setup of the new heating system will use the torch heaters in parallel to preheat air that is blown directly onto the immersion heater. Figure 9 shows the final assembled design. Our calculations indicate removing one of the Tutco HT200 torch heaters would not be detrimental to the performance of the HTTU, and the performance gains from the 1600°F immersion heater will be instrumental in achieving the design requirement of 1225°F at high flow and 1125°F at low flow. The maximum SCFM rating of the heat torches is 100 SCFM each, but as shown in Appendix E, the available electrical energy is not enough for that high of flow. This, combined with the power limitation of 39.9 kW imposed on the HTTU, is what makes the HTTU ideal for lower flow rates.

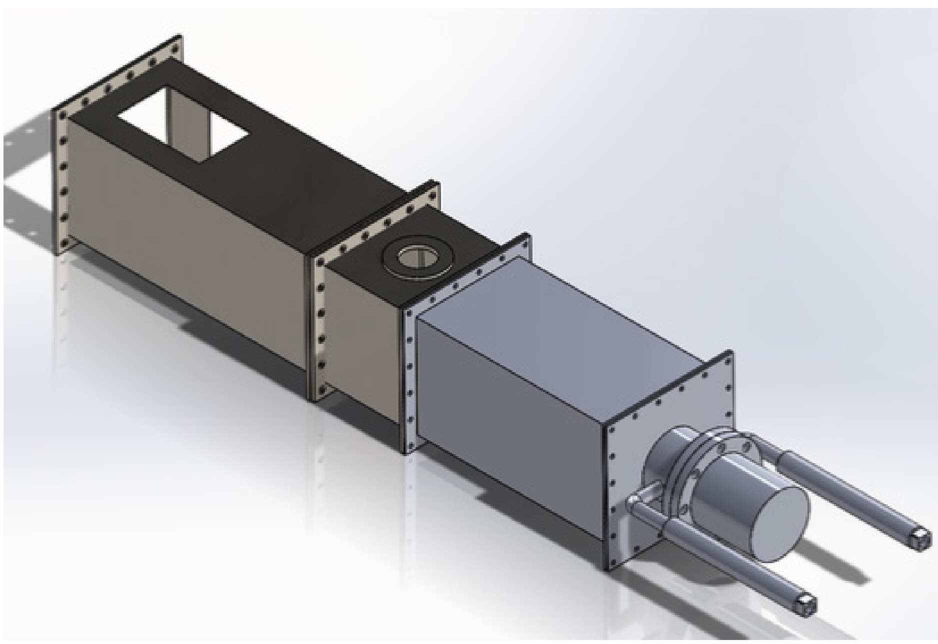

Figure 9. Modified HTTU Assembled

After consideration, it was decided to replace one of the heat torches with an immersion heater capable of reaching higher surface temperatures. Figure 10 demonstrates the new heater arrangement. At low flow rates, the immersion heater is a more efficient heat source. The heat torches will be the first heating stage, and the flow exiting the heat torches will be directed into a manifold, and consequently flow over the immersion heater. The final design calls for the immersion heater to be housed within a 6 in schedule 10 S stainless steel pipe welded in inside the existing 24-inch duct section of the HTTU. Inside the pipe, an array of 12 guidance fins of 18 ga 304 stainless steel run axially down the pipe. An overview of these parts can be seen in Figure 11. A very attractive feature of this design is the ability to reuse most of the existing HTTU, keeping material and fabrication costs to a minimum.

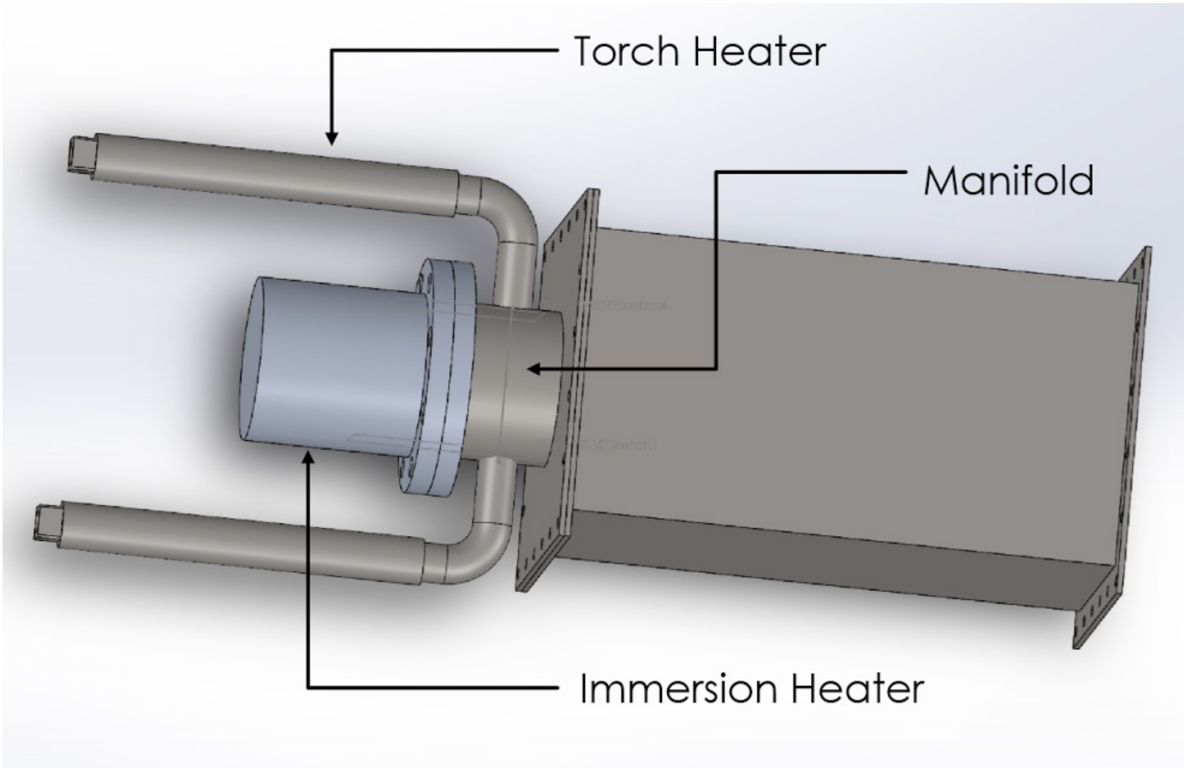

Figure 10. Entrance section

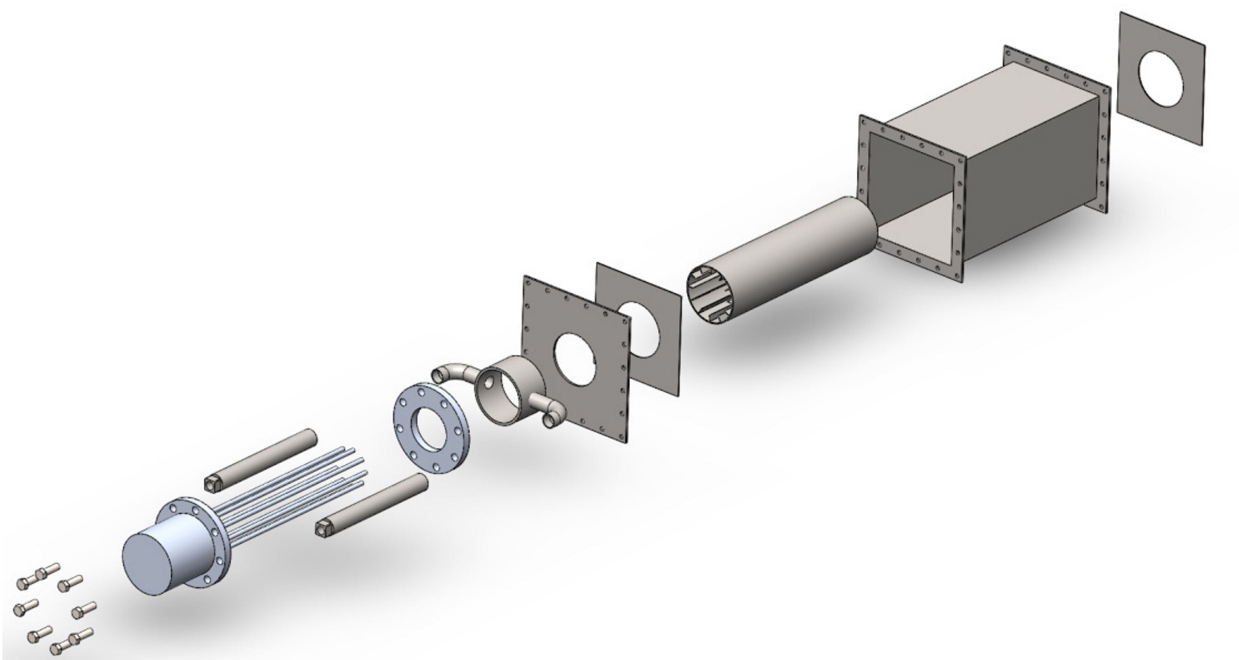

Figure 11. Exploded assembly

Detailed Design Description

Manifold

The new manifold section will be constructed with two bent sections of 1-¼ inch schedule 10S stainless steel pipe and one four-inch section of schedule 40S stainless steel pipe. The holes in the 6 inch pipe for the 1-¼ inch pipe connection will be drilled using a 1-½ inch drill bit considering the inside diameter of the schedule 10 pipe is 1.44 inches. This gives a step on the inside of the pipe so it can be welded with a ⅛ inch fillet all the way around. The outside will also receive a ⅛ fillet all the way around, and all stainless welds will be completed with the TIG process using 308L filler metal and a 2% thoriated tungsten electrode. The manifold will then be welded to the ¼ X15x15 inch Faceplate with a 3/16 inch fillet weld all the way around to seal the pipe as shown in Figure 12. The manifold needs to be bolted to the immersion heater so a 5 inch ANSI stainless steel flange will be welded to the manifold. Detailed drawings with weld diagrams can be seen in Appendix B.

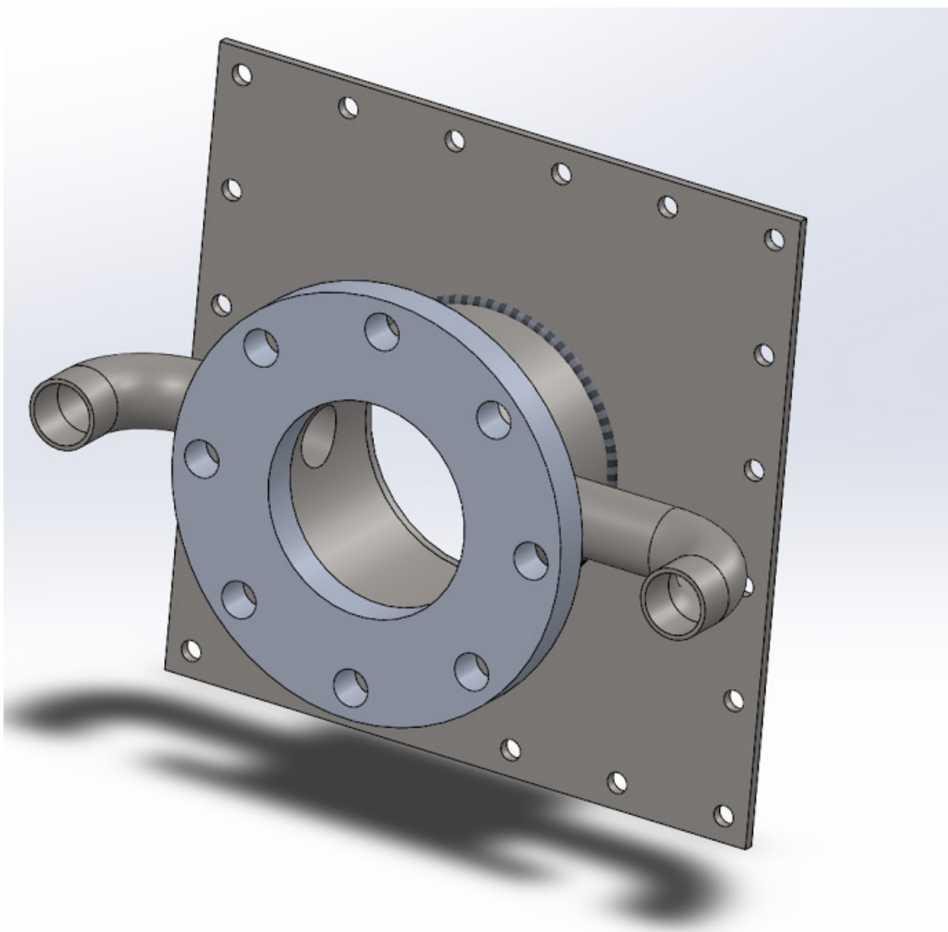

Figure 12. Manifold and face plate

Faceplate

The faceplate is the ¼ inch stainless steel plate that bears the weight of the immersion heater, torch heaters, and manifold. It has holes that match up to the flange bolt pattern. The current faceplate on the

HTTU has eight holes for torch heaters, and would require extensive fabrication to be reused in the new design. Team Flashpoint located an extra faceplate with holes already drilled for mounting to the HTTU, but this will not be used in the assembly as there is no way to machine out the hole accurately. It is easier to send it out to be waterjet cut. The faceplate will have a 6 inch hole drilled through the center, and locating this hole perfectly is of utmost importance for ease of fabrication. To ensure the accurate location of the hole center plane datums were used on the dimensioned drawings. All holes for the bolt pattern have also been referenced to this datum. For detailed drawings, see Appendix B.

Immersion Tube

The immersion tube will be constructed from a 6 inch schedule 10S stainless steel pipe. Because it is sandwiched in between two 12-gauge stainless steel plates, its total length will be under 24 inches, approximately 23.79 inches. Appendix B contains the detailed drawing. Twelve 18 gauge stainless steel fins will be welded parallel to the flow of air through the immersion tube, in a circular pattern around its circumference. The twelve fins allow for a minimum linear clearance between adjacent fin tips of 1.21 inches, just enough room to clear a TIG torch at the appropriate angle for fabrication. The fins will receive 1/8 inch fillet welds, stitch welded 2 inch O.C in ¼ inch lengths.

The immersion tube will be wrapped with a two-inch layer of Maftec® ceramic fiber insulation prior to its final placement in the duct section. The Maftec ceramic fiber insulation will be secured to the exterior of the immersion tube with .032 inch stainless steel safety wire. Special consideration of the heat input will need to be taken when welding the ends of the immersion tube to the 12 gauge stainless steel plates at both end, because welding temperatures of stainless steel can exceed 2800°F, which exceeds the maximum temperature rating of the insulation. Detailed drawings of the immersion tube can be found in Appendix B.

24 inch Duct Section

The 24-inch duct section is important because it houses the immersion tube, and the immersion heater. The exterior shell of the 24-inch duct section was already built, which is one of the benefits of its design. The open ends of the 24 inch duct section will each be capped with a 12 gauge 304 stainless steel plate, and will have a ⅛ inch flat weld all the way around. The 12 gauge plates will have a 6.375-inch hole bored directly in the center. The accuracy of this hole is of the utmost importance, because it helps locate the immersion tube, and needs to mate perfectly with the hole in the faceplate. The 6.375 inch hole will be slightly larger than the 6.36 inch inside diameter of the pipe so that the pipe can be welded to the plate with a ⅛ inch fillet weld. Assembly drawings for the 24-inch duct section can be found in Appendix B.

Assembly

The resulting three duct sections will be bolted together with ½ inch stainless steel bolts. The immersion heater calls for larger ¾ inch bolts, and because the ANSI flanges are steel, hardened steel bolts will be used to bolt the immersion heater to the manifold. A thin layer of high temperature sealant will be applied to the mating surfaces of the ANSI flanges, and around the 6 inch openings between the faceplate and the 24 inch duct section. The grafoil gaskets holding the existing faceplate to the 11 inch section will be reused.

Material, Geometry, Component Selection

Watlow 5 Inch ANSI Flanged Immersion Heater

The main design criteria for selecting an immersion heater were as follows:

- Ideal Watt density for forced air applications
- Length suitable to fit within existing 24 inch section of HTTU
- Highest possible Maximum operating temperature
- Power rating under 14.9 kW (Appendix E)

The immersion heater selected for the HTTU is a Watlow FNNA25J5X ANSI 5 inch flanged immersion heater rated at 14kW. Due to the restrictions of NEC only 39.9 kW of the available 49.8 kW from the engine's lab at Cal Poly can be utilized. The specific heater chosen has a watt density of 23W/in^2, ideal for forced air applications. In general, forced air applications use immersion heaters with watt densities under 25 W/in^2 because the viscosity of air is so low. More thermally conductive fluids such as water can handle higher watt densities. Choosing a proper watt density for the immersion heater keeps the possibility of overheating to a minimum, and maximizes the efficiency of the convective heat transfer to the fluid.

The next goal was to make the immersion heater was compatible with the existing 24 inch section of the HTTU. Because the FNNA25J5X is 25.5 inches in length, letting the extend outside of the HTTU duct section by 5 inch not only allowed the heater to be housed completely within the duct section, but also allowed for the manifold to be manufactured on the outside of the duct. (see Figure 13). The first four inches of the immersion heater are unheated, and thus there would be little benefit in attempting to ensure the entire length of the heater was inside of the duct (see Figure 13).

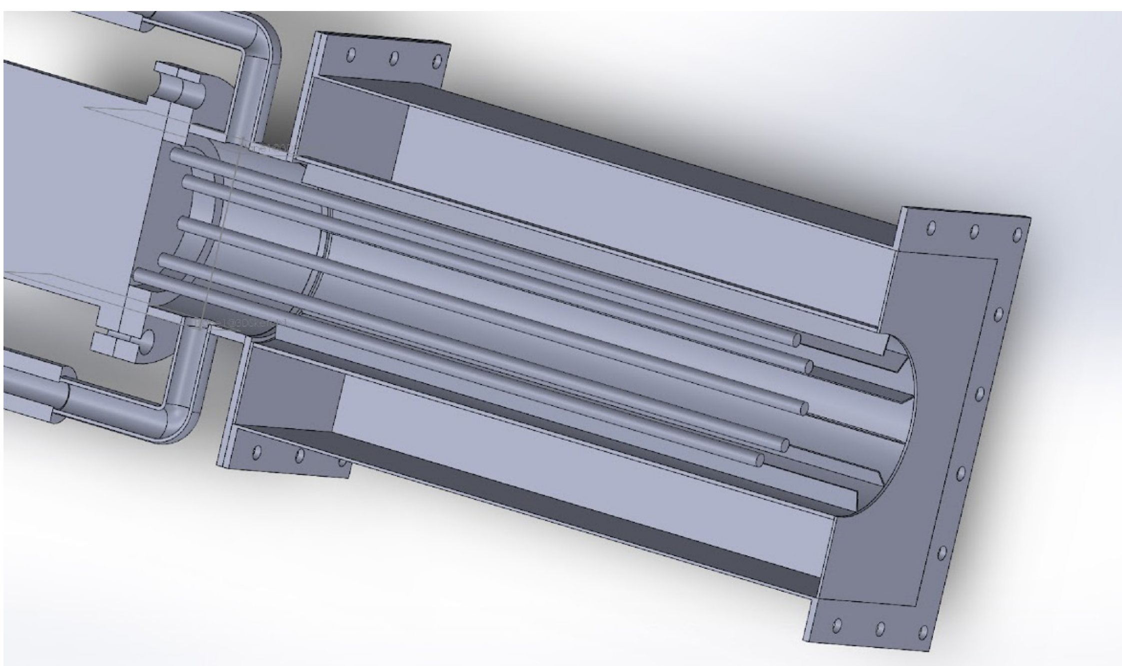

Figure 13. Entry region cross section

Immersion heaters use many different materials for their heating elements, but few reach temperatures as high as Incoloy. An immersion heater was selected with Incoloy heating elements because of its ability to maintain continuous operating temperatures of 1600°F (see Figure 14). The control system will be utilized in conjunction with a Watlow K-type thermocouple to maintain 1600°F surface temperature.

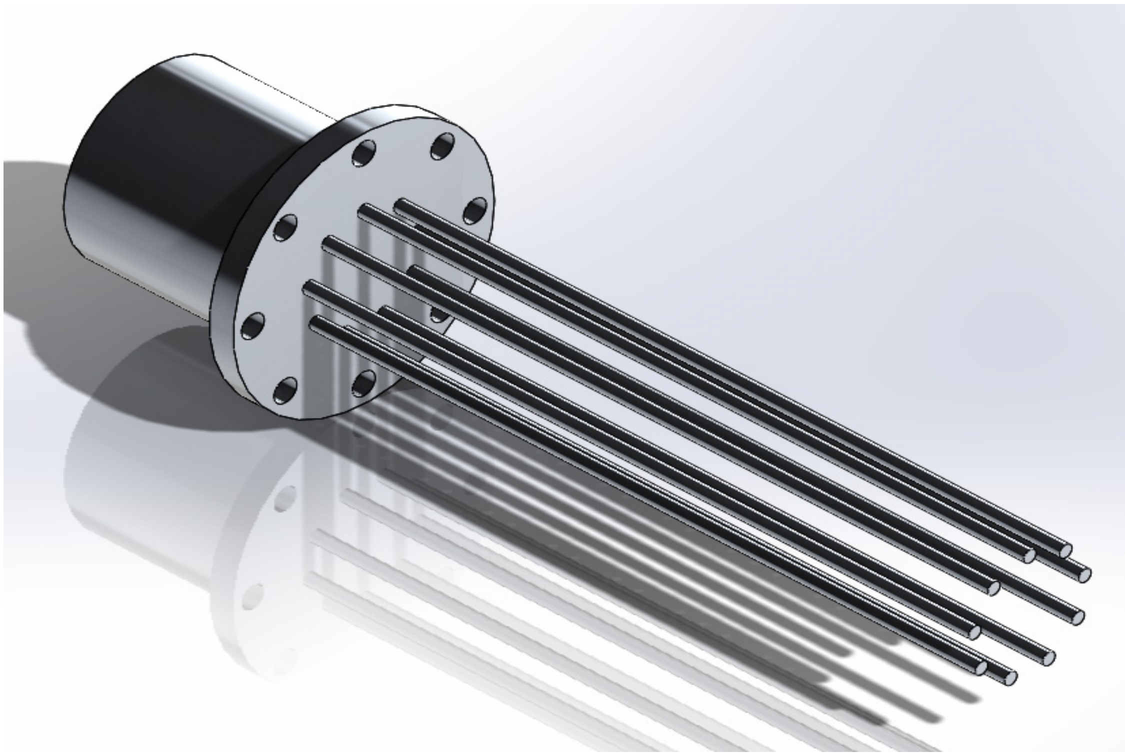

Figure 14. Immersion heater

Insulation

Maftec Ceramic Blanket

By the time the previous teams had completed their projects, the mineral wool was beginning to deteriorate. Because of the complex geometry of the viewport section, the mineral wool had to be cut into small pieces, and as a result, it was near impossible to remove the insulation and re-install it correctly. The mineral wool insulation is also composed of thin, sharp fibers, and workers must wear long sleeves pants, and a respirator when handling it. Because of the relatively inexpensive price of Maftec, Team Flashpoint decided the mineral wool insulation must be replaced with something more durable and easier to work with before continuing research. The HTTU will now be wrapped in its entirety with Maftec ceramic fiber insulation. The method of installation is shown in Figure 15. The insulation is manufactured by Morgan Thermal Ceramics, and sold in rolls. Maftec does not have fibers or particulate that can be inhaled or will irritate the skin of workers, and can be cut and shaped easily. Because it remains flexible up to 1600°F, the insulation should remain easy to work with throughout future improvements and modifications of the HTTU. Maftec does not smoke, and has a maximum operating temperature of 2400°F. As it is pliable, Maftec can be installed by fastening it with .032 ga SS safety wire. The wire itself is inexpensive and can be easily cut to remove the insulation and access the ductwork. Conversely, it can be re-installed easily. Both of these processes will be much easier to execute than the previous banding method used with the mineral wool. See Appendix D for more information on Maftec ceramic blankets.

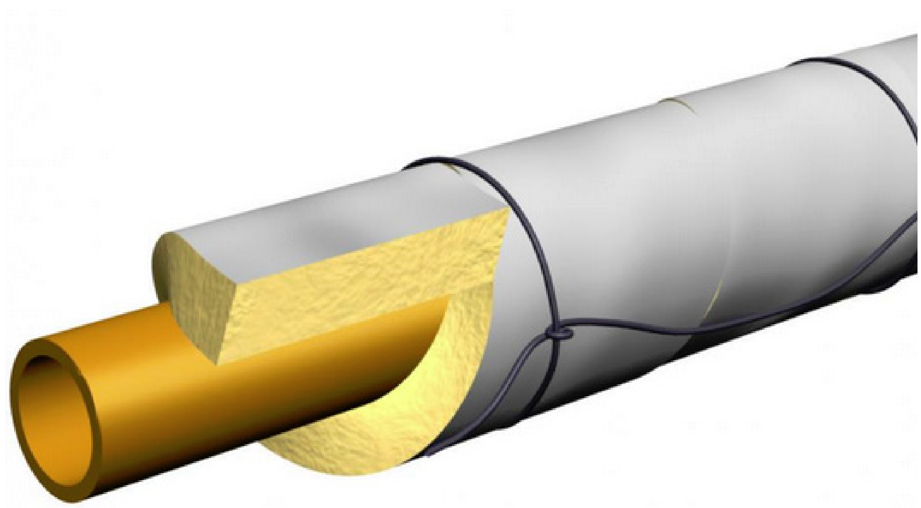

Figure 15. Wire wrap around insulation

Pyrotape 682-TB Thermal Barrier Ceramic Tape

Pyrotape is a flexible, thin, adhesive backed insulation tape capable of enduring operating temperatures up to 2500°F. Pyrotape will be used to insulate the entire manifold section. Pyrotape is shown in Figure 16. The tight fit and complex geometries of the inlet manifold cannot be effectively wrapped in the ceramic blanket. By using the 1 inch wide tape, the manifold can be insulated, preventing heat loss by directing the flow of heat downstream. To ensure the Pyrotape stays adhered to the 1-¼ inch section of the manifold .032 gauge stainless steel safety wire will be used to secure the ends of each run of tape, similar to fiberglass tape on racing headers. See Appendix D for more information on Pyro-tape thermal barrier ceramic tape.

Figure 16. Pipe wrapped in Aremco 682-TB Pyro-Tape

AREMCO 840-M High-Temperature High-Emissivity Coating

In an attempt to extract the maximum amount of radiative heat transfer from the immersion heater to the surrounding immersion tube and fins, the inside of the tube and the fins will be coated with AREMCO 840-M High-Temperature High-Emissivity Coating. 840-M is an exciting new product released on the market in November 2014 that can provide an emissivity greater than 0.9 to stainless steel at operating temperatures of up to 2000°F. It is effectively a high temperature paint that cures in under an hour and will be applied by Team Flashpoint.

Incorporation of Existing Elements

As the ducting of the existing HTTU is in excellent condition, all of the existing duct sections will be kept in service. The longest section of the HTTU will be removed, and then the pipe housing the immersion heater will be installed within it. The short entry region, which contains the pressure relief burst disk, will be installed after the 24 inch duct section (see Figure 9). By keeping both sections, the flow is given more distance to develop. Fully developed flow would require a length equal to 10 diameters of the HTTU (almost 10' of straight undisturbed flow through the duct, longer than the entire HTTU) to completely develop and the more developed the flow is, the more even the temperature distribution on the filter face.

The window section, the section where the filter will be held, and the exhaust hose will all remain assembled in their current configuration. The insulation around the viewport section will be redone, but this will only affect the exterior of the section.

Analysis Results (Details in Appendix E)

Heat loss

Mitigating heat loss was a primary concern in the new design. In the form the HTTU is currently assembled, the flanged plate to which the torch heaters attach is uninsulated. With the torch heaters discharging directly into a large duct, the airflow volume expands rapidly. This rapid expansion causes a large velocity gradient at the entrance of the HTTU, and creates eddy currents. These eddy currents are continuously transferring heat to the ¼ inch stainless steel plate at the front of the HTTU, and with such a large uninsulated mass of steel directly connected to the heaters, much of the thermal energy being put into the system is being lost to the surrounding environment.

With the new design shown in Figure 17, the air is expanded in two stages; the 6 inch stainless steel immersion heater tube, and then into full 12 inch by 12 inch duct. With a much less abrupt expansion, and a thorough and comprehensive insulation, not only will much less steel be exposed to possible eddy currents, but all exposed steel will also be insulated preventing free convection directly on the metal itself.

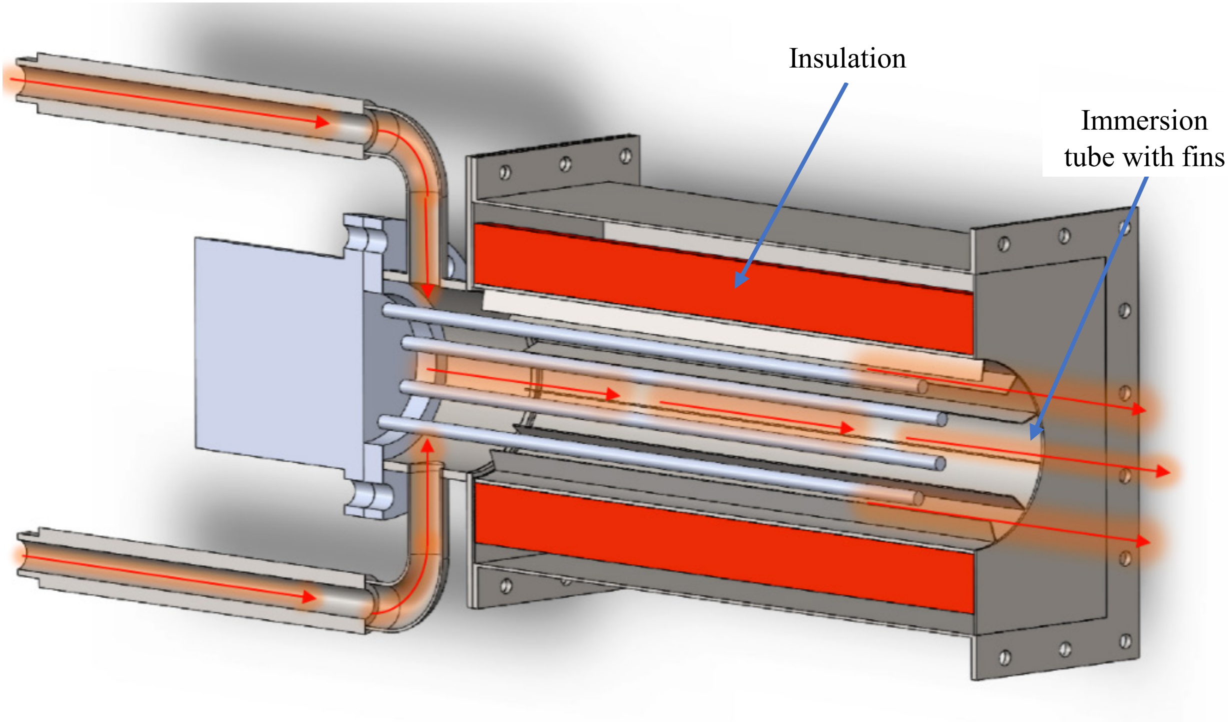

Figure 17. Cross section showing airflow

Heat addition

The existing HTTU can only lose heat after the air exits the torch heaters at the end cap. With the new design, the HTTU has a 1600°F heating element inside of its ducting, and twelve 18 gauge fins radiating heat because of being irradiated by the immersion heater. Consequently air moving through the HTTU gains heat in the first two feet, and has much less surface area for heat loss due to there being a 6 inch pipe as opposed to the original 12 inch x12 inch duct. The immersion heater takes the air that comes out at 1250°F and boosts the heat as shown in the $T_{out,G}$ line of Figure 18. The effects of adding fins to the pipe were investigated and as shown, the fins add about 40°F to the flow. The effects of this analysis justified the use of fins in the flow area. Appendix E details the equations used and calculations for this.

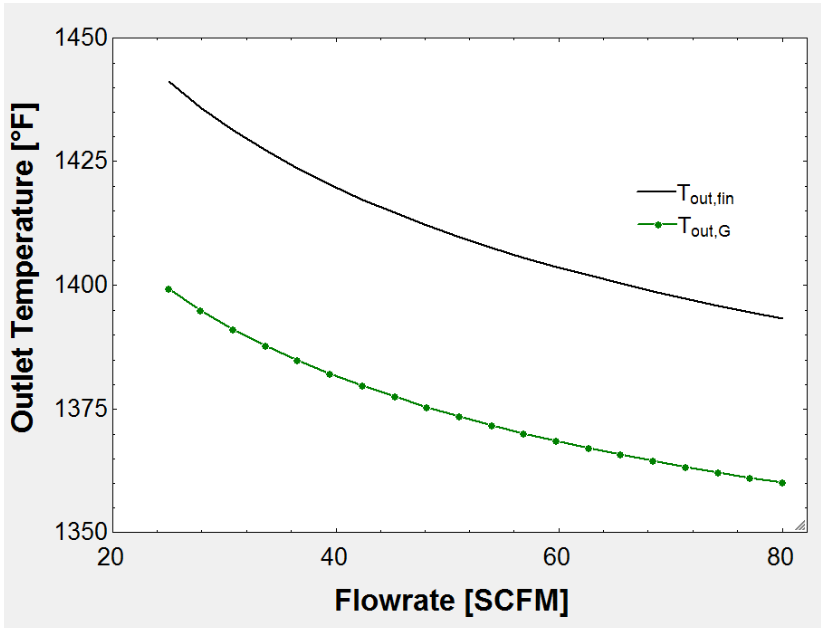

Figure 18. Effect of adding fins to the immersion tube

Insulation improvement

To determine the improvement the entrance section changes would bring, the HTTU was analyzed using conductive heat transfer through an insulation stack. The assumption was made that the internal air temperature of the HTTU in both cases would be 1300°F. An introductory heat transfer book [5] was consulted and it was determined the best model for this situation would be a convective stack. Using EES, the heat transfer coefficient was solved for each change in geometry. The exterior convective heat transfer for the atmospheric air surrounding the HTTU was an assumption from a thermal science lab experiment that was determined empirically. By plugging in the properties for each material in the insulation stack, an overall heat transfer coefficient was established. The result that the new insulation performs better is no surprise (see Figure 19). By reducing the heat transfer area and thickening the insulation, the given equation shows a notable improvement. For more detailed description refer to Appendix E.

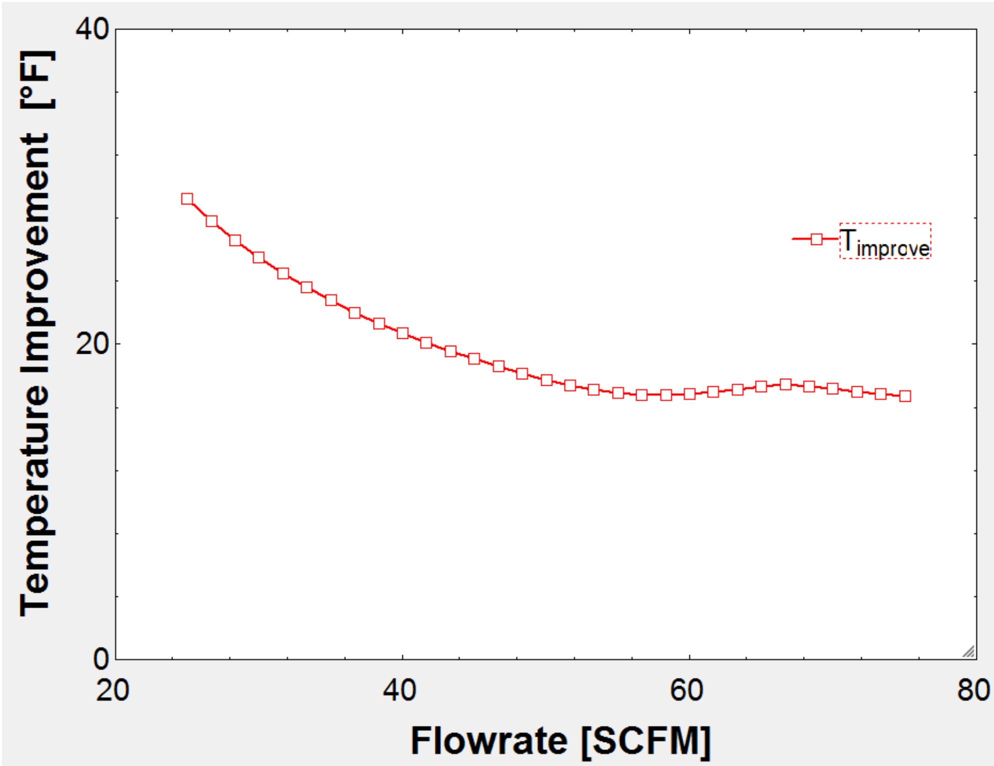

Figure 19. Temperature improvement due to insulation

Cost Analysis

A comprehensive cost analysis was conducted for all materials, fabrication processes, and travel expenditures. Assembly and fabrication was primarily preformed at on campus shops to mitigate cost, the entirety of the project being accomplished for under $5000. A detailed list of expenditures can be found in Appendix C.

Safety Considerations

FMEA

As part of the design analysis failure modes and effects analysis (FMEA) was used to try to identify areas in which the design could fail. The safety consideration were derived from the work done to produce the FMEA. The FMEA is included in Appendix E.

Electrical

The system uses extremely hazardous amounts of electrical power. The high voltage side, which powers the heaters, is insulated from the low voltage side to prevent any ground loop crossover. All electrical housings used are UL listed, and all conductors are compliant under the applicable NEC

sections. Appendix E, Electrical Calculations, show the requirements of the system for conductor size. Switching out a heat torch for a larger capacity immersion heater would require higher overcurrent protection. When the HTTU was built, the heaters were wired with 10 AWG conductors while code only required 12 AWG. This overbuilding meant the HTTU would not need to be completely rewired as the immersion heater necessitates 10 AWG.

Overcurrent protection needed to support the 14kW immersion heater is in excess of the 20 A circuit breakers and cartridge fuses in the system currently. Upgrading to 30 amp circuit breakers and 25 amp fuses provided the appropriate protection.

The connector used is a 480V pin and sleeve connector rated IP67, watertight up to a meter under water, providing adequate protection for the purpose of the HTTU.

Heat

The HTTU produces extreme temperatures. The system is only to be run when attached to the engines lab exhaust fan to ensure proper purging of all hot exhaust from the system. When in use a 10-foot safety zone is to be observed around the entire HTTU and no one is to approach nearer for any reason. Shut down, including emergency shutdown will be accomplished through the control system. As the default state for the air valves is open, if power is lost, overheating of the system will not occur.

Maintenance and repair considerations

The HTTU was designed using materials that will last the life of the unit, including all of the insulation materials. The interior insulation will be welded inside to not be taken out. If there is a pertinent reason for removing it, the side can be cut open and re-welded closed. The exterior insulation can be easily removed by hand allowing for changes as deemed necessary in the future. Due to the bolted together nature of the unit, swapping or repairing sections is simply a matter of removing the bolts and doing whatever repair is necessary.

Chapter 5 – Prototype Build

Design Changes

In the process of building the HTTU, some slight modifications to the final design were made. The primary change in the design was changing the orientation of the torch heaters from the originally proposed horizontal position, to a vertical orientation. In addition to allowing easier cable routing, the vertical orientation also provided a means for natural convection. While the additional convection inside the heaters was minimal due to the pressurized flow, the extra free convection was advantageous in cooling the heaters, and thereby the system faster. Figure 20 below shows the change to the design with the heat torches vertical instead of in line with the axis of the duct. Figure 21 shows the HTTU fully assembled after fabrication.

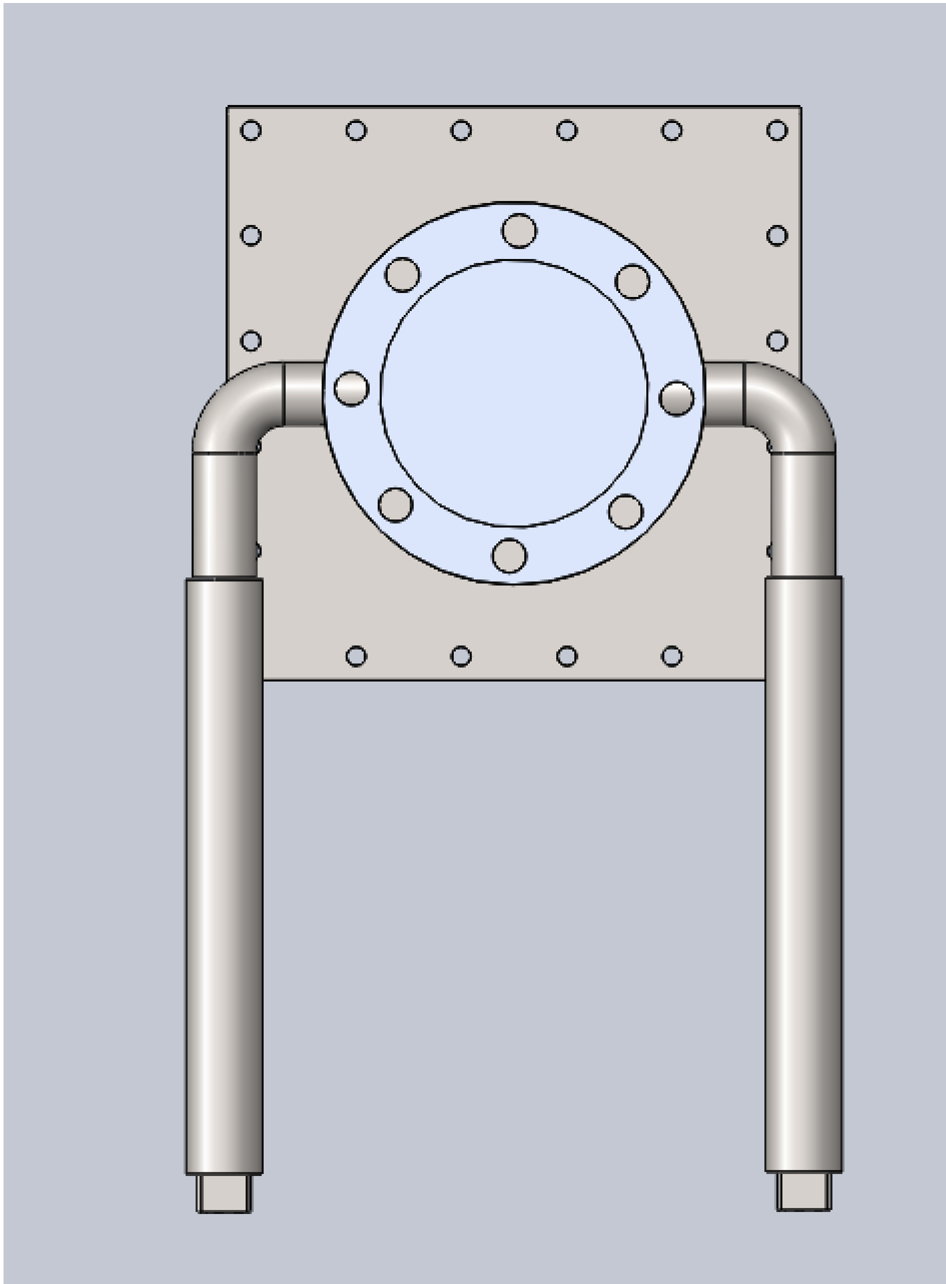

Figure 20. Modified Entrance Region

The original design called for fins on the inner surface of the 6 inch pipe to increase the available surface area for radiation. After a thorough evaluation of the Cal Poly Aero Hanger and Mustang 60 shops, it was determined the addition of the fins would be beyond the capabilities of either shop. We did not have the capabilities to accurately model and determine the fins effects on system performance. Omitting the fins was an engineering judgement call.

Figure 21. Fully Assembled HTTU

Control System

When the project began a master's student was in charge of the control system used to run the HTTU. During the course of the final quarter of the project, the master's student withdrew from the project. With only several prototype control boards available, the decision was made to use an Arduino based controller instead. As shown in Figure 2, the Arduino Control System was used in conjunction with a prototype shield. Precision resistors were soldered to the prototype shield to be used as a voltage divider. Without the dividers, the Arduino was in danger of overvoltage with the high temperatures experienced by the thermocouples. At 1500 °F the AD595AQ thermocouple amplifier outputs approximately 8.1 V. This is 3.1 V above the limit of the Arduino's analog input, so a 50% voltage divider was implemented. The maximum input the arduino should see is 4.05V.

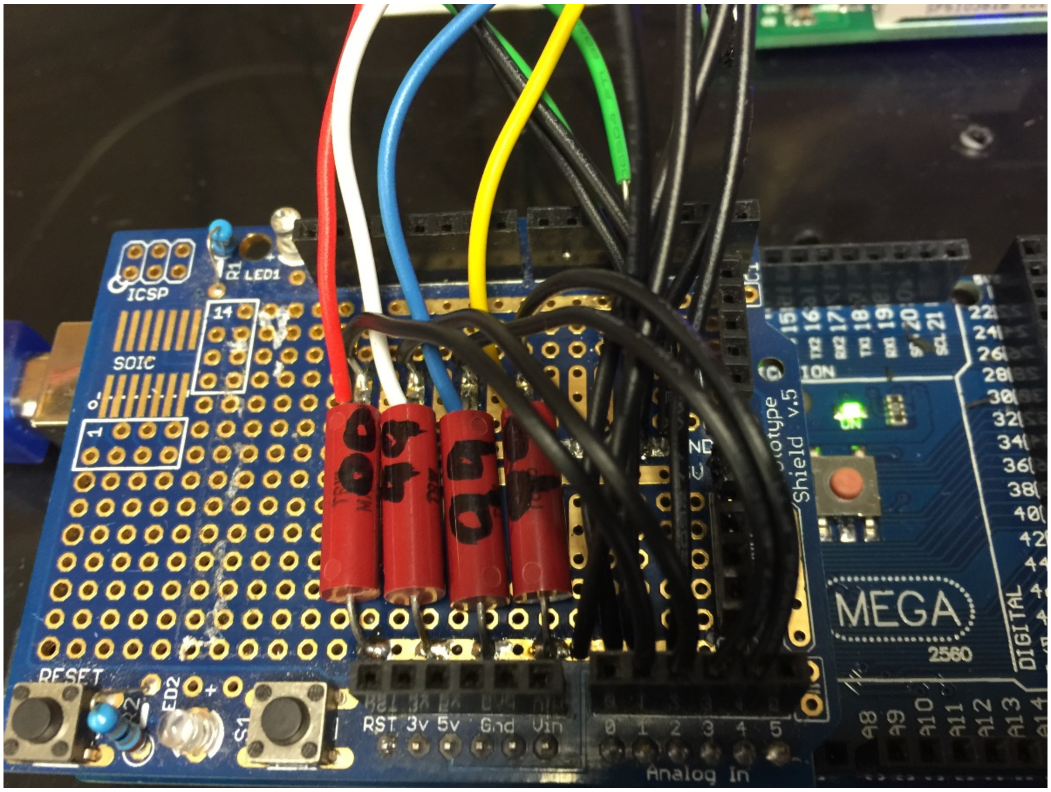

Figure 22. Arduino Control System: 15K 0.1% precision resistor bank

The use of the Arduino allowed quick coding and debugging of a control system. The control system utilized four thermocouples and three solid-state relays. One relay controlled to power to each torch. Three of the thermocouples were feedback sensors; primarily used for controlling the output of the heaters to ensure none of them overheated. The final thermocouple was installed in front of the filter face to capture the temperatures an actual filter would see.

Fabrication

The pre-fabrication plan was followed during the build process. The final fabrication took place at Cal Poly in both the Aero hangar and Mustang ’60 machine shops. The full fabrication schedule is presented in Appendix G. The parts that were waterjet cut required some edge grinding to achieve perfect fit up. The attention to detail regarding the fit up meant that the welds rarely required any filler metal to close gaps, ensuring a strong weld. Figure 23 show such a fit up prior to welding. Figure 24 shows the entry region fully welded together including the immersion tube.

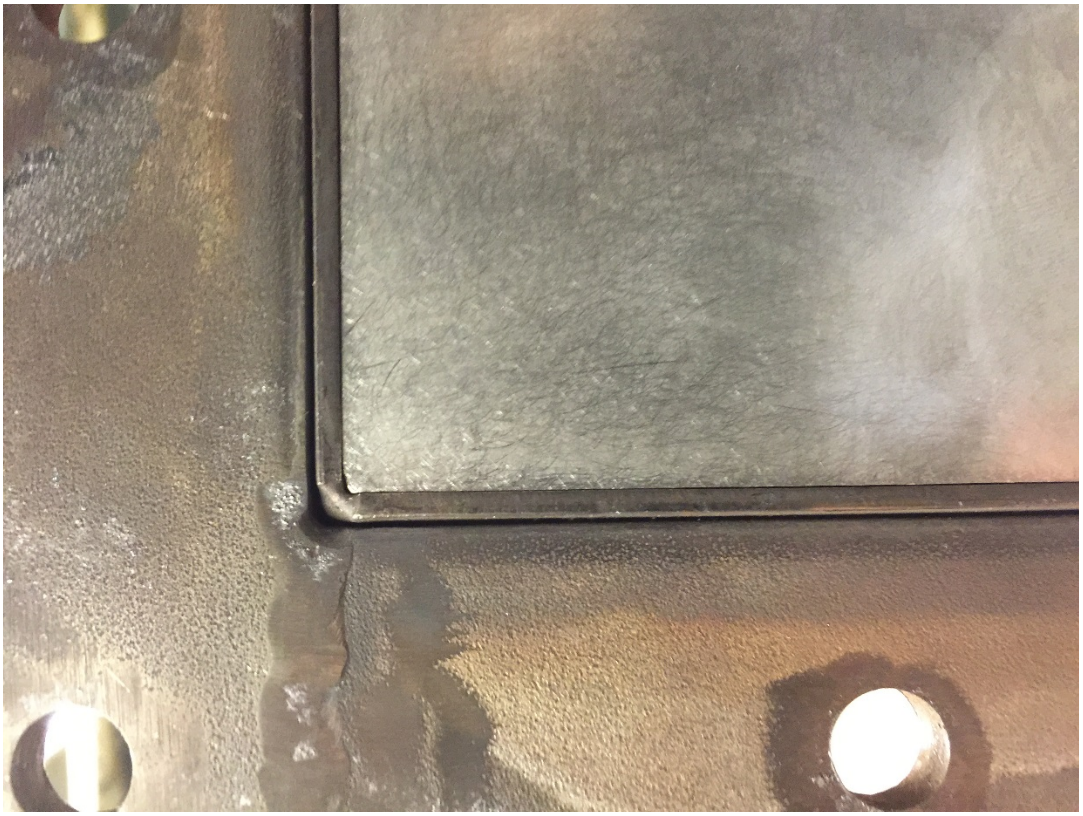

Figure 23 Fit up Prior to Welding

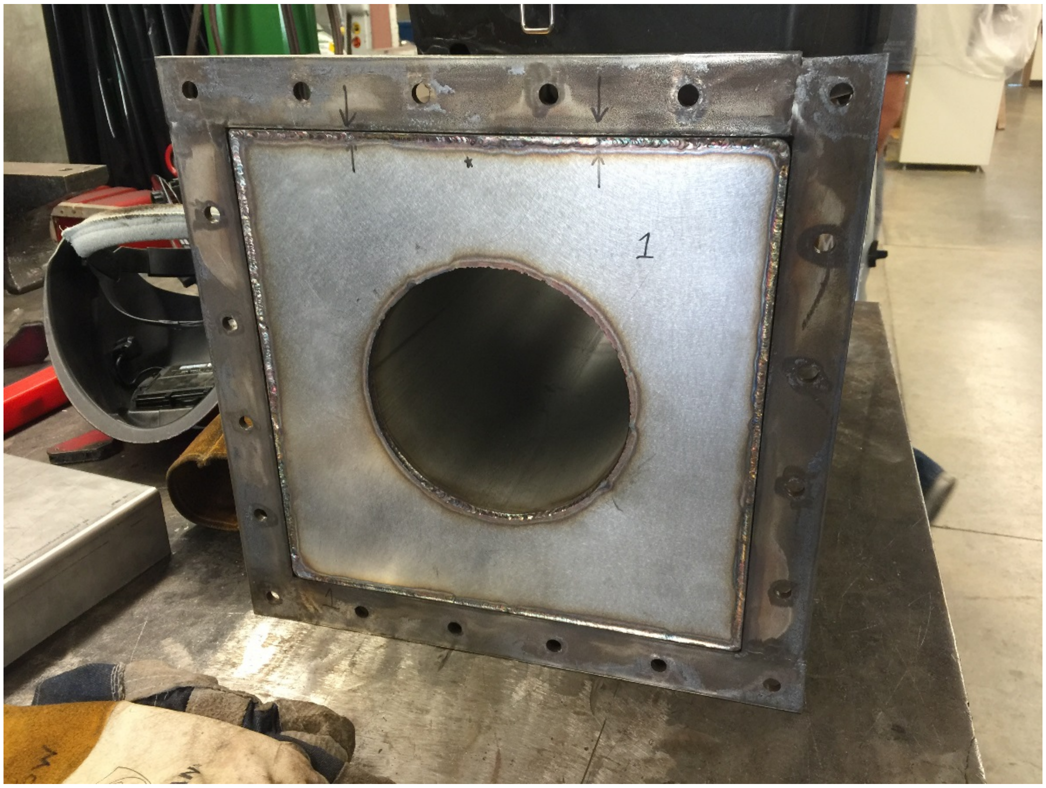

Figure 24 Immersion Tube and Entry Duct

Chapter 6 – Design Verification Plan

Test Descriptions

Testing of the HTTU to ensure that it meets the design specifications is an involved process. The actual data acquisition is straightforward; the difficulty comes into play with gathering the required people together to be able to run the HTTU. Due to the safety concerns with the use of the HTTU, especially the ones involving the high levels of electrical power and the high temperatures, certain facility members are required to be in attendance at all tests. The first needed is the mechanical engineering facility manager, along with an electrician to ensure that the electrical connections are wired properly. Once all of these are in place, the actual testing can take place. The full testing procedure is laid out in Appendix J.

With approval received from both the facilities manager and a Cal Poly electrician, all that remains is actual testing. With a failure of facilities equipment, actual testing has been delayed until the equipment is fully repaired and certified.

With the testing the first several runs will be to verify the control system is functioning. The control code is new, and while it has been tested, it would be foolish to blindly trust it without testing it while it controls the full system. For testing, three startup routines were created, one for each heating element. Code for the test runs can be found in Appendix J. Testing procedure was as follows:

1. Run immersion heater startup routine for 15 minutes, shut off HTTU, inspect unit for damage
2. Run torch 1 startup routine for 15 minutes, shut off HTTU, inspect unit for damage
3. Run torch 2 startup routine for 15 minutes, shut off HTTU, inspect unit for damage

Once each heating element is as functional, and the HTTU shows no signs of damage from operation (i.e. burnt wires, leaking gaskets, insulation damage), the main testing routine can be run at full temperature. It is recommend that future groups develop a feedback control system model that accommodates the physical system's heat transfer to the thermocouples from each respective heater in the systems transfer function. In the essence of time, a factor of safety was applied, and the HTTU's cutoff temperature is 1500 °F, similarly to the mini HTTU, and the original HTTU design.

The flow control equipment in the engines lab is not optimized for low flow. For the testing of the HTTU, a new system from a different airline was used. The flowrate is controlled using a pressure regulator and flowrate is measured using a calibrated rotameter flowmeter. A flow rate of 75 SCFM was selected for the first test run. The flow rate will provide sufficient data for high flow conditions. The final test will reduce the flow at 25 SCFM to test the capabilities at low flow. The low flow test is being saved for last as the risk of overheating is much greater if the control system fails. While the test is running, the temperature is constantly being recorded and sent to a serial output monitor. Table 3 shows the requirements necessary for the design to meet all specifications. The test specifications are also found in Appendix K.

Table 3. Test Specifications from DVPR

Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage
1	Cust specifications	25 SCFM Temp	>1150°F	Team	Final
2	Cust specifications	75 SCFM Temp	>1225°F	Team	Final
3	Cust specifications	Heat up time to 1000°F	<40 mins	Team	Final

Chapter 7 – Project Management Plan

At this stage in the design and build process, after approval of the final design, the next steps can be taken. Upon approval, all of the necessary parts will be ordered. Following the Gantt chart in Appendix F, once parts are acquired the fabrication phase begins. All of the suppliers of the needed materials have short lead times, which will expedite the beginning of the build phase. The actual testing of the HTTU is rather straightforward. The HTTU was plugged into air, the exhaust hose and power and turned on. The major constraint for testing was lab availability; however, there were no classes in the engines lab during the fall quarter. The largest amount of time was spent on fabrication. The intricacies relating to GTAW and necessity of a well-prepped surface slowed down fabrication.

Team Assignments

With only three members of the team, it was unfeasible to separate all tasks and duties. The larger tasks, such as fabrication, writing reports, analysis, testing, and research will be shared amongst the team. Team members have been assigned roles to lead in these areas and these assignments are noted below.

Alex Krippner: In charge of communications with our sponsor and coordination of testing facilities.

Ian Corcorran: In charge of team budget, reimbursements and fabrication lead.

Michael Burlando: In charge of keeping team records, creating test procedures, and final preparation of reports.

Project Milestones

Critical Design Review with sponsor on May 11, 2015

Progress Report to sponsor and advisor on June 5, 2015

Design Expo on December 3, 2015

Final Design Report due to advisor and sponsor on December 9, 2015

Chapter 8 – Conclusions and Recommendations

The HTTU has been retrofit according to the budget and power available. The simplest means to increase the final temperature and decrease heat up time is to add more torch heaters. The manifold has enough room on it for more heaters to be onto it. This necessitates more power than is available at Cal Poly. The amount of heaters able to be added would depend on how much power is available.

The control system currently on the HTTU was a quick fix. While cheap, simple and effective it does not provide enough capacity for more than four thermocouples. It also does not have enough inputs for flow meters such as the Honeywell differential transmitter currently installed on the HTTU. There is no GUI or appreciable UI either. Once the Arduino is plugged in, the program begins to run. A more powerful controller is certainly needed for further testing, as well as a GUI for lab technicians to use.

As the HTTU was unable to be tested this quarter with the failure of the electrical box, it is recommended that the next group run the testing procedures outlined to get the necessary data

References

[1] M. A. Mitchell, W. Bergman, J. Haslam, E. P. Brown, S. Sawyer, R. Beaulieu, P. Althouse and A. Meike, "Ceramic HEPA Filter Program," 3 May 2012. [Online]. Available: https://e-reports-ext.llnl.gov/pdf/612638.pdf.

[2] G. Brown, G. Dong and J. Marino, "“High Temperature HEPA Filter Test Unit Final Design Report”," California Polytechnic State University, San Luis Obispo, 2012.

[3] M. Gainer, M. Goupil and A. Woolrich, "“HEPA Filter Evaluation Furnace Control Unit Final Report”," California Polytechnic State University , San Luis Obispo, 2012.

[4] B. Frandeen, W. Schill, E. Shrewmaker and J. Turgeon, "“Final Senior Project High Temperature Test"," California Polytechnic State University, San Luis Obispo, 2013.

[5] F. P. Incropera and T. L. Bergman, Introduction to Heat Transfer, John Wiley & Sons, 2011.

Appendix A QFD, Decision Matrices

The HTTU Quality Function Deployment, shown in Figure 20 was used to determine a plan of attack to improve the operation of the HTTU.

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\+ +
\+ + +

Row	Weight Chart	tive Wt	k Br				m Re	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Weight	Temperature at Filter Face	Heat up Time	Temperature Drop	Power Consumption
								Column #	1	2	3	4	5
								Direction of Improvement	▼	▲	▼	▼	▼
1		14%	8				9	Reach Temperature in 45 minutes	▽	●	●	●	○
2		18%	10				9	Higher Temperature at Filter Face	▽	●	○	●	○
3		4%	2				9	Portability of Unit	●				
4		12%	7				1	Clean up Exterior Insulation	▽				
5		14%	8				9	Improving Insulation Performance	●	●	●	●	
6		12%	7				1	Measure Velocity Distribution	▽				▽
7		12%	7				1	Measure Temperature Distribution	▽				▽
8		14%	8				9	Operate between 25 and 250 CFM	▽	●	●	●	▽
								HOW MUCH: Target	1000	1200	15 min	100 deg F	39.9k W
								Max Relationship	9	9	9	9	3
								Technical Importance Rating	240.4	536.8	431.6		
								Relative Weight	20%	44%	36%		
								Weight Chart					

WHO: Customers

Figure 25. QFD

Table 4: Pugh Matrices

Heaters	Existing design	Immersion	Blanket	Ceramic Rod	Sylvania
Max temp	D	+	-	+	+
Max temp speed	A	+	s	+	s
Portability	T	s	s	s	s
Heat Loss	U	+	s/-	+	s
Operate at 25 SCFM	M	+	+	+	+

Entrance Region	Existing design	Cone	Square	Composite	Cast ceramic
Max temp	D	s	s	+	+
Max temp speed	A	+	s	+	+
Portability	T	+	s	s	-
Heat Loss	U	+	s	+	+
Operate at 25 SCFM	M	s	s	s	s

Ex. Insulation	Existing design	ceramic	composite	aerogel
Max temp	D	s	s	s
Removal ease	A	+	s	-
Portability	T	-	s	s
Heat Loss	U	+	+	+
Operate at 25 SCFM	M	s	s	s

Int. Insulation	Existing design	Fiberglass	Firebrick	Refractory cement
Max temp	D	+	+	+
Max temp speed	A	+	+	+
Portability	T	s	s	s
Heat Loss	U	+	+	+
Operate at 25 SCFM	M	s	s	s

Section connection	Existing design	Flared	Clammed
Max temp	D	s	s
Max temp speed	A	s	s
Portability	T	s	s
Heat Loss	U	+	s/'+
Operate at 25 SCFM	M	s	s

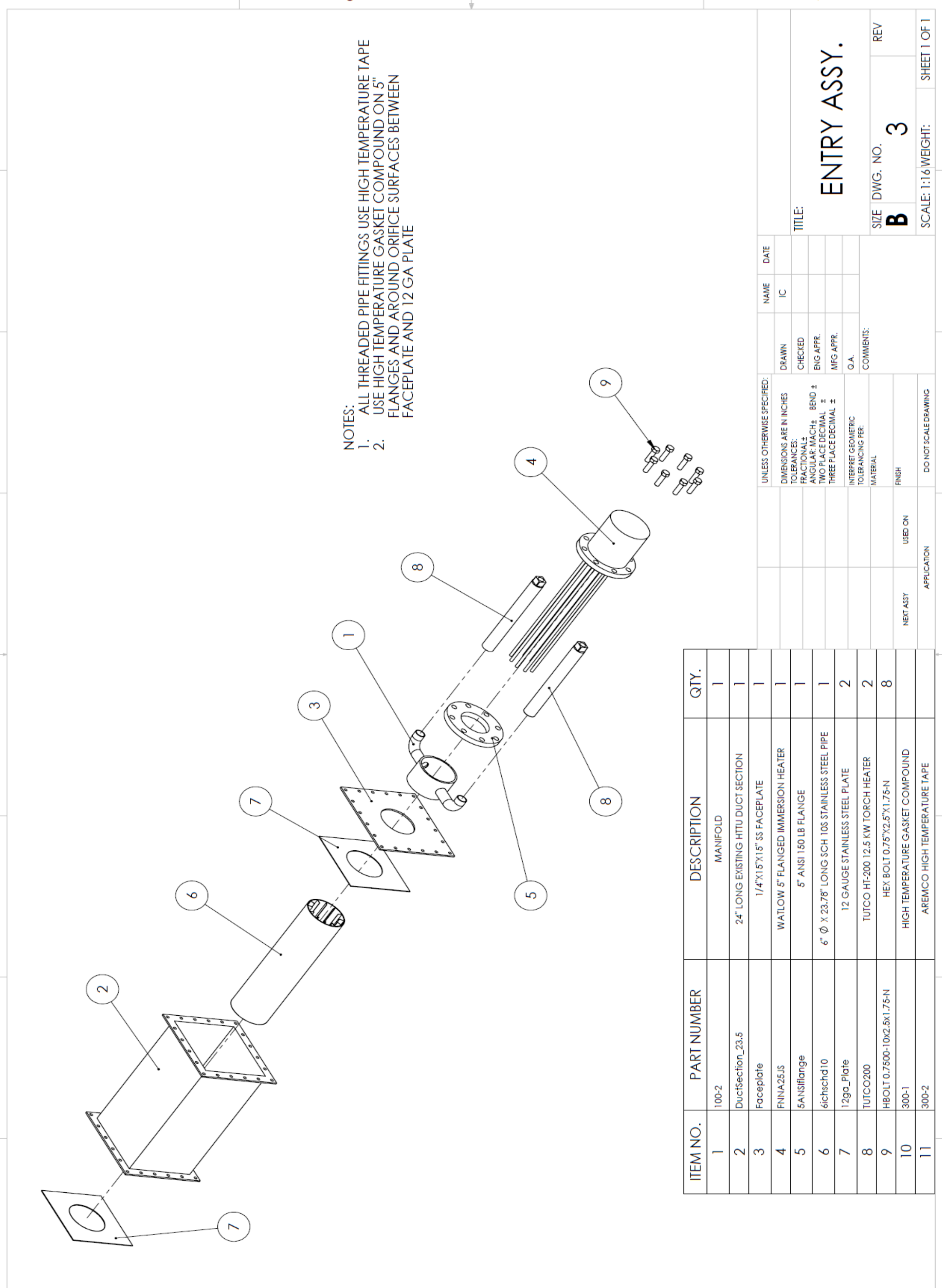
Gasket Material	Existing design	Fiberglass	Copper
Max temp	D	s	s
Max temp speed	A	s	s
durability	T	+	+
Heat Loss	U	s	s
Operate at 25 SCFM	M	s	s

The decision matrices shown in Table 4 that decided what ideas should be pursued in the design. Design 1 is preliminary design 1, Design 2 is preliminary design 2 and design 3 is the final design concept.

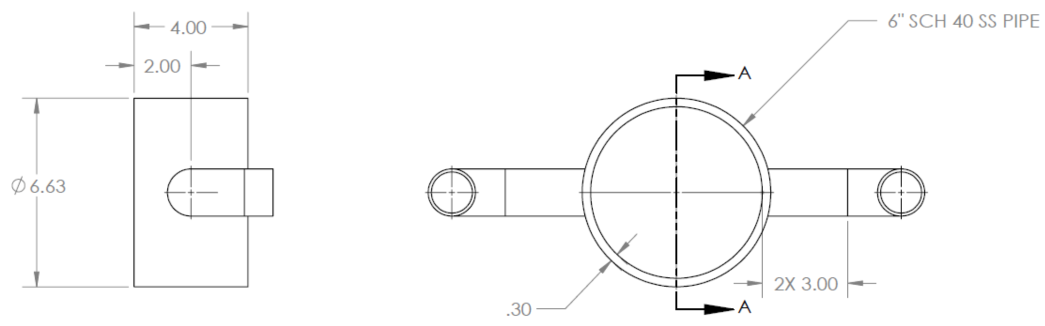
Table 5. Decision Matrix

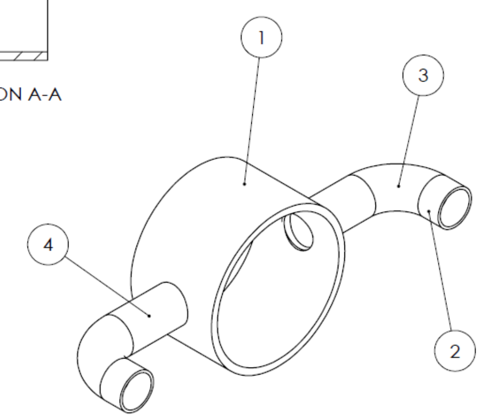
Design Criterion	Thermal Mass		Heat up time (filter)		Heat loss		mobility		Cost		Fabrication Difficulty		Sum
Weight	0.159		0.079		0.317		0.048		0.238		0.159		1.0
Weighting Factor	10.0		5.0		20.0		3.0		15.0		10.0		
1	30	4.8	85	6.7	87	27.6	40	1.9	60.0	14.3	50.0	7.9	63.254
2	33	5.2	80	6.3	90	28.6	40	1.9	65.0	15.5	65.0	10.3	67.857
3	80	12.7	90	7.1	90	28.6	50	2.4	40	9.5	75.0	11.9	72.222

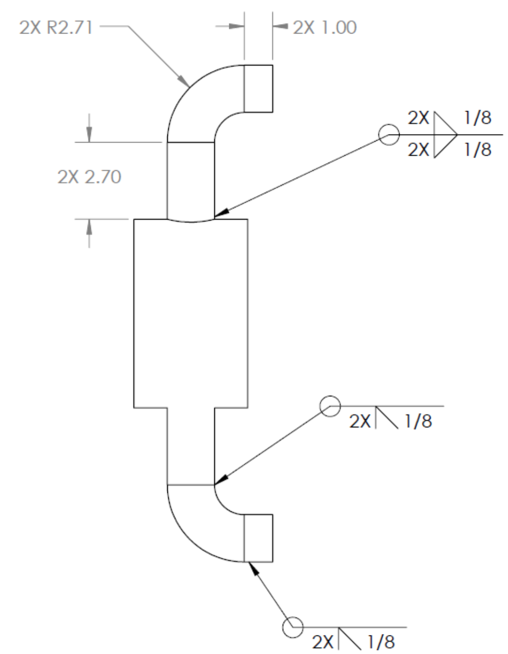
Appendix B Drawing Packet



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	100-2	MANIFOLD	1
2	DuctSection_23.5	24" LONG EXISTING HTTU DUCT SECTION	1
3	Faceplate	1/4"X15"X15" SS FACEPLATE	1
4	FNNA25JS	WATLOW 5" FLANGED IMMERSION HEATER	1
5	5ANSIflange	5" ANSI 150 LB FLANGE	1
6	6ichschd10	6" Ø X 23.78" LONG SCH 10S STAINLESS STEEL PIPE	1
7	12ga_Plate	12 GAUGE STAINLESS STEEL PLATE	2
8	TUTCO200	TUTCO HT-200 12.5 KW TORCH HEATER	2
9	HBOLT 0.7500-10x2.5x1.75-N	HEX BOLT 0.75"X2.5"X1.75-N	8
10	300-1	HIGH TEMPERATURE GASKET COMPOUND	
11	300-2	AREMCO HIGH TEMPERATURE TAPE	







NOTES
1. ALL PIPE 1-1/4 SCH 10 SS PIPE U.N.O
2. USE 1.5" DRILL BIT FOR ALL HOLES

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	100-1	6"Ø X 4" LONG SCHEDULE 40s STAINLESS STEEL PIPE	1
2	100-2	1-1/4" Ø X 1" LONG SCH 10s STAINLESS STEEL PIPE THREADED ON ONE END	2
3	45735K217	1-1/4"Ø THIN WALL BUTT-WELD 90° STAINLESS STEEL PIPE FITTING	2
4	100-4	1-1/4" Ø X 3" LONG SCHEDULE 10S STAINLESS STEEL PIPE SECTION	2

NEXT ASSY | USED ON
APPLICATION

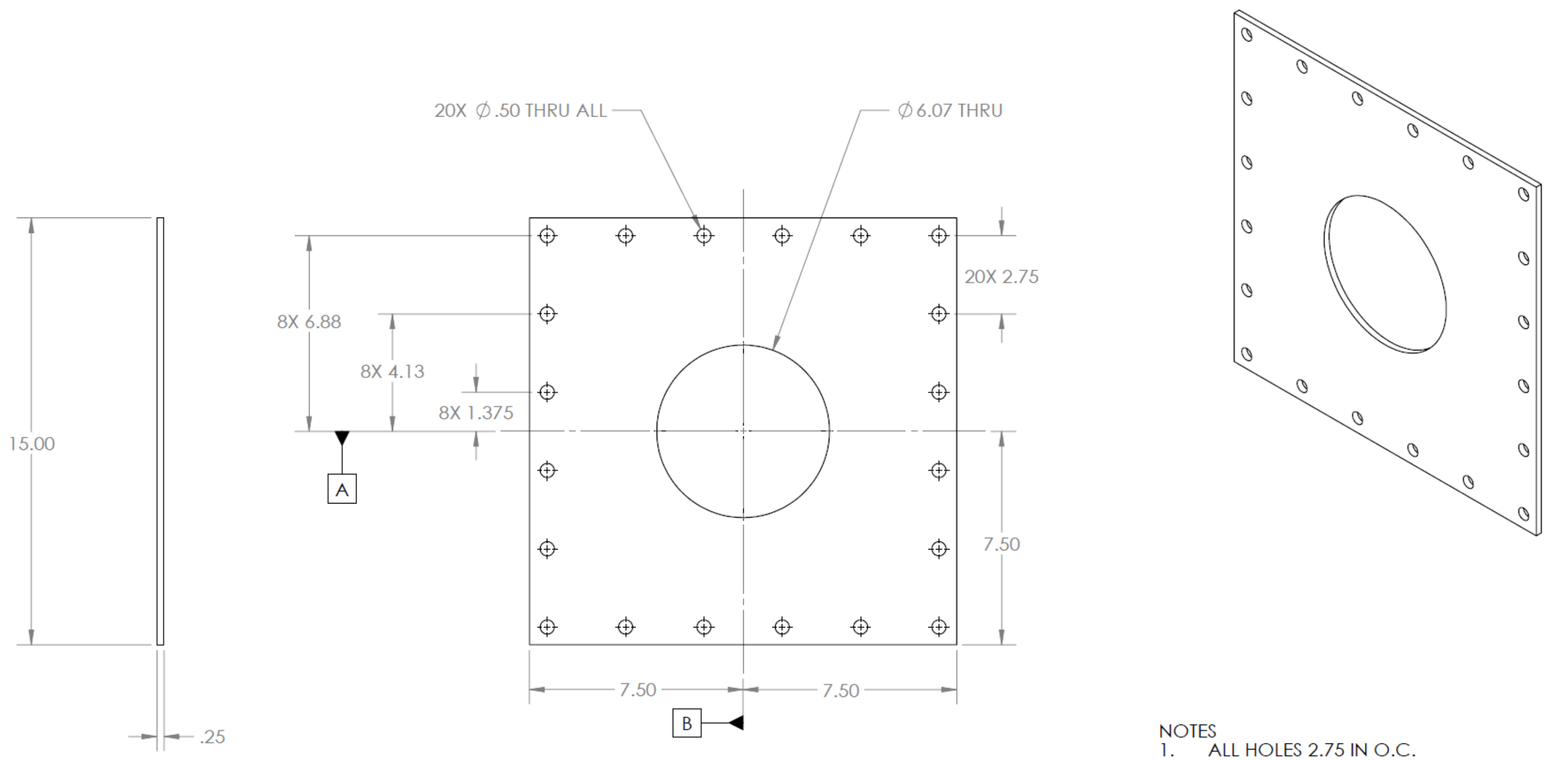
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IC	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
MANIFOLD

SIZE B | DWG. NO. 1 | REV 2
SCALE: 1:4 | WEIGHT: | SHEET 1 OF 2

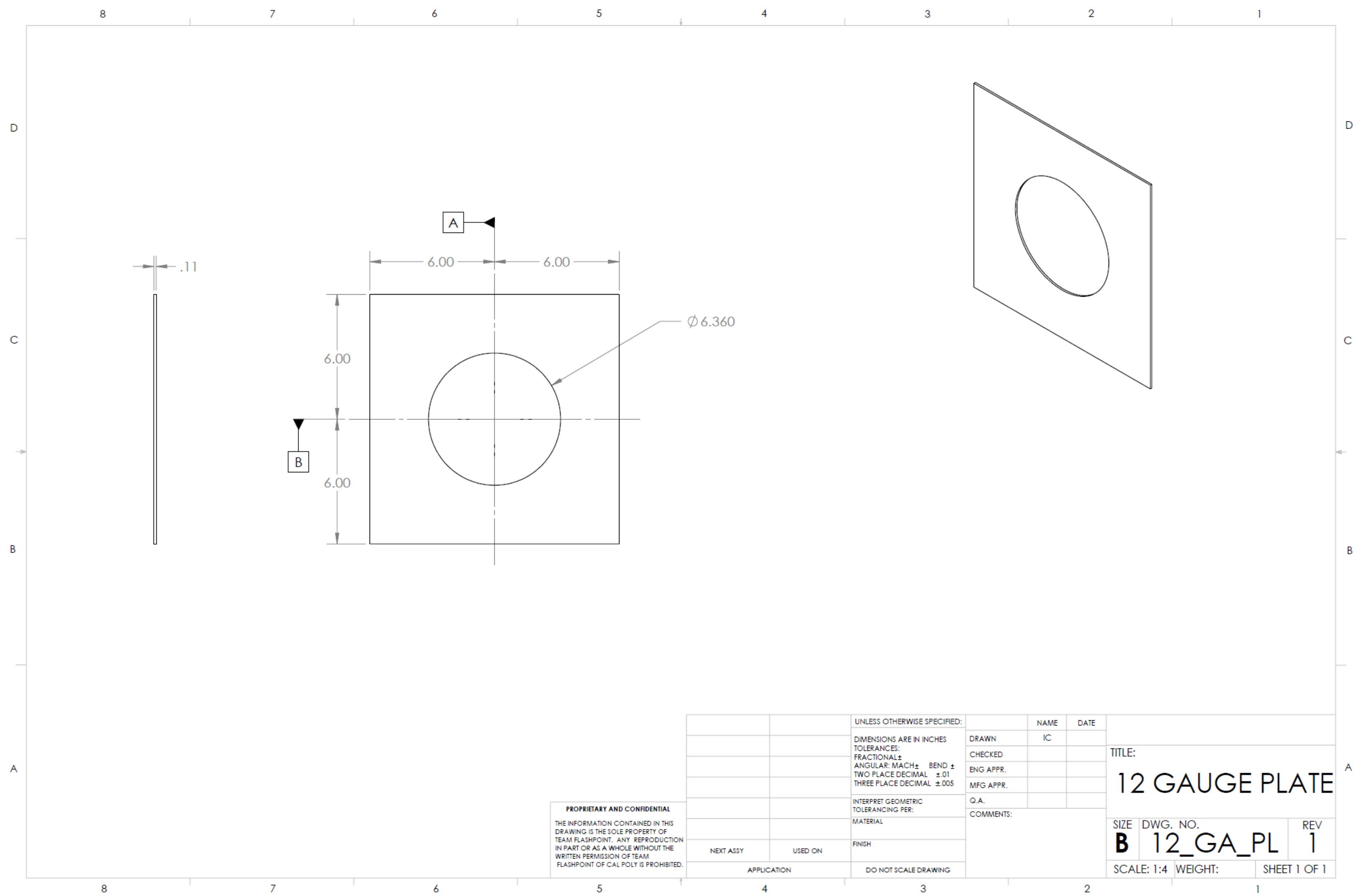


NOTES
1. ALL HOLES 2.75 IN O.C.
2. ALL MATERIAL 1/4" STAINLESS STEEL PLATE

UNLESS OTHERWISE SPECIFIED:		NAME / DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	IC
	CHECKED	
	ENG APPR.	
	MFG APPR.	
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.	
MATERIAL 304 STAINLESS STEEL	COMMENTS:	
FINISH		
NEXT ASSY / USED ON — APPLICATION	DO NOT SCALE DRAWING	

TITLE: FACEPLATE

SIZE	DWG. NO.	REV
B	2	1
SCALE 1: 4	WEIGHT:	SHEET 1 OF 1



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PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM FLASHPOINT. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM FLASHPOINT OF CAL POLY IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
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DRAWN
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
12 GAUGE PLATE
SIZE
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DWG. NO.
12_GA_PL
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SCALE: 1:4
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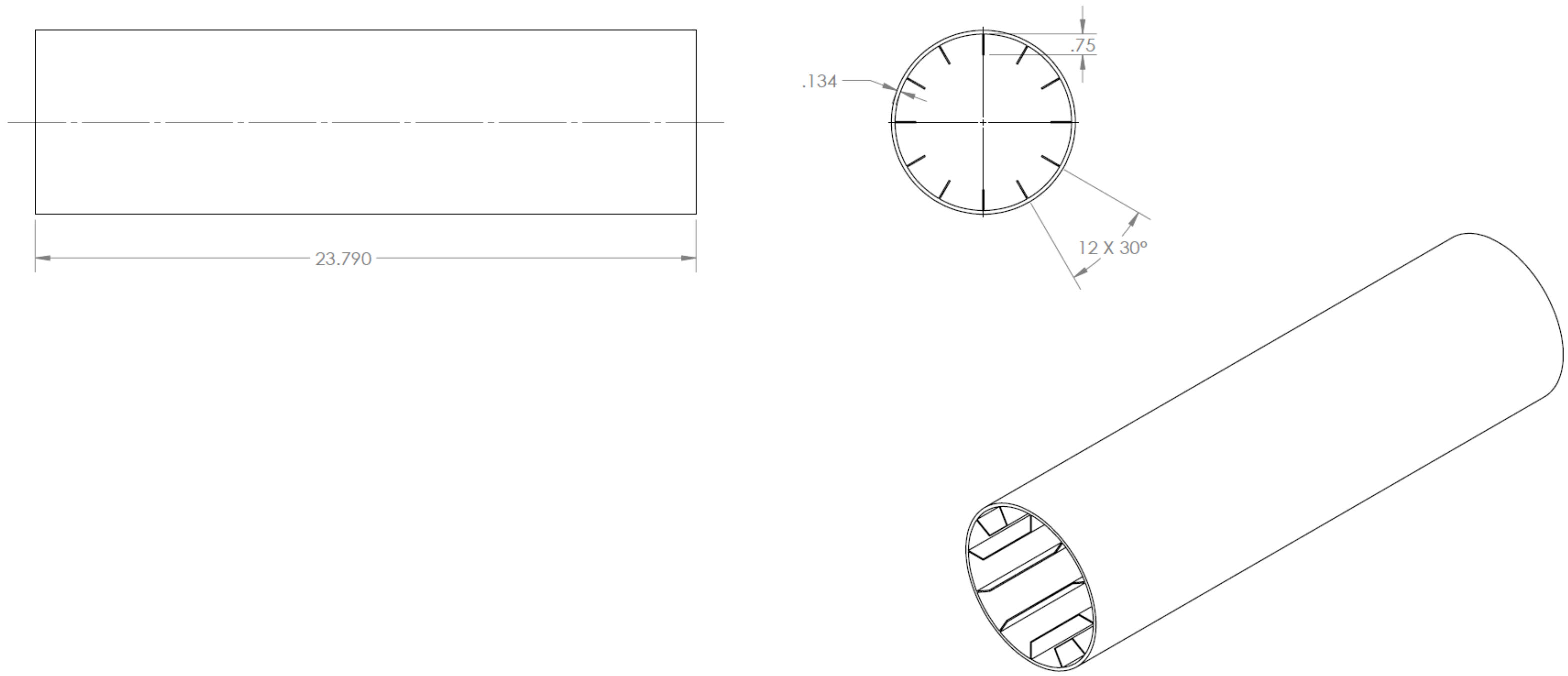
SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6ichschd10	6" Ø X 23.79" LONGSCH 10S STAINLESS STEEL PIPE	1
2	FIN	23.75X0.75 18 GA STAINLESS STEEL PLATE FINS	12

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: .XXX
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
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ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
IMMERSION TUBE

SIZE **B** DWG. NO. 4 REV
SCALE: 1:4 WEIGHT: SHEET 1 OF 1

Appendix C List of Vendors, Contact information and pricing

Estimated Costs

Description	Part Number	Vendor	Unit cost	Qty.	Total	est shipping
Immersion Heater with K Type thermocouple	FNNA25J5X-SK	Watlow Distributor	2614.00	1	2614.00	60
6" Sch 10 SS pipe 3' *	4347K412	McMaster Carr	174.43	1	174.43	
1.25" Sch 10 SS pipe 1' *	4347K341	McMaster Carr	19.70	1	19.70	
Thin-Wall Butt-Weld 304/304L Stainless Steel Pipe Fitting, Unthreaded, 1-1/4 Pipe Size 90 Degree Long Radius Elbow	45735K217	McMaster Carr	9.63	2	19.26	
Standard-Wall Type 304/304L Stainless Steel Thread Pipe Nipple 1-1/4 Pipe Size x 3" Length	4830K245	McMaster Carr	27.30	1	27.30	
Air/Immersion Thermocouple Probes with Round-Pin Male Plug	3857K212		34.44	2	68.88	60
12"x12" 304 stainless	8983K44	McMaster Carr	22.40	1	22.40	
Type 18-8 Stainless Steel Flat Washer 3/4" Screw Size, 0.812" ID, 1.750" OD	92141A056	McMaster Carr	5.81	2	11.62	
3/4-10x4 bolts	92240A844	McMaster Carr	3.14	8	25.12	
Type 18-8 Stainless Steel Hex Nut 3/4"-10 Thread Size, 1-1/8" Wide, 41/64" High	91845A330	McMaster Carr	7.11	1	7.11	
1 lb 1/16" 308L ss filler rod	308L116361	industrial-toolcrib.com/	13.34	1	13.34	7.15
Ceramic Fiber Blanket	HP61048300	Ceramaterials.com	107.00	1	107.00	20
Malin .032 SS tie wire	MS20995CSS1L	Amazon	17.99	1	17.99	0
Stainless Steel 304/304L Pipe Fitting, Flange, Threaded, Class 150, 5" NPT Female	B003ULOJNU	Amazon	125.00	1	125.00	0
Pyro-tape	682-TB2-1		93.00	1	93.00	20
Travel Costs	N/A	N/A			200.00	
Eaton 25A single Pole circuit breaker	CL125	Home Depot	5.95	3	17.85	0
25A Cartridge Fuse	BP/NON-25	Home Depot	2.38	2	4.76	0
6" Safety Wire Twister Pliers	RIDGE02127	Amazon	10.99	1	10.99	0
					0.00	
			Total		3866.13	167.15
			Grand Total		4033.28	

Vendor List

Home Depot <homedepot.com> in store

Amazon <amazon.com>

McMaster-Carr <mcmaster.com> la.sales@mcmaster.com

Watlow Distributors<westcoastplastics.com> sales@westcoastplastics.com

Industrial Tool Crib <industrial-toolcrib.com> 908-823-4188

Cera Materials <ceramaterials.com> jerryw@ceramaterials.com

Final Expenditures

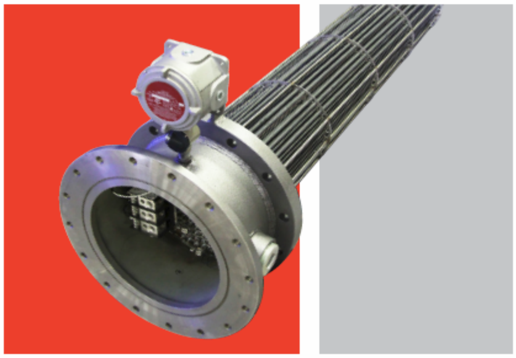
Date	Vendor	Description	Amount
5/20/2015	Waterjet Central	2X Waterjet 10 ga. SS plate	80.00
5/26/2015	West Coast Plastics	Watlow FNNA25J5X-SK 14 kW 5" flange immersion heater	2883.80
5/26/2015	McMaster Carr	Thin-Wall 304/304L Stainless Steel Pipe, Unthreaded Ends, 6 Pipe Size X 3' Length	174.43
5/26/2015	McMaster Carr	Thin-Wall 304/304L Stainless Steel Pipe, Unthreaded Ends, 1-1/4 Pipe Size X 1' Length	19.70
5/26/2015	McMaster Carr	Thin-Wall Butt-Weld 304/304L Stainless Steel Pipe Fitting, Unthreaded, 1-1/4 Pipe Size 90 Degree Long Radius Elbow	18.72
5/26/2015	McMaster Carr	Standard-Wall Type 304/304L Stainless Steel Thread Pipe Nipple, 1-1/4 Pipe Size X 3" Length	7.54
5/26/2015	McMaster Carr	Thermocouple Probe with Round-Pin Plug and Cable, 3' Cable, Type K, 6" Length, 1/8" Probe Diameter	68.88
5/26/2015	McMaster Carr	Multipurpose 304 Stainless Steel Sheet, .090" Thick, 12" X 12"	21.72
5/26/2015	McMaster Carr	Type 18-8 Stainless Steel Flat Washer, 3/4" Screw Size, 0.812" ID, 1.750" OD, Packs of 10	11.62
5/26/2015	McMaster Carr	18-8 Stainless Steel Hex Head Cap Screw, 3/4"-10 Thread, 2-1/2" Long, Fully Threaded, Packs of 1	25.12
5/26/2015	McMaster Carr	Type 18-8 Stainless Steel Hex Nut, 3/4"-10 Thread Size, 1-1/8" Wide, 41/64" High, Packs of 10	7.11
5/26/2015	McMaster Carr	Sales Tax & Shipping McMaster Carr order 5/26/2015	39.73
9/30/2015	Aremco	840-M HiE Coat, 1 pint	93.50
9/30/2015	Aremco	1" Pyrotape X 50'	132.50
9/30/2015	Aremco	Shipping and tax Aremco 9/30 order 202387	32.50
10/1/2015	Waterjet Central	1X Waterjet 1/4 plate (Faceplate)	100.00
10/5/2015	Ceramaterials	100 sq. ft 1" ceramic Fiber Blanket	270.00
10/22/2015	Amazon	Amazon.com, Donop Mega 2560 atmega2560-16au dev board, 10/22/15	13.99
10/26/2015	Amazon	4X SainSmart MAX6675 Module + K Type Thermocouple Thermocouple Sensor	55.96
10/26/2015	Amazon	2X Wall Adapter Power Supply - 9V DC 650mA	10.98
10/26/2015	Amazon	2 of: Comprehensive ST Series USB Cable 2.0 A to B Cable 25 FT	21.12
10/26/2015	Amazon	Electronix Express- Hook up Wire Kit (Solid Wire Kit) 22 Gage (25 Feet)	22.00
10/26/2015	Amazon	2 of: SunFounder Mega 2560 R3 ATmega2560-16AU Board	35.98
10/28/2015	Amazon	amazon.com Gikfun Screw Shield Expansion Board for Arduino UNO R3, 10/28/15	10.68
10/28/2015	Amazon	Amazon.com, 3X DROK DC Boost Converter 10/28/15	47.85
10/28/2015	Amazon	Amazon.com 2X SS 316 pipe fitting 10/28/15	7.12
11/4/2015	Mouser	Mouser Invoice no 39323683, precision resistors, 11/4/15	27.11
11/4/2015	Ebay	Ebay, 10-pack vintage TRW/ IRC 15K 0.1% ultra precision metal, 11/4/15	8.50
11/5/2015	Mouser	Mouser invoice no 39332022, AD595AQ TC amplifiers, 11/5/15	49.65
11/7/2015	Amazon	Amazon.com, Screw Shield V2 terminal expansion board 11/7/15	11.38
		TOTAL:	4309.19

Appendix D Vendor supplied Component Specifications and Data Sheets

1. Watlow FNNA25J5X

Flange Immersion Heaters

Agency Certified Tubular Heaters Ideal For Heating Liquids, Gases, Tanks and Pressure Vessels Requiring Higher Kilowatts



Watlow® flange heaters, with IECEx and ATEX Ex'd' or Ex'e' certification, are easy to install and maintain. Designed for heating liquids and gases in tanks and pressure vessels, flange immersion heaters are ideal for applications requiring higher kilowatts.

Watlow flange heaters are made with WATROD™ or FIREBAR® tubular elements brazed or welded to a flange. Stock flange heaters are equipped with a general purpose terminal enclosure.

Watlow flange heaters possess IECEx and ATEX Ex'd' or Ex'e' ratings certifying that the flange heater enclosure is flameproof. Every enclosure is pressure tested to ensure heaters are safe and reliable and meet rigorous standards for electrical safety.

Flange heaters, with FIREBAR elements, also answer the need for liquid immersion applications requiring high kilowatts in small tanks. The FIREBAR element's unique flat surface geometry packs more power in a smaller bundle, with lower watt density, making it especially well-suited for petroleum-based liquid heating applications.

Performance Capabilities

- Watt densities up to 100 W/in² (15.5 W/cm²)
- Wattages up to three megawatts
- UL® and CSA component recognition up to 600VAC and IEC and ATEX recognition up to 690VAC
- Alloy 800/840 sheath temperatures up to 1600°F (870°C)
- Passivated 316 stainless steel sheath temperatures up to 1200°F (650°C)
- 304 stainless steel sheath temperatures up to 1200°F (650°C)
- Steel sheath temperatures up to 750°F (400°C)
- FIREBAR flange heaters deliver more killowatts in smaller bundles
- A conventional round tubular 10-inch ANSI flange can be replaced by a 6-inch ANSI FIREBAR flange with same immersed length
- Hazardous area ratings:
  - ATEX II 2 G Ex d IIB+H2, T1-6 Gb
  - IEC Ex d IIC: TI-6 Gb
  - ATEX II 2 G Ex e IIC T1-6 Gb
  - IEC Ex e IIC TI-6 Gb
  - Class 1, Divisions 1 & 2, Groups B, C & D
  - PESO, Zone 1 Group IIC

Features and Benefits

ANSI and ANSI compatible 2, 2¹/₂, 3 thru 48 inch flanges
- Provides appropriate heater size-to-application and fit

Element sheath and flange materials
- Meets your application needs

Integral thermowells
- Provides convenient temperature sensor insertion and replacement without draining the fluid being heated

Standard, general purpose terminal enclosure
- Offers easy access to wiring

Element support(s)
- Provides proper element spacing to maximizing heater performance and life

All units are inspected and/or tested
- Ensures element-to-flange pressure seals do not leak

Drilled and tapped eyebolt holes or lift lugs on larger flange heaters
- Facilitates lifting during installation

WATROD hairpins are repressed (recompacted)
- Provides improved heater life, insulation resistance and heat transfer

FIREBAR flange heaters pack more kilowatts into a smaller bundle
- Includes a conventional round tubular 10 in. (254 mm) ANSI flange which can be replaced by a 6 in. (152 mm) ANSI FIREBAR flange with the same immersed length

Branch circuits are designed for 48 amperes per circuit maximum
- Reduces risk of failure due to excessive temperatures generated by high amperage

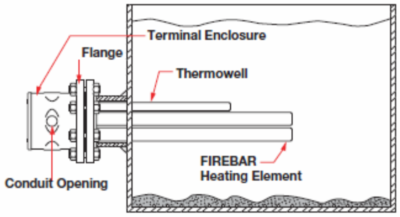
UL® and CSA component recognition under file numbers E52951 and 31388 respectively
- Simplifies obtaining third-party recognition for assembly

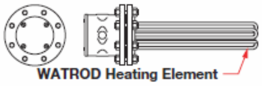
WATLOW®

HAN-FIH-0115

Typical Applications

- Water:
  - Deionized
  - Demineralized
  - Clean
  - Potable
  - Process
- Industrial water rinse tanks
- Vapor degreasers
- Hydraulic oil, crude, asphalt
- Lubricating oils at API specified watt densities
- Air and gas flow
- Caustic solutions
- Chemical baths
- Process air equipment
- Boiler equipment
- Freeze protection of any fluid
- Anti-freeze (glycol) solutions
- Paraffin





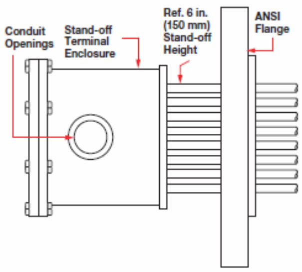
Options

Terminal Enclosures

General purpose terminal enclosures, without thermostats, are standard on all flange immersion heaters. Optional terminal enclosures include:

- General purpose with a single or double pole thermostat.
- Moisture resistant. Available with or without a single or double pole thermostat.
- Corrosion resistant. Available with or without a single or double pole thermostat.
- Explosion resistant Class 1, Div. 1 and 2, Groups B, C and D, T1 - T6. Available with or without a single or double pole thermostat.
- Explosion/moisture resistant combinations. Available with or without a single or double pole thermostat.

Stand-off Terminal Enclosures



Stand-off terminal enclosures provide an air-insulating barrier between the flange and terminal enclosure by mounting the terminations and wiring away from the flange. Stand-off terminal enclosures are recommended whenever a process operating temperature exceeds 210°F (100°C). This helps minimize terminal enclosure temperatures.

To order, specify **stand-off terminal enclosure**.

Certified Enclosures

CSA, ATEX, IECEx or PESO certified enclosures protect wiring in hazardous gas environments. For additional information contact a Watlow representative.

To order, specify **CSA or ATEX, IECEx or PESO certified enclosure, area classification, protection method, desired temperature code, process temperature** (°F), maximum ambient temperature, maximum **working pressure** of application (psig), **media** being heated and heater **mounting orientation** (horizontal or vertical) and **flange size**.

For products that will be installed in hazardous locations, please provide the following information:

- Operating conditions
- Minimum and maximum ambient temperatures for the installation location
- Mounting orientation

Watlow must understand this information so that an appropriate design can be provided.

ASME Pressure Vessel Code Welding

Flange assemblies can be provided with an ASME Section VIII, Div. I pressure vessel stamp upon request.

Thermostats

To provide process temperature control, Watlow offers optional single pole, single throw (SPST) and double pole, single throw (DPST) thermostats.

Unless otherwise specified, thermostats are mounted inside the terminal enclosure. Please verify that the thermostat's sensing bulb outside diameter is compatible with the flange heater's thermowell inside diameter.

Thermocouples

ASTM Type J or K thermocouples offer more accurate sensing of process and/or sheath temperatures. A thermocouple may be inserted into the thermowell or attached to the heater's sheath.

Thermocouples are supplied with 120 in. (3050 mm) leads (longer lead lengths available). Unless otherwise specified, thermocouples are supplied with temperature ranges.

Using a thermocouple requires an appropriate temperature and power controller. These must be purchased separately. Watlow offers a wide variety of temperature and power controllers to meet virtually all applications. Temperature controllers can be configured to accept process variable inputs, too. Contact a Watlow representative for details.

To order, specify **Type J** or **K** thermocouple and lead length. Indicate if the thermocouple is for **process temperature sensing** or heater sheath **high-limit protection**. Please specify if the flange heater will be mounted **vertical** or **horizontal** in the tank. **If vertical, specify if the housing is on top or bottom**.

If the flange heater is part of an in-line circulation heating application, indicate flow direction relative to the heater's enclosure.

Tubular and Process Assemblies

Flange Immersion Heaters

Applications

- Water:
  - Deionized
  - Demineralized
  - Clean
  - Potable
  - Process
- Industrial water rinse tanks
- Vapor degreasers
- Hydraulic oil, crude, asphalt
- Lubricating oils at API specified watt densities
- Air and gas flow
- Caustic solutions
- Chemical baths
- Process air equipment
- Boiler equipment
- Freeze protection of any fluid
- Anti-freeze (glycol) solutions
- Paraffin

Options

Terminal Enclosures

General purpose terminal enclosures, without thermostats, are standard on all flange immersion heaters. Optional terminal enclosures include:

- General purpose (NEMA 1) with a single or double pole thermostat.
- Moisture resistant (NEMA 4–steel). Available with or without a single or double pole thermostat.
- Corrosion resistant (NEMA 4X). Available with or without a single or double pole thermostat.
- Explosion resistant (NEMA 7) class 1 groups C and D. Available with or without a single or double pole thermostat.
- Explosion/moisture resistant (NEMA 7/4) combinations. Available with or without a single or double pole thermostat.
- For class 1, group B enclosures, consult your Watlow representative.

Enclosure Enhancements

- Enclosure heater to solve condensation and freeze problems.
- Power distribution blocks to facilitate power feed line wiring.

Prior to ordering, refer to the terminal enclosure dimensions on page 341. Order by adding the appropriate suffix letter(s) to the base flange heater code number, as shown on the Build-a-Code chart. Heater code numbers and suffix letters are depicted on the *Stock* and *Options* charts, pages 345 to 362. Specify class and group, if applicable.

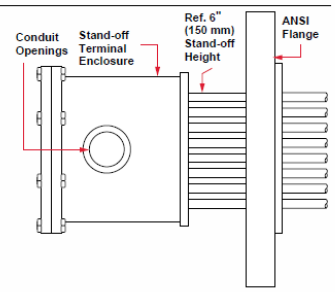
Caution

Explosion-resistant terminal enclosures are intended to provide explosion containment in the electrical termination/wiring enclosure only. No portion of the assembly outside of this enclosure is covered under this NEMA rating. NEMA rating effectiveness may be compromised by abuse or misapplication.

Stand-off Terminal Enclosures

Stand-off terminal enclosures provide an air-insulating barrier between the flange and terminal enclosure by mounting the terminations and wiring away from the flange. Stand-off terminal enclosures are recommended whenever a process operating temperature exceeds 400°F (205°C). This helps minimize terminal enclosure temperatures.

To order, specify **stand-off terminal enclosure**.



CSA Certified Enclosures

CSA certified moisture and/or explosion resistant terminal enclosures protect wiring in hazardous gas environments. These terminal enclosures, covered under CSA file number 61707, are available on all WATROD and FIREBAR flange heaters. For additional information, consult your Watlow representative.

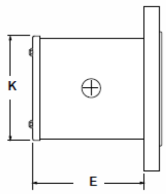
To order, specify **CSA certified enclosure**, **process temperature** (°F), maximum **working pressure** of application (psig), **media** being heated and heater **mounting orientation** (horizontal or vertical) and **flange size**.

Tubular and Process Assemblies

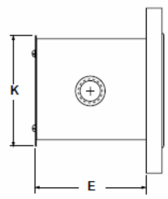
Flange Immersion Heaters

Options

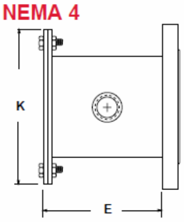
4-8 inches NEMA 1 and NEMA 4



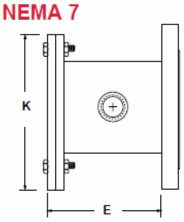
10-14 inches NEMA 1



10-14 inches NEMA 4



4-14 inches NEMA 7



Terminal Enclosure Dimensions

Enclosure Type	Flange Size inch	Without Thermostat				With Thermostat							
						Single Pole				Double Pole			
		E Dimension inch	E Dimension (mm)	K Dimension inch	K Dimension (mm)	E Dimension inch	E Dimension (mm)	K Dimension inch	K Dimension (mm)	E Dimension inch	E Dimension (mm)	K Dimension inch	K Dimension (mm)
General	2①	1 ½	(38)	3 ⅜	(86)	—	—	—	—	—	—	—	—
Purpose	2½①	2 ⅛	(54)	4	(102)	—	—	—	—	—	—	—	—
(NEMA 1)	3	3 13/16	(97)	4 ⅝	(117)	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)
	4	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)
	5	7 1/16	(179)	7	(178)	7 1/16	(179)	7	(178)	7 1/16	(179)	7	(178)
	6	7 1/16	(179)	8	(203)	7 1/16	(179)	8	(203)	7 1/16	(179)	8	(203)
	8	7 1/16	(179)	10 1/32	(255)	7 1/16	(179)	10 1/32	(255)	7 1/16	(179)	10 1/32	(255)
	10	7 1/16	(179)	11 ⅝	(295)	7 1/16	(179)	11 ⅝	(295)	7 1/16	(179)	11 ⅝	(295)
	12	7 1/16	(179)	13 ½	(343)	7 1/16	(179)	13 ½	(343)	7 1/16	(179)	13 ½	(343)
	14	7 1/16	(179)	15 ⅛	(384)	7 1/16	(179)	15 ⅛	(384)	7 1/16	(179)	15 ⅛	(384)
Moisture	2	2 ⅝	(67)	3 ½	(89)	—	—	—	—	—	—	—	—
Resistant	2 ½	2 ⅝	(67)	3 ½	(89)	—	—	—	—	—	—	—	—
(NEMA 4)	3	2 ⅛	(54)	4	(102)	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)
	4	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)	9 ⅜	(238)	7	(178)
	5	7 1/16	(179)	7	(178)	7 1/16	(179)	7	(178)	7 1/16	(179)	7	(178)
	6	7 1/16	(179)	8	(203)	7 1/16	(179)	8	(203)	7 1/16	(179)	8	(203)
	8	7 1/16	(179)	10 1/32	(255)	7 1/16	(179)	10 1/32	(255)	7 1/16	(179)	10 1/32	(255)
	10	7 ¾	(197)	13 ¾	(349)	7 ¾	(197)	13 ¾	(349)	7 ¾	(197)	13 ¾	(349)
	12	7 ¾	(197)	15 ⅞	(403)	7 ¾	(197)	15 ⅞	(403)	7 ¾	(197)	15 ⅞	(403)
	14	7 ¾	(197)	17 ¼	(438)	7 ¾	(197)	17 ¼	(438)	7 ¾	(197)	17 ¼	(438)
Explosion	2	3 1/16	(78)	3 ¾	(95)	—	—	—	—	—	—	—	—
Resistant	2 ½	3 1/16	(78)	3 ¾	(95)	—	—	—	—	—	—	—	—
(NEMA 7)	3	7 ⅛	(181)	5 ¾	(146)	7 ⅛	(181)	5 ¾	(146)	7 ⅛	(181)	5 ¾	(146)
Class 1,	4	7 ⅛	(181)	5 ¾	(146)	7 ⅛	(181)	5 ¾	(146)	7 ⅛	(181)	5 ¾	(146)
Groups	5	7 ⅞	(200)	8 ⅞	(225)	7 ⅞	(200)	8 ⅞	(225)	7 ⅞	(200)	8 ⅞	(225)
C and D	6	7 ⅞	(200)	9 ⅞	(251)	7 ⅞	(200)	9 ⅞	(251)	7 ⅞	(200)	9 ⅞	(251)
Consult	8	7 ⅞	(200)	12 ⅛	(308)	7 ⅞	(200)	12 ⅛	(308)	7 ⅞	(200)	12 ⅛	(308)
Factory	10	7 ⅞	(200)	14 ⅝	(371)	7 ⅞	(200)	14 ⅝	(371)	7 ⅞	(200)	14 ⅝	(371)
for	12	7 ⅞	(200)	15 ⅞	(403)	7 ⅞	(200)	15 ⅞	(403)	7 ⅞	(200)	15 ⅞	(403)
Group B)	14	7 ⅞	(200)	19 ⅜	(492)	7 ⅞	(200)	19 ⅜	(492)	7 ⅞	(200)	19 ⅜	(492)

① Terminal enclosure is octagonal, not round.

Tubular and Process Assemblies

Flange Immersion Heaters

Options

Thermostats

To provide process temperature control, Watlow offers optional single pole, single throw (SPST) and double pole, single throw (DPST) thermostats.

Unless otherwise specified, thermostats are mounted inside the terminal enclosure. For details and ordering information, refer to ***Thermostats*** on **pages 423 to 425**. Please verify that the thermostat's sensing bulb O.D. is compatible with the flange heater's thermowell I.D.

Thermocouples

ASTM Type J or K thermocouples offer more accurate sensing of process and/or sheath temperatures. A thermocouple may be inserted into the thermowell or attached to the heater's sheath.

Thermocouples are supplied with 120 inch (3050 mm) leads (longer lead lengths available). Unless otherwise specified, thermocouples are supplied with temperature ranges detailed on the *Thermocouple Types* chart.

Using a thermocouple requires an appropriate temperature and power control. These must be purchased separately. Watlow offers a wide variety of temperature and power controls to meet virtually all applications. Temperature controls can be configured to accept process variable inputs, too.

Consult your Watlow representative for details.

To order, specify **Type J** or **K** thermocouple and lead length. Indicate if the thermocouple is for **process temperature sensing** or heater sheath **high-limit protection**. Please specify if the flange heater will be mounted **vertical** or **horizontal** in the tank. **If vertical, specify if the housing is on top or bottom**.

If the flange heater is part of an in-line circulation heating application, indicate flow direction relative to the heater's enclosure.

RTDs

If your process requires greater temperature sensing accuracy than is possible with thermocouples, Watlow can also supply RTDs in DIN or JIS calibrations. Consult Watlow for details.

Thermocouple Types

ASTM Type	Conductor Characteristics Positive	Conductor Characteristics Negative	Recommended① Temperature Range °F	(°C)
J	Iron (Magnetic)	Constantan (Non-magnetic)	0 to 1000	(-20 to 540)
K	Chromel® (Non-magnetic)	Alumel® (Magnetic)	0 to 2000	(-20 to 1100)

① Type J and Type K thermocouples are rated 32 to 1382°F and 32 to 2282°F (0-750°C and 0-1250°C), respectively. Watlow does not recommend exceeding temperature ranges shown on this chart for the tubular product line.

Wattages and Voltages

Watlow routinely supplies flange immersion heaters with 240 to 480V~(ac) as well as wattages from 150 watts to one megawatt. If required, Watlow will make heaters with voltage up to 600V~(ac) and wattage beyond one megawatt. For more information on special voltage and wattage configurations, consult your Watlow representative.

Branch Circuits

Branch circuits are subdivided by National Electrical Code (NEC) requirements to a maximum of 48 amps per circuit. Consult factory for circuit requirements other than those listed in the stock charts.

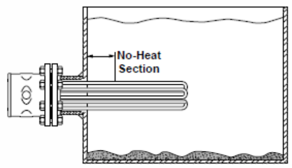
Alumel® and Chromel® are registered trademarks of the Hoskins Manufacturing Company.

Tubular and Process Assemblies

Flange Immersion Heaters

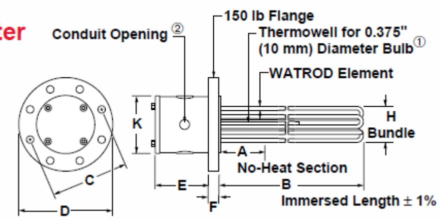
Application Hints

- Select the recommended heating element sheath material and watt density for the substance being heated. Use the ***Supplemental Applications Chart*** on pages 263 to 266. If unable to determine the correct heating element sheath material and type, consult your Watlow representative.
- Extend the element no-heat section completely into the fluid being heated to help prevent premature heater failure. See accompanying illustration for proper no-heat section placement.
- Locate flange heater low in the tank, but above the sludge level.



- Choose a FIREBAR element when your application requires a smaller system package or lower watt density.
- Ensure wiring integrity by keeping terminal enclosure temperature below 400°F (205°C).
- Keep electrical connections clean, dry and tight.
- Minimize problems associated with low liquid level conditions by using low liquid level sensor or sheath temperature high-limit control.
- Periodically remove the flange assembly to inspect and clean the heating element(s). This preventive maintenance will reduce premature failure and optimize heater performance.
- Refer to the *Installation and Maintenance Instructions* for correct orientation of FIREBAR elements. This is important in air applications with customer supplied circulation tanks. Correct element orientation to flow minimizes pressure drop, increases buoyancy force and heater performance.

Flange Immersion Heater



For terminal enclosure dimensions (K and E) see page 341.

Flange Immersion Heater Dimensions

Element Type	Flange Size in	Flange Mounting Hole Size in	(mm)	Flange Mounting Hole Number	Thermowell Length in	(mm)	A Dimension in	(mm)	C Dimension in	(mm)	D Dimension in	(mm)	F Dimension in	(mm)	H Dimension in	(mm)	Number of Elements Std	Max
WATROD	2①	3/4	(19)	4	—	—	2	(51)	4 3/4	(121)	6	(152)	9/16	(14)	2	(51)	3	3
WATROD	2 1/2①	3/4	(19)	4	—	—	3	(76)	5 1/2	(140)	7	(178)	3/8	(10)	2 1/4	(57)	3	3
WATROD	3	3/4	(19)	4	12	(305)	4	(102)	6	(152)	7 1/2	(191)	15/16	(24)	2 3/4	(70)	3	6
WATROD	4	3/4	(19)	8	12	(305)	4	(102)	7 1/2	(191)	9	(229)	15/16	(24)	3 7/8	(98)	6	6
WATROD	5	7/8	(22)	8	12	(305)	4	(102)	8 1/2	(216)	10	(254)	15/16	(24)	5	(127)	6	9
WATROD	6	7/8	(22)	8	12	(305)	4	(102)	9 1/2	(241)	11	(279)	1	(25)	6	(152)	12	15
WATROD	8	7/8	(22)	8	18	(457)	6	(152)	11 3/4	(298)	13 1/2	(343)	1 1/8	(29)	7 13/16	(198)	18	24
WATROD	10	1	(25)	12	18	(457)	6	(152)	14 1/4	(362)	16	(406)	1 3/16	(30)	9 3/4	(248)	27	36
WATROD	12	1	(25)	12	18	(457)	6	(152)	17	(432)	19	(483)	1 1/4	(32)	11 3/4	(298)	36	54
WATROD	14	1 1/8	(29)	12	18	(457)	6	(152)	18 3/4	(476)	21	(533)	1 3/8	(35)	12 3/4	(324)	45	72

① Thermowells are not provided on two and 2 1/2 inch units. 150 lb rating is not available on two and 2 1/2 inch stock units.

Note: The number and size of conduit openings will comply with the National Electrical Code standards.

Tubular and Process Assemblies

Flange Immersion Heaters

5" 150 lb ANSI Flange—WATROD Element

WATROD Description	kW	Immersed B Dimension inch (mm)	Code No. 240V~(ac) 1-Phase	No. of Circuits	240V~(ac) 3-Phase	No. of Circuits	480V~(ac) 1-Phase	No. of Circuits	480V~(ac) 3-Phase	No. of Circuits	Est. Ship. Weight lbs (kg)
Applications: Forced Air and Gases, Caustic Solutions, Degreasing Solutions											
23 W/in^2 Steel Flange 9-Incoloy® (3.6 W/cm^2)	9	18 (457)	FNNA18A10X	1	FNNA18A3X	1	FNNA18A11X	1	FNNA18A5X	1	39 (18)
	14	25½ (648)	FNNA25J10X	3	FNNA25J3X	1	FNNA25J11X	1	FNNA25J5X	1	45 (21)
	18	33 (838)	FNNA33A10X	3	FNNA33A3X	1	FNNA33A11X	1	FNNA33A5X	1	48 (22)
	23	40½ (1029)	FNNA40J10X	3	FNNA40J3X	3	FNNA40J11X	1	FNNA40J5X	1	53 (24)
	27	48 (1219)	FNNA48A10X	3	FNNA48A3X	3	FNNA48A11X	3	FNNA48A5X	1	60 (28)
	38	64½ (1638)			FNNA64J3X	3	FNNA64J11X	3	FNNA64J5X	1	68 (31)
	45	77 (1956)			FNNA77A3X	3	FNNA77A11X	3	FNNA77A5X	3	78 (36)
Applications: Lightweight Oils, Degreasing Solutions, Heat Transfer Oils											
23 W/in^2 Steel Flange 6-Steel (3.6 W/cm^2)	6	18 (457)	FNS718A10	1	FNS718A3	1	FNS718A11	1	FNS718A5	1	36 (17)
	9	25½ (648)	FNS725J10	1	FNS725J3	1	FNS725J11	1	FNS725J5	1	40 (18)
	12	33 (838)	FNS733A10	2	FNS733A3	1	FNS733A11	1	FNS733A5	1	43 (20)
	15	40½ (1029)	FNS740J10	2	FNS740J3	1	FNS740J11	1	FNS740J5	1	47 (22)
	18	48 (1219)	FNS748A10	2	FNS748A3	3	FNS748A11	1	FNS748A5①	1	52 (24)
	25	64½ (1638)			FNS764J3	2	FNS764J11	2	FNS764J5	1	57 (26)
	30	77 (1956)			FNS777A3	2	FNS777A11	2	FNS777A5	1	65 (30)
23 W/in^2 Steel Flange 9-Steel (3.6 W/cm^2)	9	18 (457)	FNS718A10X	1	FNS718A3X	1	FNS718A11X	1	FNS718A5X	1	39 (18)
	14	25½ (648)	FNS725J10X	3	FNS725J3X	1	FNS725J11X	1	FNS725J5X	1	45 (21)
	18	33 (838)	FNS733A10X	3	FNS733A3X	1	FNS733A11X	1	FNS733A5X	1	48 (22)
	23	40½ (1029)	FNS740J10X	3	FNS740J3X	3	FNS740J11X	1	FNS740J5X	1	53 (24)
	27	48 (1219)	FNS748A10X	3	FNS748A3X	1	FNS748A11X	3	FNS748A5X	1	60 (28)
	38	64½ (1638)			FNS764J3X	3	FNS764J11X	3	FNS764J5X	1	68 (31)
	45	77 (1956)			FNS777A3X	3	FNS777A11X	3	FNS777A5X	3	78 (36)
Applications: Medium Weight Oils, Heat Transfer Oils, Liquid Paraffin											
16 W/in^{2}③ Steel Flange 6-Incoloy® (2.5 W/cm^2)	3	13½ (343)			FNN713J12	1			FNN713J13	1	36 (17)
	4	18 (457)			FNN718A12	1			FNN718A13	1	40 (18)
	5	20½ (521)			FNN720J12	1			FNN720J13	1	43 (20)
	6	25½ (648)			FNN725J12	1			FNN725J13	1	47 (22)
	8	33 (838)			FNN733A12	1			FNN733A13	1	52 (24)
	10	40½ (1029)			FNN740J12	1			FNN740J13	1	57 (26)
	12	48 (1219)			FNN748A12	1			FNN748A13	1	65 (30)
16 W/in^{2}③ Steel Flange 9-Incoloy® (2.5 W/cm^2)	4.5	13½ (343)			FNN713J12X	1			FNN713J13X	1	39 (18)
	6	18 (457)			FNN718A12X	1			FNN718A13X	1	45 (21)
	7.5	20½ (521)			FNN720J12X	1			FNN720J13X	1	48 (22)
	9	25½ (648)			FNN725J12X	1			FNN725J13X	1	53 (24)
	12	33 (838)			FNN733A12X	1			FNN733A13X	1	60 (28)
	15	40½ (1029)			FNN740J12X	1			FNN740J13X	1	68 (31)
	18	48 (1219)			FNN748A12X	1			FNN748A13X	1	78 (36)

CONTINUED

All flange immersion heaters are Assembly Stock unless otherwise noted.

Availability

Stock: Same day shipment

Assembly Stock: Five to seven working days

Standard: 10 working days, depending on size

① Stock

③ Must be operated 3-phase wye

Flange Immersion Heaters

Build-a-Code

_ _ _ _ _ _ - _ _ - _ _ _ - _

Flange Immersion Heater Base Code Number①
(Includes general purpose enclosure without thermostat)

Terminal Enclosure Type
S = General purpose (NEMA 1)
W = Moisture resistant (NEMA 4)
E = Explosion resistant (NEMA 7)
E/W = Explosion/moisture resistant (NEMA 7/4)

Thermostat②

Thermocouple③
J = Type J
K = Type K

① Flange immersion heaters are supplied with a standard, general purpose (NEMA 1) terminal enclosure. A thermostat will not fit the standard general purpose terminal enclosure on 2, 2½ and 3 inch flange sizes.
② Code numbers are shown on the Thermostat stock chart on page 425. Check the temperature sensing bulb O.D. to be certain it will fit into the thermowell's I.D.
③ Specify Type J or K thermocouple. If overtemp thermocouple specify orientation horizontal, vertical up or vertical down.

How to Order

To order a stock flange heater, please specify:

- Watlow code number
- Flange size and material
- Volts/watts
- Phase
- Options
- Quantity

If the flange immersion heater is to be configured with options, add the suffix letter(s) to the base flange heater code number, as indicated on the Build-a-Code chart.

If our stock units do not meet your application needs, Watlow will make-to-order.

For **made-to-order** units please specify:

- Application, including media heated, flow rate, pressure, and process operating temperatures
- Volts/watts
- Watt density
- Phase
- Number of circuits
- Number of heating elements
- Element diameter (WATROD only)
- Immersed ('B' dimension) length
- Flange size, rating and material
- No-heat section below the flange
- Terminal enclosure type
- Options
- Quantity

Availability

Stock: Same day shipment

Assembly Stock: Five to seven working days

Modified Stock③: Five to seven working days

Standard: 10 working days

Made-to-Order: Five to seven weeks

Options, complexity and quantity may affect availability and lead times. Consult factory.

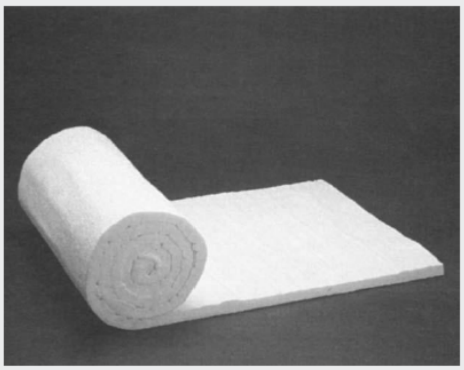
③ Stock or Assembly Stock units with catalog options.

2. Maftec Ceramic Blanket Insulation

Morgan ThermalCeramics

MAFTEC Blanket

Datasheet Code 5-6-09 E | MSDS Code 104-9-EURO REACH



DESCRIPTION

MAFTEC Blanket is made from pure mullite fibre only, needled on both sides, and contains no binder or other added constituent. It can be used at continuous operating temperatures up to 1600°C, under oxidizing, neutral or slightly gas-rich conditions, retaining its original toughness, strength and soft, fibrous structure after extended use at this temperature.

MAFTEC Blanket is more resistant to acid and alkaline solutions than conventional alumino-silicate fibre blankets.

Being virtually free of shot, it has exceptionally good thermal insulation characteristics.

TYPE

Refractory fibre blanket.

MAXIMUM CONTINUOUS USE TEMPERATURE

1600°C

The maximum continuous use temperature depends on the application. In case of doubt, refer to your local Morgan Thermal Ceramics distributor for advice.

FEATURES

- Because of its microcrystalline structure, MAFTEC Blanket is suited for continuous operation at 1600°C
- Very low thermal conductivity
- Very low shrinkage at 1600°C
- Resistant to thermal shock
- MAFTEC Blanket is ideal for the manufacturing of modular blocks because it remains soft up to 1600°C
- Good sound absorption
- High strength make it easy to handle and prevents tearing or punching around anchors
- Chemically stable and free of corrosive agents
- Low heat storage

APPLICATIONS

- Furnace and kiln lining (heat treatment, ceramic fast firing, petroleum and chemical)
- High temperature gaskets
- Furnace door seals
- High temperature filter media

Morgan ThermalCeramics

MAFTEC Blanket

Main properties

Maximum continuous use temperature	**°C**		**1600**	
Properties Measured at Ambient Conditions (23°C/50% RH)				
Colour			white	
Density	Kg/m3	96		128
Tensile strength (NF-B-40-454)	kPa	93		103
High Temperature Performance				
Permanent linear shrinkage after 24 hours isothermal heating at:				
1300°C	%		0.3	
1400°C	%		0.8	
1500°C	%		0.9	
1600°C	%		1.0	
Thermal conductivity (NFB-40-456) at mean temperature of:		96kg/m^3		128kg/m^3
400°C	W/m.K	0.08		0.08
500°C	W/m.K	0.10		0.09
600°C	W/m.K	0.13		0.12
700°C	W/m.K	0.17		0.14
800°C	W/m.K	0.19		0.17
900°C	W/m.K	0.23		0.20
1000°C	W/m.K	0.27		0.24
1200°C	W/m.K	0.39		0.33
1400°C	W/m.K	0.58		0.48
Specific heat capacity at 1090°C	kJ/kg.K		1.25	
Chemical Composition				
SiO_2	%		28	
Al_2O_3	%		72	
Fe_2O_3	%		0.03	
TiO_2	%		0.01	
CaO + MgO	%		traces	
Na_2O + K_2O	%		0.06	

MAFTEC Blanket

Availability and Packaging
MAFTEC Blankets are packed in cartons, on pallets.

Thick	Density kg/m^3		Length	Width	Blankets/	m^2/
mm	96	128	mm	mm	carton	carton
6	X	❍	3600	610	12	26.52
12.5	X	X	3600	610	6	13.17
25	X	X	3600	610	3	6.58

3. Pyrotape 682-TB Thermal Barrier Ceramic Tape

PYRO-TAPE™ 682-TB THERMAL BARRIER CERAMIC TAPE

The new 682-TB tape is a woven silica fabric tape with temperature resistance as high as 2500 °F used to offer thermal insulation for pipes. The Pyro-Tape 682-TB has an adhesive backing which is used to ease wrapping around pipes. The adhesive will burn off at 275 °F, and then the tape is secured to the pipe in intervals with stainless steel wire.

No. 682-TB thermal barrier ceramic tape

PRODUCT SPECIFICATIONS		
Silica Content		96% +
Tape Thickness	682-TB1	0.76 MM (0.030")
	682-TB2	1.37 MM (0.054")
Tape Widths*	682-TB1-1	1 inch wide
	682-TB1-2	2 inch wide
	682-TB1-4	4 inch wide
	682-TB2-1	1 inch wide
	682-TB2-2	2 inch wide
	682-TB2-4	4 inch wide
Typical Roll Length	682-TB1	150 feet
	682-TB2	75 feet
Thermal Conductivity	682-TB1	600 °F Mean Temp. - 1.00 BTU-in/hrs-ft^2-°F
	682-TB2	600 °F Mean Temp. - 1.10 BTU-in/hrs-ft^2-°F

*Sizes to 4" wide available upon request.

4. Promat Microtherm Insulation Panel

Promat

MICROTHERM ® PANEL

High temperature microporous insulation panel

1000-1200°C

The MICROTHERM® PANEL range of products are custom made microporous insulation panels with very good thermal properties. The panels are produced in a glass cloth outer envelope, making them clean & easy to handle. The formulation is an opacified blend of filament reinforced pyrogenic silica (alumina for 1200 grade).

MICROTHERM® PANEL-1000R is a lightweight, custom made insulation panel.

MICROTHERM® PANEL-1000R HY is a custom made insulation panel with a hydrophobic core treatment to repel water. It is ideal for applications where contact with liquid water or condensation (dew point) is possible.

MICROTHERM® PANEL-1200 is an alumina based, custom made insulation panel which is capable of withstanding peak temperatures of 1200°C.

Properties & advantages

- Custom made
- Extremely low thermal conductivity
- High thermal stability
- Available in different temperature grades, including a hydrophobic version
- Non combustible
- Clean & easy to handle
- Simple to cut & shape (procedure can be found on our website)
- No harmful respirable fibres
- Environmentally friendly, free of organic binders
- Resistant to most chemicals

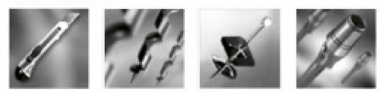
Typical applications

Microporous insulation offers an extremely low thermal conductivity, close to the lowest theoretically possible at high temperatures. Microporous materials are the preferred choice when a large temperature reduction is required within a limited space, or when strict heat loss or surface temperature requirements are specified.

- Back-up insulation in industrial furnaces
- Aluminium industry (launders, holding furnace, ...)
- Glass & ceramics industry
- Petrochemical industry (cracking furnace, hydrogen reformer, ...)
- Annealing & galvanizing lines
- Night storage heaters

Working & Processing

MICROTHERM® PANEL can be shaped easily with a simple cutter (the procedure can be found on our website). The panels can be fixed in place with glue or by mechanical means such as anchors, pins and clips. They can also be fitted between the anchors.



Also available in HYDROPHOBIC

MICROTHERM ® PANEL

Promat

MICROTHERM® PANEL

High temperature microporous insulation panel

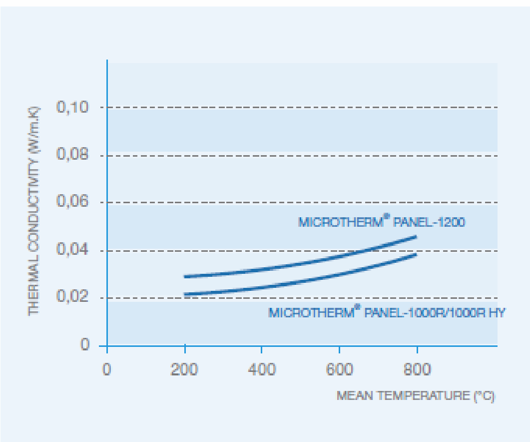
1000-1200°C

Technical data

Brand		MICROTHERM® PANEL		
Grade		1000R	1000R HY	1200
Standard finishing		Glass cloth (E-Glass)*		
Classification Temperature	°C	1000	1000	1200
Nominal density	kg/m³	240	260	400
Compressive strength(ASTM C 165)	MPa = N/mm²	0,13	0,12	0,36
Thermal Conductivity (ISO 8302, ASTM C177)				
200°C mean	W/m.K	0,023	0,023	0,029
400°C mean	W/m.K	0,026	0,026	0,033
600°C mean	W/m.K	0,031	0,031	0,039
800°C mean	W/m.K	0,039	0,039	0,044
Specific Heat Capacity				
200°C	kJ/kg.K	0,92	0,92	0,89
400°C	kJ/kg.K	1,00	1,00	0,99
600°C	kJ/kg.K	1,04	1,04	1,04
800°C	kJ/kg.K	1,08	1,08	1,07
Shrinkage				
1-sided 12h @1000°C	%	< 0,5	< 0,5	< 0,05
Full soak 24h @1000°C	%	< 3	< 3	< 0,1
Full soak 24h @1150°C	%	-	-	< 3

* Special coverings and coatings are available on request.

Thermal Conductivity Graph



Product dimensions & size availability

Although there are some standard stock sizes available, MICROTHERM® PANEL can be custom made according to customer specifications. Please contact your regional Promat agency to request your MICROTHERM® PANEL sizes.

The available thickness range depends on the material grade:

Brand	MICROTHERM® PANEL		
Grade	1000R	1000R HY	1200
Thickness range [mm]	3 – 50	3 – 40	3 – 40

Production tolerances

IF length	≤ 1,6m	
Length [mm]	± 3	
Width [mm]	± 3	
Thickness [mm]	T ≤ 10	± 0,5
	10 < T ≤ 30	± 0,8
	30 < T ≤ 50	± 1,5

Note: Only valid for rectangular & square shapes

www.promat-hpi.com

Promat High Performance Insulation

MICROTHERM THERMAL INSULATION SOLUTIONS

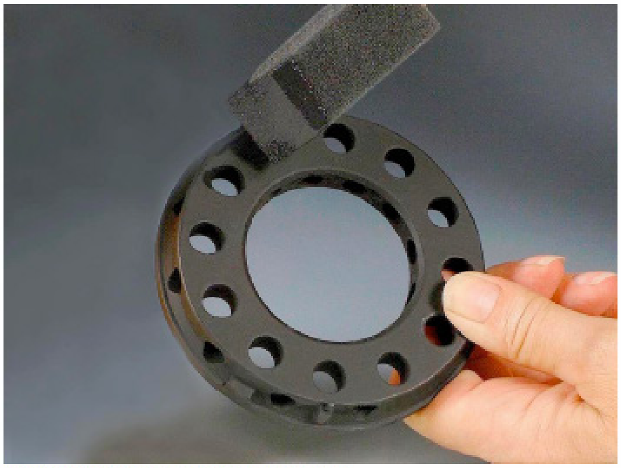
an etex company

105566 - 15102012 - V1

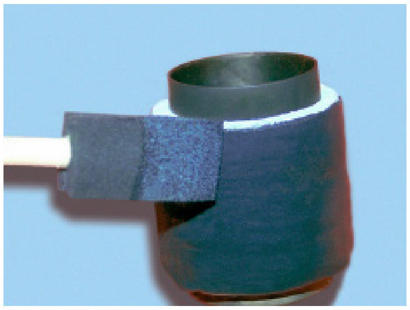
4. Aremco 840-M High-Temperature High-Emissivity Coating

AREMCO

HIGH TEMPERATURE HIGH EMISSIVITY COATINGS
Technical Bulletin A5-S2



HiE-Coat™ 840-M coats gas burner component.



HiE-Coat™ 840-C coats exhaust pipe insulation.

HiE-Coat™ 840-C coats ceramic fiberboard infrared heater.

HiE-Coat™ 840-CM coats cast steel part.

PRODUCT HIGHLIGHTS

The HiE-Coat™ line of high emissivity coatings are black-body formulations designed to significantly improve the thermal efficiency of infrared heaters, furnaces, incinerators, and ovens used throughout the appliance, ceramics, chemical processing, metallurgical, and refining industries. Natural gas and oil savings in the range of 5–10% are typical using these coatings.

840-C	Ceramic-based, black-pigmented coating for ceramic fiber modules and refractories to 2500 °F (1371 °C).
840-CM	Ceramic-based, black-pigmented coating for dense refractories to 2500 °F (1371 °C) and stainless steel to 900 °F (482 °C).
840-M	Ceramic-based, black-pigmented coating for carbon and stainless steel to 2000 °F (1093 °C).
840-MS	Silicone-ceramic, black-pigmented coating for aluminum, brass, copper, and carbon and stainless steels to 1100 °F (593 °C).

Aremco Products, Inc., 707-B Executive Boulevard, Valley Cottage, NY 10989 T (845) 268-0039 E aremco@aremco.com W aremco.com
Rev. 4/15

HIGH EMISSIVITY COATINGS

Type	INORGANIC-CERAMIC			SILICONE-CERAMIC
Product Number	840-C	840-CM	840-M	840-MS
Tradename	HIE-Coat™			
Color (cured)	Jet Black	Jet Black	Jet Black	Jet Black
Maximum Temperature, °F (°C)	2500 (1371)	Ceramics: 2500 (1371) Stainless: 900 (482)	2000 (1093)	1100 (593)
No. Components	1	1	1	1
Mix Ratio, by Weight (by Volume)	NA	NA	NA	NA
Viscosity, cP[1]	70–160	600–800	600–900	250–500
Specific Gravity, g/cc	1.60	1.54	1.54	1.49
Solids by Weight, %	58.5	48.0	50.0	57.1
Solids by Volume, %	27.3	19.9	46.3	42.5
WFT, mils (microns)[2]	3.66 (92.9)	5.03 (127.7)	2.12 (54.9)	2.40 (61.0)
DFT, mils (microns)[3]	1.00 (25.4)	1.00 (25.4)	1.00 (25.4)	1.00 (25.4)
Theoretical Dry Film Coverage[4] @ 1 mil, ft^2/gal (m^2/liter)	438 (10.8)	319 (7.8)	742 (18.2)	681 (16.7)
Curing, Min Air Set, hrs[5]	1.0–2.0	1.0	1.0	1.0
Curing, Heat Cure, °F, hrs	200, 1	200, 0.5 + 500 / 1	200, 1 + 500 / 1	480 / .75
Application Temperature, °F	50–90	50–90	50–90	50–120
Thinner	840-C-T	840-CM-T	840-M-T	PM Acetate
Flash Point, °F/°C	NA	NA	NA	~118 (48)
Volatiles, lbs/gal	0.0	0.0	0.0	5.3
Shelf Life, months	6	6	6	6
Storage Temperature, °F	55–85	55–85	55–85	40–90

Reference Notes

[1] Viscosity is measured using a Brookfield LV Viscometer; spindle and speed selection vary depending on the product.
[2] Estimated Wet Film Thickness (WFT).
[3] Recommended Dry Film Thickness (DFT).
[4] Actual coverage will vary depending on material losses during mixing and application.
[5] Where a value is provided for "Min Air Set", it is recommended to set the coating at room temperature for, at minimum, the specified time prior to curing.

Surface Preparation Notes

All surfaces should be free of oil, grease, dirt, corrosives, oxides, paints or other foreign matter. No further preparation is required when coating ceramics, refractories or graphites. Quartz should be sandblasted whenever possible. Smooth metal surfaces should be sandblasted or etched using Aremco's Corr-Prep™ CPR2000.

Abbreviations

NA Not Applicable
NR Not Required
DFT Dry Film Thickness
WFT Wet Film Thickness

Refer to Price List for complete order information.

5. AD595AQ Thermocouple Amplifier

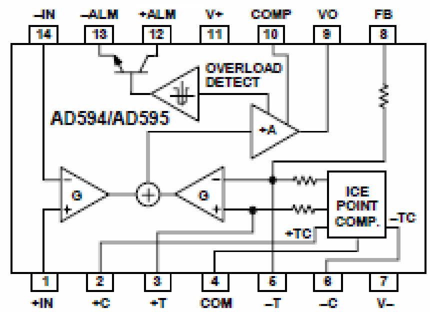
ANALOG DEVICES

Monolithic Thermocouple Amplifiers with Cold Junction Compensation

AD594/AD595

FEATURES
- Pretrimmed for Type J (AD594) or Type K (AD595) Thermocouples
- Can Be Used with Type T Thermocouple Inputs
- Low Impedance Voltage Output: 10 mV/°C
- Built-In Ice Point Compensation
- Wide Power Supply Range: +5 V to ±15 V
- Low Power: <1 mW typical
- Thermocouple Failure Alarm
- Laser Wafer Trimmed to 1°C Calibration Accuracy
- Setpoint Mode Operation
- Self-Contained Celsius Thermometer Operation
- High Impedance Differential Input
- Side-Brazed DIP or Low Cost Cerdip

FUNCTIONAL BLOCK DIAGRAM



PRODUCT DESCRIPTION

The AD594/AD595 is a complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip. It combines an ice point reference with a precalibrated amplifier to produce a high level (10 mV/°C) output directly from a thermocouple signal. Pin-strapping options allow it to be used as a linear amplifier-compensator or as a switched output setpoint controller using either fixed or remote setpoint control. It can be used to amplify its compensation voltage directly, thereby converting it to a stand-alone Celsius transducer with a low impedance voltage output.

The AD594/AD595 includes a thermocouple failure alarm that indicates if one or both thermocouple leads become open. The alarm output has a flexible format which includes TTL drive capability.

The AD594/AD595 can be powered from a single ended supply (including +5 V) and by including a negative supply, temperatures below 0°C can be measured. To minimize self-heating, an unloaded AD594/AD595 will typically operate with a total supply current 160 µA, but is also capable of delivering in excess of ±5 mA to a load.

The AD594 is precalibrated by laser wafer trimming to match the characteristic of type J (iron-constantan) thermocouples and the AD595 is laser trimmed for type K (chromel-alumel) inputs. The temperature transducer voltages and gain control resistors are available at the package pins so that the circuit can be recalibrated for the thermocouple types by the addition of two or three resistors. These terminals also allow more precise calibration for both thermocouple and thermometer applications.

The AD594/AD595 is available in two performance grades. The C and the A versions have calibration accuracies of ±1°C and ±3°C, respectively. Both are designed to be used from 0°C to +50°C, and are available in 14-pin, hermetically sealed, side-brazed ceramic DIPs as well as low cost cerdip packages.

PRODUCT HIGHLIGHTS

1. The AD594/AD595 provides cold junction compensation, amplification, and an output buffer in a single IC package.
2. Compensation, zero, and scale factor are all precalibrated by laser wafer trimming (LWT) of each IC chip.
3. Flexible pinout provides for operation as a setpoint controller or a stand-alone temperature transducer calibrated in degrees Celsius.
4. Operation at remote application sites is facilitated by low quiescent current and a wide supply voltage range +5 V to dual supplies spanning 30 V.
5. Differential input rejects common-mode noise voltage on the thermocouple leads.

REV. C

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 World Wide Web Site: http://www.analog.com
Fax: 781/326-8703

AD594/AD595–SPECIFICATIONS (@ +25°C and V_S = 5 V, Type J (AD594), Type K (AD595) Thermocouple, unless otherwise noted)

Model	AD594A Min	AD594A Typ	AD594A Max	AD594C Min	AD594C Typ	AD594C Max	AD595A Min	AD595A Typ	AD595A Max	AD595C Min	AD595C Typ	AD595C Max	Units
ABSOLUTE MAXIMUM RATING													
$+V_S$ to $-V_S$			36			36			36			36	Volts
Common-Mode Input Voltage	$-V_S - 0.15$		$+V_S$	$-V_S - 0.15$		$+V_S$	$-V_S - 0.15$		$+V_S$	$-V_S - 0.15$		$+V_S$	Volts
Differential Input Voltage	$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	Volts
Alarm Voltages													
+ALM	$-V_S$		$-V_S + 36$	$-V_S$		$-V_S + 36$	$-V_S$		$-V_S + 36$	$-V_S$		$-V_S + 36$	Volts
–ALM	$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	Volts
Operating Temperature Range	–55		+125	–55		+125	–55		+125	–55		+125	°C
Output Short Circuit to Common	Indefinite			Indefinite			Indefinite			Indefinite			
TEMPERATURE MEASUREMENT (Specified Temperature Range 0°C to +50°C)													
Calibration Error at +25°C[1]			**±3**			**±1**			**±3**			**±1**	°C
Stability vs. Temperature[2]			**±0.05**			**±0.025**			**±0.05**			**±0.025**	°C/°C
Gain Error			**±1.5**			**±0.75**			**±1.5**			**±0.75**	%
Nominal Transfer Function			10			10			10			10	mV/°C
AMPLIFIER CHARACTERISTICS													
Closed Loop Gain[3]		**193.4**				**193.4**			**247.3**			**247.3**	
Input Offset Voltage		(Temperature in °C) × 51.70 μV/°C			(Temperature in °C) × 51.70 μV/°C			(Temperature in °C) × 40.44 μV/°C			(Temperature in °C) × 40.44 μV/°C		μV
Input Bias Current		0.1			0.1			0.1			0.1		μA
Differential Input Range	–10		+50				–10		+50	–10		+50	mV
Common-Mode Range	$\mathbf{-V_S - 0.15}$		$\mathbf{-V_S - 4}$	$\mathbf{-V_S - 0.15}$		$\mathbf{-V_S - 4}$	$\mathbf{-V_S - 0.15}$		$\mathbf{-V_S - 4}$	$\mathbf{-V_S - 0.15}$		$\mathbf{-V_S - 4}$	Volts
Common-Mode Sensitivity – RTO			**10**			**10**			**10**			**10**	mV/V
Power Supply Sensitivity – RTO			**10**			**10**			**10**			**10**	mV/V
Output Voltage Range													
Dual Supply	$\mathbf{-V_S + 2.5}$		$\mathbf{+V_S - 2}$	$\mathbf{-V_S + 2.5}$		$\mathbf{+V_S - 2}$	$\mathbf{-V_S + 2.5}$		$\mathbf{+V_S - 2}$	$\mathbf{-V_S + 2.5}$		$\mathbf{+V_S - 2}$	Volts
Single Supply	0		$+V_S - 2$	0		$-V_S - 2$	0		$+V_S + 2$	0		$+V_S - 2$	Volts
Usable Output Current[4]		±5			±5			±5			±5		mA
3 dB Bandwidth		15			15			15			15		kHz
ALARM CHARACTERISTICS													
$V_{CE(SAT)}$ at 2 mA		0.3			0.3			0.3			0.3		Volts
Leakage Current			**±1**			**±1**			**±1**			**±1**	μA max
Operating Voltage at –ALM			$\mathbf{+V_S - 4}$			$\mathbf{+V_S - 4}$			$\mathbf{+V_S - 4}$			$\mathbf{+V_S - 4}$	Volts
Short Circuit Current		20			20			20			20		mA
POWER REQUIREMENTS													
Specified Performance		$+V_S = 5, -V_S = 0$			$+V_S = 5, -V_S = 0$			$+V_S = 5, -V_S = 0$			$+V_S = 5, -V_S = 0$		Volts
Operating[5]		$+V_S$ to $-V_S \leq 30$			$+V_S$ to $-V_S \leq 30$			$+V_S$ to $-V_S \leq 30$			$+V_S$ to $-V_S \leq 30$		Volts
Quiescent Current (No Load)													
$+V_S$		160	300		160	300		160	300		160	300	μA
$-V_S$		100			100			100			100		μA
PACKAGE OPTION													
TO-116 (D-14)		AD594AD			AD594CD			AD595AD			AD595CD		
Cerdip (Q-14)		AD594AQ			AD594CQ			AD595AQ			AD595CQ		

NOTES

[1] Calibrated for minimum error at +25°C using a thermocouple sensitivity of 51.7 μV/°C. Since a J type thermocouple deviates from this straight line approximation, the AD594 will normally read 3.1 mV when the measuring junction is at 0°C. The AD595 will similarly read 2.7 mV at 0°C.

[2] Defined as the slope of the line connecting the AD594/AD595 errors measured at 0°C and 50°C ambient temperature.

[3] Pin 8 shorted to Pin 9.

[4] Current Sink Capability in single supply configuration is limited to current drawn to ground through a 50 kΩ resistor at output voltages below 2.5 V.

[5] $-V_S$ must not exceed –16.5 V.

Specifications shown in **boldface** are tested on all production units at final electrical test. Results from those tests are used to calculate outgoing quality levels. All min and max specifications are guaranteed, although only those shown in **boldface** are tested on all production units.

Specifications subject to change without notice.

INTERPRETING AD594/AD595 OUTPUT VOLTAGES

To achieve a temperature proportional output of 10 mV/°C and accurately compensate for the reference junction over the rated operating range of the circuit, the AD594/AD595 is gain trimmed to match the transfer characteristic of J and K type thermocouples at 25°C. For a type J output in this temperature range the TC is 51.70 μV/°C, while for a type K it is 40.44 μV/°C. The resulting gain for the AD594 is 193.4 (10 mV/°C divided by 51.7 μV/°C) and for the AD595 is 247.3 (10 mV/°C divided by 40.44 μV/°C). In addition, an absolute accuracy trim induces an input offset to the output amplifier characteristic of 16 μV for the AD594 and 11 μV for the AD595. This offset arises because the AD594/AD595 is trimmed for a 250 mV output while applying a 25°C thermocouple input.

Because a thermocouple output voltage is nonlinear with respect to temperature, and the AD594/AD595 linearly amplifies the compensated signal, the following transfer functions should be used to determine the actual output voltages:

AD594 output = (Type J Voltage + 16 μV) × 193.4

AD595 output = (Type K Voltage + 11 μV) × 247.3 or conversely:

Type J voltage = (AD594 output/193.4) – 16 μV

Type K voltage = (AD595 output/247.3) – 11 μV

Table I lists the ideal AD594/AD595 output voltages as a function of Celsius temperature for type J and K ANSI standard thermocouples, with the package and reference junction at 25°C. As is normally the case, these outputs are subject to calibration, gain and temperature sensitivity errors. Output values for intermediate temperatures can be interpolated, or calculated using the output equations and ANSI thermocouple voltage tables referred to zero degrees Celsius. Due to a slight variation in alloy content between ANSI type J and DIN FE-CUNI

Table I. Output Voltage vs. Thermocouple Temperature (Ambient +25°C, V_S = –5 V, +15 V)

Thermocouple Temperature °C	Type J Voltage mV	AD594 Output mV	Type K Voltage mV	AD595 Output mV
–200	–7.890	–1523	–5.891	–1454
–180	–7.402	–1428	–5.550	–1370
–160	–6.821	–1316	–5.141	–1269
–140	–6.159	–1188	–4.669	–1152
–120	–5.426	–1046	–4.138	–1021
–100	–4.632	–893	–3.553	–876
–80	–3.785	–729	–2.920	–719
–60	–2.892	–556	–2.243	–552
–40	–1.960	–376	–1.527	–375
–20	–.995	–189	–.777	–189
–10	–.501	–94	–.392	–94
0	0	3.1	0	2.7
10	.507	101	.397	101
20	1.019	200	.798	200
25	1.277	250	1.000	250
30	1.536	300	1.203	300
40	2.058	401	1.611	401
50	2.585	503	2.022	503
60	3.115	606	2.436	605
80	4.186	813	3.266	810
100	5.268	1022	4.095	1015
120	6.359	1233	4.919	1219
140	7.457	1445	5.733	1420
160	8.560	1659	6.539	1620
180	9.667	1873	7.338	1817
200	10.777	2087	8.137	2015
220	11.887	2302	8.938	2213
240	12.998	2517	9.745	2413
260	14.108	2732	10.560	2614
280	15.217	2946	11.381	2817
300	16.325	3160	12.207	3022
320	17.432	3374	13.039	3227
340	18.537	3588	13.874	3434
360	19.640	3801	14.712	3641
380	20.743	4015	15.552	3849
400	21.846	4228	16.395	4057
420	22.949	4441	17.241	4266
440	24.054	4655	18.088	4476
460	25.161	4869	18.938	4686
480	26.272	5084	19.788	4896
500	27.388	5300	20.640	5107
520	28.511	5517	21.493	5318
540	29.642	5736	22.346	5529
560	30.782	5956	23.198	5740
580	31.933	6179	24.050	5950
600	33.096	6404	24.902	6161
620	34.273	6632	25.751	6371
640	35.464	6862	26.599	6581
660	36.671	7095	27.445	6790
680	37.893	7332	28.288	6998
700	39.130	7571	29.128	7206
720	40.382	7813	29.965	7413
740	41.647	8058	30.799	7619
750	42.283	8181	31.214	7722
760	–	–	31.629	7825
780	–	–	32.455	8029
800	–	–	33.277	8232
820	–	–	34.095	8434
840	–	–	34.909	8636
860	–	–	35.718	8836
880	–	–	36.524	9035
900	–	–	37.325	9233
920	–	–	38.122	9430
940	–	–	38.915	9626
960	–	–	39.703	9821
980	–	–	40.488	10015
1000	–	–	41.269	10209
1020	–	–	42.045	10400
1040	–	–	42.817	10591
1060	–	–	43.585	10781
1080	–	–	44.439	10970
1100	–	–	45.108	11158
1120	–	–	45.863	11345
1140	–	–	46.612	11530
1160	–	–	47.356	11714
1180	–	–	48.095	11897
1200	–	–	48.828	12078
1220	–	–	49.555	12258
1240	–	–	50.276	12436
1250	–	–	50.633	12524

thermocouples Table I should not be used in conjunction with European standard thermocouples. Instead the transfer function given previously and a DIN thermocouple table should be used. ANSI type K and DIN NiCr-Ni thermocouples are composed

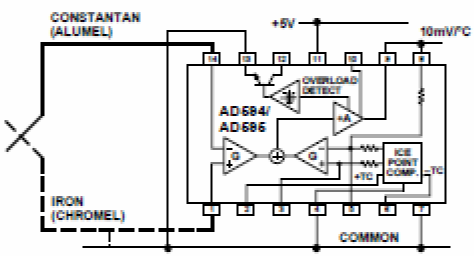


Figure 1. Basic Connection, Single Supply Operation

of identical alloys and exhibit similar behavior. The upper temperature limits in Table I are those recommended for type J and type K thermocouples by the majority of vendors.

SINGLE AND DUAL SUPPLY CONNECTIONS

The AD594/AD595 is a completely self-contained thermocouple conditioner. Using a single +5 V supply the interconnections shown in Figure 1 will provide a direct output from a type J thermocouple (AD594) or type K thermocouple (AD595) measuring from 0°C to +300°C.

Any convenient supply voltage from +5 V to +30 V may be used, with self-heating errors being minimized at lower supply levels. In the single supply configuration the +5 V supply connects to Pin 11 with the V– connection at Pin 7 strapped to power and signal common at Pin 4. The thermocouple wire inputs connect to Pins 1 and 14 either directly from the measuring point or through intervening connections of similar thermocouple wire type. When the alarm output at Pin 13 is not used it should be connected to common or –V. The precalibrated feedback network at Pin 8 is tied to the output at Pin 9 to provide a 10 mV/°C nominal temperature transfer characteristic.

By using a wider ranging dual supply, as shown in Figure 2, the AD594/AD595 can be interfaced to thermocouples measuring both negative and extended positive temperatures.

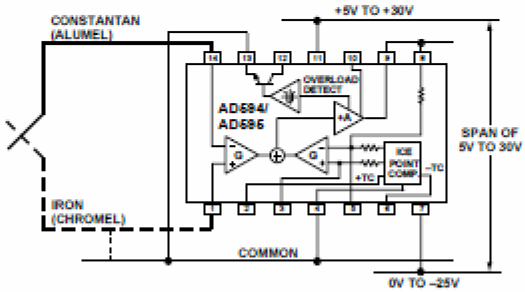


Figure 2. Dual Supply Operation

With a negative supply the output can indicate negative temperatures and drive grounded loads or loads returned to positive voltages. Increasing the positive supply from 5 V to 15 V extends the output voltage range well beyond the 750°C temperature limit recommended for type J thermocouples (AD594) and the 1250°C for type K thermocouples (AD595).

Common-mode voltages on the thermocouple inputs must remain within the common-mode range of the AD594/AD595, with a return path provided for the bias currents. If the thermocouple is not remotely grounded, then the dotted line connections in Figures 1 and 2 are recommended. A resistor may be needed in this connection to assure that common-mode voltages induced in the thermocouple loop are not converted to normal mode.

THERMOCOUPLE CONNECTIONS

The isothermal terminating connections of a pair of thermocouple wires forms an effective reference junction. This junction must be kept at the same temperature as the AD594/AD595 for the internal cold junction compensation to be effective.

A method that provides for thermal equilibrium is the printed circuit board connection layout illustrated in Figure 3.

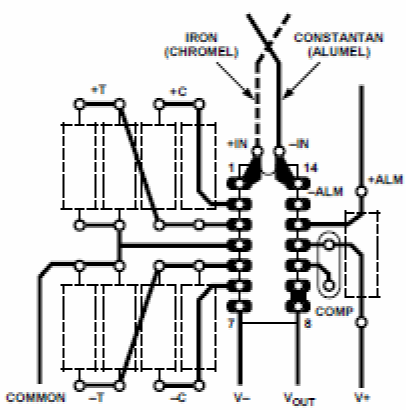


Figure 3. PCB Connections

Here the AD594/AD595 package temperature and circuit board are thermally contacted in the copper printed circuit board tracks under Pins 1 and 14. The reference junction is now composed of a copper-constantan (or copper-alumel) connection and copper-iron (or copper-chromel) connection, both of which are at the same temperature as the AD594/AD595.

The printed circuit board layout shown also provides for placement of optional alarm load resistors, recalibration resistors and a compensation capacitor to limit bandwidth.

To ensure secure bonding the thermocouple wire should be cleaned to remove oxidation prior to soldering. Noncorrosive rosin flux is effective with iron, constantan, chromel and alumel and the following solders: 95% tin-5% antimony, 95% tin-5% silver or 90% tin-10% lead.

FUNCTIONAL DESCRIPTION

The AD594 behaves like two differential amplifiers. The outputs are summed and used to control a high gain amplifier, as shown in Figure 4.

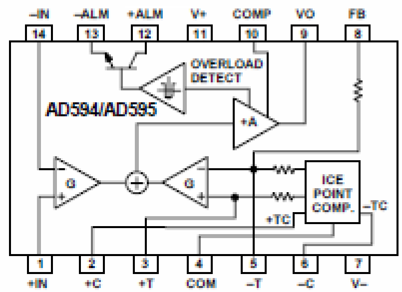


Figure 4. AD594/AD595 Block Diagram

In normal operation the main amplifier output, at Pin 9, is connected to the feedback network, at Pin 8. Thermocouple signals applied to the floating input stage, at Pins 1 and 14, are amplified by gain G of the differential amplifier and are then further amplified by gain A in the main amplifier. The output of the main amplifier is fed back to a second differential stage in an inverting connection. The feedback signal is amplified by this stage and is also applied to the main amplifier input through a summing circuit. Because of the inversion, the amplifier causes the feedback to be driven to reduce this difference signal to a small value. The two differential amplifiers are made to match and have identical gains, G. As a result, the feedback signal that must be applied to the right-hand differential amplifier will precisely match the thermocouple input signal when the difference signal has been reduced to zero. The feedback network is trimmed so that the effective gain to the output, at Pins 8 and 9, results in a voltage of 10 mV/°C of thermocouple excitation.

In addition to the feedback signal, a cold junction compensation voltage is applied to the right-hand differential amplifier. The compensation is a differential voltage proportional to the Celsius temperature of the AD594/AD595. This signal disturbs the differential input so that the amplifier output must adjust to restore the input to equal the applied thermocouple voltage.

The compensation is applied through the gain scaling resistors so that its effect on the main output is also 10 mV/°C. As a result, the compensation voltage adds to the effect of the thermocouple voltage a signal directly proportional to the difference between 0°C and the AD594/AD595 temperature. If the thermocouple reference junction is maintained at the AD594/AD595 temperature, the output of the AD594/AD595 will correspond to the reading that would have been obtained from amplification of a signal from a thermocouple referenced to an ice bath.

The AD594/AD595 also includes an input open circuit detector that switches on an alarm transistor. This transistor is actually a current-limited output buffer, but can be used up to the limit as a switch transistor for either pull-up or pull-down operation of external alarms.

The ice point compensation network has voltages available with positive and negative temperature coefficients. These voltages may be used with external resistors to modify the ice point compensation and recalibrate the AD594/AD595 as described in the next column.

The feedback resistor is separately pinned out so that its value can be padded with a series resistor, or replaced with an external resistor between Pins 5 and 9. External availability of the feedback resistor allows gain to be adjusted, and also permits the AD594/AD595 to operate in a switching mode for setpoint operation.

CAUTIONS:

The temperature compensation terminals (+C and –C) at Pins 2 and 6 are provided to supply small calibration currents only. The AD594/AD595 may be permanently damaged if they are grounded or connected to a low impedance.

The AD594/AD595 is internally frequency compensated for feedback ratios (corresponding to normal signal gain) of 75 or more. If a lower gain is desired, additional frequency compensation should be added in the form of a 300 pF capacitor from Pin 10 to the output at Pin 9. As shown in Figure 5 an additional 0.01 µF capacitor between Pins 10 and 11 is recommended.

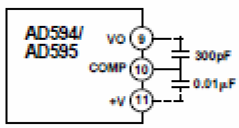


Figure 5. Low Gain Frequency Compensation

RECALIBRATION PRINCIPLES AND LIMITATIONS

The ice point compensation network of the AD594/AD595 produces a differential signal which is zero at 0°C and corresponds to the output of an ice referenced thermocouple at the temperature of the chip. The positive TC output of the circuit is proportional to Kelvin temperature and appears as a voltage at +T. It is possible to decrease this signal by loading it with a resistor from +T to COM, or increase it with a pull-up resistor from +T to the larger positive TC voltage at +C. Note that adjustments to +T should be made by measuring the voltage which tracks it at –T. To avoid destabilizing the feedback amplifier the measuring instrument should be isolated by a few thousand ohms in series with the lead connected to –T.

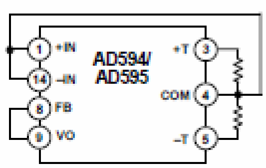


Figure 6. Decreased Sensitivity Adjustment

Changing the positive TC half of the differential output of the compensation scheme shifts the zero point away from 0°C. The zero can be restored by adjusting the current flow into the negative input of the feedback amplifier, the –T pin. A current into this terminal can be produced with a resistor between –C and –T to balance an increase in +T, or a resistor from –T to COM to offset a decrease in +T.

If the compensation is adjusted substantially to accommodate a different thermocouple type, its effect on the final output voltage will increase or decrease in proportion. To restore the nominal output to 10 mV/°C the gain may be adjusted to match the new compensation and thermocouple input characteristics. When reducing the compensation the resistance between –T and COM automatically increases the gain to within 0.5% of the correct value. If a smaller gain is required, however, the nominal 47 kΩ internal feedback resistor can be paralleled or replaced with an external resistor.

Fine calibration adjustments will require temperature response measurements of individual devices to assure accuracy. Major reconfigurations for other thermocouple types can be achieved without seriously compromising initial calibration accuracy, so long as the procedure is done at a fixed temperature using the factory calibration as a reference. It should be noted that intermediate recalibration conditions may require the use of a negative supply.

EXAMPLE: TYPE E RECALIBRATION—AD594/AD595

Both the AD594 and AD595 can be configured to condition the output of a type E (chromel-constantan) thermocouple. Temperature characteristics of type E thermocouples differ less from type J, than from type K, therefore the AD594 is preferred for recalibration.

While maintaining the device at a constant temperature follow the recalibration steps given here. First, measure the device temperature by tying both inputs to common (or a selected common-mode potential) and connecting FB to VO. The AD594 is now in the stand alone Celsius thermometer mode. For this example assume the ambient is 24°C and the initial output VO is 240 mV. Check the output at VO to verify that it corresponds to the temperature of the device.

Next, measure the voltage –T at Pin 5 with a high impedance DVM (capacitance should be isolated by a few thousand ohms of resistance at the measured terminals). At 24°C the –T voltage will be about 8.3 mV. To adjust the compensation of an AD594 to a type E thermocouple a resistor, R1, should be connected between +T and +C, Pins 2 and 3, to raise the voltage at –T by the ratio of thermocouple sensitivities. The ratio for converting a type J device to a type E characteristic is:

$$r\,(AD594) = (60.9\ \mu V/°C)/(51.7\ \mu V/°C) = 1.18$$

Thus, multiply the initial voltage measured at –T by r and experimentally determine the R1 value required to raise –T to that level. For the example the new –T voltage should be about 9.8 mV. The resistance value should be approximately 1.8 kΩ.

The zero differential point must now be shifted back to 0°C. This is accomplished by multiplying the original output voltage VO by r and adjusting the measured output voltage to this value by experimentally adding a resistor, R2, between –C and –T, Pins 5 and 6. The target output value in this case should be about 283 mV. The resistance value of R2 should be approximately 240 kΩ.

Finally, the gain must be recalibrated such that the output VO indicates the device's temperature once again. Do this by adding a third resistor, R3, between FB and –T, Pins 8 and 5. VO should now be back to the initial 240 mV reading. The resistance value

of R3 should be approximately 280 kΩ. The final connection diagram is shown in Figure 7. An approximate verification of the effectiveness of recalibration is to measure the differential gain to the output. For type E it should be 164.2.

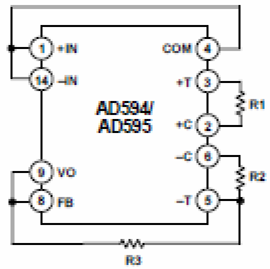


Figure 7. Type E Recalibration

When implementing a similar recalibration procedure for the AD595 the values for R1, R2, R3 and r will be approximately 650 Ω, 84 kΩ, 93 kΩ and 1.51, respectively. Power consumption will increase by about 50% when using the AD595 with type E inputs.

Note that during this procedure it is crucial to maintain the AD594/AD595 at a stable temperature because it is used as the temperature reference. Contact with fingers or any tools not at ambient temperature will quickly produce errors. Radiational heating from a change in lighting or approach of a soldering iron must also be guarded against.

USING TYPE T THERMOCOUPLES WITH THE AD595

Because of the similarity of thermal EMFs in the 0°C to +50°C range between type K and type T thermocouples, the AD595 can be directly used with both types of inputs. Within this ambient temperature range the AD595 should exhibit no more than an additional 0.2°C output calibration error when used with type T inputs. The error arises because the ice point compensator is trimmed to type K characteristics at 25°C. To calculate the AD595 output values over the recommended –200°C to +350°C range for type T thermocouples, simply use the ANSI thermocouple voltages referred to 0°C and the output equation given on page 2 for the AD595. Because of the relatively large nonlinearities associated with type T thermocouples the output will deviate widely from the nominal 10 mV/°C. However, cold junction compensation over the rated 0°C to +50°C ambient will remain accurate.

STABILITY OVER TEMPERATURE

Each AD594/AD595 is tested for error over temperature with the measuring thermocouple at 0°C. The combined effects of cold junction compensation error, amplifier offset drift and gain error determine the stability of the AD594/AD595 output over the rated ambient temperature range. Figure 8 shows an AD594/AD595 drift error envelope. The slope of this figure has units of °C/°C.

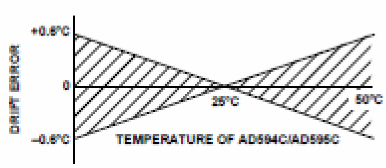


Figure 8. Drift Error vs. Temperature

THERMAL ENVIRONMENT EFFECTS

The inherent low power dissipation of the AD594/AD595 and the low thermal resistance of the package make self-heating errors almost negligible. For example, in still air the chip to ambient thermal resistance is about 80°C/watt (for the D package). At the nominal dissipation of 800 μW the self-heating in free air is less than 0.065°C. Submerged in fluorinert liquid (unstirred) the thermal resistance is about 40°C/watt, resulting in a self-heating error of about 0.032°C.

SETPOINT CONTROLLER

The AD594/AD595 can readily be connected as a setpoint controller as shown in Figure 9.

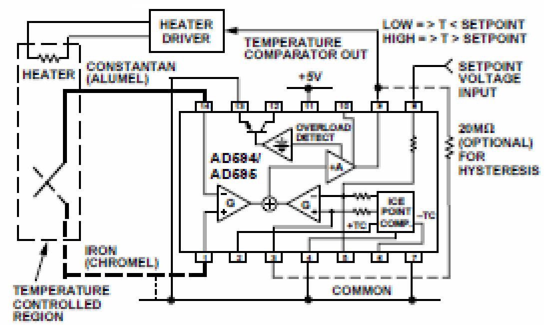


Figure 9. Setpoint Controller

The thermocouple is used to sense the unknown temperature and provide a thermal EMF to the input of the AD594/AD595. The signal is cold junction compensated, amplified to 10 mV/°C and compared to an external setpoint voltage applied by the user to the feedback at Pin 8. Table I lists the correspondence between setpoint voltage and temperature, accounting for the nonlinearity of the measurement thermocouple. If the setpoint temperature range is within the operating range (–55°C to +125°C) of the AD594/AD595, the chip can be used as the transducer for the circuit by shorting the inputs together and utilizing the nominal calibration of 10 mV/°C. This is the centigrade thermometer configuration as shown in Figure 13.

In operation if the setpoint voltage is above the voltage corresponding to the temperature being measured the output swings low to approximately zero volts. Conversely, when the temperature rises above the setpoint voltage the output switches to the positive limit of about 4 volts with a +5 V supply. Figure 9 shows the setpoint comparator configuration complete with a heater element driver circuit being controlled by the AD594/AD595 toggled output. Hysteresis can be introduced by injecting a current into the positive input of the feedback amplifier when the output is toggled high. With an AD594 about 200 nA into the +T terminal provides 1°C of hysteresis. When using a single 5 V supply with an AD594, a 20 MΩ resistor from V_O to +T will supply the 200 nA of current when the output is forced high (about 4 V). To widen the hysteresis band decrease the resistance connected from VO to +T.

ALARM CIRCUIT

In all applications of the AD594/AD595 the –ALM connection, Pin 13, should be constrained so that it is not more positive than (V+) – 4 V. This can be most easily achieved by connecting Pin 13 to either common at Pin 4 or V– at Pin 7. For most applications that use the alarm signal, Pin 13 will be grounded and the signal will be taken from +ALM on Pin 12. A typical application is shown in Figure 10.

In this configuration the alarm transistor will be off in normal operation and the 20 k pull up will cause the +ALM output on Pin 12 to go high. If one or both of the thermocouple leads are interrupted, the +ALM pin will be driven low. As shown in Figure 10 this signal is compatible with the input of a TTL gate which can be used as a buffer and/or inverter.

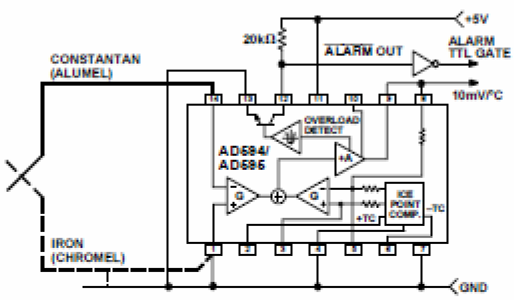


Figure 10. Using the Alarm to Drive a TTL Gate ("Grounded" Emitter Configuration)

Since the alarm is a high level output it may be used to directly drive an LED or other indicator as shown in Figure 11.

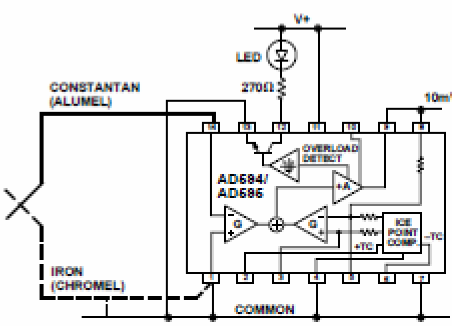


Figure 11. Alarm Directly Drives LED

A 270 Ω series resistor will limit current in the LED to 10 mA, but may be omitted since the alarm output transistor is current limited at about 20 mA. The transistor, however, will operate in a high dissipation mode and the temperature of the circuit will rise well above ambient. Note that the cold junction compensation will be affected whenever the alarm circuit is activated. The time required for the chip to return to ambient temperature will depend on the power dissipation of the alarm circuit, the nature of the thermal path to the environment and the alarm duration.

The alarm can be used with both single and dual supplies. It can be operated above or below ground. The collector and emitter of the output transistor can be used in any normal switch configuration. As an example a negative referenced load can be driven from –ALM as shown in Figure 12.

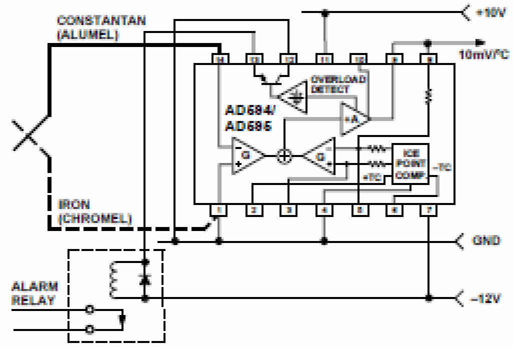


Figure 12. –ALM Driving A Negative Referenced Load

The collector (+ALM) should not be allowed to become more positive than (V–) +36 V, however, it may be permitted to be more positive than V+. The emitter voltage (–ALM) should be constrained so that it does not become more positive than 4 volts below the V+ applied to the circuit.

Additionally, the AD594/AD595 can be configured to produce an extreme upscale or downscale output in applications where an extra signal line for an alarm is inappropriate. By tying either of the thermocouple inputs to common most runaway control conditions can be automatically avoided. A +IN to common connection creates a downscale output if the thermocouple opens, while connecting –IN to common provides an upscale output.

CELSIUS THERMOMETER

The AD594/AD595 may be configured as a stand-alone Celsius thermometer as shown in Figure 13.

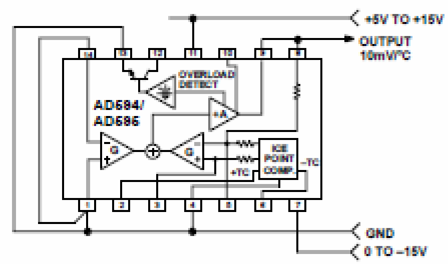


Figure 13. AD594/AD595 as a Stand-Alone Celsius Thermometer

Simply omit the thermocouple and connect the inputs (Pins 1 and 14) to common. The output now will reflect the compensation voltage and hence will indicate the AD594/AD595 temperature with a scale factor of 10 mV/°C. In this three terminal, voltage output, temperature sensing mode, the AD594/AD595 will operate over the full military –55°C to +125°C temperature range.

THERMOCOUPLE BASICS

Thermocouples are economical and rugged; they have reasonably good long-term stability. Because of their small size, they respond quickly and are good choices where fast response is important. They function over temperature ranges from cryogenics to jet-engine exhaust and have reasonable linearity and accuracy.

Because the number of free electrons in a piece of metal depends on both temperature and composition of the metal, two pieces of dissimilar metal in isothermal and contact will exhibit a potential difference that is a repeatable function of temperature, as shown in Figure 14. The resulting voltage depends on the temperatures, T1 and T2, in a repeatable way.

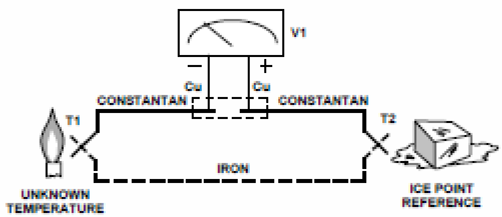


Figure 14. Thermocouple Voltage with 0°C Reference

Since the thermocouple is basically a differential rather than absolute measuring device, a know reference temperature is required for one of the junctions if the temperature of the other is to be inferred from the output voltage. Thermocouples made of specially selected materials have been exhaustively characterized in terms of voltage versus temperature compared to primary temperature standards. Most notably the water-ice point of 0°C is used for tables of standard thermocouple performance.

An alternative measurement technique, illustrated in Figure 15, is used in most practical applications where accuracy requirements do not warrant maintenance of primary standards. The reference junction temperature is allowed to change with the environment of the measurement system, but it is carefully measured by some type of absolute thermometer. A measurement of the thermocouple voltage combined with a knowledge of the reference temperature can be used to calculate the measurement junction temperature. Usual practice, however, is to use a convenient thermoelectric method to measure the reference temperature and to arrange its output voltage so that it corresponds to a thermocouple referred to 0°C. This voltage is simply added to the thermocouple voltage and the sum then corresponds to the standard voltage tabulated for an ice-point referenced thermocouple.

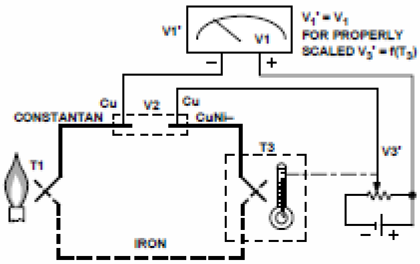


Figure 15. Substitution of Measured Reference Temperature for Ice Point Reference

The temperature sensitivity of silicon integrated circuit transistors is quite predictable and repeatable. This sensitivity is exploited in the AD594/AD595 to produce a temperature related voltage to compensate the reference of "cold" junction of a thermocouple as shown in Figure 16.

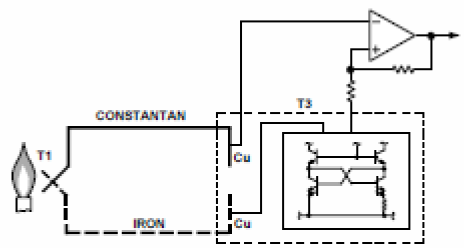


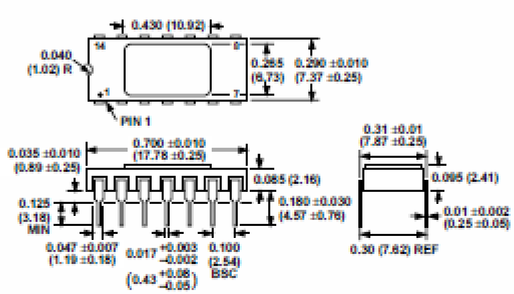
Figure 16. Connecting Isothermal Junctions

Since the compensation is at the reference junction temperature, it is often convenient to form the reference "junction" by connecting directly to the circuit wiring. So long as these connections and the compensation are at the same temperature no error will result.

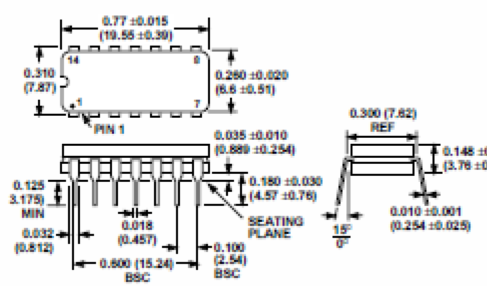
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

TO-116 (D) Package



Cerdip (Q) Package



Appendix E Detailed Supporting Analysis

Maximum flow calculation

The purpose of the maximum flow calculation is to determine the maximum SCFM of air that can possibly be heated to 1225°F. Knowing that there was 39kW of electrical energy in the system with the addition of the immersion heater. Using the built in property table of EES to determine the specific heat capacity of air, the mass flow rate was calculated using

$$\dot{q} = \dot{m} * c_p * \Delta T$$

This generated a number of 101.2 SCFM. Accounting for losses and inefficiencies in the heater, the settled flow rate is 80 SCFM

Determining the Maximum SCFM to get to 1225°F

Input Air Assumptions

$T_{in} = 70$ [F]

Output Air Requirement

$T_{out} = 1225$ [F]

Total Electrical Power

$q_{x,kW} = 39$ [kW]

Maximum Heat Input

$$q_x = q_{x,kW} \cdot \left| 3412 \cdot \frac{\text{Btu/hr}}{\text{kW}} \right|$$

Mean Temperature for property lookup

$$T_m = \frac{T_{in} + T_{out}}{2}$$

Specific Heat of Air

c_p = **Cp** (Air_{ha} , $T = T_m$, $P = 14.7$ [psia])

Solving for $\dot{m}$

$$q_x = \dot{m} \cdot c_p \cdot \Delta T$$

$$\Delta T = T_{out} - T_{in}$$

Mass Flow Rate to Volumetric Flow Rate

$$\dot{m} = \dot{Q} \cdot \rho \cdot \left| 60 \cdot \frac{\text{lbm/hr}}{\text{lbm/min}} \right|$$

Density of air at standard conditions

ρ = ρ (Air_{ha} , $T = 70$ [F] , $P = 14.7$ [psia])

Preliminary Analysis

Insulation comparison calculations

The main idea behind the insulation comparison calculation is how each insulation performs with keeping all other factors consistent. Using examples from the Introduction to Heat Transfer textbook [4], the assumptions used for this calculation was the air leaving the heat torches was 1300°F and the flow rate was 25 SCFM. The other assumption was using a flat plate one dimensional insulation stack as shown in Figure 21 .

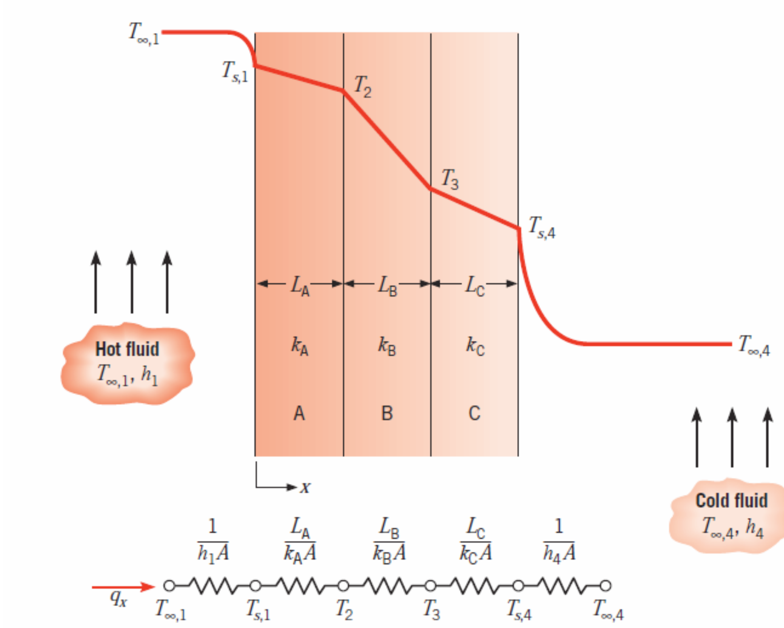


Figure 26. Thermal Circuit for an insulation wall *[5]*

The EES code below demonstrates how Figure 8 was generated. By creating a table in EES and commenting out and altering different values for variables, the multiple graphs could be obtained.

Calculating Improvement of Changing Insulation

Assumptions

Standard Flowrate

$Q_{air} = 25$ [cfm]

Density of Air

$\rho_{air} = \rho[Air_{ha}, T = 70 \text{ [F]}, P = 14.7 \text{ [psia]}]$

Mass Flow Rate

$\dot{m} = \rho_{air} \cdot Q_{air} \cdot 60$

Temperature of air leaving heater

$T_{in} = 1300$ [F]

Temperature of ambient air

$T_{amb} = 70$ [F]

Pressure of Input Air

$P = 16$ [psia]

Length of Section

$$L2 = \frac{64}{12 \text{ [ft]}}$$

Height of Section

$H = 1$ [ft]

Width of Section

$W = 1$ [ft]

Area of Heat Transfer surface (assuming retangular cross section)

$$A2 = L2 \cdot \left[H - \frac{t_{1a}}{6} + W - \frac{t_{1a}}{6} \right] \cdot 2$$

K value of inner insulation (Refractory Concrete)

$k_{1a} = 1.5$ [BTU-in/hr-ft^2-F]

Mean Thickness of inner insulation

$t_{1a} = 0$ [in]

K value of wall

$$k_{2a} = 19 \cdot \left| 6.933 \cdot \frac{BTU\text{–}in/hr\text{–}ft^2\text{–}F}{W/m\text{–}K} \right|$$

Thickness of wall (Stainless Steel)

$t_{2a} = 0.1025$ [in]

K value of outer insulation (Mineral Wool)

$k_{3a} = 1.5$ [BTU-in/hr-ft^2-F]

Thickness of outer insulation

$t_{3a} = 2$ [in]

using EES to call forth parameters about duct flow

Call **DuctFlow** $\left[\text{'Air'}, T_{in}, P, \dot{m}, H, W, L2, RelRough : h_1, h_H, \Delta P, Nusselt_T, f, Re \right]$

Rough Estimate for H of ambient air

$$h_4 = 5 \cdot \left| 0.17611016 \cdot \frac{Btu/hr\text{–}ft^2\text{–}F}{W/m^2\text{–}K} \right|$$

Concrete Relative Roughness

$RelRough = 1000 \cdot 10^{-6}$

Heat Loss in the duct

$$q_{x2} = \frac{T_{in} - T_{amb}}{\frac{1}{h_1 \cdot A2} + \frac{t_{1a}}{k_{1a} \cdot A2} + \frac{t_{2a}}{k_{2a} \cdot A2} + \frac{t_{3a}}{k_{3a} \cdot A2} + \frac{1}{h_4 \cdot A2}}$$

Temperature drop in the air

$cp = \mathbf{Cp} \left[Air_{ha}, T = 1200 \text{ [F]}, P = 16 \text{ [psia]} \right]$

$q_{x2} = \dot{m} \cdot cp \cdot \Delta T_{air2}$

$T_{final} = T_{in} - \Delta T_{air2}$

FMEA

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev.	Potential Cause(s) / Mechanism(s) of Failure	Occ.	Crit.	Recommended Action(s)
Fuses/Circuit breakers	Overloading/ current spike	failure of system	2	Lightening/grid crash	1	2	Prevent lightning storms and grid spikes.
Heaters short circuit	overheating causes shorting	heaters fail	8	thermocouple failure	2	16	Code controller such that loss of input causes a system wide shutdown
Heaters short circuit	overheating causes shorting	heaters fail	8	thermocouple failure	2	16	Test thermocouples to ensure good readings prior to running test/ use a larger board to enable use of all 6 heater thermocouples
High voltage box shorts to low voltage power box	Short	Low box overloaded	8	conductive media/improper grounding	3	24	Inspection of Electrical system prior to running of HTTU/don't run when wet
connection becomes undone	loss of power	machine shuts down	4	loose connections	3	12	inspect electrical connections prior to startup
Heaters	Too much power pull	Melting overload	5	Too much power	3	15	ensure electrical lockouts exists
Cement	cracking	Debris generated, unknown effects on system	2	Improper heat up schedule, reinforcing steel expanding	3	6	Properly code heater system
Cement	crumbling	damage to filter and test section	3	transporting, impurities in corners of cement block	4	12	none

Cement	exploding	Severe injury, hot air expulsion	10	improper cure time	2	20	Properly cure
Thermocouple	False reading	Overheat situation	6	melted, burned stuff	1	6	Calibration
Torch	Plugged	Overheat	6	damaged heater	1	6	Ensure heat torches clear prior to beginning heat cycle
Torch	Short	electrical wear, galvanic corrosion, damage to torch	8	overheat/ irreparable damage to torch	1	8	Inspect torches before testing

Final design Analysis

Analysis of the final design involved a much more in depth analysis than the preliminary design. The first step was to identify problems with the function of the system as shown in the FMEA below. The next step was to show how well the immersion heater added heat and justify the use of fins within the immersion tube. The final step was to take the immersion heater out of the equation and see how well the new style of insulation retained temperatures within the duct.

FMEA

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev.	Potential Cause(s) / Mechanism(s) of Failure	Occ.	Crit.	Recommended Action(s)
Fuses/Circuit breakers	Overloading/ current spike	failure of system	2	Lightening/grid crash	1	2	Prevent lightning storms and grid spikes.
Heaters short circuit	overheating causes shorting	heaters fail	8	thermocouple failure	2	16	Code controller such that loss of input causes a system wide shutdown

Heaters short circuit	overheating causes shorting	heaters fail	8	thermocouple failure	2	16	Test thermocouples to ensure good readings prior to running test/ use a larger board to enable use of all 6 heater thermocouples
High voltage box shorts to low voltage power box	Short	Low box overloaded	8	conductive media/improper grounding	3	24	Inspection of Electrical system prior to running of HTTU/don't run when wet
connection becomes undone	loss of power	machine shuts down	4	loose connections	3	12	inspect electrical connections prior to startup
Heaters	Too much power pull	Melting overload	5	Too much power	3	15	ensure electrical lockouts exists
Immersion Heater	Burned up	Overheat situation	8	Control System messed up	1	8	ensure control system is working properly
Thermocouple	False reading	Overheat situation	6	melted, burned stuff	1	6	Calibration
Torch	Plugged	Overheat	6	damaged heater	1	6	Ensure heat torches clear prior to beginning heat cycle
Torch	Short	electrical wear, galvanic corrosion, damage to torch	8	overheat/ irreparable damage to torch	1	8	Inspect torches before testing

Immersion Heater Heat Addition.

Although the addition of a more efficient insulation system is going to improve performance of this design, the customer requirements will be achieved mainly due to the addition of the immersion heater. Because of this, developing a model for the heat input to the system is of utmost importance. Heat input was modeled essentially as a concentric tube annulus, and multiple correlations for Nusselt numbers were cross-referenced to assure accuracy.

The first step in the analysis was modeling the immersion heater as a flat plate. This was done because the surface area of the parallel immersion heater elements is much larger than modeling it as a single cylinder. The flat plate analysis showed little difference between laminar and turbulent flow.

Because the immersion heater elements are going to be glowing red hot, a significant amount of heat will be transferred through radiation heat transfer to the surrounding immersion tube. An analysis was conducted for pipe flow using the Gnielinski correlation, and a constant surface temperature of the immersion heater was assumed. It was decided after looking at parametric data that installing fins to this surface would increase the convective heat transfer (see Figure 14. Effect of adding fins to the immersion tube). To achieve the ultimate amount of radiation absorption possible in the pipe, it will be coated with a high emissivity paint with $\varepsilon \approx 0.9$.

The heat transfer from the pipe, fins and immersion heater surface were added, and the first law of thermodynamics applied to find the difference between inlet and outlet temperatures.

HTTU Immersion Heater Model

Team Flashpoint

Ian Corcorran

4/18/15

Variables

$Pr = \mathbf{Pr}[Air, T = T_{air}]$

$\mu = \mathbf{Visc}[Air, T = T_{air}]$ *in lbm/ft*hr *convert('lbm/(ft*hr)', 'lbf*s/ft^2') in lbf*s/ft^2*

$rho2 = \rho[Air_{ha}, T = T_{air}, P = 15.1 \ [psia]]$ *lbm/ft^3*

$\nu = \frac{\mu}{\rho}$ *ft^2/hr*

$T_{air} = 1250 \ [F]$ *810K*

$L_{immersion} = \frac{21.5}{12} \cdot 1 \ [ft]$

$N_{elements} = 9$

$A_{pipe} = \pi \cdot 6 \cdot 21.5 \ [ft^2]$

$A_{incoloy} = \frac{14000}{23 \cdot 144} \cdot 1 \ [ft^2]$ *total surface area of incoloy elements*

$V_{air} = \frac{\dot{Q}}{A_{airflow}}$ *velocity in ft/min*

$k_{air} = \mathbf{k}[Air, T = T_{air}]$ *btu/hr-ft-R*

$R_{incoloy,rod} = \frac{A_{incoloy}}{L_{immersion} \cdot 4 \cdot \pi \cdot N_{elements}}$ *Radius of one incoloy rod element in ft*

$\dot{m} = Q_{SCFM} \cdot \rho \cdot 60$ *lbm/hr*

$\dot{m} = \dot{Q} \cdot rho2$

$\rho = \rho[Air_{ha}, T = 70 \ [F], P = 14.7 \ [psia]]$

Cross sectional area of free moving air in immersion tube

$A_{airflow} = \pi \cdot \left[\frac{3 \ [ft]}{12}\right]^2 - 18 \cdot \pi \cdot R_{incoloy,rod}{}^2$

Reynold's Number

$Re_x = V_{air} \cdot \frac{L_{immersion}}{\nu}$

$Nusselt_{xl} = 0.0296 \cdot Re_x^{[4/5]} \cdot Pr^{[1/3]}$ *Nusselt number for turbulent flow over an isothermal plate*

$Nusselt_{xl} = 0.664 * Re_{x(1/2)} * Pr^{(1/3)}$

Nusselt number for laminar flow over an isothermal plate

Convective Heat transfer Coefficient

$$h_{banxt} = Nusselt_{xl} \cdot \frac{k_{air}}{L_{Immersion}}$$

Heat transfer from Immersion Heater

$$q_{convection,fp} = h_{banxt} \cdot A_{Incoloy} \cdot [T_{air} - 1600 \ [F]]$$

$$q_{kW} = q_{convection,fp} \cdot \left| 0.000293071 \cdot \frac{kW}{Btu/hr} \right|$$

******Heat transfer from Fins*********

Assume constant fin temperature of 1450 F

$$T_f = T_{stainlessf}$$

Assume 10 fins, .75 [in] h x 21.5 [in] L

$$A_{fin} = 2 \cdot 12 \cdot \frac{0.75}{12} \cdot 21.5 \ [ft^2]$$

Heat transfer from Fins

$$q_{fin} = h_{banxt} \cdot A_{fin} \cdot [T_{air} - T_f]$$

******************* Heat transfer from Isothermal Pipe Wall*********************

$$P = \pi \cdot D$$

$$T_s = 1450 \ [F]$$

$$\overline{T}_m = 1280 \ [F]$$

$$T_{m,l} = 1250 \ [F]$$

$$D = 0.5 \ [ft]$$

$$k_{air,p} = \mathbf{k}[Air, T = \overline{T}_m]$$

$$cp = Cp[Air, T = \overline{T}_m]$$

$$\mu_p = \mathbf{Visc}[Air, T = \overline{T}_m] \quad \textit{in lbf*s/ft}^2$$

$$\rho_p = \rho[Air_{ha}, T = \overline{T}_m, P = 15.1 \ [psia]] \quad \textit{in slug/ft}^3$$

$$\nu_p = \frac{\mu_p}{\rho} \quad ft^2/s$$

$$Re_D = V_{air} \cdot \frac{D}{\nu_p}$$

Graetz Number for Entry Region Flow

$$G_{zd} = \frac{D}{L_{immersion}} \cdot Re_D \cdot Pr \quad \textit{unitless}$$

Nusselt Number for Entrance Region Pipe Flow

$$\overline{Nusselt_d} = 3.66 + \frac{0.0668 \cdot G_{zd}}{1 + 0.04 \cdot G_{zd}^{[2/3]}}$$

Average Convective Heat Transfer Coefficient for Entry Region Pipe Flow

$$\overline{h} = \overline{Nusselt_d} \cdot \frac{k_{air,p}}{D}$$

Constant Surface Temperature

$$T_{m,o} = T_{stainlessf} - [T_{stainlessf} - T_{m,i}] \cdot \exp\left[-P \cdot L_{immersion} \cdot \frac{\overline{h}}{\dot{m} \cdot cp} \right]$$

Energy Balance

$$q_{pipe} = \dot{m} \cdot cp \cdot [T_{m,i} - T_{m,o}]$$

Converting overall heat trasfer from the pipe from BTU to kiloWatts

$$q_{pipe,kW} = q_{pipe} \cdot \left| 0.000293071 \cdot \frac{kW}{Btu/hr} \right|$$

Total Energy Transfer

$$q_{total} = q_{pipe} + q_{convection,fp} \quad \textit{Btu/hr}$$

$$q_{total} = \dot{m} \cdot cp \cdot [T_{m,i} - T_{out}]$$

Friction Factor

$$RR = \frac{0.000015}{6} \quad \textit{Relative Roughness for SS pipe: RR = .015E-3/6}$$

$$f = \mathbf{MoodyChart}[Re_D, RR]$$

Gnielinski Correlation

$$\nu_{D,G} = \frac{\frac{f}{8} \cdot [Re_D - 1000] \cdot Pr}{1 + 12.7 \cdot \left[\frac{f}{8}\right]^{0.5} \cdot [Pr^{(2/3)} - 1]}$$

$$q_{pipe,G} = \dot{m} \cdot cp \cdot [T_{m,i} - T_{m,o}]$$

Total Heat Transfer using Gnielinski

$q_{total,G} = q_{pipe,G} + q_{convection,fp}$

$q_{total,G} = \dot{m} \cdot cp \cdot [T_{m,I} - T_{out,G}]$

Total Heat transfer including fins (using Gnielinski correletion)

$q_{total,fin} = q_{pipe,G} + q_{convection,fp} + q_{fin}$

$q_{total,fin} = \dot{m} \cdot cp \cdot [T_{air} - T_{out,fin}]$

Radiation to 6_{in} pipe

$$r_1 = \frac{4.75}{2 \cdot 12}$$

$$r_2 = \frac{6}{2 \cdot 12}$$

$$l = \frac{21.5}{12}$$

emissivity of inconel at 1600 F

$$T_{Incoloy} = 1600 \quad [F] \cdot \left| 0.55555556 \cdot \frac{K}{F} \right|$$

*$T_{stainless}$ = 1400 [F]*convert('F', 'K')*

$E_{Incoloy} = 0.76$ *monarchserver.com/tableofemissivity.pdf*

$E_{stainless} = 0.92$

W = 14000 [W]

$c = \mathbf{Cp}\,[\text{Stainless}_{AISI304}, T = \overline{T}_m]$

$$\sigma = 5.6703 \times 10^{-8} \quad [W/m^2\text{-}K^4] \cdot \left| 0.09290304 \cdot \frac{w/ft^2\text{–}K^4}{W/m^2\text{–}K^4} \right|$$

$k = \mathbf{k}\,[\text{Stainless}_{AISI304}, T = \overline{T}_m]$

View Factor for Concentric Cylinders

$F_{view} = \mathbf{F3D_4}\,[r_1, r_2, l]$

$$q_{rad} = 15 \quad [W/in^2] \cdot \left| 144 \cdot \frac{W/ft^2}{W/in^2} \right|$$

$q_{rad} = A_{Incoloy} \cdot F_{view} \cdot \sigma \cdot [E_{Incoloy} \cdot T_{Incoloy}^{\ 4} - E_{stainless} \cdot T_{stainless}^{\ 4}]$

Energy Balance

$$T_{stainlessf} = T_{stainless} \cdot \left| 1.8 \cdot \frac{F}{K} \right|$$

Insulation comparison.

The basics of this calculation was to see how the insulation performed under different ranges of flow. Part of the EES calculation calculates the heat transfer coefficient as a function of the Reynolds number and Nusselt number. This accounts for differing flow rates within the system. The EES built in functions for annular flow and duct flow calculate all the necessary values to perform a thorough analysis of the heat transfer out of the air. Much like the preliminary design analysis, the insulation was modelled as a one-dimensional setup. Using examples from the Introduction to Heat Transfer textbook [4], the inner pipe and insulation wrap were analyzed as a radial insulation system as shown in Figure 22.

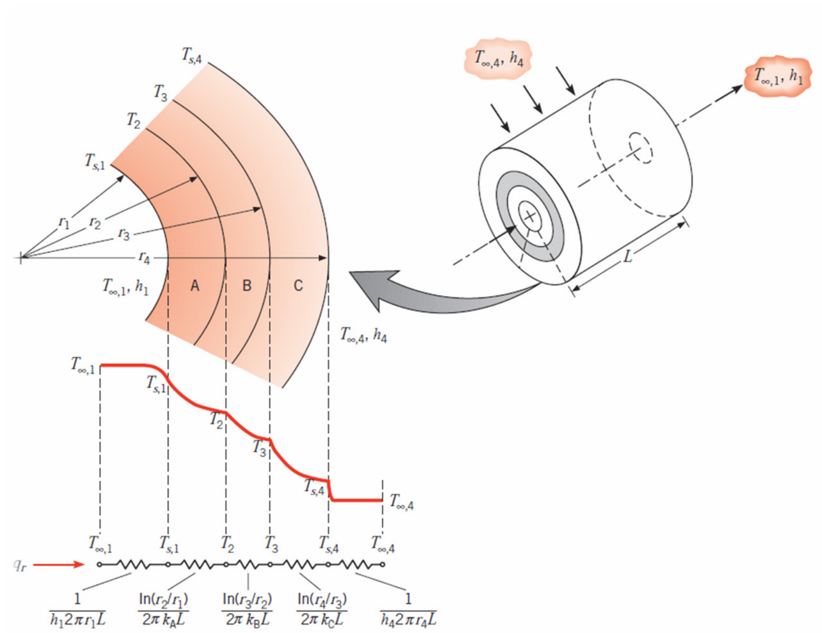


Figure 27. Radial Thermal Resistance Network *[5]*

Appendix D is where the values for insulations are listed specific to the vendors.

Calculating improvement of changing insulation

Assumptions

Standard Flowrate

$Q_{air} = 25$ [cfm]

Density of Air

$\rho_{air} = \rho Air_{ha}$, T = 70 [F], P = 14.7 [psia]

Mass Flow Rate

$\dot{m} = \rho_{air} \cdot Q_{air} \cdot 60$

Temperature of air leaving heater

$T_{in} = 1300$ [F]

Temperature of ambient air

$T_{amb} = 70$ [F]

Pressure of Input Air

$P = 16$ [psia]

Length of Section

$$L = \frac{23}{12} \text{ [ft]}$$

Area of Heat Transfer surface (assuming retangular cross section)

$A = 0.5 \cdot 3.14 \cdot L$

K value of pipe wall

$$k_2 = 19 \cdot \left| 6.933 \cdot \frac{\text{BTU–in/hr–ft}^2\text{–F}}{\text{W/m–K}} \right|$$

Thickness of wall (Stainless Steel)

$t_2 = 0.1025$ [in]

K value of inner insulation cermalite

$$k_3 = 0.3 \cdot \left| 6.933 \cdot \frac{\text{BTU–in/hr–ft}^2\text{–F}}{\text{W/m–K}} \right|$$

Thickness of inner insulation

$t_3 = 2$ [in]

K value of air space

$$k_4 = 0.06 \cdot \left| 6.933 \cdot \frac{\text{BTU–in/hr–ft}^2\text{–F}}{\text{W/m–K}} \right|$$

Mean Thickness of inner insulation

$t_4 = 1$ [in]

K value of wall

$$k_5 = 19 \cdot \left| 6.933 \cdot \frac{\text{BTU–in/hr–ft}^2\text{–F}}{\text{W/m–K}} \right|$$

Thickness of wall (Stainless Steel)

$t_5 = 0.1025$ [in]

K value of outer insulation (Mineral Wool)

$k_6 = 1.5$ [BTU-in/hr-ft^2-F]

Thickness of outer insulation

$t_6 = 2$ [in]

$$r_i = \frac{1.75}{12 \quad [\text{ft}]}$$

$$r_o = \frac{3}{12 \quad [\text{ft}]}$$

Call **AnnularFlow** ['Air' , T_{In} , P , $\dot{m}$, r_i , r_o , L2 , RelRough : h_{T2} , h_{H2} , ΔP2 , Nusselt_{T2} , f2 , Re2]

Heat Loss in the duct

$$q_x = \frac{T_{In} - T_{amb}}{\frac{1}{h_1 \cdot A} + \frac{\ln\left[\frac{6.625}{6.357}\right]}{k_2 \cdot 2 \cdot 3.14 \cdot L} + \frac{\ln\left[\frac{8.625}{6.625}\right]}{k_3 \cdot 2 \cdot 3.14 \cdot L} + \frac{t_4}{k_4 \cdot A} + \frac{t_5}{k_5 \cdot A} + \frac{t_6}{k_6 \cdot A} + \frac{1}{h_4 \cdot A}}$$

Temperature drop in the air

$$q_x = \dot{m} \cdot cp \cdot \Delta T_{air}$$

$$qxw = q_x \cdot \left| 0.000293071 \cdot \frac{\text{kW}}{\text{Btu/hr}} \right|$$

$cp = \text{Cp}\,[\,\text{Air}_{ha}\,, T = 1300$ [F], $P = 16$ [psia]]

$$T_{Input} = T_{In} - \Delta T_{air}$$

Length of Section

$$L2 = \frac{64 - 23}{12} \quad [ft]$$

Height of Section

$$H = 1 \quad [ft]$$

Width of Section

$$W = 1 \quad [ft]$$

Area of Heat Transfer surface (assuming retangular cross section)

$$A2 = L2 \cdot \left[H - \frac{t_{1a}}{6} + W - \frac{t_{1a}}{6} \right] \cdot 2$$

K value of inner insulation (Refractory Concrete)

$$k_{1a} = 1.5 \quad [BTU\text{-}in/hr\text{-}ft^2\text{-}F]$$

Mean Thickness of inner insulation

$$t_{1a} = 0 \quad [in]$$

K value of wall

$$k_{2a} = 19 \cdot \left| 6.933 \cdot \frac{BTU\text{–}in/hr\text{–}ft^2\text{–}F}{W/m\text{–}K} \right|$$

Thickness of wall (Stainless Steel)

$$t_{2a} = 0.1025 \quad [in]$$

K value of outer insulation (Mineral Wool)

$$k_{3a} = 1.5 \quad [BTU\text{-}in/hr\text{-}ft^2\text{-}F]$$

Thickness of outer insulation

$$t_{3a} = 2 \quad [in]$$

using EES to call forth parameters about duct flow

$$\text{Call } \textbf{DuctFlow}\left['Air', T_{Input}, P, \dot{m}, H, W, L2, RelRough : h_1, h_H, \Delta P, Nusselt_T, f, Re \right]$$

Rough Estimate for H of ambient air

$$h_4 = 5 \cdot \left| 0.17611016 \cdot \frac{Btu/hr\text{–}ft^2\text{–}F}{W/m^2\text{–}K} \right|$$

Concrete Relative Roughness

$$RelRough = 1000 \cdot 10^{-6}$$

Heat Loss in the duct

$$q_{x2} = \frac{T_{Input} - T_{amb}}{\frac{1}{h_1 \cdot A2} + \frac{t_{1a}}{k_{1a} \cdot A2} + \frac{t_{2a}}{k_{2a} \cdot A2} + \frac{t_{3a}}{k_{3a} \cdot A2} + \frac{1}{h_4 \cdot A2}}$$

Temperature drop in the air

$$q_{x2} = \dot{m} \cdot cp \cdot \Delta T_{air2}$$

$$T_{final} = T_{Input} - \Delta T_{air2}$$

Old Setup

Length of Section

$$Lb = \frac{64}{12 \ \text{[ft]}}$$

Area of Heat Transfer surface (assuming retangular cross section)

$$Ab = Lb \cdot \left[H - \frac{t_{1b}}{6} + W - \frac{t_{1b}}{6} \right] \cdot 2$$

K value of inner insulation (Refractory Concrete)

$$k_{1b} = 1.5 \quad \text{[BTU-in/hr-ft}^2\text{-F]}$$

Mean Thickness of inner insulation

$$t_{1b} = 0 \quad \text{[in]}$$

K value of wall

$$k_{2b} = 19 \cdot \left| 6.933 \cdot \frac{\text{BTU–in/hr–ft}^2\text{–F}}{\text{W/m–K}} \right|$$

Thickness of wall (Stainless Steel)

$$t_{2b} = 0.1025 \quad \text{[in]}$$

K value of outer insulation (Mineral Wool)

$$k_{3b} = 1.5 \quad \text{[BTU-in/hr-ft}^2\text{-F]}$$

Thickness of outer insulation

$$t_{3b} = 2 \quad \text{[in]}$$

using EES to call forth parameters about duct flow

Call **DuctFlow** ['Air' , T_{In} , P , $\dot{m}$, H , W , Lb , RelRough : h_{1b} , h_{Hb} , ΔPb , $Nusselt_{Tb}$, fb , Reb]

Rough Estimate for H of ambient air

Heat Loss in the duct

$$q_{xb} = \frac{T_{in} - T_{amb}}{\frac{1}{h_{1b} \cdot Ab} + \frac{t_{1b}}{k_{1b} \cdot Ab} + \frac{t_{2b}}{k_{2b} \cdot Ab} + \frac{t_{3b}}{k_{3b} \cdot Ab} + \frac{1}{h_4 \cdot Ab}}$$

Temperature drop in the air

$$q_{xb} = \dot{m} \cdot cp \cdot \Delta T_{airb}$$

$$T_{final,b} = T_{in} - \Delta T_{airb}$$

Improvement

$$T_{improve} = T_{final} - T_{final,b}$$

Electrical Calculations

Power Available to the System

$$V = 480V$$

$$I = 60A3\phi$$

$$P = VI * \sqrt{\phi}$$

Power able to be used

$$P_{avail} = P * 0.8$$

$$P_{avail} = 39.9kW$$

Total Power Draw

$$2 \quad \text{Tutco200} \quad @ \quad 12.5\text{kW} \quad \text{Each}$$

$$1 \quad \text{Watlow} \quad \text{Immersion} \quad \text{Heater} \quad 14.0\text{kW} \quad @ \quad \text{Each}$$

$$P_{total} = 39kW$$

Max Load as Percentage of Maximum Available

$$\eta = 39kW/49.9kW * 100\%$$

$$\eta = 78.2\%$$

Tutco Heat Torches

$$A = P/(V\sqrt{3})$$

$$A = 15.035A$$

As per NEC 215.2(A)(1) Overcurrent protection for a continuous load is 125% of current

$$A_overcurrent = 15.035 * 125\%A$$

$$A_overcurrent = 18.78A$$

20A circuit breakers and fuses already installed in the system. Solid state relays are rated to 30A. NEC 310.15(B)(16) (formerly NEC 310.16) requires 14 AWG THHN concuctors. Refers to NEC 240.4D for small coductor sizes NEC 240.4D requires 12 AWG THHN HTTU is wired with 10 AWG THHN

Watlow FNNA25J5X

$$A = P/(V\sqrt{3})$$

$$A = 16.84A$$

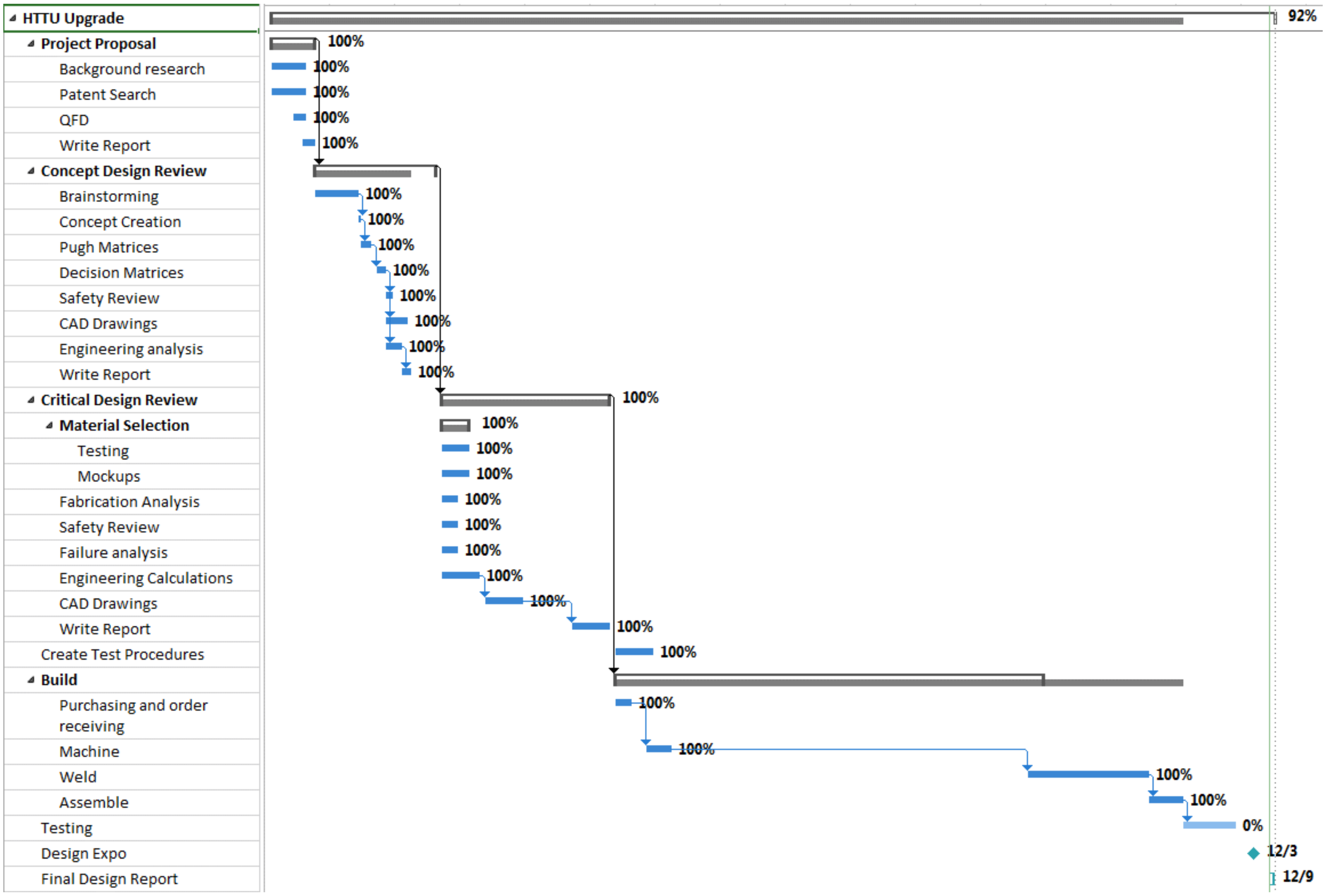
As per NEC 215.2(A)(1) Overcurrent protection for a continuous load is 125% of current

$$A_overcurrent = 16.84 * 125\%A$$

$$A_overcurrent = 21.05A$$

NEC 310.15(B)(16) (formerly NEC 310.16) requires 12AWG THHN concuctors. Refers to NEC 240.4D for small coductor sizes NEC 240.4D requires 10 AWG THHN HTTU is wired with 10 AWG THHN

Appendix F Gantt Chart



Appendix G Fabrication schedule

Disassembly

1. Remove wires and conduit for torch heaters
   a. Label wires, wrap ends with electrical tape, coil wires neatly and band
2. Remove torch heaters – use large wrench
3. Unbolt and remove faceplate
4. Unbolt and remove camera assembly
   a. Store camera equipment properly in boxes
   b. Order foam from amazon if necessary
5. Unbolt and remove 24” duct section from frame
6. Unbolt and remove 11” duct section from frame

Fabrication

Cutting and Prep:

1. Cut holes in 12 ga plate (waterjet)
2. Cut hole in ¼” plate (use hole saw on drill press or by hand)
3. Shear edges of ¼” plate
4. Make sure edges of 12 ga plate fit snugly inside duct to reduce welding time
5. Cut 6” pipe to length
   a. 23.78” section
   b. 3.25” section
6. Drill holes in 3.25” SS pipe section to ID of 1-¼” pipe
7. Cut 3” threaded pipe in half
8. Fit 1-¼” pipe to outside diameter of 6” pipe, cut to length on opposite end
9. Drill 4 ¼ “ holes on bottom of 24” duct section (ventilation)
10. ~~Cut 23.78” SS pipe in half~~

Welding

Faceplate

1. Weld threaded 1- ¼ “ pipe to 90 degree bend section (X2)
2. Weld 90 degree bend and threaded rod to coped pipe section
3. Weld ANSI 5” flange to 3- ¼ “ SS pipe
4. Weld 3- ¼ “ SS pipe to faceplate
5. Weld 1- ¼” SS pipe bend assembly to 3- ¼ “ SS pipe

6” pipe

1. ~~Weld .75” strips to inside of pipe half (X12)~~
2. Paint inside of pipe, leaving .5” gap in paint between areas to be welded.
3. ~~Weld pipe halves together~~
4. Paint the inside of the seam along pipes length, leaving ½” unpainted on either end.

24” Duct Section

1. Tack weld 12 ga plate 1 to inside of 24” duct
2. Wrap 6”x 23.78” SS pipe with ceramic blanket insulation
3. Tack weld to 6”x23.78” pipe to 12 ga plate 1.

4. Loosely stuff 24” duct with pieces of ceramic blanket insulation
5. Insert 12 ga SS plate 2 on other end of duct, align with duct, tack weld to 6” x 23.78” SS pipe.
6. Tack weld plate 2 to 24” duct.
7. Make sure fitment is correct to maximize weld quality, and apply a second tack weld on either ends of the 23.78” SS pipe
8. Make sure hole in 24” duct section and hole in faceplate align perfectly
9. Weld out 24” duct section

Assembly

1. Apply gasket sealant around interior side of faceplate around 6” hole
2. Apply gasket material to 24” duct section
3. Bolt faceplate to 24” duct section
4. Apply gasket material to far end of 24” duct section
5. Bolt 11” section to 24” section
6. Repeat step 4 on far side of 11” duct section
7. Bolt 11” duct section to viewport section
8. Apply gasket sealant to 5” ANSI flange on faceplate
9. Bolt immersion heater to faceplate
10. Apply thread sealant to 1- ¼” threads on faceplate
11. Install Tutco 12.5 kW torch heaters (X2)
12. Install wiring to immersion heater
13. Install wiring for torch heaters (X2)
14. Install air line for torch heaters (X2)
15. Install pyrotape on outside of faceplate assembly pipe
16. Install 2 layers of ceramic blanket on exterior of faceplate assembly pipe
17. Insulate exterior of HTTU, use .032 ga SS wire to hold blanket in place, using plastic corner clips so as to not pinch insulation

Appendix H Safety Checklist

SENIOR PROJECT CONCEPT DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

Y	N	
	x	Will any part of the design create hazardous revolving, reciprocating, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing, or similar actions, including pinch points and shear points?
	x	Can any part of the design undergo high accelerations/decelerations?
	x	Will the system have any large moving masses or large forces?
	x	Will the system produce a projectile?
		Is it possible for the system to fall under gravity creating injury?
	x	Will a user be exposed to overhanging weights as part of the design?
	x	Will the system have any sharp edges?
	x	Will the system have any ungrounded electrical systems?
x		Will there be any large batteries or electrical voltage in the system above 40 V (either AC or DC)?
	x	Will there be any stored mechanical energy in the system such as flywheels, hanging weights or pressurized fluids?
x		Will the system produce high heat (>120°F) at any location?
	x	Will there be any explosive or flammable liquids, gases, or dust as part of the system?
	x	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	x	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	x	Might the system generate high levels of noise?
x		Is the system easy to use unsafely?
	x	Will the system be used in extreme environmental conditions such as fog, humidity, cold, high temperatures, etc…?
	x	Are there any other potential hazards not listed above? If yes, please explain below.

Appendix I Testing Procedures

WARNING: HTTU produces very high temperatures and uses very high voltage power. Unauthorized personnel are not permitted to run the HTTU. Read and thoroughly understand all testing procedures. Permission from Cal Poly Facilities MUST be obtained before any tests with the HTTU may be run.

System Setup

1. Ensure that the device is unplugged from 480V and that all breakers are in the off position
2. Ensure the testing area is clear of debris and all flammable material
3. Ensure that the control cart's DC power supply is unplugged
4. Ensure that all personnel in the test area are wearing safety glasses and are aware of the test protocol
5. Ensure that there are at least two fire extinguishers accessible one should be by the control cart, and another a safe distance from the HTTU.
6. Connect one torch to an external thermocouple reader; this serves as a checksum against the control system’s thermocouples.
7. Remove the burst disk protective cap.
8. Attach the air supply hose firmly to both HTTU and supply line
9. Firmly attach the exhaust pipe to HTTU and the exhaust fan duct in the engines lab
10. Power on exhaust fan and supply air
11. Inspect 480V and low voltage power cables for wear

12. Tape any loose cables to the ground

13. Detach front panel from relay box

14. Attach 7 pin control cable to valve interface box

15. Open terminal view for controller information, ensure that startup message displays

16. Readout should report torch temperatures as 32° F if DC power is unplugged

17. Plug control cable (DB25) into the jack on the control cart, and then to the HTTU

18. Plug DC power cable into control cart and then to HTTU

19. Connect power to DC supply at control cart

20. Verify thermocouple temperature readout on PC against the external thermocouple reader
21. Check flow and temperature set points are correct
22. Ensure that control valve is in the off position\
23. Turn shutoff valve into the OPEN position, ensure lines leading to the control valve pressurize
24. Power on control valve
25. Engage flow control
26. Check to ensure the flow feedback transducer is working if the readings are not going up, shut the control off immediately

Energizing

1. Engage main breaker and only the breakers for torches to be used in the planned test.
2. Shut breaker cabinet door
3. Have facilities unlock power jack after verifying HTTU power connections
4. Prepare to connect to 480V power-notify all personnel that the device is going to be energized.
5. One person should monitor the control cart, another should prepare to connect power, and the rest should remain 10 feet away from the HTTU.
6. Plug 480V into the jack, wait for final confirmation from control cart operator to energize
7. When confirmed, throw switch to energize circuit.
8. Control cart operator should now engage the temperature control and verify the thermocouples are reading correctly and the heaters have powered on
9. Once proper operation is verified, personnel may not now approach the HTTU and must observe the 10 foot safety clearance.

While test is running

1. Ensure at least one trained person is at the control cart at all times monitoring the temperature

2. For safety reasons, the controller software does not allow flow control to be disengaged while the torch control is active. If, for any reason flow control must be shut off, torch must be first disengaged. Note that when flow control is disengaged, the valve will close and flow through the system will stop.

3. Gating valves default to "open"-if power or air pressure is lost.

4. If the control cable is detached for any reason, the torches will automatically shutoff, the control valve will close and the gating valves will open.

Posttest

1. Once test is complete, disable torch control, but allow flow control to remain engaged.
2. Throw breaker switch on 480V outlet and detach cable.
3. Lock the 480V supply
4. Once internal temperature is at or below 85°F, flow control may be disengaged.
5. Once control valve is closed, shut off power to the actuator and close the supply airline.
6. Begin system disassembly. Detach control cables from the control box
7. Shut off air supply and ensure pressure has been released
8. Detach air supply hose and coil. Place onto carrier loop
9. Coil power cable around carrier loop ensure no part will drag on the ground.
10. Shut off exhaust fan
11. Remove exhaust hose and coil onto carrying bracket
12. Replace burst disk cover

Appendix J Arduino Code

Main Controller Code

```
//HTTU Control System

//version 1.0.0.0.0.0.1

//Ian Corcorran

//10.21.2015

//WHO CONTROLLZ DA HTTUZ?

//FLASHPOINT CONTROLLZ DA HTTUZ.



//Create pin instances

int immersionTC = A1;

int torch1TC = A3;

int torch2TC = A2;

int filter1TC = A4;

int filter2TC = A5;

int immersionPower = 3;

int torch1Power = 5;

int torch2Power = 4;

char ByteReceived;



// A coupling of Chromel and Alumel wires, has a range of -270 °C to 1260 °C and an output of -6.4 to
54.9 mV over maximum temperature range.

// ^^^ http://www.thermometricscorp.com/thertypk.html#sthash.siFljprF.dpuf ^^^

//Float creates an instance of a decimal from -3.4028235E+38 to +3.4028235E+38

//Thermocouple constants to convert measured voltage to a Fahrenheit float.

float K_amp = 10;  //mV/C

float K_immersion = 2.0001 ;  //33.912/1500 =.022608 mv/F

float K_torch_1 = 2.0001;
```

```
float K_torch_2 = 2.0001;
float K_filter_1 = 2.0001;
float K_filter_2 = 2.0001;
float immersionVoltage;
float torch1Voltage;
float torch2Voltage;
float filter1Voltage;

// This code needs to be put inside void loop() once everything is complete
//Convert voltage reading to Degrees C
//we need to scale 0-5 volts per 1024 units, i.e 5V=1024 units
//following code is written assuming input voltage divided by two, which would give us approx 4.05 volts
into arduino at 1500F
float immersionTempC; // = immersionVoltage/(5*10*(1024/5));
float torch1TempC; // = torch1Voltage/(5*10*(1024/5));
float torch2TempC; // = torch1Voltage/(5*10*(1024/5));
float filter1TempC;

//Celsius to Fahrenheit conversions
double immersionTempF;
float torch1TempF;
float torch2TempF;
float filter1TempF;

//counter
int count=0;
int immersionState;
int torch1State;
int torch2State;
int immersionIsOn = 1;
```

```
int torch1IsOn = 1;
int torch2IsOn = 1;

//*****************************************************************

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
delay(5000);
}

//*******************************************************************

void loop() {
  // Main Loop runs repeatedly....




// ****** Immersion Heater Temperature Control ******

//Set pin 2 to Immersion heater thermocouple
//pinMode(immersionTC,INPUT);

//Set pin 7 to Immersion Heater Power Relay
pinMode(immersionPower,OUTPUT);

//Check Temperature of K-type thermocouple in Immersion heater
//Read voltage from immersion heater *TC1*
immersionVoltage = analogRead(immersionTC);
```

```
//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
 immersionTempC = immersionVoltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
immersionTempF = immersionTempC*1.8 + 32 - 16.7;

//Cut power to immersion heater if temperature is above 1500 Degrees Fahrenheit (33.912mV)



if(immersionTempF >= 1500)
{
digitalWrite(immersionPower, LOW);
}
//Turn on power to immersion heater if temperature is below 1500 Degrees Fahrenheit (33.912mV)
if(immersionTempF < 1500 && immersionIsOn ==1)
  {
  digitalWrite(immersionPower, HIGH);
  }

immersionState = digitalRead(immersionPower);



//****** Torch Heater 1 Temperature Control******

//Set pin 3 to Torch Heater 1 thermocouple
pinMode(torch1Voltage,INPUT);

//Set pin 8 to Torch Heater 1 Power Relay
pinMode(torch1Power,OUTPUT);
```

```
//Check Temperature of K-type thermocouple in Torch Heater 1
//Read voltage from Torch Heater 1
torch1Voltage = analogRead(torch1TC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch1TempC = torch1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch1TempF = torch1TempC*1.8 + 32 - 16.7;

//Cut power to torch 1 if temperature is above 1500 Degrees Fahrenheit (33.912mV)

if(torch1TempF >= 1500)
  {
  digitalWrite(torch1Power, LOW);
  }

//Turn on power to torch 1 if temperature is below 1500 Degrees Fahrenheit (33.912mV)
  if(torch1TempF < 1500 && torch1IsOn ==1)
   {
    digitalWrite(torch1Power, HIGH);
  }


torch1State = digitalRead(torch1Power);


//****** Torch Heater 2 Temperature Control******
```

```
//Set pin 4 to read Torch Heater 2 thermocouple
pinMode(torch2Voltage,INPUT);

//Set pin 9 to Torch Heater 2 Power Relay
pinMode(torch2Power,OUTPUT);

//Check Temperature of K-type thermocouple in Torch Heater 2
//Read voltage from Torch Heater 2
torch2Voltage = analogRead(torch2TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
float torch2TempC = torch2Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius Degrees Fahrenheit
torch2TempF = torch2TempC*1.8 + 32 - 16.7;

//Cut power to torch 2 if temperature is above 1500 Degrees Fahrenheit (33.912mV)

  if(torch2TempF >= 1500)
  {
  digitalWrite(torch2Power, LOW);
  }

//Turn on power to torch 2 if temperature is below 1500 Degrees Fahrenheit (33.912mV)
if(torch2TempF < 1500 && torch2IsOn ==1)
  {
  digitalWrite(torch2Power, HIGH);
  }
```

```
torch2State = digitalRead(torch2Power);

//******Read Filter-Face Temperature******



//set pin 5 to filter-face thermocouple 1
//pinMode(filter1TC, INPUT);

//Check temperature of K-Type thermocouple at filter face
filter1Voltage = analogRead(filter1TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
filter1TempC = filter1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius Degrees Fahrenheit
filter1TempF = filter1TempC*1.8 + 32 - 16.7;




//***************PRINT DATA******************

//print header every 10 seconds
count = count+1;
if(count%15 == 0)
{
Serial.println("Immersion Temp [F] \t\tTorch 1 Temp [F] \t\tTorch 2 Temp [F] \t\tFilter Temp [F] \t\tTime [s]");
}

//print thermocouple temperature data
```

```
Serial.print("\t");
Serial.print(immersionTempF,0);
Serial.print("\t\t");
Serial.print(immersionState);
Serial.print("\t\t");
Serial.print(torch1TempF,0);
Serial.print("\t\t");
Serial.print(torch1State);
Serial.print("\t\t");
Serial.print(torch2TempF,0);
Serial.print("\t\t");
Serial.print(torch2State);
Serial.print("\t\t");
Serial.print(filter1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(count, DEC);
Serial.print("\n");

//
if (Serial.available() > 0)
 {
   ByteReceived = Serial.read();
//    Serial.print(ByteReceived);
//    Serial.print("        ");
//    Serial.print(ByteReceived, HEX);
//    Serial.print("       ");
//    Serial.print(char(ByteReceived));

  if(ByteReceived == 48) // Single Quote! This is a character.
   {
```

```
  //End Serial Communication
  Serial.print(" End Serial Communication, NOOO BILLY!!! ");

  //Turn OFF power to ALL heaters
  digitalWrite(immersionPower, LOW);
  digitalWrite(torch1Power, LOW);
  digitalWrite(torch2Power, LOW);

  delay(100000000);
  ;
}
if(ByteReceived == 49) // Single Quote! This is a character.
{

  Serial.print("\n IMMERSION HEATER POWER OFF \n");
  immersionIsOn = 0;
  digitalWrite(immersionPower, LOW);
}
  if(ByteReceived == 50) // Single Quote! This is a character.
{

  Serial.print("\n TORCH 1 POWER OFF \n");
  torch1IsOn = 0;
  digitalWrite(torch1Power, LOW);
}
  if(ByteReceived == 51) // Single Quote! This is a character.
{

  Serial.print("\n TORCH 2 POWER OFF \n");
  torch2IsOn = 0;
```

```
      digitalWrite(torch2Power, LOW);
    }


  }

//Delay loop 1.00 seconds
delay(999);

}
```

Immersion Heater Startup Code

```
//HTTU Control System
//version 1.0.0.0.0.0.1
//Ian Corcorran
//10.21.2015
//WHO CONTROLLZ DA HTTUZ?
//FLASHPOINT CONTROLLZ DA HTTUZ.


//Create pin instances
int immersionTC = A1;
int torch1TC = A3;
int torch2TC = A2;
int filter1TC = A4;
int filter2TC = A5;
int immersionPower = 3;
int torch1Power = 5;
int torch2Power = 4;
char ByteReceived;
```

```
// A coupling of Chromel and Alumel wires, has a range of -270 °C to 1260 °C and an output of -6.4 to 54.9 mV over maximum temperature range.

// ^^^ http://www.thermometricscorp.com/thertypk.html#sthash.siFljprF.dpuf ^^^

//Float creates an instance of a decimal from -3.4028235E+38 to +3.4028235E+38

//Thermocouple constants to convert measured voltage to a Fahrenheit float.

float K_amp = 10;  //mV/C

float K_immersion = 2.0001 ;  //33.912/1500 =.022608 mv/F

float K_torch_1 = 2.0001;

float K_torch_2 = 2.0001;

float K_filter_1 = 2.0001;

float K_filter_2 = 2.0001;

float immersionVoltage;

float torch1Voltage;

float torch2Voltage;

float filter1Voltage;


// This code needs to be put inside void loop() once everything is complete

//Convert voltage reading to Degrees C

//we need to scale 0-5 volts per 1024 units, i.e 5V=1024 units

//following code is written assuming input voltage divided by two, which would give us approx 4.05 volts into arduino at 1500F

float immersionTempC; // = immersionVoltage/(5*10*(1024/5));

float torch1TempC; // = torch1Voltage/(5*10*(1024/5));

float torch2TempC; // = torch1Voltage/(5*10*(1024/5));

float filter1TempC;


//Celsius to Fahrenheit conversions

double immersionTempF;

float torch1TempF;
```

```
float torch2TempF;
float filter1TempF;

//counter
int count=0;

//****************************************************************

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}

//******************************************************************

void loop() {
  // Main Loop runs repatedly....

//Read voltage from Torch Heater 1
torch1Voltage = analogRead(torch1TC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch1TempC = torch1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch1TempF = torch1TempC*1.8 + 32 - 16.7;

//Read voltage from Torch Heater 2
torch2Voltage = analogRead(torch2TC);
```

```
//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch2TempC = torch2Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch2TempF = torch2TempC*1.8 + 32 - 16.7;




// ****** Immersion Heater Temperature Control ******

//Set pin 2 to Immersion heater thermocouple
//pinMode(immersionTC,INPUT);

//Set pin 7 to Immersion Heater Power Relay
pinMode(immersionPower,OUTPUT);

//Check Temperature of K-type thermocouple in Insertion heater ( ͡° ͜ʖ ͡°)
//Read voltage from immersion heater *TC1*
immersionVoltage = analogRead(immersionTC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
 immersionTempC = immersionVoltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
immersionTempF = immersionTempC*1.8 + 32 - 16.7;

//Cut power to immersion heater if temperature is above 1500 Degrees Fahrenheit (33.912mV)
if(immersionTempF >= 300)
digitalWrite(immersionPower, LOW);
```

```
//Turn on power to immersion heater if temperature is below 1500 Degrees Fahrenheit (33.912mV)
if(immersionTempF < 300)
digitalWrite(immersionPower, HIGH);



//******Read Filter-Face Temperature******


//set pin 5 to filter-face thermocouple 1
//pinMode(filter1TC, INPUT);

//Check temperature of K-Type thermocouple at filter face
filter1Voltage = analogRead(filter1TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
filter1TempC = filter1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius Degrees Fahrenheit
filter1TempF = filter1TempC*1.8 + 32 - 16.7;



//**************PRINT DATA*****************

//print header every 10 seconds
count = count+1;
if(count%15 == 0)
{
```

```
Serial.println("Immersion Temp [F] \t\tTorch 1 Temp [F] \t\tTorch 2 Temp [F] \t\tFilter Temp [F] \t\tTime [s]");
}


//print thermocouple temperature data
Serial.print("\t");
Serial.print(immersionTempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch2TempF,0);
Serial.print("\t\t\t\t");
Serial.print(filter1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(count, DEC);
Serial.print("\n");


//
if (Serial.available() > 0)
 {
   ByteReceived = Serial.read();
//    Serial.print(ByteReceived);
//    Serial.print("        ");
//    Serial.print(ByteReceived, HEX);
//    Serial.print("       ");
//    Serial.print(char(ByteReceived));

  if(ByteReceived == 48) // Single Quote! This is a character.
   {
    //digitalWrite(led,HIGH);
```

```
      Serial.print(" All Power OFF, End Serial Communication, NOOO BILLY!!! ");
      digitalWrite(immersionPower, LOW);
      delay(100000000);
      ;
    }
  }

//Delay loop 1.00 seconds
delay(999);

}
```

Torch 1 Startup Code

```
//HTTU Control System
//version 1.0.0.0.0.0.1
//Ian Corcorran
//10.21.2015
//WHO CONTROLLZ DA HTTUZ?
//FLASHPOINT CONTROLLZ DA HTTUZ.


//Create pin instances
int immersionTC = A1;
int torch1TC = A3;
int torch2TC = A2;
int filter1TC = A4;
int filter2TC = A5;
int immersionPower = 3;
int torch1Power = 5;
```

```
int torch2Power = 4;

char ByteReceived;



// A coupling of Chromel and Alumel wires, has a range of -270 °C to 1260 °C and an output of -6.4 to 54.9 mV over maximum temperature range.

// ^^^ http://www.thermometricscorp.com/thertypk.html#sthash.siFljprF.dpuf ^^^

//Float creates an instance of a decimal from -3.4028235E+38 to +3.4028235E+38

//Thermocouple constants to convert measured voltage to a fahrenheit float.

float K_amp = 10;  //mV/C

float K_immersion = 2.0001 ;  //33.912/1500 =.022608 mv/F

float K_torch_1 = 2.0001;

float K_torch_2 = 2.0001;

float K_filter_1 = 2.0001;

float K_filter_2 = 2.0001;

float immersionVoltage;

float torch1Voltage;

float torch2Voltage;

float filter1Voltage;


// This code needs to be put inside void loop() once everything is complete

//Convert voltage reading to Degrees C

//we need to scale 0-5 volts per 1024 units, i.e 5V=1024 units

//following code is written assuming input voltage divided by two, which would give us approx 4.05 volts into arduino at 1500F

float immersionTempC; // = immersionVoltage/(5*10*(1024/5));

float torch1TempC; // = torch1Voltage/(5*10*(1024/5));

float torch2TempC; // = torch1Voltage/(5*10*(1024/5));

float filter1TempC;


//Celsius to Fahrenheit conversions
```

```
double immersionTempF;
float torch1TempF;
float torch2TempF;
float filter1TempF;

//counter
int count=0;

//****************************************************************

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}

//******************************************************************

void loop() {
  // Main Loop runs repatedly....



//****** Instantiate Thermocouple readings on unused heaters******
//Read voltage from immersion heater *TC1*
immersionVoltage = analogRead(immersionTC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
 immersionTempC = immersionVoltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
```

```
immersionTempF = immersionTempC*1.8 + 32 - 16.7;

//Read voltage from Torch Heater 2
torch2Voltage = analogRead(torch2TC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch2TempC = torch2Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch2TempF = torch2TempC*1.8 + 32 - 16.7;



//****** Torch Heater 1 Temperature Control******

//Set pin 3 to Torch Heater 1 thermocouple
pinMode(torch1Voltage,INPUT);

//Set pin 8 to Torch Heater 1 Power Relay
pinMode(torch1Power,OUTPUT);

//Check Temperature of K-type thermocouple in Torch Heater 1
//Read voltage from Torch Heater 1
torch1Voltage = analogRead(torch1TC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch1TempC = torch1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch1TempF = torch1TempC*1.8 + 32 - 16.7;
```

```
//Cut power to immersion heater if temperature is above 1500 Degrees Fahrenheit (33.912mV)
if(torch1TempF >= 300)
digitalWrite(torch1Power, LOW);

//Turn on power to immersion heater if temperature is below 1500 Degrees Fahrenheit (33.912mV)
if(torch1TempF < 300)
digitalWrite(torch1Power, HIGH);



//******Read Filter-Face Temperature******



//set pin 5 to filter-face thermocouple 1
//pinMode(filter1TC, INPUT);

//Check temperature of K-Type thermocouple at filter face
filter1Voltage = analogRead(filter1TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
filter1TempC = filter1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius Degrees Fahrenheit
filter1TempF = filter1TempC*1.8 + 32 - 16.7;



//**************PRINT DATA*****************
```

```
//print header every 10 seconds
count = count+1;
if(count%15 == 0)
{
Serial.println("Immersion Temp [F] \t\tTorch 1 Temp [F] \t\tTorch 2 Temp [F] \t\tFilter Temp [F] \t\tTime [s]");
}

//print thermocouple temperature data
Serial.print("\t");
Serial.print(immersionTempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch2TempF,0);
Serial.print("\t\t\t\t");
Serial.print(filter1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(count, DEC);
Serial.print("\n");

//
if (Serial.available() > 0)
 {
   ByteReceived = Serial.read();
//    Serial.print(ByteReceived);
//    Serial.print("        ");
//    Serial.print(ByteReceived, HEX);
//    Serial.print("       ");
//    Serial.print(char(ByteReceived));
```

```
  if(ByteReceived == 48) // Single Quote! This is a character.
   {
    //digitalWrite(led,HIGH);
    Serial.print("All Power OFF, End Serial Communication, NOOO BILLY!!! ");
    digitalWrite(torch1Power, LOW);
    delay(100000000);
    ;
   }
 }

//Delay loop 1.00 seconds
delay(999);

}
```

Torch 2 Startup Code

```
//HTTU Control System
//version 1.0.0.0.0.0.1
//Ian Corcorran
//10.21.2015
//WHO CONTROLLZ DA HTTUZ?
//FLASHPOINT CONTROLLZ DA HTTUZ.



//Create pin instances
int immersionTC = A1;
int torch1TC = A3;
int torch2TC = A2;
```

```
int filter1TC = A4;
int filter2TC = A5;
int immersionPower = 3;
int torch1Power = 5;
int torch2Power = 4;
char ByteReceived;


// A coupling of Chromel and Alumel wires, has a range of -270 °C to 1260 °C and an output of -6.4 to 54.9 mV over maximum temperature range.
// ^^^ http://www.thermometricscorp.com/thertypk.html#sthash.siFljprF.dpuf ^^^
//Float creates an instance of a decimal from -3.4028235E+38 to +3.4028235E+38
//Thermocouple constants to convert measured voltage to a fahrenheit float.
float K_amp = 10;  //mV/C
float K_immersion = 2.0001 ;  //33.912/1500 =.022608 mv/F
float K_torch_1 = 2.0001;
float K_torch_2 = 2.0001;
float K_filter_1 = 2.0001;
float K_filter_2 = 2.0001;
float immersionVoltage;
float torch1Voltage;
float torch2Voltage;
float filter1Voltage;

// This code needs to be put inside void loop() once everything is complete
//Convert voltage reading to Degrees C
//we need to scale 0-5 volts per 1024 units, i.e 5V=1024 units
//following code is written assuming input voltage divided by two, which would give us approx 4.05 volts into arduino at 1500F
float immersionTempC; // = immersionVoltage/(5*10*(1024/5));
float torch1TempC; // = torch1Voltage/(5*10*(1024/5));
```

```
float torch2TempC; // = torch1Voltage/(5*10*(1024/5));
float filter1TempC;

//Celsius to Fahrenheit conversions
double immersionTempF;
float torch1TempF;
float torch2TempF;
float filter1TempF;

//counter
int count=0;

//*****************************************************************

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}

//******************************************************************

void loop() {
  // Main Loop runs repeatedly....



//****** Instantiate Thermocouple readings on unused heaters******
//Read voltage from immersion heater *TC1*
immersionVoltage = analogRead(immersionTC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
```

```
immersionTempC = immersionVoltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
immersionTempF = immersionTempC*1.8 + 32 - 16.7;

//Read voltage from Torch Heater 1
torch1Voltage = analogRead(torch1TC);

//convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
torch1TempC = torch1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius to Degrees Fahrenheit
torch1TempF = torch1TempC*1.8 + 32 - 16.7;



//****** Torch Heater 2 Temperature Control******

//Set pin 4 to read Torch Heater 2 thermocouple
pinMode(torch2Voltage,INPUT);

//Set pin 9 to Torch Heater 2 Power Relay
pinMode(torch2Power,OUTPUT);

//Check Temperature of K-type thermocouple in Torch Heater 2
//Read voltage from Torch Heater 2
torch2Voltage = analogRead(torch2TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
float torch2TempC = torch2Voltage*5/1024*1000*2/10;
```

```
//Convert Degrees Celsius Degrees Fahrenheit
torch2TempF = torch2TempC*1.8 + 32 - 16.7;

//Cut power to immersion heater if temperature is above 1500 Degrees Fahrenheit (33.912mV)
if(torch2TempF >= 300)
digitalWrite(torch2Power, LOW);

//Turn on power to immersion heater if temperature is below 1500 Degrees Fahrenheit (33.912mV)
if(torch2TempF < 300)
digitalWrite(torch2Power, HIGH);


//******Read Filter-Face Temperature******


//set pin 5 to filter-face thermocouple 1
//pinMode(filter1TC, INPUT);

//Check temperature of K-Type thermocouple at filter face
filter1Voltage = analogRead(filter1TC);

//Convert voltage output from TC/Amplifier to deg C: (5V/1024unit)(1000mV/V)(1C/10mV)
filter1TempC = filter1Voltage*5/1024*1000*2/10;

//Convert Degrees Celsius Degrees Fahrenheit
filter1TempF = filter1TempC*1.8 + 32 - 16.7;
```

```
//***************PRINT DATA******************

//print header every 10 seconds
count = count+1;
if(count%15 == 0)
{
Serial.println("Immersion Temp [F] \t\tTorch 1 Temp [F] \t\tTorch 2 Temp [F] \t\tFilter Temp [F] \t\tTime [s]");
}

//print thermocouple temperature data
Serial.print("\t");
Serial.print(immersionTempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(torch2TempF,0);
Serial.print("\t\t\t\t");
Serial.print(filter1TempF,0);
Serial.print("\t\t\t\t");
Serial.print(count, DEC);
Serial.print("\n");

//
if (Serial.available() > 0)
 {
   ByteReceived = Serial.read();
//    Serial.print(ByteReceived);
//    Serial.print("        ");
//    Serial.print(ByteReceived, HEX);
```

```
//    Serial.print("       ");
//    Serial.print(char(ByteReceived));

   if(ByteReceived == 48) // Single Quote! This is a character.
    {
     //digitalWrite(led,HIGH);
     Serial.print(" End Serial Communication, NOOO BILLY!!! ");
     digitalWrite(torch2Power, LOW);
     delay(100000000);
     ;
    }
  }

//Delay loop 1.00 seconds
delay(999);

}
```

Appendix K DVPR

Table 6: Test Results Form

ME428 DVP&R Format										
Report Date		Sponsor			Component/Assembly					
TEST PLAN										
Item No	Specification or Clause Reference	Test	Acceptance Criteria	Test Respon-sibility	Test Stage	SAMPLES TESTED		TIMING		
						Quantity	Type	Start date	Finish date	
1	Cust specifications	25 CFM Temp	>1150	Team	Final					
2	Cust specifications	High flow temp	>1225	Team	Final					
3	Cust specifications	Heat up time	<40 mins	Team	Final					

TEST REPORT			
TEST RESULTS			NOTES
Test Result	Quantity Pass	Quantity Fail	