Rayleigh Test Apparatus Design Report

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Introduction

The Rayleigh Test Apparatus is a device that will be used to test the thermodynamic properties of Nitrous Oxide to assess the feasibility of using this fluid as a coolant for a hybrid rocket aero spike. The aero spike is intended to redirect the propulsion flow as it leaves the engine to create a more efficient flow pattern at low and high altitudes. However, there are issues of overheating which leads to melting of the aero spike. For this reason, the use of nitrous oxide (N_2O) as a coolant is being explored. N_20 is being considered because it is already present as an oxidizer in many hybrid rockets. By redirecting the N_2O through the inside of the aero spike it will cool the aero spike and then be used as the oxidizer in propulsion. Since there is currently little information on the thermodynamic properties of N_2O, it is essential to know the possible outcomes of using this fluid as a coolant. N_2O decomposes exothermically releasing, pound for pound, twice the energy as TNT; this characteristic is obviously not favorable inside a cooling system. By knowing the heat transfer coefficient of N_2O, it can be ensured that decomposition of the N_2O does not occur inside the aero spike. This achieved by choosing a proper flow rate of N_2O to avoid decomposition while maximizing the amount of thermal energy removed from the aero spike.

As a check to the apparatus accuracy, helium will first be tested and the known heat transfer coefficient of helium will be verified. In addition, the helium will be taken to temperatures and pressures where N_2O is believe to decompose, therefore proving the concept that N_20 may be used in the apparatus. At this point the final objective of RF Testing will be complete.

Background

Previous Project:

A previous project was performed by Lauren May Nelson in which N_2O was tested. Nelson used a modified rocket nozzle that had a separated annular channel around the throat of the nozzle. When the rocket expels hot gas, the annulus becomes heated by the stream of exhaust which is assumed to be at a temperature of T_∞. Nelson's apparatus used N_2O flowing through the annulus in an attempt to keep the nozzle cool. Temperature and pressure readings were recorded as the N_2O was heated outside of the vapor dome (as a superheated vapor) and potentially past its decomposition point. The vapor dome is a graphical representation of the matter's state (gas or liquid and the transition between) for a given set of properties such as pressure and enthalpy. The vapor dome exist as a three dimensional surface and is usually

cross sectioned by its third parameter, specific volume. Nelson's apparatus drawing can be seen in Figure 1.

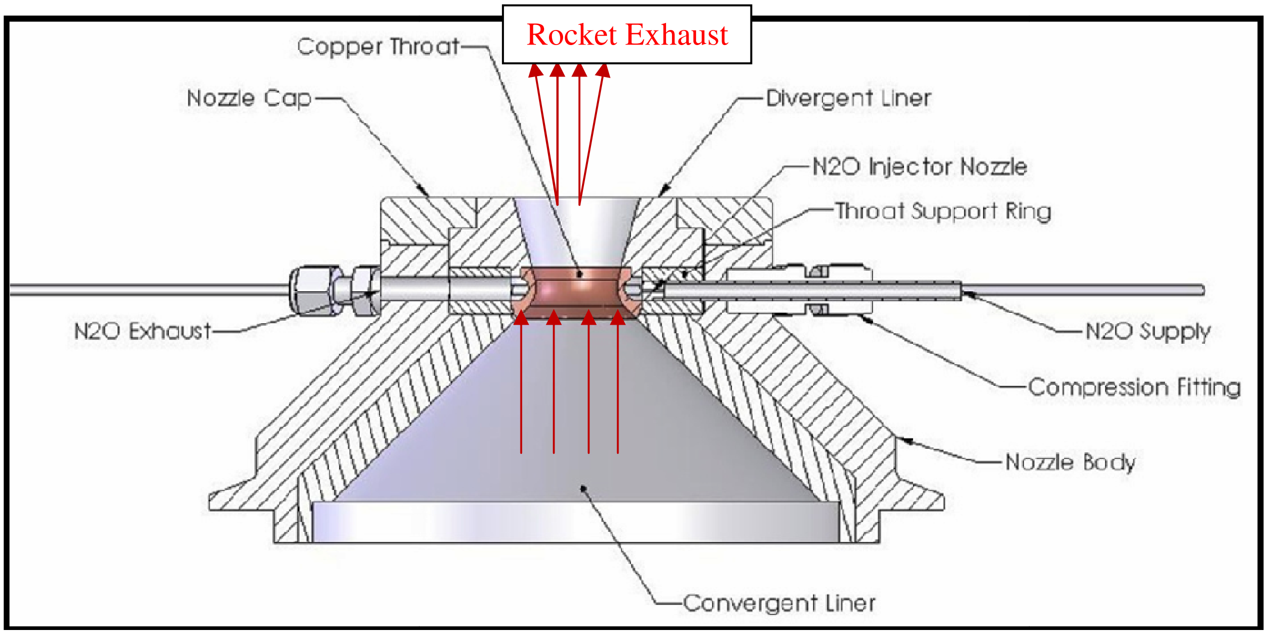


Figure 1- *Cross section view of Nelson's apparatus. N_20 flows around the inside of the copper annulus.*

Main drawbacks of Nelson's design include:

1. Unknown Heat Flux- Uses rocket's exhaust which produces "T_∞" This input must be controlled and changeable which will require a different heat source.

2. Heat source produces soot- As a result, the test area is uncontrollably insulated thus creating more inaccuracies in testing. New heat source should not create soot on the test area.

3. Apparatus is too small- Makes individual part replacement difficult. Larger parts are easier to isolate and replace.

Technical paper # 1: Boiling heat transfer in Vertical Tube with Freon 114

The paper *Boiling Heat Transfer in Vertical Tube with Freon 114 [5]* by Fagerhol, Ghazanfari, and Kivioja documents the experimental setup and results of an experiment that tested the cooling properties of Freon 114. This experiment was done by E. Fagerholm, A. R. Ghazanfari, and K. Kivioja, Helsinki. The experimental setup consisted of a stainless steel tube with two up-flow sections and two down-flow sections. This experiment is similar to the Rayleigh

flow experiment in several ways. The types and placement of measurements on the two experiments are very similar. The Freon experiment also used a resistive heating element like the one planned for the Rayleigh flow experiment. The major difference however, is that the Rayleigh experiment will consist of a straight pipe and the R114 experiment had 180 degree bends which leads the flow in two directions with respect to gravity. These bends were found to have a large effect on heat transfer. Similar to the Rayleigh Flow experiment heat conduction along thermocouple probe was an issue in this experiment. Using the inefficient fin reasoning, the Freon 114 experiment used a thermocouple probe length of 5 cm to mitigate this effect.

The correlation of heat transfer for the fluid through the tube was compared with correlations derived by other scientists. The study compiled different correlations from other research and showed boiling regions where each correlation applied best.

This paper stresses the importance of nucleate boiling on heat transfer. Intuition might suggest that a boiling fluid would have lower heat transfer than the same fluid in liquid phase because of its gaseous part, but the effect is actually an increase in heat transfer from that of single phase fluid. The most prominent effect of nucleate boiling is a pumping action which causes high amounts of mixing in the liquid phase.

Technical paper # 2: Kinetics of Decomposition of Nitrous Oxide

The paper *Kinetics of Decomposition of Nitrous Oxide* [6] by Kalback and Sllepcevich notes the rate of the decomposition of Nitrous Oxide at different temperatures and pressures. The data collected for this paper is only for higher temperatures. One very important note is about a mishap they encountered at a low temperature and a low pressure. The Nitrous Oxide came in contact with graphite used to lubricate threads on a check valve. This completely destroyed the valve and a rupture disk both which were rated to a max pressure of 3000 psi. To insure no sudden unexpected pressure events, they recommend that the equipment be thoroughly cleaned with trichloroethylene which is a degreaser certified for use in oxygen systems. In the Rayleigh Flow experiment, all components must be thoroughly cleaned in order to avoid this situation.

Objectives

There are several main design requirements which the Rayleigh test apparatus must fulfill in order to determine the decomposition point and thermal properties of N_2O. These

requirements are summarized in Table 1 and are explained in more detail in the following paragraphs.

First, a constant but controllable heat flux must be applied to the fluid throughout the flow. This heat flux will be applied from a heat source designed specifically for this test apparatus. The heat source must have at a range of input settings. For all settings, the amount of heat being added to the system must also be known. The highest heat setting must have the capability of heating the moving fluid to at least 570 ºF in order to test for decomposition of Nitrous Oxide. Heat losses throughout the system are minimized as well through the use of insulation.

To measure the temperature of the moving fluid and the surrounding wall there will be sixteen temperature ports evenly spaced throughout the flow as specified by the sponsors. Eight of which to measure the moving fluid and eight to measure the surrounding wall temperatures. In addition to the temperature sensors, there will be eight pressure transducers at the same vertical locations as the temperature sensors.

The final subsystem that will be integrated into the apparatus is a mass flow meter. This flow meter will be located as close to the helium and nitrous oxide tank as possible to ensure the liquid enters at a high pressure and avoids changing into a two phase liquid.

Testing done during the senior project timeline will be done with helium in order to verify that the thermodynamic properties of a fluid can be found from this apparatus. After the apparatus is handed off, the device will be used with N_20. The apparatus must be able to apply heat flux to the moving fluid and take all of the measurements within a specified run time (see Table 2). The reasoning behind this run time is to conserve helium. The helium tanks already exist in the engines lab.

The data acquisition system must collect at least twenty samples per second (20Hz) for each piece of instrumentation. Because the experiment will have a short run-time and because flow patterns will change throughout the experiment, many data points are required to pinpoint the nature of the flow at any single time and location.

Table 1: *Requirements specified by the customer; these standards are necessary to have accurate results.*

• Constant and controllable heat flux	• Measure Pressure
• Adjustable heat input (more or less)	• Calibrate with He, design for N_20 test
• Minimal Heat loss	• Measure input flow of He and N_20
• Measure Temperature of working fluid and apparatus wall	• Run time short, to conserve He
	• Use current lab setup in engines lab

Design Development

The major design components of the project include a flow meter, flow tube, interface of pressure and thermocouples to the tube, thermocouples, heat source, insulation and the DAQ system. Each system design was brainstormed to come up with probable solutions. In most cases there has been more than one adequate solution. Deciding between design options was done by weighing functionality, cost, labor, accuracy, ease of reassembly/manufacturing and compatibility with other systems. Below, Table 2 shows a specific set of engineering requirements as specified by the project sponsors.

Table 2: *Formal engineering requirements as interpreted by RF Testing. Note the compliance column shows the method by which the specification will be met. 'A' is by analysis, 'S' is by similarity to existing designs, 'T' is by testing and 'I' is by Inspection.*

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Flow Meter Flow Range	0.05 to 1 lb/sec	Max	L	S
2	Fluid Pressure	1050 psi	Max	M	S,I
3	Production Budget	$2000	±$1000	H	A
4	Test Run Time	15 seconds	Min	M	A, T
5	Enthalpy In	400 kJ/kg	±25 kJ/kg	H	A,T
6	# of Pressure Ports	8	Exact	L	S, I
7	# of Thermocouples	16	Exact	L	S, I
8	DAQ Sample Rate	20 Hz	Exact	L	S

Each critical component will be individually verified to assure that it reliably meets specifications. To validate the system instrumentation, tests will be conducted with other known-to-be-accurate experiments/data. The text books *Fundamentals of Fluid Mechanics* by Bruce Munson and *Heat Transfer* by David Dewitt will be heavily used to validate our design. EES will also been used to gather information on gas properties from databases; one of which is provided by NASA.

A Solid Works project has been made to model the system along with a bill of materials (Appendix B). This model includes most of the parts for every component involved in the system. Every component has a part name and is integrated into a full assembly. Sufficient safety factors have been applied when working with high pressures or other potentially dangerous conditions. When designing around our maximum pressure, a safety factor of 1.5 was used. The following section describes the room that testing will occur in and the subsystems that have been chosen for the apparatus design.

Testing Room:

The Rayleigh Test Apparatus was designed to be used in the Cal Poly engines lab, located in room 13-126. The lab includes an overhead exhaust vent, blast containment walls, pressure transducers, blast plate, necessary wiring, thermocouple amplifiers, and Ethernet connection cables. The Rayleigh Test Apparatus uses sixteen of the rooms thermocouple ports, and eight of the pressure transducers. A thirty foot extension chord is run from the north facing wall to facilitate the heaters electrical requirements. There is an exhaust vent in the engines lab that is usually used when rocket related tests are run, but it has been deemed sufficient to let the Rayleigh Test Apparatus exhaust into the open room. The area to work within the engines lab is roughly a 5ft by 5ft area with high ceilings.

Technology Considered

Heat Sources- A controllable, accurate and isolated heating source is required to heat the working fluid flow. The power requirement for the heat source is determined by the following analysis.

Required power for the heat source is a function of N_2O mass flow rate and change in enthalpy, Δh. The enthalpy requirement of 400 kJ/kg is based on low pressure operation at 1000 kPa. It should be noted that if higher run temperature is used a lower Δh may also be used. Assuming low pressure with a Δh of 400 kJ/kg from the pressure-enthalpy graph in Figure 2 and using a mass flow rate of 0.0114 kg/sec equates to a power requirement of 4.55 kW. If a higher pressure of 5000 kPa is used, Δh may decrease to 250 kJ/kg. In this case, the power requirement lowers to 2.84 kW. The process to arrive at these numbers can be seen in Appendix C, section 1. This is a 37% reduction in the power requirement and is an option still being considered. As of now, the conservative approach is being taken and a power source capable of 18.14 kW is needed.

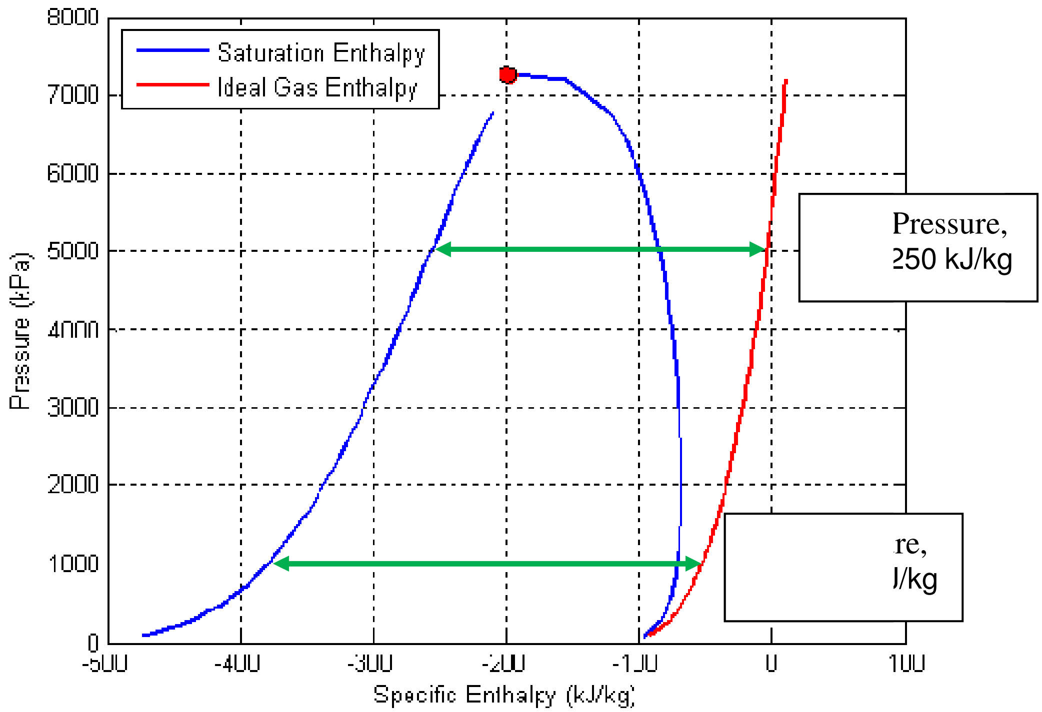


Figure 2: *Relationship between pressure and enthalpy of N_2O leading to enthalpy requirement.*

Below is a summary of the research of various heat sources that were considered.

- **Heating Chord**: Uses resistance heating packed into a flexible insulated fiberglass chord. Max temperature of roughly 900°F. Cheap, readily available. Downside is large exposed tube area from winding a small diameter chord.
- **Molybdenum Disilicide**: High quality, long lasting heating coil type element capable of temperatures of 1800 C°. Runs off of electricity. Yet relatively expensive and must be custom made for this application.
- **Shell and Tube Heat Exchanger**: Can customize with number of passes. Still needs a hot fluid flow to pass heat to working fluid, N20/He. Also relatively expensive and must be custom made for this application.
- **Heat Tape**: Uses resistance heating packed into a flexible insulated fiberglass tape. Max temperature of roughly 1400°F. Covers pipes well. Cheap, readily available.

In order to pick the optimal heat source key characteristics of each source were evaluated. Controllability is crucial for determining exactly how much heat is being delivered to the system. Measuring and controlling the heat input will guarantee an accurate calculation of the thermodynamic properties of the test fluid. In addition, the heat source must be able to

transfer enough thermal energy to the test fluid in order to have a complete phase change within the test run time. Cost, ease of integration into the system and response time is also considered. The final decision matrix can be seen in Table 3; all five criteria were given a value from one to five then the numbers were summed. The option with the highest total resembles the most ideal heat source for our application.

Table 3*: Heat element decision matrix points to McMaster Heat Tape as the heat element to be implemented.*

	Controllability	Response Time	Max Heat Transfer	Ease of Integration	Cost	**Total**
Rocket Plume	1	3	5	2	2	**13**
Molybdenum Element	4	2	5	2	2	**15**
Crossflow Heat Exchanger	2	2	3	1	1	**9**
Cole Parmer Heat Chord	5	4	4	4	3	**20**
McMaster Heat Chord	5	5	4	4	3	**21**
McMaster Heat Tape	5	5	5	4	4	**23**

As shown in the decision matrix, the "Extreme High Temperature Heat Tape" from McMaster Carr was chosen for this application. The heat source temperature input is controlled via a variable voltage controller. Specifications include: Heat output of 1400° F, maximum wattage of 78 Watts/foot and flexible fiberglass insulation. Advised by the heat tape supplier, the tape should not be butted up against itself in order to avoid burnout or hot spots. However, this advice is given under arbitrary operating conditions: internal tube flow with the outside open to ambient temperature and pressure.

RF Testing's design introduces a special setup for the heat tape. In this setup the flow tube's outside surface will be wrapped with the heat tape and covered with insulation wrap. The inside surface of the flow tube is cooled by the test fluid. Because of this special setup the heat tape may be able to handle zero spacing and thus reduce the heat lost to atmospheric cooling and increase wattage density from the heat source. In order to confirm this hypothesis, a preliminary experiment was conducted to find the orientation which provides the maximum heat flux. The overall efficiency and heat loss of the system was also determined.

In the Proof of Concept section a brief overview of the Heat Tape experiment in explained. For a detailed procedure and analysis see Appendix A.

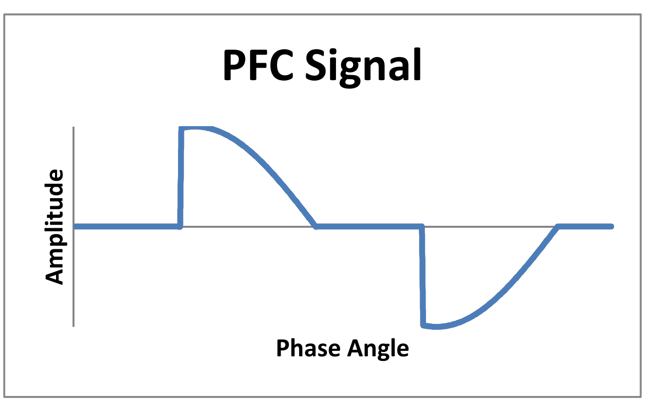
Power Source: James, use the file u emailed me and add some graphs or something

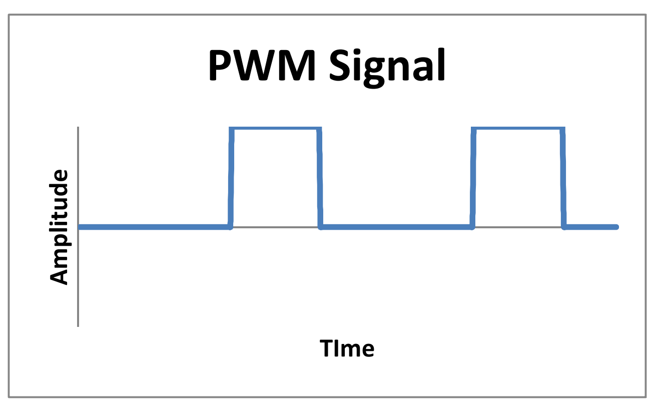
The power supply is used to regulate the energy input into the testing system. Like with the Heat Tape Experiment, a variable AC voltage is required. However, a Variac like on used on the Heat Tape Experiment was not sufficent enough to deliver the power required for the final project. To measure the electrical power input in the Heat Tape Experiment a volt meter and a current meter were used. The scheeme will be the same for the Rayleigh Test Apparatus.

In order to controll our energy ballacne for the Rayleigh Test Apparatus, we needed a power supply that would be able to supply seven heat tapes to their maximum rated input. We calculated that to achieve RESULTS we would need an power input to the system of BLA BLA killowatts. This translates to HOO HA amps at 120 V.

RF Testing decided that a Phase Fired Controller should be used to regulate the electrical power input. After talking with Professor Toffik, RF Testing learned that a SCR & Firing Board was the best solution. They were put in touch with Enerpro in Goleta who graciously donated the power supply used.

The power supply controlls the apparent voltage in AC by means of Phase Fired Controll (PFC), which is similar to Puls Width Modulation (PWM) in that it switches the supply on and off, however PFC modulates in reference to the suply waveform's phase. The paramater that controlls the amplitude of the output is called a delay angle for PFC and a duty cycle on PWM.





With similar scales, Both Waveforms Have the same RMS value.

The main parts of the power source are the FCRO21HV Firing Board and the Silicon-Controled Rectifier (SCR). The Firing Board is the device that synchronises with the supply waveform and turns the SCR on and off according to the desired voltage.

For a low voltage a high delay angle is used. This means that after a zero crossing is detected, the Firing Board will wait up to 180 Degrees to let the SCR turn on letting current flow. The SCR is reset to off every 180 degrees. For large voltages the delay angle is small and the portion of the supply waveform conducted through the SCR is larger. The delay angle and ultimatley the output voltage is controlled via a potentiometer on the Hand Held Control Device (HHCD).

Insulation:

Insulation will be wrapped around the test tube in order to minimize heat loss. An aluminum foil coating will be wrapped on the inside of the insulation so that radiation effects may be neglected. This is a valid assumption because the foil coating will eliminate the emissivity of the heating element. The insulation will be purchased from Industrial Insulation Group. IIG is one of the largest insulation companies in America with factories in California which will help cut down on shipping costs. IIG has three types of piping insulation; calcium silicate, mineral wool, and perlite insulation. The shape of the piping insulation is cylindrical with a specified ID and thickness. The minimum inner diameter is 0.5 inches and can come with thicknesses from 1 to 6 inches in 0.5 inch increments. All three types are rated at 1200 degrees Fahrenheit and have tables and graphs which provide the thermal conductivity of the material at different temperatures as seen below in Figure 4. These materials are easy to cut and shape to fit around our measurement ports. Once all the other parts have been finalized and ordered we will order the insulation and cut it to shape.

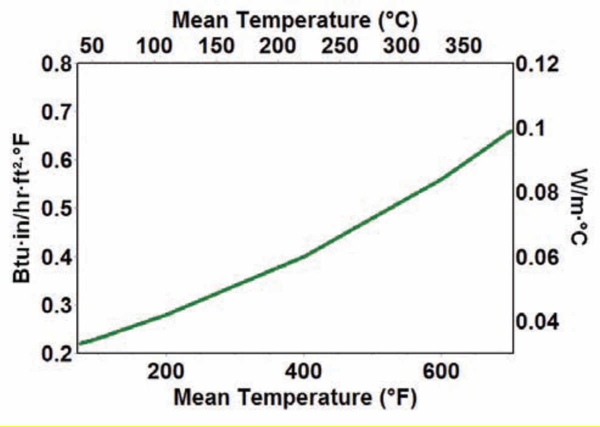


Figure 4: *Change in thermal conductivity for changing temperatures, this graph is for the mineral wool insulation and is supplied from IIG.*

Flow meters:

Several different types of flow meters have been explored to find the most viable type. Accuracy, flow requirements, and flow conditions of the fluids have narrowed our options to two types of flow meters; a Venturi volumetric flow meter or a Coriolis mass flow meter. The conditions for measuring the flow are listed below followed by the pros and cons of both types of flow meters.

Most of the requirements were specified by the sponsors primarily based on their experience with previous projects and experiments. The temperature was determined from the room temperature as well as the temperature drop that would occur from reducing the pressure in a control volume. The pressure of the helium is the pressure of the fluid after it has passed through the regulator. The regulator is attached to the helium tank and allows the operating pressure to be specified. Max pressure for the N_2O meter was determined from the pressure at the triple point for N_2O (~1050psi) with a safety factor of 1.5; this is done so the expensive equipment will be saved when complete decomposition of N_2O occurs. An accuracy of 0.5% full scale was established in order to have more reliable and accurate data and therefore decrease the uncertainty of the calculations. The flow rates were specified by the project sponsors to help conserve the substances as well as to have a more versatile mass flow meter for future projects.

Nitrous Oxide Flow Meter Requirements:

- Substance: Nitrous Oxide (enters in liquid phase)
- Flow Rate Range: 0.05-1.0 lb/sec
- Max Pressure: 1575psi
- Operating Pressure: 300-900 psi
- Temperature Range: 45-100 °F
- Inner Diameter of Entrance Tube: 0.4 inches
- Accuracy: 0.5% Full Scale (can accept 1% FS)
- Other: pressure drop must be low enough to keep fluid in liquid phase

Helium Flow Meter Requirements:

- Substance: Helium (enters in gas phase)
- Flow Rate Range: 0.01-0.1 lb/sec
- Max Pressure: 800psi
- Operating Pressure: 600psi
- Temperature Range:45-100 °F
- Inner Diameter of Entrance Tube: 0.4 inches
- Accuracy: 0.5% Full Scale (can accept 1% FS)

As a result of the differences in flow rates, pressures, and phase of the fluids two flow meters are being considered. For the helium flow meter, a orifice flow meter from a previous Cal Poly experiment will be used; this flow meter is currently connected, calibrated and ready to be used. For measuring N2O flow rates a Venturi and a Coriolis meter were considered.

Venturi Flow Meter

***Pros*:**

- Can achieve accuracy of 1% with proper calibration
- Low pressure drop
- Can measure different gases/liquids

***Cons*:**

- Measures volumetric flow rate, extra uncertainty in density
- Mildly Expensive
- Typical Turndown ratio of 4:1

Coriolis Flow Meter

***Pros*:**

- Most accurate type of flow meter
- Measures direct mass flow rate
- Not dependent on pressure, density, or temperature
- No moving parts -> long lifetime
- Low pressure drop for low viscous fluids
- Turndown ratio of 100:1
- Self-draining in vertical position

***Cons*:**

- Relatively Expensive!
- Large Pressure drop for high viscous fluids

Due to the turndown ratio, accuracy, and the fact that the Coriolis flow meter is a direct mass flow meter, a Coriolis flow meter has been selected. RF Testing is in the process of finding a company with an affordable flow meter which meets all of the requirements. Some general trends in the Coriolis flow meters have been observed. When operating near the lower limit of the specified flow rate the uncertainty increases and the pressure drop over the flow meter decreases. For this reason a flow meter will be selected that can operate below the minimum flow rate that will be used. Also, when operating near the higher limits of the flow meter, the pressure drop increases dramatically. To accommodate for this trend a meter will be selected with a higher maximum flow rate than needed.

Another design issue that now must be considered is the connection processes. Some of the connection options include female threads, male threads, ½" AMSI flanges, and several other types of flanges. Although most companies have several options, these connections are

generally the limiting factor for the pressure rating. For this reason, the ½" AMSI flange seems the most promising, but connecting the flange to the supply line then becomes an issue. RF testing is currently working with Jim Gerhardt to determine the most plausible option for the connecting processes.

Flow Tube:

A metal flow tube is required to direct the test fluid (He and then N_20) and to withstand the high temperatures. The flow tube must have high thermal conductivity in order to transfer thermal energy from the heat tape to the test fluid as fast as possible. In order to achieve this, several different materials were considered. These are shown in Table 6.

***Table 6**: Flow tube material conductivity.*

Material	W/m-K
Aluminum	250
Copper	**401**
Stainless Steel	16
Brass	109

Helium Flow Estimates

As part of the justification for the selected flow tube diameter to use, Fanno flow calculations were performed to determine how long a container of helium would last. More specifically, for a given regulator pressure, how long can data be collected by draining one tank of helium. The results of these calculations can be seen below in figure 5. Helium is a strategic resource, so it is beneficial to society to use as little as possible to achieve the desired results.

The system modeled starts with a helium tank at 1800 psi. The helium is then released from the tank and passes through a pressure regulator before flowing through the tube. The two flow tube sizes under inspection were 1/4" and 3/8 ". The basis of these calculations was that friction was the only effect on the fluid and that the flow was choked at the tube outlet. Because these assumptions were made, Fanno flow tables were used to determine flow properties at the pipe inlets such as Mach number and velocity. Because of the uncertainty of the gas expansion across the regulator, calculations were performed for isothermal and isentropic cases. In both cases, pressure and temperature were known, and because helium is an ideal gas, the density

could then be determined by the ideal gas law. Then, by knowing density, velocity and pipe cross-sectional area, flow rate can be determined. It was found that flow rates in 3/8" pipe were more than double that of 1/4" pipe. Therefore a pipe size of 1/4" is more appropriate for reasons of cost, runtime, and environmental footprint.

Many sizes of helium canisters are available. The below graphs show that with larger tanks, the run times remain more constant across the domain of regulator pressure. See Appendix C for detailed calculations which led to the following graphs.

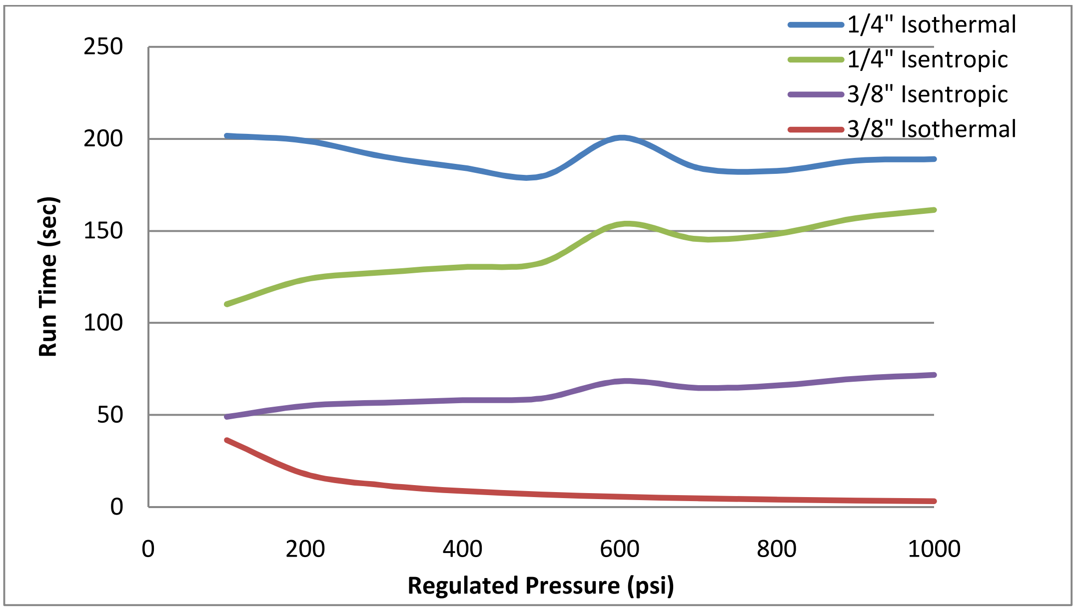


Figure 5: *Run time estimates for Helium using a 250scf tank at 1800psi.*

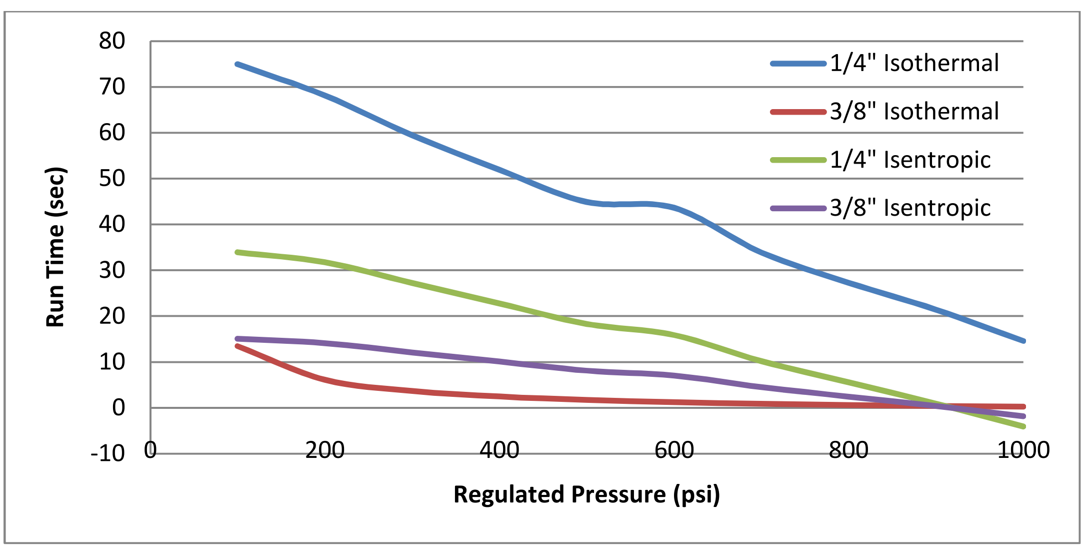


Figure 6: *Run times estimates for Helium using a 100scf tank at 1800psi.*

Once flow rates were justified, a check on the friction effects yielded the result that choked flow does occur for a wide range of pipe lengths. The smallest maximum pipe length that would still achieve choked flow was found to be 20 feet.

The inner diameter of the tube has been chosen to be ¼ inch. This was chosen because it is a common size (i.e. supply lines are ¼ inch) and is in the range of what will be used in the final application. The length of the tube is still to be determined pending on results from the heat tape experiment. Once the amount of heat added to the fluid per foot of heat tape and the heat transfer efficiency is known, the correct length of pipe can be chosen.

Flow Restrictor

A flow restriction component is to be added to the end of the flow tube. This component comes in three parts: flow restrictor socket; flow restrictor; flow restrictor cap. The socket will be brazed to the end of the flow tube and will locate the flow restrictor concentrically with the flow tube. The flow restrictor will be secured to the end of the pipe by a cap that will screw onto the socket, holding the restrictor firmly between the cap and the socket. The restrictor will be an interchangeable part and will be produced in different sizes to give the experiment technician options of flow rate control.

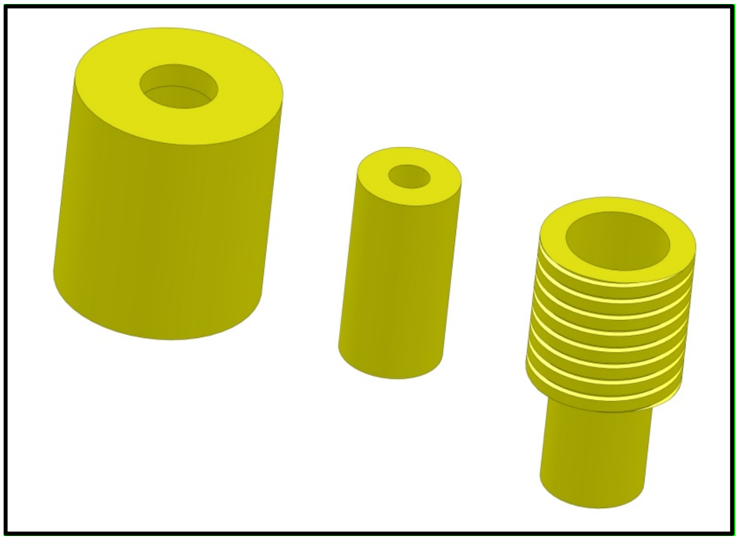


Figure 7: *(Right to left) Socket, restrictor, cap. Arbitrary threads are shown and are subject to tooling available in the machine shop.*

Tee Junctions for Single Port Pressure and Temperature Readings:

The flow tube has eight single hole ports for simultaneous readings of pressure and temperature. A tee connection will split the single port and enable flow access for pressure taps and thermocouples. Figure 8 shows two ideas for the connection of the tee junction.

Note: Pressure readings may be affected by nearby thermocouple wires. To avoid inaccurate pressure readings the pressure port end of the Tee junction will be placed two diameters away from thermocouple.

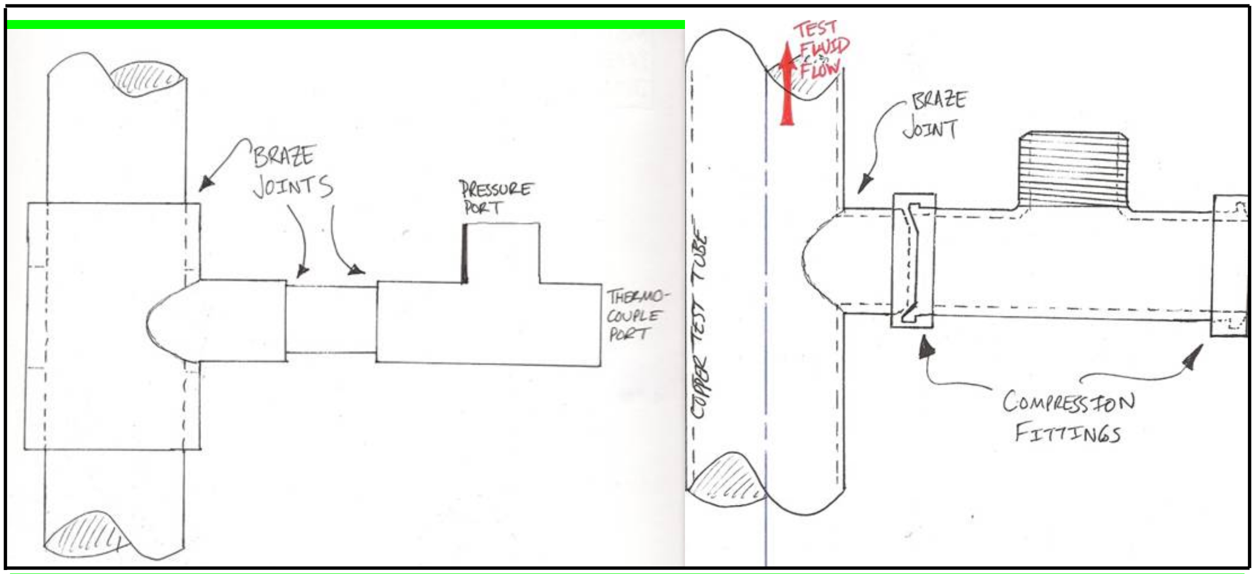


Figure 8: *Tee joint possibilities. Left shows a more modular tube yet may interrupt the flow. Right shows a more desired straight flow tube.*

The idea on the right uses a brazed joint to attach to the flow tube. This will ensure smooth flow tube inner diameter. However, manufacturing of this setup is very difficult due to the lack of surface area for brazing. Table 7 shows a decision matrix that was used to determine a port design.

Table 7: *Port decision matrix shows a tee fitting to be superior.*

Porting Method	Manufacturability	Strength	Flow Interruption	Modularity	Total
Tee Fitting	4	4	2	3	13
Drill & Braze	1	2	4	2	9

Final port design uses a copper tee fitting to split the flow tube and reduce the port from 1/4" to 1/8" pipe diameter. Although flow interruption is an issue with this design, there are certain manufacturing techniques and or better tee junction selection can be done to reduce this effect. Two Swagelok reducers and one Swagelok tee fitting will be used to seal the thermocouple and pressure tap to their respective diameters. Figures 9, 10 and 11 show the solid model layout of the ports final set-up. See Appendix B for the bill of materials and dimensioned part drawings. Total cost for all eight ports is $449.

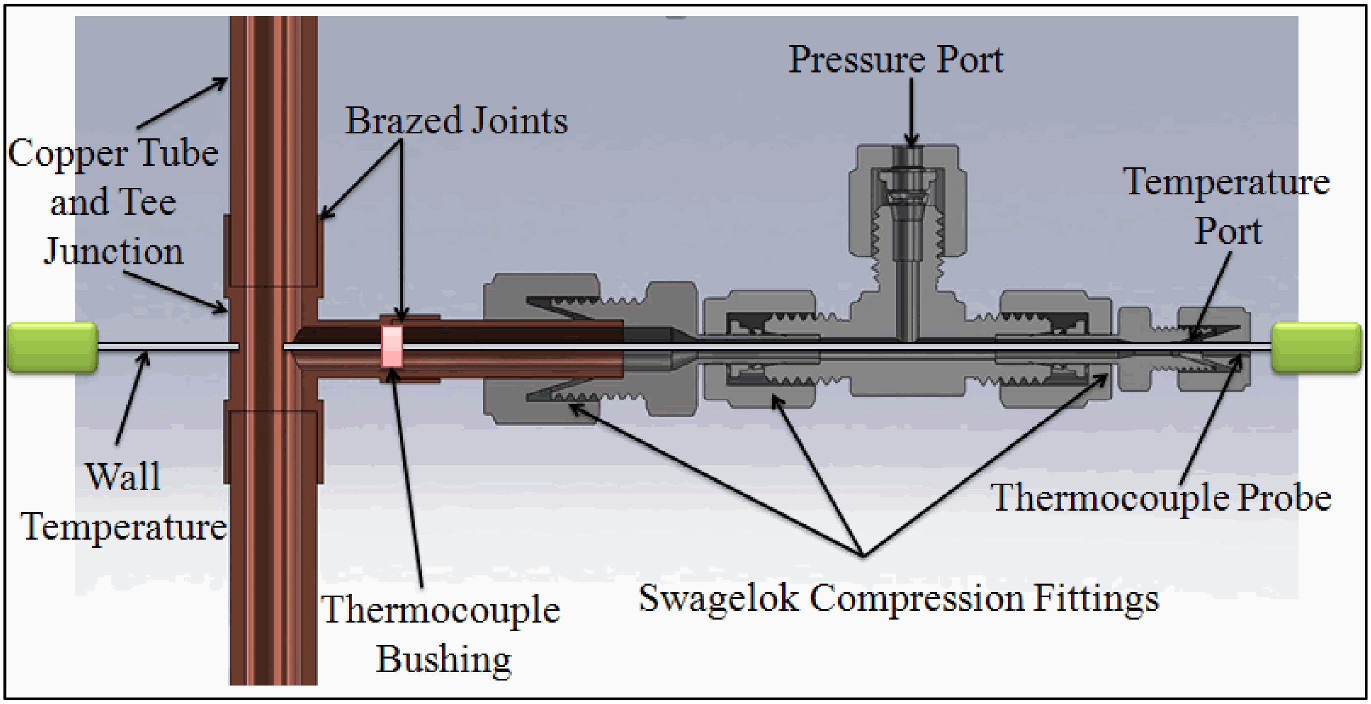


Figure 9: *Cross section view of tee junction with measurement ports.*

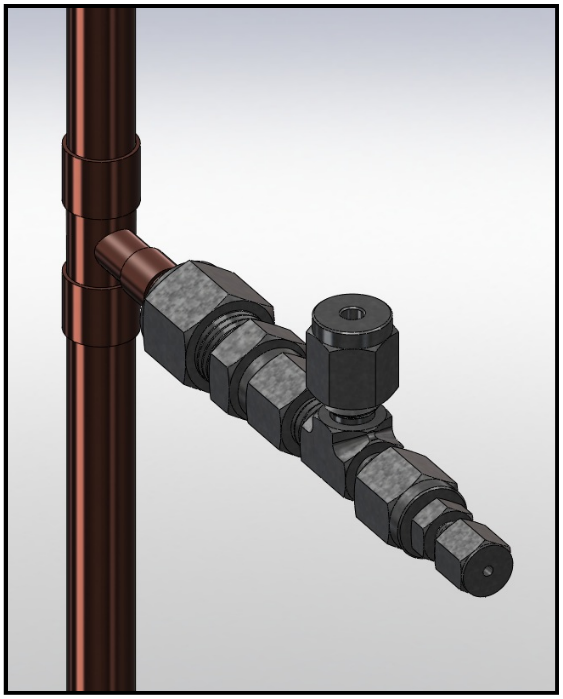


Figure 10: *Solid model render showing one of the eight ports.*

Figure 11: *Model showing three ports in line.*

Modular Tube Connectors:

As stated above, the flow tube will be broken up into sections by semi-modular brazed couplings. The purpose of this setup is to create a destructible flow tube where sections can be replaced easily and quickly. This way, decomposition of N_20 can be reached without the risk of losing expensive equipment. The sections will be modular tee fittings that will be brazed together. If an inside diameter discontinuity is seen during fabrication, several manufacturing techniques can be done to avoid skewed pressure readings in the flow tube. An inner diameter sleeve could be made to go inside the tee junction to give a smoother transition between the tubes. Or, the outside of the tubes can be lathed down till they fit the profile of the tee junction, that way the tubes can butt up against each other. In both cases, after the tubes have been brazed together, a hole will be drilled through the small tee junction into the flow tube for the measurement ports.

All the connections between the copper tee fitting and the copper tubes will be brazed together using Saftey-Silv 45, silver solder. The melting point of this solder is between 1225 and 1370 °F which is far above any temperatures seen during the Heat Tape Experiment. The

solidus temperature is 1225 °F which means below this temperature the solder is purely in its solid phase. The liquid temperature was also specified at 1370 °F. Above this temperature the solder is purely liquid.

Pressure Ports:

The pressure ports currently being used in the Engines lab at Cal Poly will be used on the final apparatus. Eight preexisting pressure ports are connected to a pressure transducer located on the wall. This pressure transducer is also connected to the DAQ system in the engines lab. 1/8" Swagelok compression fittings will be used to secure the pressure tap lines to the tee junction tube design. All of the pressure lines will be the same length to avoid any delay differences in the measurements. The ports provide static pressure and will need to withstand pressures up to 1,050 psi.

Thermocouples:

Eight, type K, grounded thermocouples will be positioned throughout the test tube to measure the fluid temperature. They will be designed around the preexisting thermocouple probes and thermocouple amplifiers to minimize costs. The *Inefficient Fin Thermocouple Probe* method will be implemented to avoid conduction from the wall effecting measurements. Using the inefficient fin theory a length, L, must be determined based on an accepted error of measurement (1% is preferred), thermocouple diameter (D), material conductivity (k), and convection coefficient, h. The base equation for this calculation is:

$$ln\frac{100}{\%\ error} = L\sqrt{\frac{4h_{He}}{k_{ss}D_{T.C.}}}$$

This method has been in practice for some time and was suggested by Cal Poly Professors; the NASA Tech brief can be found in Appendix B. The insertion length, L, was calculated for Helium with a range of flow rates from 0.01 – 0.1 lb/s flow rates, temperature ranges from 27-727 °C, and a percent error of 1% for ¼ and 3/8 inch inner diameter tubes, these results can be seen in Appendix C. The worst case scenario (largest insertion length) was for the lowest flow rates at the lowest temperatures. This value was L=0.30 inches for the ¼ inch tube and L = 0.43 inches for the 3/8 inch tube. For even better results a standard value of 0.5 inches will be used for the insertion length. This distance will be the length from the tip of the thermocouple probe to the thermocouple bushing. The thermocouple bushing is discussed

below. To prevent any leaks, the thermocouples will be connected to the system by using a Swagelok compression fitting on one of the ports in the tee junctions.

There will also be eight wall thermocouple thermocouples in the apparatus; each at the same vertical position as the fluid ports. The purpose of these measurements is to calculate the heat transfer from the walls to the fluid and to calculate the thermal energy stored in surrounding wall. These thermocouples will also be type K, grounded, 1/16 inch diameter, 6 inch probe length thermocouples. The method of attachment for these thermocouples was presented by Jim Gerhardt. First, a 20 thousands inch hole is drilled into the tube the same diameter as the thermocouple. Then the thermocouple is inserted into the slot. Finally, using a modified center punch, 3 or 4 holes will be punched around the perimeter of the thermocouple deforming the copper tube to pinch the thermocouple into place.

Thermocouple Bushing

The flow temperature thermocouples are prevented from violating the inefficient fin requirement by a component that supports them from touching the instrumentation pipe wall. The Permaxial (permeable in the axial direction) Thermocouple Bushing (PTB) was designed to do just that and can be seen in Figure 12 and in Appendix B with dimensions. The key features of the PTB are that it securely holds the thermocouple centered in the instrumentation pipe, and allows for fluid to transfer pressure information past it, hence the description Permaxial.

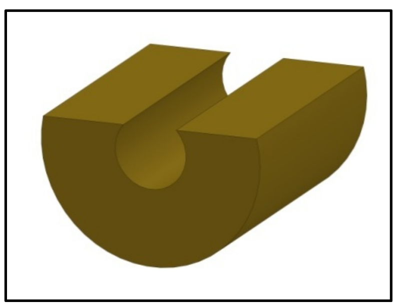


Figure 12: *Permaxial thermocouple bushing.*

Because of its size, the PTB had to be manufactured as simply as possible. Several designs were considered that had a circular form and material removed from within the outer perimeter of the part. It was deduced that a section of slightly more than a half circle would position itself concentrically in the instrumentation pipe, secure the thermocouple and be machined without the use of small tooling.

In assembly, the PTB will be attached to the thermocouple after it is threaded through the instrumentation fittings and before the fittings are attached to the pipe. The PTB can either

be crimped to the thermocouple with a pair of pliers, or can be secured by deforming the top face around the thermocouple with a center punch.

Prototypes of the PTB have been fabricated, and with the use of a lathe and a mill, one person could make a set of 8 in one day. It is estimated that two people with 2 lathes could make four sets in a day based on the time spent tooling vs. the time spent machining. The initial prototypes were machined at Mustang 60 out of 2” slugs of 3/8” aluminum rod.

Frame:

A frame will be constructed to hold the experiment in the vertical position while testing. The purpose of vertically mounting the flow tube is to eliminate gravitational effects on the fluid which affect the heat transfer characteristics of a two phase fluid. The instrumentation ports will extend out of the experiment a significant length and could be easily damaged. This frame will serve as a protective cage for the experiment in case it is accidentally bumped into.

The current frame will be made out of 80/20 speed rail. This type of material is easy to design frames for experiments and incorporate mounts for attaching the tube. There is currently more than enough 80/20 speed rail around campus to build the frame, this helps cut back on costs, and provides easy disposal of the apparatus when the sponsors are done with the testing. The frame design features two casters mounted at the bottom that will allow for mobility when the frame is tilted. It is important to be able to move the experiment because it will be used in a small space that will also be used for other experiments.

The experiment will be mounted inside the frame with three or more U-bolts. Because clamping the experiment to the frame with U-bolt alone will cause the insulation to be compressed, strops will be used to disperse the clamping force over a larger area of insulation. The experiment will be mounted off the ground high enough for the supply line to be attached. It is under investigation whether or not a pressure event due to decomposition of nitrous oxide would cause

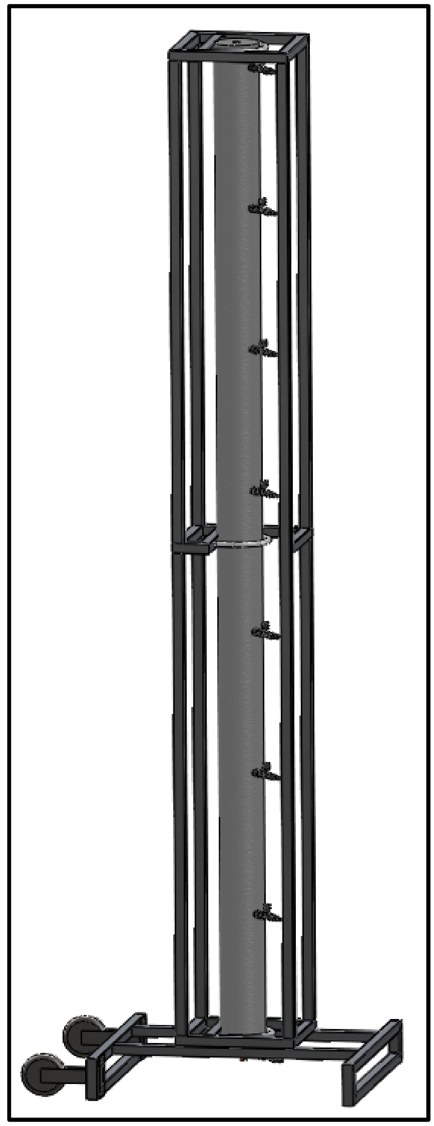


Figure 13: *Apparatus frame is designed to be mobile and nonconductive to heat.*

significant damage to the engines room. The concern is that instrumentation ports could be blown off. If determined that the frame should also serve as a blast shield, aluminum plating will be bolted or riveted to the outside of the frame. See Figure 13 for a solid model render of the frame and Table 8 for a cost breakdown.

Table 8: *Cost break down for frame materials comes out to about $20 plus hardware.*

Function	Part	Supplier	PN	Quantity	Unit Cost	Sub Total
Main Frame	80/20 Speed Rail	Cal Poly	N/A	N/A	N/A	N/A
Mobility	Rigid 3" caster	McMaster	2406T29	2	$6.96	$13.92
Mounting	3" U bolts	McMaster	3201T24	3	$1.88	$5.64

Proof of Concept

Heat Tape Experiment

Note: Detailed procedure and analysis is in Appendix A

- Purpose:
  1) Quantifiably determine the ideal heat tape setup for RF Testing's intended setup. The changing variable of each setup is the heat tape coil spacing. In all setups insulation was used.
  2) Determine the efficiency (η_{sys}) of system's ability to transfer heat to the test fluid (Q_{out}) from the heat source (Q_{in}).
  3) Find a max heat tape surface temperature.
  4) Determine the mode of failure and relate this to max operating temperature with ideal setup.
- Layout:

  The heat tape was wrapped around a ¼" copper flow tube with various setups. As stated above, the changing variable of each setup is heat tape coil spacing. Constant water flow was provided via a water tank which was maintained at a prescribed water level. This mass flow rate was documented using a scale and stopwatch method. A temperature gradient was avoided by maintaining turbulent flow. See Appendix D for a calculation confirming that turbulent flow was achieved. Once steady state was reached, inlet and outlet test fluid

temperatures were recorded with thermocouples, which were placed in the flow. Data was collected using Dr. Lemieux's "Squirrel Data Logger" DAQ system.

- Results:

  Three setups were considered, A, B and C. Setup A uses ¼" coil spacing, setup B uses butted spacing and setup C uses a two layer overlap. Max efficiency of 95% was observed with the setup A. Max heat input per foot of flow tube is 424 W/ft which was achieved with setup C. It should be noted that the cases in Table 4 with over 100% efficiency are a result of a low power input which caused the water to be colder than the ambient temperature. These cases, therefore, represent heat pulled from the environment into the water.

Table 4: *Heat tape experiment results showing heat pulled by the water per foot of flow tube.*

Setup	Power In (W)	Heat Out (W)	Efficiency (%)	Heat Tape Wrap Length (m)	Power per meter of Flow Tube (W/m)	Power per Foot of Flow Tube (W/ft.)
1/4" Spacing	32	26	81	0.559	47	14
	135	127	94	0.559	227	69
	292	276	95	0.559	494	150
Butted	33	38	113	0.381	99	30
	132	124	94	0.381	324	99
	290	267	92	0.381	699	213
Overlapped Twice	33	34	102	0.178	191	58
	128	109	86	0.178	616	188
	282	248	88	0.178	1392	424

Losses were tracked using two methods. Method 1 is based on the conduction losses through the insulation. Method 2 is based on the convection losses to the surrounding air. In addition, the convection losses through the top and bottom portions of the tube, Q_{u12} and Q_{u34}, were tracked. These were added to both methods to find total power lost from the flow tube based on conduction and convection and are summarized in Table 5.

Table 5: *Losses tracked in the heat tape experiment.*

Setup	Power In (W)	Heat Out (W)	Total Heat Loss Cond. (W)	Total Heat Loss Conv. (W)	Efficiency (%)
1/4" Spacing	32	26	-0.4	-0.1	81
	135	127	0.2	0.2	94
	292	276	1.1	1.4	95
Butted	33	38	-0.4	0.0	113*
	132	124	0.4	0.3	94
	290	267	1.6	1.4	92
Overlapped Twice	33	34	-0.3	0.3	102*
	128	109	0.4	0.9	86
	282	248	0.8	10.8	88

The losses from setup C, however, were not found to be similar when set at max power. The reason for this is most likely because of thermocouple placement. As seen in Figure 3, if close heat tape spacing is used less of the loss-tracking thermocouples are covered by the heat tape. In this setup, only one thermocouple that was tracking losses was covered by the heat tape while the other three were not. Using one thermocouple as described does not account for the losses related to the temperature gradient around the heat tape and is the reason for the loss discrepancy in setup C at full power.

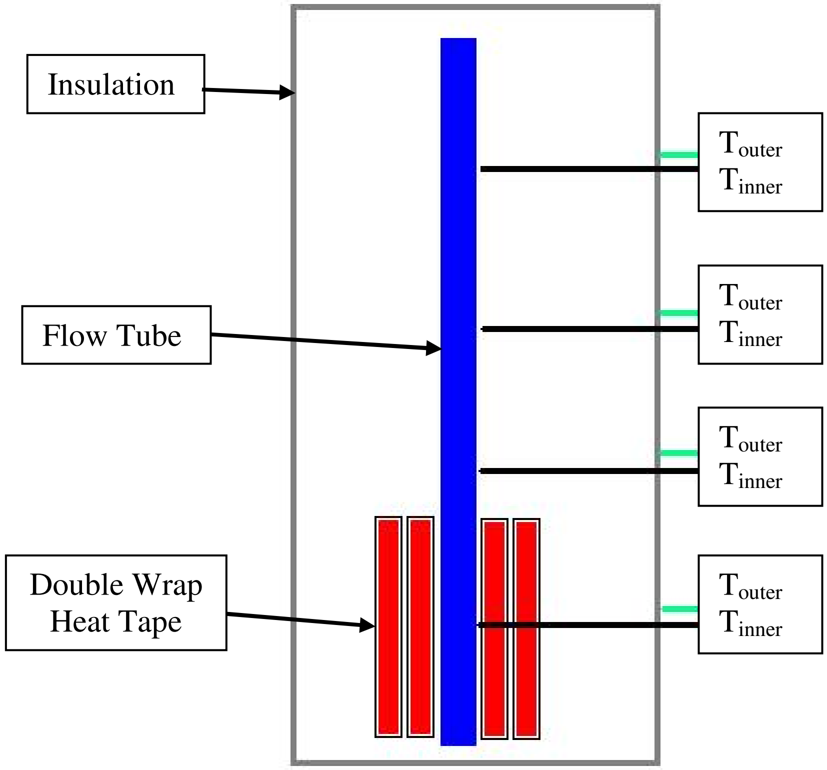


Figure 3: *Loss thermocouple placement illustrated with heat tape in a two layer wrap.*

After running the heat tape experiment the required flow tube length was determined to be 42.8 feet. This calculation is based on the conservative power requirement of 18.14 KW previously discussed and a running flow rate of 0.1 lb/sec and can be seen in Appendix C.

The conclusion of the heat tape experiment shows that a new heat source is needed. A heat source that can supply more power per foot is aggressively being searched for. The heat tape experiment will be used with the new heat source to verify and characterize its performance.

N2O Mass Flow Rate and Flow Tube Dimension Analysis:

Project Cost:

The Heat Tape Experiment cost was predicted to be $141.86. The highest costing component is the heat tape, shown in Table 9.

Table 9: *Heat Tape Experiment Cost.*

Part	Supplier	Details	Cost/Unit	# Parts	Total Cost
Copper Tube	McMaster	¼" Tube with 3/8" OD, 3ft long	$14.52	1	$14.52
Copper Tube	McMaster	1/8" Tube with 1/4" OD, 3ft long	$5.29	1	$5.29
Heating Element	McMaster	High-Temp Fiberglass Ins. 1400°F, 4ft long	$44.95	1	$44.95
Insulation	McMaster	1"x24"x96"	$14.10	1	$14.10
Compression Fittings	McMaster	1/4" tube to 1/16" tube	$6.50	2	$13.00
Miscellaneous	Home Depot	Bucket, Transfer Tubes, etc.	N/A	N/A	Estimated $50

Project cost is predicted to be $3,588. This assumes the flow meter will cost $3,000, which could vary depending on the final decision for a flow meter. As seen in Table 10, other costs are much lower than the cost of the flow meter. Also, the pressure ports consist of many cheaper parts but the cost of the ports adds up quick since eight ports are required.

Table 10*: Cost breakdown of final apparatus.*

Part	Supplier	Details	Cost/Unit	# Parts	Total Cost
Heat Tape	TBD	TBD	TBD	TBD	TBD
Insulation	McMaster	1"x24"x96"	$14.10	2	$28.20
Copper Tube	Aircraft Spruce	5/16" O.D. 0.32"	$2.75/ft	10ft	$27.50

		wall			
Measuring Ports	McMaster	Pipe Compression Fittings	$56.13	8	$449.00
Test Stand	Custom built by RF Testing	Materials from McMaster	$83.00	1	$83.00
Flow Meter	TBD	Coriolis	TBD	TBD	Estimated $3000

Management plan Josef, just read it and update it a little, change word tense of things

RF Testing's management plan is centered on dividing tasks and subsystem designs between the three members. Each subsystem is headed by a single person while the others will assist this "subsystem manager."

James, DAQ Systems Manager/Complex Fluid Analysis Leader: Responsibilities include setting up the Data Acquisition System. This DAQ system must be able to record results in a timely, accurate and orderly manner that is easy to interpret. James will have final say in any software and programming that will be done on this project. In addition to managing the DAQ system, James will be leading the computational fluid analysis by researching related fluid regimes and methods on analyzing the fluid characteristics.

Owen, Fluids Systems Manager: Responsibilities include proper thermocouple, pressure transducer and flow meter design. In order to find the appropriate flow meter that will meet the specifications, Owen will do background research on different flow meter companies to find adequate meters. Once several flow meters have been selected Owen will call these companies to find out more information including but not limited to; connection types, pressure drops, accuracy, price, and availability for the selected flow meters.

Josef, Heat Transfer System Manager and Manufacturing Manager: Responsibilities include managing the heat tape experiment and to ensuring proper steps are taken to size heating element thereafter. Manufacturing of custom built parts will be group collaboration but Josef will be in charge of organizing related requirements and deadlines. All custom parts

should be identified as such so they can be designed first and sent off to manufacture as soon as possible. Deadlines will be given to set parts.

References

1)http://www.grievecorp.com/catalog/Furnaces/High-Temperature-Heavy-Duty-Box-Furnaces/High-Temperature-Heavy-Duty-Box-Furnaces.html

2) http://www.engineeringtoolbox.com

3) http://www.neon-john.com/Induction/Roy/Roy.htm

4) "Rayleigh Flow of Two-Phase Nitrous Oxide as a Hybrid Rocket Nozzle Coolant" by Lauren May Nelson

5) Boiling heat transfer in Vertical Tube with Freon 114 by Fagerhol, Ghazanfari, Kivioja

6) Kinetics of Decomposition of Nitrous Oxide by Kalback,Sllepcevich

Appendices:

Appendix A- *Heat Tape Experiment Details and Procedure*

Appendix B- *Design Drawings*

Appendix C- *Calculations*

Appendix D- *EES File for N2O Mass Flow Rate*

Appendix E- *Gant Chart*

Appendix A- Heat Tape Calibration Experiment

Object

The object of this experiment is to characterize the performance and failure of a heat source. The heat source, known as “Extreme-Temperature Heat Tape” from McMaster Carr, is specified by the supplier with temperature and setup limitations which may not applicable to RF Testing’s intended set-up. The supplier’s specified limits are based on a heat source wrapped around stagnate fluid with no outer insulation. RF testing’s setup will introduce inside tube flow and outside insulation wrap, thus requiring new limits of performance (max temperature) to be found.

The efficiency of RF testing’s setup will be determined based on theoretical electrical heat input supplied by vendor and the actual measured heat input. In addition, different heat tape wraps, such as overlapping and butting, will be tested for heat tape failure. The temperature of failure will also be determined for the various set-ups.

Introduction

The actual heat input will be based an energy balance equation where mass flow rate is assumed constant. Inlet and outlet temperatures will be found for various heat settings. Insulation temperatures will also be recording in order to verify that the temperature limits of the specified insulation are not exceeded and to track heat losses.

Experiment

Equipment (see Figure A.1)

- Two 5 gallon buckets
- Flow tube- 1/4" I.D. , 5/16 O.D. by 3 feet long (2 foot test section)
- Heat tape element- 0.5" W x 0.125" T by 4 feet long @ 78 Watts/ft
- Variable voltage controller
- Amp and volt meters
- Fiberglass insulation- 1.0” thick x 24” wide x 8’ long (Use two wraps).
- Mass scale with hook
- Stopwatch
- Flow valve
- 80/20 aluminum frame with tank

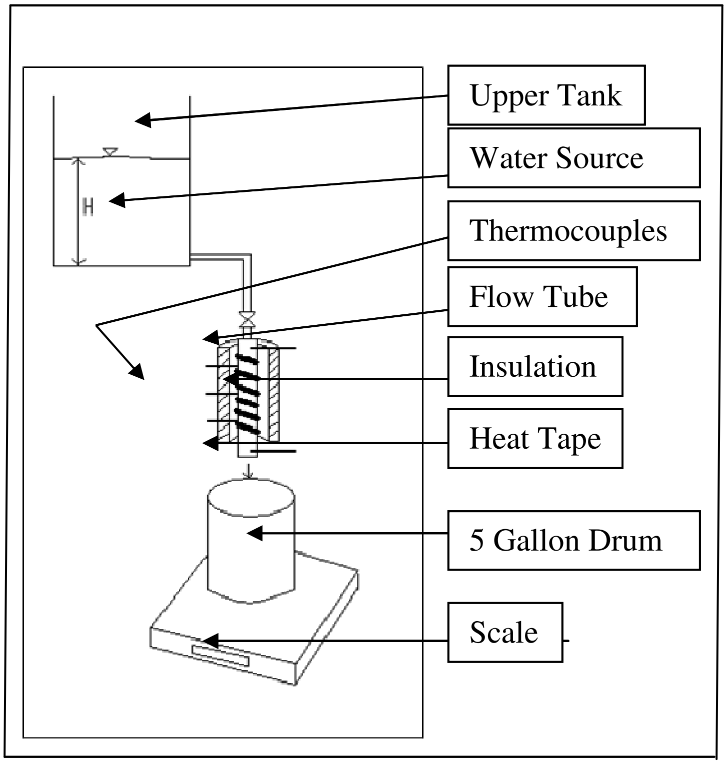


***Figure A.1:** Heat tape experiment equipment.*

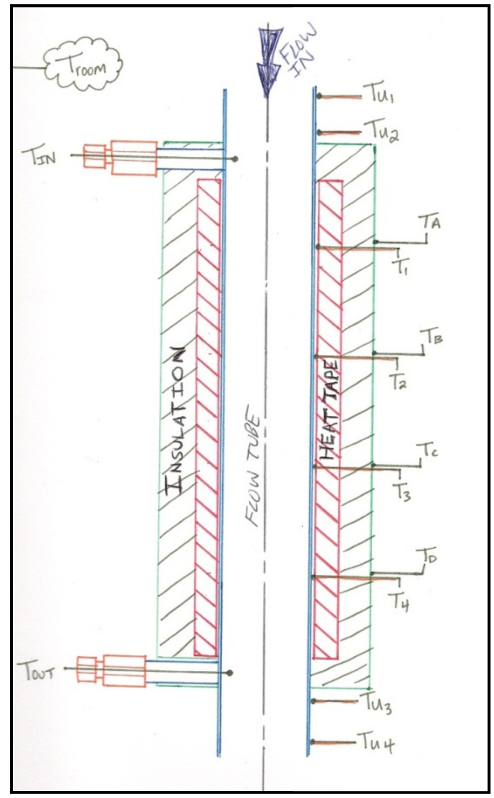


***Figure A.2**- Thermocouple Layout*

Equations used for Analysis

Heat loss based on conduction: *Eq. 1*

Heat loss based on convection: *Eq. 2*

Where h is found based on Eq. 3, 4 & 5:

Eq. 3

Ra is found to be less than 10^9, therefore laminar and Equation 4 is used for Nu:

$$\overline{Nu}_L = 0.68 + \frac{0.670(Ra_L)^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}} \qquad Eq.\ 4$$

$$\bar{h} = \frac{\overline{Nu}_L\, k}{L} \qquad Eq.\ 5$$

Heat input to system:

$$Q_{in} = IV \qquad Eq.\ 6$$

Heat absorbed by water:

$$Q_{out} = \dot{m} C_P (T_{out} - T_{in}) \qquad Eq.\ 7$$

Experimental Procedures

Procedure Overview

Various heat tape setups will initially be tested, from which an "ideal set-up" will be determined. The ideal set-up will be based on maximum heat input, Q_{exp}, minimum heat loss, Q_{loss}, and a non-failing mode of heat tape wrap. The various setups will test coil spacing of the heating tape and the use of insulation.

Procedure to find mass flow rate

1. Fill top tank ¾ full to pre-marked black line (Figure A.3). Open flow valve, simultaneously start the stopwatch and have assistant add water to maintain water level in the top bucket at the black line. Be sure to maintain this water height throughout entire experiment.

2. When the lower bucket is almost at capacity, switch it with the other empty bucket. Stop the stopwatch at the moment when water stops entering the first bucket. Measure the first bucket's mass and determine mass flow rate.

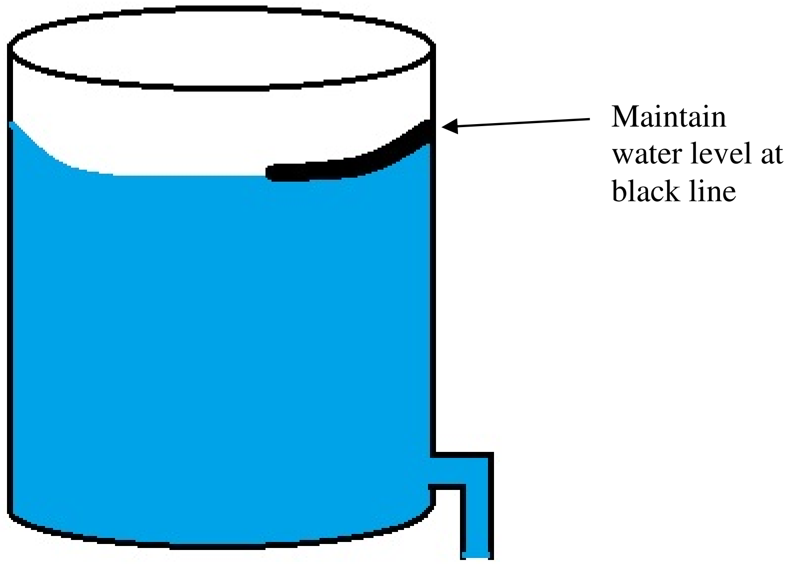


Figure A.3*- Top bucket fill line.*

Procedure to find Ideal Setup

NOTE: For the following setups, preheat heat tape at each voltage setting until T_2 reaches steady state, open flow valve and maintain water flow as described in the procedure to measure mass flow rate.

Setup A- ¼" coil spacing

1. Setup heat tape with ¼" coil spacing. Wrap with insulation. Record heat tape wrap length.

2. Open Flow valve and set variable voltage controller to 40 VAC. Wait for T_2 to reach steady state. Once steady state is achieved record all thermocouple's readings for 15 seconds. In analysis take the average reading over the 15 second period.

3. Repeat step 2 with different heat tape voltage settings while maintaining water level at black line. Set voltage controller to 80 and 120 VAC and record the corresponding steady state temperatures for each voltage setting.

Setup B- Butted Wrap

1. Setup experiment with heat tape edges butted up against each other. Wrap with insulation. Record heat tape wrap length.

2. Open Flow valve and set variable voltage controller to 40 VAC. Wait for T_2 to reach steady state. Once steady state is achieved record all thermocouple's readings for 15 seconds. In analysis take the average reading over the 15 second period.

3. Repeat step 2 with different heat tape voltage settings while maintaining water level at black line. Set voltage controller to 80 and 120 VAC and record the corresponding steady state temperatures for each voltage setting.

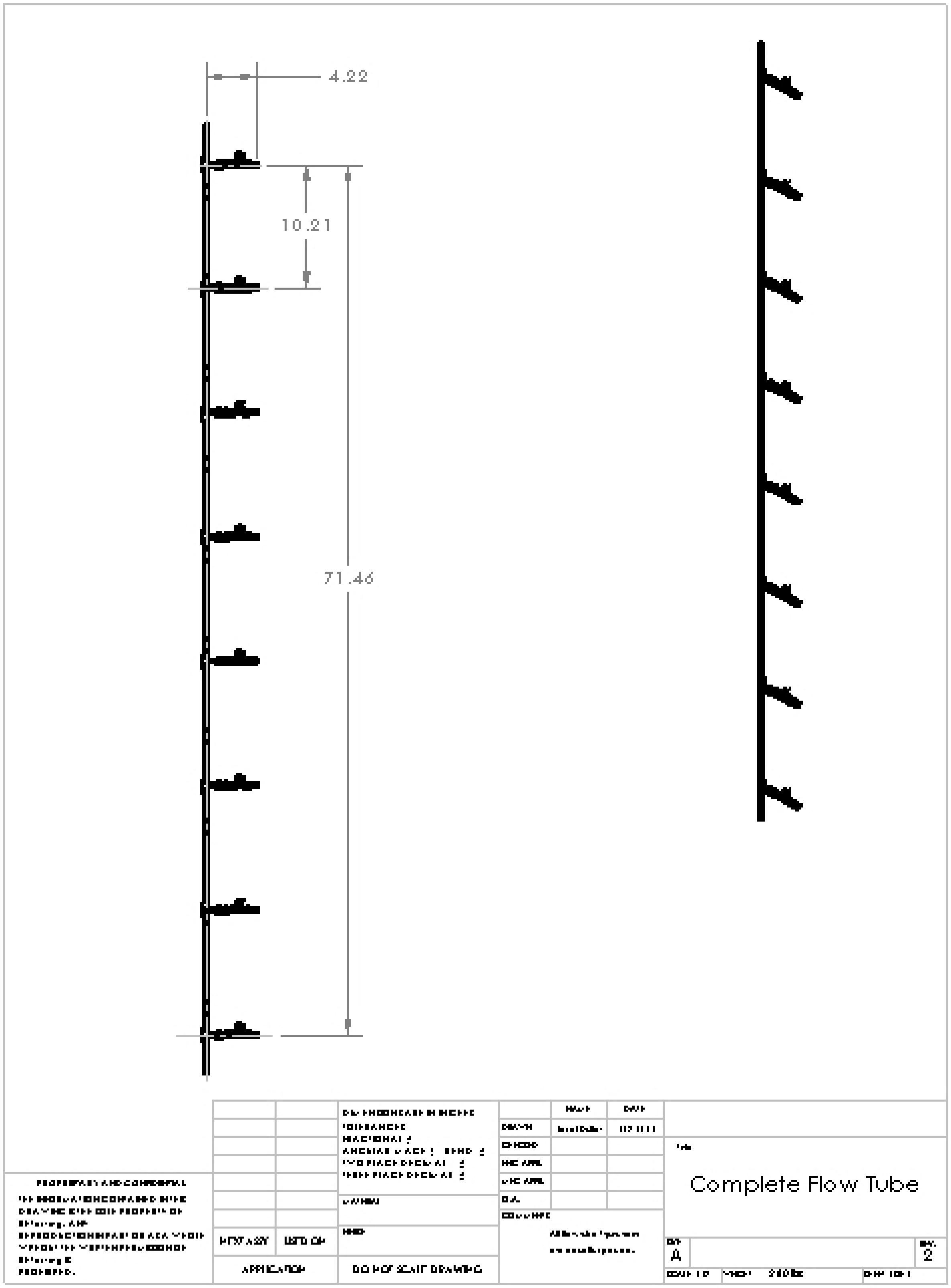
Setup C- Butted Wrap

1. Setup experiment with heat tape edges butted up against each other and wrap with insulation. Record heat tape wrap length

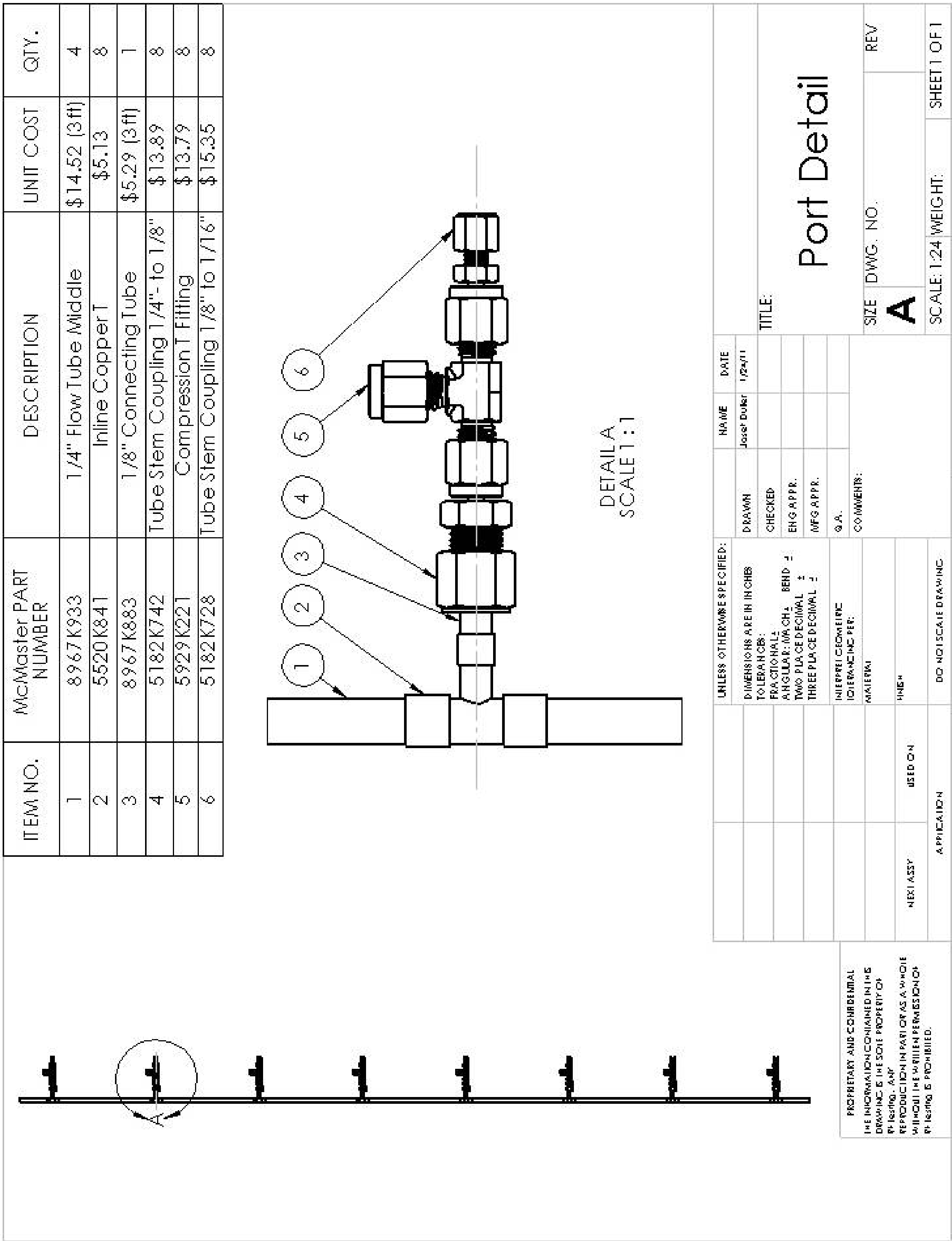
2. Open Flow valve and set variable voltage controller to 40 VAC. Wait for T_2 to reach steady state. Once steady state is achieved record all thermocouple's readings for 15 seconds. In analysis take the average reading over the 15 second period.

3. Repeat step 2 with different heat tape voltage settings while maintaining water level at black line. Set voltage controller to 20, 40, 60, and 80 VAC and record the corresponding steady state temperatures for each voltage setting.

Complete Flow tube

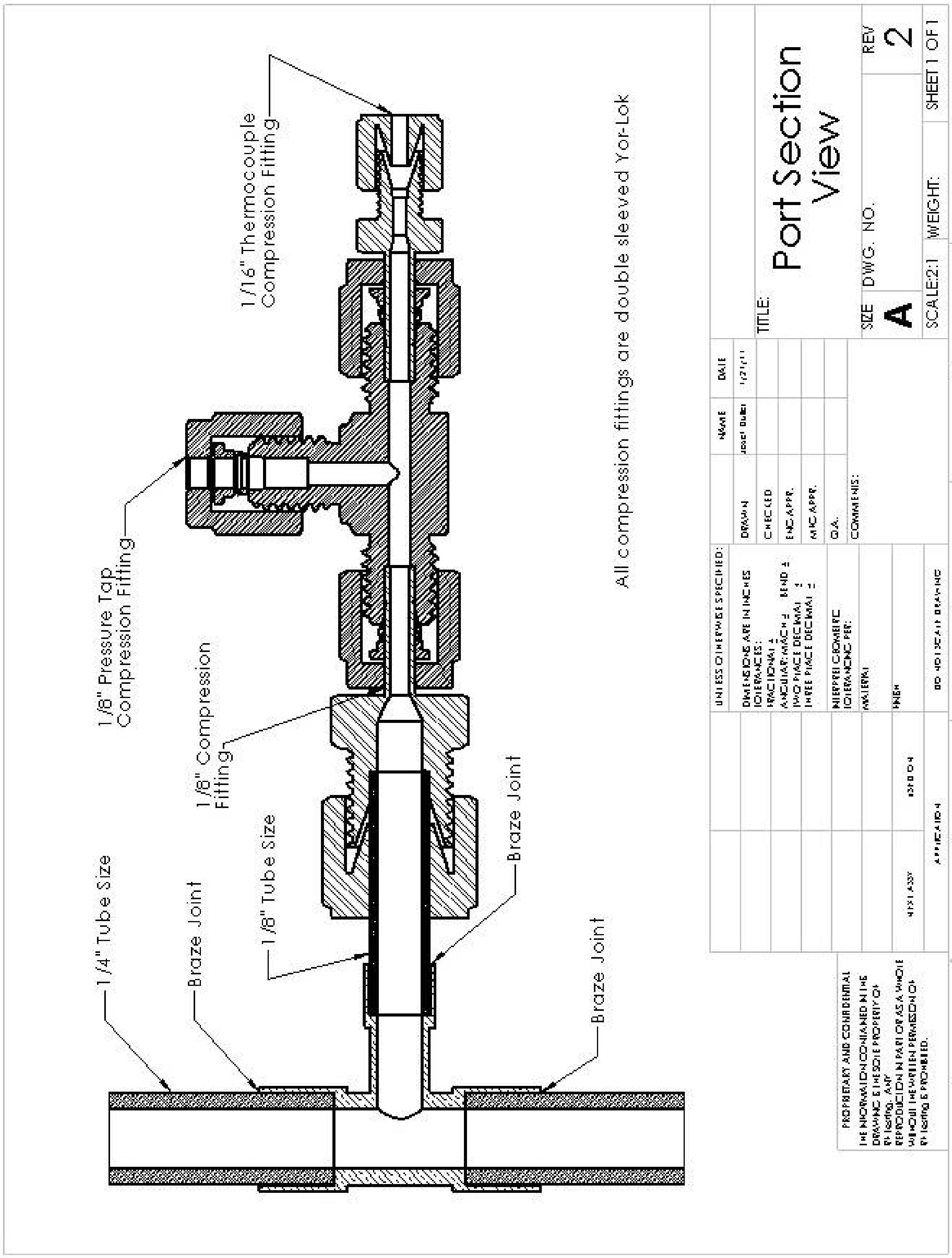


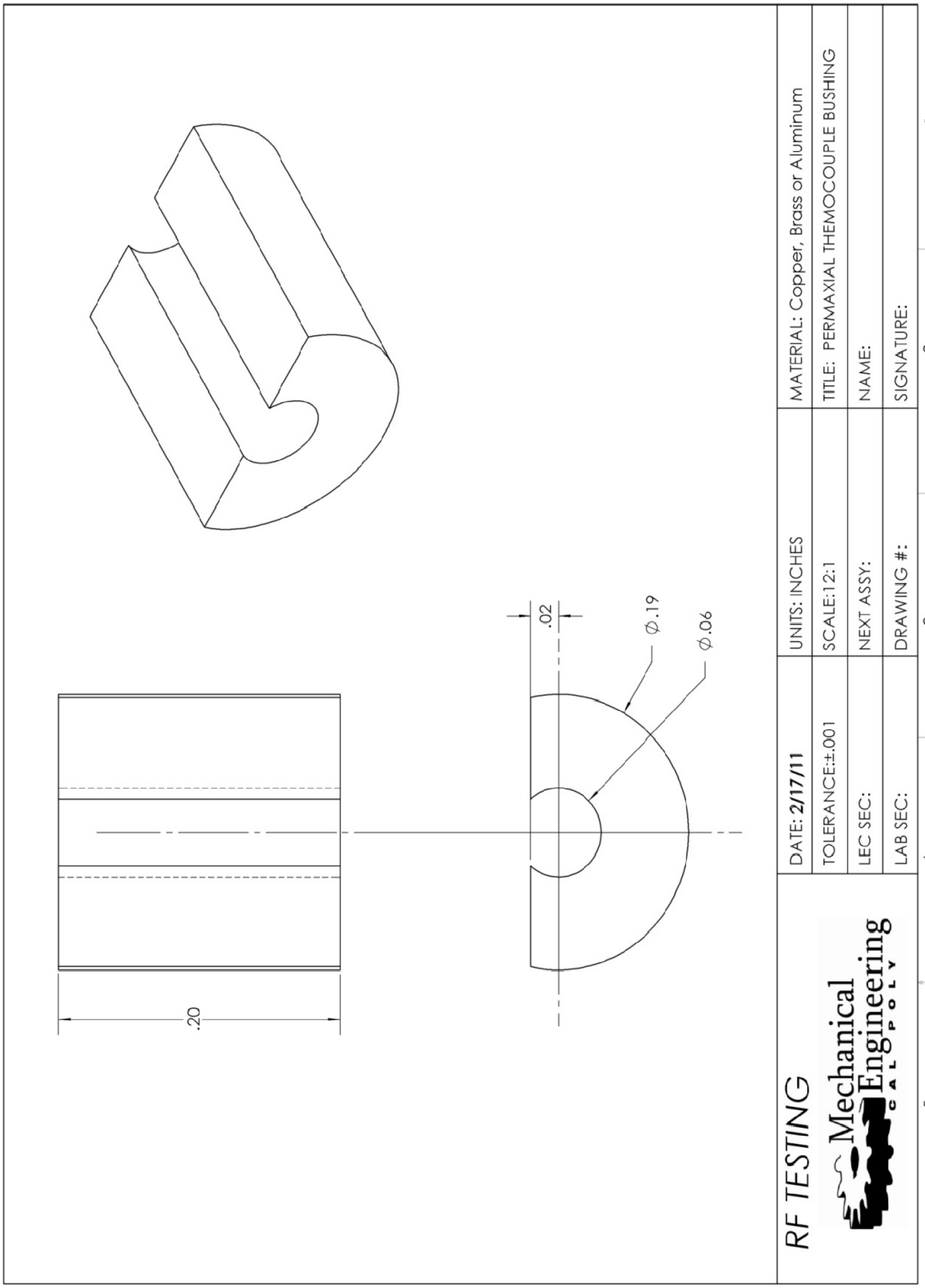
Measuring port bill of materials for eight ports.



ITEM NO.	McMaster PART NUMBER	DESCRIPTION	UNIT COST	QTY.
1	8967K933	1/4" Flow Tube Middle	$14.52 (3 ft)	4
2	5520K841	Inline Copper T	$5.13	8
3	8967K883	1/8" Connecting Tube	$5.29 (3 ft)	1
4	5182K742	Tube Stem Coupling 1/4"- to 1/8"	$13.89	8
5	5929K221	Compression T Fitting	$13.79	8
6	5182K728	Tube Stem Coupling 1/8" to 1/16"	$15.35	8

Section view of port connections showing tube sizes.





RF TESTING
Mechanical Engineering CAL POLY
DATE: 2/17/11
TOLERANCE:±.001
LEC SEC:
LAB SEC:
UNITS: INCHES
SCALE:12:1
NEXT ASSY:
DRAWING #:
MATERIAL: Copper, Brass or Aluminum
TITLE: PERMAXIAL THEMOCOUPLE BUSHING
NAME:
SIGNATURE:
.20
.02
Ø.19
Ø.06

Appendix C- Hand Calculations & Excel Spread Sheets

C.1) **Initial Power Calculations: Note this section is subject to change.**

Q_{sys}, POWER ESTIMATES – Δh & pressures taken from N_2O P-h diagram.
TWO CASES CONSIDERED: LOW & HIGH PRESSURE:

LOW PRESSURE: @ P = 1000 kPa
& Δh = 400 kJ/kg
$\dot{m}$ = 0.1 lb/sec
= 0.04536 kg/sec

$Q_{sys} = \dot{m}\,\Delta h$
$= (0.04536 \frac{kg}{sec})(400 \frac{kJ}{kg})$

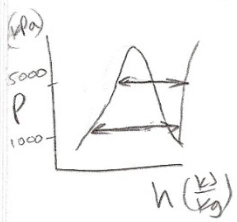
Q_{sys} = 18.14 kW

HIGH PRESSURE: @ P = 5000 kPa
& Δh = 400 kJ/kg
$\dot{m}$ = 0.1 lb/sec
= 0.04536 kg/sec

$Q_{sys} = \dot{m}\,\Delta h$
$= (0.04536 \frac{kg}{sec})(250 \frac{kJ}{kg})$

Q_{sys} = 11.34 kW

CONCLUSION: Using the low pressure route will ~~increase~~ widen test range of N_2O but require a large amount of energy. Using the high pressure route will decrease the range of measurement but decrease the power requirement by 37%.



WITH TWO LAYER WRAP
424 W/ft achieved

$\Rightarrow L_{TUBE} = \frac{18.14\ kW}{424\ W/ft} \left(\frac{1000\ W}{1\ kW}\right)$

L_{TUBE} = 42.8 ft

424 W/ft

$L_{TUBE} = \frac{11.34\ kW}{424\ W/ft}$

L_{TUBE} = 26.7 ft

⇒ BOTH LENGTHS NOT REASONABLE.

C.2) Turbulent Flow Verification

Reynolds number based on experimental flow rate:

$$Re = \frac{4\dot{m}}{\pi D \mu}$$

$$Re = \frac{4\left(0.1218\frac{lb}{s}\right)\left(\frac{1s^2}{32.2ft}\right)}{\pi(0.245in)(\frac{1ft}{12in})(2.344x10^{-5}\frac{lb\cdot s}{ft^2})}$$

$$Re = 10{,}063 > 4{,}000$$

Because an Re # of 4000 or greater determines fully developed turbulent flow and the flow investigated here has an Re # of 10,000 it is fully developed turbulent flow.

C.3) Inefficient Fin Insertion Length

Inefficient Fin Insertion Length equations. For different Reynolds numbers there are different equations to use for the friction factor and for the Nusselt number.

2/11/11

Inefficient Fin Length again (Helium)

$$\ln\left(\frac{100}{\%\,error}\right) = L \cdot \sqrt{4h/kD}$$

$$\Rightarrow L = \frac{\ln(100/\%\,error)}{\sqrt{4h/kD}}$$

$$Re = \frac{VD}{\nu} \quad \text{or} \quad = \frac{4\dot{m}}{\pi D \mu}$$

D = 1/16" (.0015875 m)
= 1/32" (0.00079375 m)

$K_{ss} = 15\ \frac{W}{m\cdot K}$

% error

h_{He}

$\dot{m} = 0.01\ lb/s = 0.0045361\ kg/s$

K_{He}

Turbulent, fully developed

$f = 0.316\, Re_D^{-1/4}$ for $Re_D \le 2\times10^4$
$f = 0.184\, Re_D^{-1/5}$ for $Re_D \ge 2\times10^4$ } check Moody $\frac{\varepsilon}{D}$ = .245

$Nu_D = 0.023\, Re_D^{4/5} Pr^n$ ($n = 0.4$ for $T_s > T_m$) & for $Re_D \ge 10{,}000$; $0.6 \le Pr \le 16{,}700$

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$ for $3{,}000 \le Re_D \le 5\times10^6$, $0.5 \le Pr \le 2000$

$Nu = \frac{h_{He} D}{K_{He}} \Rightarrow h_{He} = \frac{Nu \cdot K_{He}}{D}$ $\left(\frac{W/m\cdot K}{m}\right) \Rightarrow \left(\frac{W}{K}\right)$

We want worst case so biggest L:

∴ 1% error, smallest h ⇒ smallest Nu ⇒ smallest Re & Pr

. Pr pretty constant so $Re \downarrow$, ⇒ smallest $\dot{m}$ (0.01 lb/s) & biggest μ,

biggest μ @ high temp (1000 K)

Moody Diagram

drawn copper $e = 5\times10^{-6}$ ft   3.28 - 6.7... ft

$\frac{e}{D} = \frac{5\times10^{-6} ft\left(\frac{3.28}{ft}\right)}{0.245\ m} = 244.9\times10^{-6}$
$= 2.45\times10^{-4}$

$\frac{e}{D} = 0.000245$

$Re = 26000 = 26\times10^{3}$

$\Rightarrow f = 2.5\times10^{-2}$

Insertion lengths for fluid thermocouple using the "Inefficient Fin" method from above. This calculation was done for helium at 700 K (427°C) and for a ¼" ID tube.

Sample Calc, Helium @T=700K

$\mu_{He} = 350\times10^{-7}$
$Pr = 0.654$
$K_{He} = .278$
$K_{ss} = 15 \frac{W}{mK}$
$D_{tube} = 0.25 in$
$D_{T.C.} = 1/16"$
% error = 1%

$$Re = \frac{4\dot{m}}{\pi D_T \mu} = \frac{4\left(0.01\frac{lbm}{s}\right)\left(\frac{0.4536 kg}{1 lb}\right)}{\pi\left(0.25 in\right)\left(\frac{0.0254 m}{1 in}\right)\left(350\times10^{-7}\frac{N\cdot s}{m^2}\right)\left(\frac{1 kg\cdot m/s^2}{1 N}\right)}$$

$$Re = 25,986.1$$

$$\therefore\ f = 0.184\, Re_D^{-1/5}$$

$$f = 0.02409 \qquad 2.409\times10^{-7}$$

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

$$Nu_D = \frac{\left(\frac{0.02409}{8}\right)(25,986.1 - 1000)(0.654)}{1 + 12.7\left(\frac{f}{8}\right)^{1/2}(.654^{2/3} - 1)}$$

$$Nu_D = 59.4$$

$$Nu = \frac{h_{He} D_{tube}}{K_{He}} \Rightarrow h = \frac{Nu\, D_{tube}}{K} = \frac{Nu\, K_{He}}{D_{tube}}$$

$$h_{He} = \frac{(59.4)(0.25 in)\left(\frac{0.0254 m}{1 in}\right)}{278,000 \frac{W}{mK}} = \frac{(59.4)\left(0.278 \frac{W}{mK}\right)}{(0.25 in)\left(\frac{0.0254 m}{1 in}\right)}$$

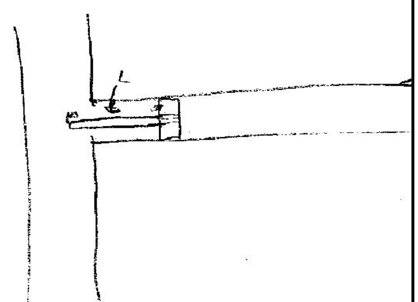
$$h_{He} = 2600.5 \frac{W}{m^2K}$$

$$L = \frac{\ln(100/\%\ error)}{\sqrt{4 h_{He}/K_{ss} D_{T.C.}}}$$

$$L = \frac{\ln(100/1)}{\sqrt{\frac{4\left(2600.5 \frac{W}{m^2K}\right)}{\left(15\frac{W}{mK}\right)\left(\frac{1}{16}in\right)\left(\frac{0.0254 m}{1 in}\right)}}}$$

$$L = 0.006968 m \left(\frac{1 in}{0.0254 m}\right)$$

$$L = 0.274 in$$



Constants for Inefficient Fin Calculations		
Tube Diameter (in)	mass flow rate (lbs/s)	mass flow rate (kg/s)
0.25 in 0.375 in	0.01 0.02	0.004536 0.009072
T.C. Diameter	0.03	0.013608
0.0625 in 0.03125 in	0.04 0.05	0.018144 0.02268
K_{ss} (W/m-K) @	0.06	0.027216
300K	0.07	0.031752
15 W/m-K	0.08	0.036288
% Error	0.09	0.040824
1 %	0.1	0.04536

The following tables are for 1% error for different flow rates and different temperature ranges. The worst case scenarios are highlighted in yellow for the ¼" and 3/8" inner diameter tubes.

1% Error, Mass Flow Rate of 0.01 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	4.573E+04	0.02152	96.2	2302	0.00741	0.3023
77	4.118E+04	0.02197	88.2	2361	0.00731	0.2985
127	3.745E+04	0.02239	81.5	2400	0.00725	0.2961
177	3.460E+04	0.02275	76.2	2448	0.00718	0.2931
227	3.215E+04	0.02309	71.6	2480	0.00714	0.2912
277	3.018E+04	0.02338	67.7	2515	0.00709	0.2892
327	2.844E+04	0.02366	64.4	2554	0.00703	0.2870
377	2.741E+04	0.02384	62.3	2589	0.00698	0.2851
427	2.600E+04	0.02409	59.4	2602	0.00697	0.2843
477	2.500E+04	0.02428	57.6	2638	0.00692	0.2824
527	2.382E+04	0.02451	55.3	2649	0.00690	0.2818
627	2.198E+04	0.02491	51.8	2691	0.00685	0.2796
727	2.040E+04	0.02529	48.7	2714	0.00682	0.2784

1% Error and Mass Flow Rate of 0.03 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	1.372E+05	0.01727	230.8	5525	0.00478	0.1951
77	1.235E+05	0.01764	211.9	5673	0.00472	0.1925
127	1.123E+05	0.01798	196.1	5775	0.00468	0.1908
177	1.038E+05	0.01826	183.6	5897	0.00463	0.1889
227	9.646E+04	0.01853	172.6	5980	0.00459	0.1875
277	9.054E+04	0.01877	163.3	6070	0.00456	0.1861
327	8.531E+04	0.01899	155.5	6172	0.00452	0.1846
377	8.223E+04	0.01913	150.5	6259	0.00449	0.1833
427	7.800E+04	0.01934	143.9	6299	0.00448	0.1827
477	7.500E+04	0.01949	139.5	6391	0.00444	0.1814
527	7.146E+04	0.01968	134.2	6425	0.00443	0.1809
627	6.594E+04	0.02000	125.9	6541	0.00439	0.1793
727	6.121E+04	0.02030	118.6	6613	0.00437	0.1783

1% Error and Mass Flow Rate of 0.05 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	2.286E+05	0.01560	345.7	8275	0.00391	0.1594
77	2.059E+05	0.01593	317.4	8498	0.00385	0.1573
127	1.872E+05	0.01623	293.8	8652	0.00382	0.1559
177	1.730E+05	0.01649	275.0	8836	0.00378	0.1543
227	1.608E+05	0.01673	258.7	8962	0.00375	0.1532
277	1.509E+05	0.01695	244.8	9097	0.00373	0.1521
327	1.422E+05	0.01715	233.1	9251	0.00369	0.1508
377	1.370E+05	0.01728	225.6	9381	0.00367	0.1497
427	1.300E+05	0.01746	215.7	9442	0.00366	0.1493
477	1.250E+05	0.01760	209.1	9581	0.00363	0.1482
527	1.191E+05	0.01777	201.2	9635	0.00362	0.1478
627	1.099E+05	0.01806	188.8	9813	0.00359	0.1464
727	1.020E+05	0.01833	178.0	9924	0.00357	0.1456

1% Error and Mass Flow Rate of 0.07 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	3.201E+05	0.01458	450.9	10793	0.00342	0.1396
77	2.882E+05	0.01489	414.0	11084	0.00337	0.1378
127	2.621E+05	0.01517	383.2	11285	0.00334	0.1365
177	2.422E+05	0.01542	358.8	11525	0.00331	0.1351
227	2.251E+05	0.01564	337.4	11690	0.00329	0.1341
277	2.113E+05	0.01584	319.3	11866	0.00326	0.1331
327	1.991E+05	0.01603	304.1	12067	0.00323	0.1320
377	1.919E+05	0.01615	294.3	12236	0.00321	0.1311
427	1.820E+05	0.01632	281.3	12316	0.00320	0.1307
477	1.750E+05	0.01645	272.7	12499	0.00318	0.1297
527	1.667E+05	0.01661	262.5	12569	0.00317	0.1294
627	1.539E+05	0.01688	246.4	12804	0.00314	0.1282
727	1.428E+05	0.01713	232.3	12951	0.00312	0.1274

1% Error and Mass Flow Rate of 0.09 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	4.115E+05	0.01387	549.8	13159	0.00310	0.1264
77	3.706E+05	0.01416	504.8	13515	0.00306	0.1248
127	3.370E+05	0.01443	467.2	13760	0.00303	0.1236
177	3.114E+05	0.01466	437.4	14053	0.00300	0.1223
227	2.894E+05	0.01488	411.4	14253	0.00298	0.1215
277	2.716E+05	0.01507	389.3	14467	0.00295	0.1206
327	2.559E+05	0.01525	370.7	14713	0.00293	0.1196
377	2.467E+05	0.01536	358.8	14919	0.00291	0.1187
427	2.340E+05	0.01552	343.0	15015	0.00290	0.1184
477	2.250E+05	0.01565	332.5	15239	0.00288	0.1175
527	2.144E+05	0.01580	320.1	15325	0.00287	0.1172
627	1.978E+05	0.01605	300.4	15613	0.00284	0.1161
727	1.836E+05	0.01629	283.3	15794	0.00283	0.1154

1% Error and Mass Flow Rate of 0.1 lb/sec, and Tube I.D. of 0.25"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	4.573E+05	0.01358	597.4	14300	0.00297	0.1213
77	4.118E+05	0.01386	548.6	14686	0.00293	0.1197
127	3.745E+05	0.01413	507.7	14952	0.00291	0.1186
177	3.460E+05	0.01435	475.3	15270	0.00288	0.1174
227	3.215E+05	0.01457	447.0	15488	0.00286	0.1165
277	3.018E+05	0.01475	423.0	15720	0.00283	0.1157
327	2.844E+05	0.01493	402.9	15987	0.00281	0.1147
377	2.741E+05	0.01504	389.9	16211	0.00279	0.1139
427	2.600E+05	0.01520	372.7	16316	0.00278	0.1135
477	2.500E+05	0.01532	361.3	16559	0.00276	0.1127
527	2.382E+05	0.01547	347.8	16653	0.00275	0.1124
627	2.198E+05	0.01572	326.5	16966	0.00273	0.1113
727	2.040E+05	0.01595	307.9	17162	0.00271	0.1107

1% Error and Mass Flow Rate of 0.01 lb/s, and Tube I.D. of 0.375"					1/16" T.C.	
He Temp (C)	Re	f	Nu_D	h (W/K)	L (m)	L (in)
27	3.048E+04	0.02333	69.3	1105	0.01069	0.4363
77	2.745E+04	0.02383	63.4	1132	0.01056	0.4310
127	2.497E+04	0.02429	58.6	1150	0.01048	0.4278
177	2.307E+04	0.02467	54.7	1171	0.01038	0.4237
227	2.144E+04	0.02504	51.3	1185	0.01032	0.4212
277	2.012E+04	0.02536	48.5	1201	0.01025	0.4185
327	1.896E+04	0.02566	46.1	1219	0.01018	0.4154
377	1.827E+04	0.02585	44.5	1234	0.01011	0.4128
427	1.733E+04	0.02612	42.5	1240	0.01009	0.4119
477	1.667E+04	0.02633	41.1	1256	0.01003	0.4093
527	1.588E+04	0.02659	39.5	1260	0.01001	0.4086
627	1.465E+04	0.02702	36.9	1277	0.00994	0.4058
727	1.360E+04	0.02742	34.6	1286	0.00991	0.4045

C.4) Fanno Flow Calculations

Procedure:

Determine p/p*, where p is the regulator pressure and p* is atmospheric pressure.

On a choked Fanno flow table reference p/p* to find Ma.

Use the ideal gas law to find density at the regulator

$$\rho = \frac{p_{reg}}{RT}$$

Calculate speed of sound at regulator

$$c = \sqrt{\gamma RT}$$

Calculate mass flow in pipe

$$\dot{m} = \rho \cdot \pi r^2 \cdot cMa$$

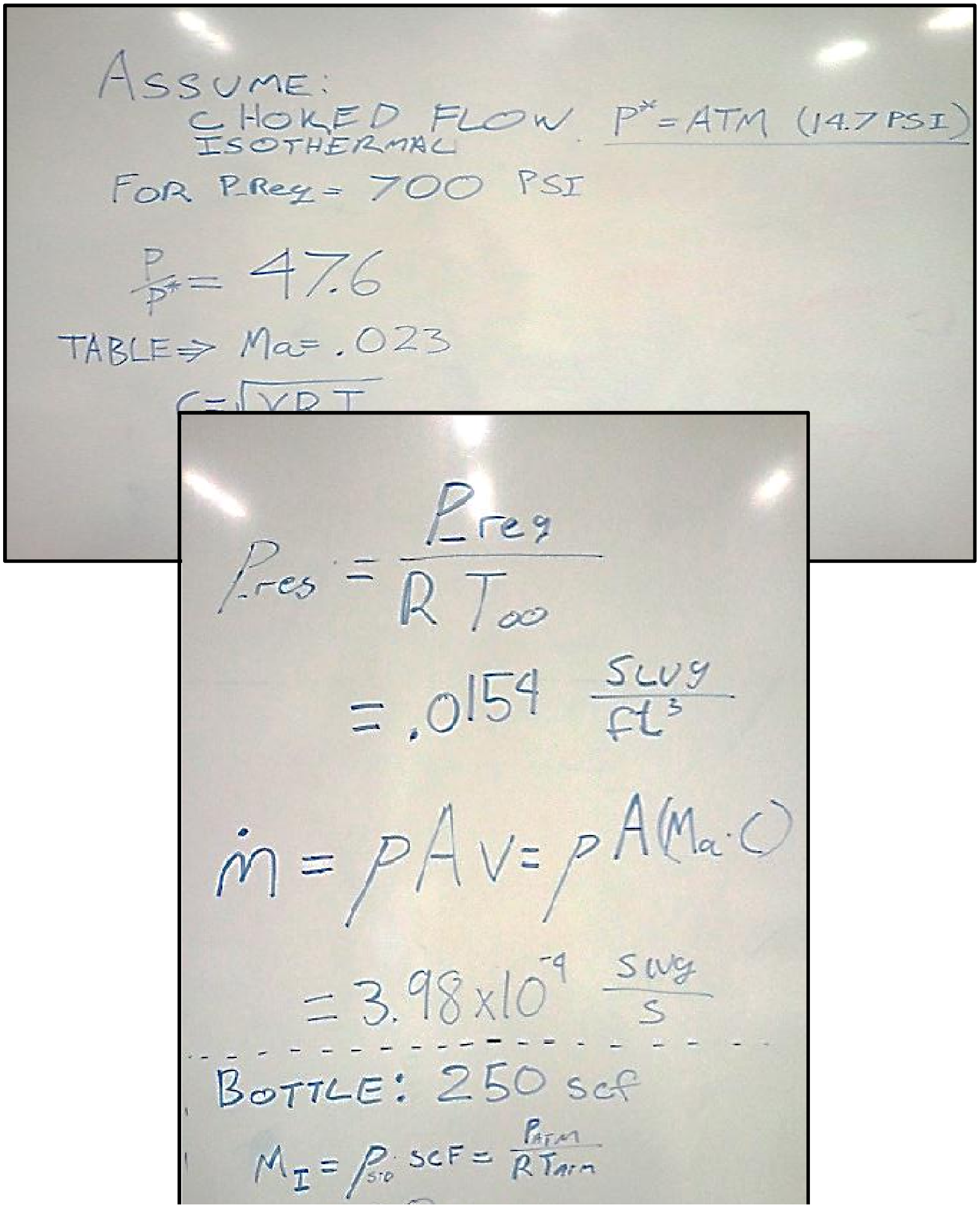
Calculate Reynolds number

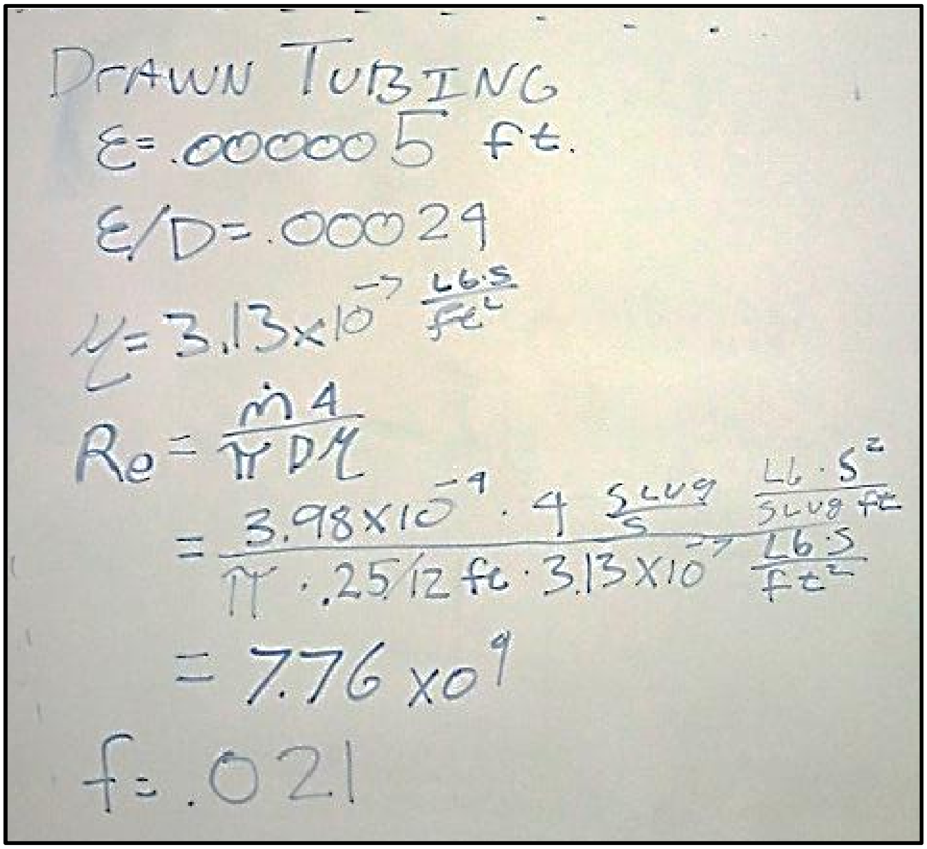
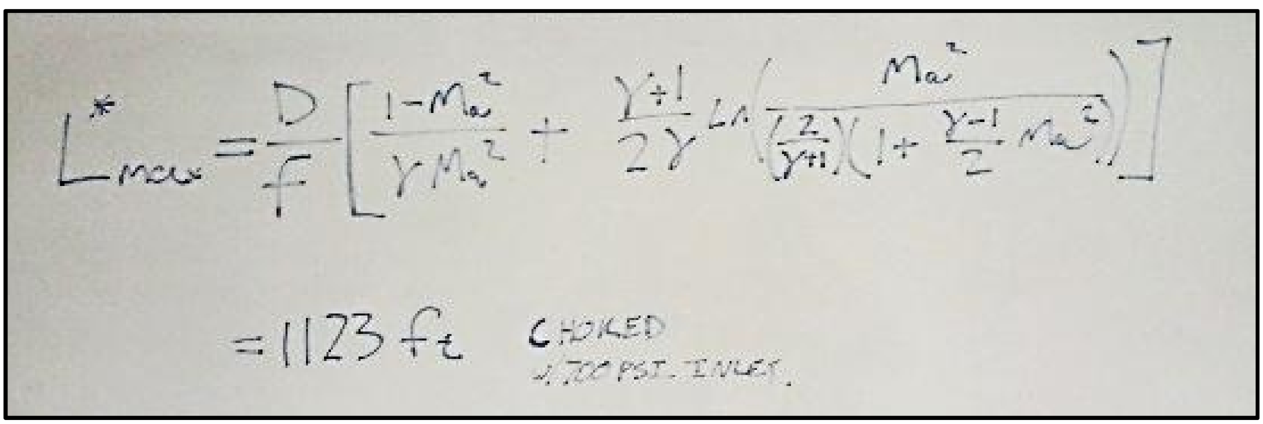
$$Re = \frac{4\dot{m}}{\pi D\mu}$$

Use moody chart to find friction factor of drawn Tubing $\varepsilon = .000005\ ft$

Determine maximum pipe length to achieve choked flow

$$L = \frac{d}{f}\left[\left(\frac{1 - Ma^2}{\gamma Ma^2}\right) + \left(\frac{\gamma + 1}{2\gamma}\right) * ln\left(\frac{Ma^2}{\frac{2}{\gamma + 1} * \left(1 + \frac{\gamma - 1}{2} * Ma^2\right)}\right)\right]$$


ASSUME:
CHOKED FLOW P* = ATM (14.7 PSI)
ISOTHERMAL
FOR P_Reg = 700 PSI
P/P* = 47.6
TABLE ⇒ Ma = .023
ρres = Preg / R T∞
= .0154 slug/ft³
ṁ = ρAV = ρA(Ma·C)
= 3.98x10⁻⁴ slug/s
BOTTLE: 250 scf
MI = ρSTD · SCF = PATM / RTATM


DRAWN TUBING
ε=.000005 ft.
ε/D=.00024
μ=3.13×10^-7 Lb·s/ft²
Re = ṁ 4 / π D μ
= 3.98×10^-9 · 4 slug/s · Lb·s²/slug ft / π · .25/12 ft · 3.13×10^-7 Lb·s/ft²
= 7.76 x0^9
f=.021

L*max = D/f [(1−Ma²)/(γMa²) + (γ+1)/(2γ) ln(Ma² / ((2/(γ+1))(1+ (γ−1)/2 Ma²)))]
=1123 ft CHOKED
w/ 700 PSI. INLET.

Appendix D- EES Code for N2O Mass Flow Rate

Appendix E

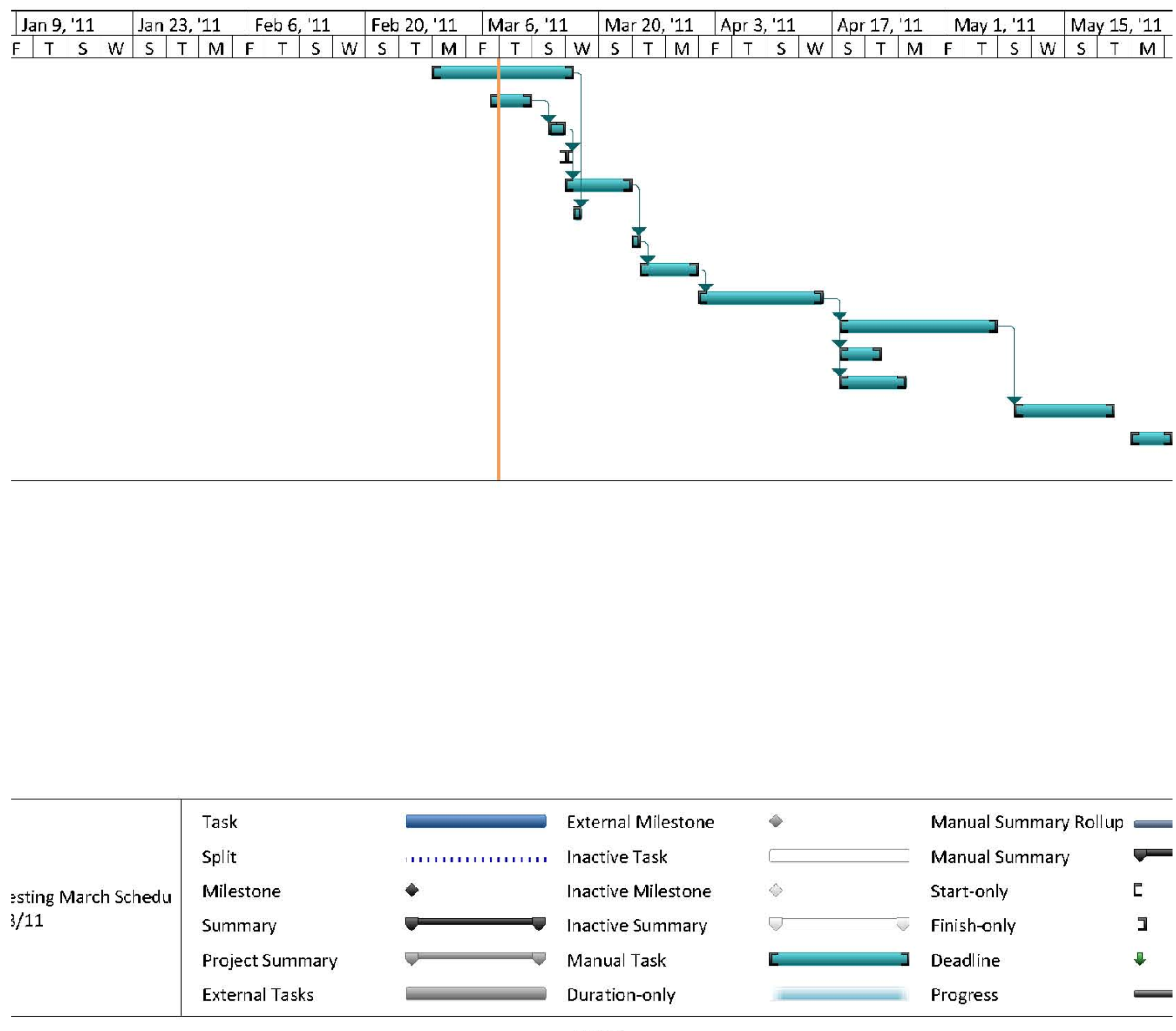
Task Mode	Task Name	Duration	Start
	Finalize Flowmeter	104 hrs	Mon 2/28/11
	Calculate Heat Source Power Requirement	5 days	Mon 3/7/11
	Size Test Tube	2 days	Mon 3/14/11
	Purchase Test Tube Materials	1 hr	Wed 3/16/11
	Frame Design	6 days	Wed 3/16/11
	Order Flow Meter	1 day	Thu 3/17/11
	Purchase/Find Frame Materials	1 day	Thu 3/24/11
	Frame Fabrication	5 days	Fri 3/25/11
	Assemble Project	2.2 wks	Fri 4/1/11
	Write Lab Procedure	3 wks	Mon 4/18/11
	Manufacturing Test Review (in Lab)	1 wk	Mon 4/18/11
	Hardware Demo	6 days	Mon 4/18/11
	Test With Helium	2 wks	Mon 5/9/11
	Prep. For Design Expo	1 wk	Mon 5/23/11
	Design Expo	1 wk	Mon 5/30/11

Oct 31, '10 | Nov 14, '10 | Nov 28, '10 | Dec 1
S T M F T S W S T M F T

Testing March Schedu
/8/11

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Deadline
External Tasks	Duration-only	Progress

Page 1


Jan 9, '11
Jan 23, '11
Feb 6, '11
Feb 20, '11
Mar 6, '11
Mar 20, '11
Apr 3, '11
Apr 17, '11
May 1, '11
May 15, '11
F T S W S T M F T S W S T M F T S W S T M F T S W S T M F T S W S T M
esting March Schedu
3/11
Task
Split
Milestone
Summary
Project Summary
External Tasks
External Milestone
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
Deadline
Progress
Page 2