ROCKET FUEL PRESSURIZATION

FINAL DESIGN REPORT

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Under Pressure (UP) Engineering has completed the design process and initial testing for a helium-fed pressurization system analytical tool to accurately size a liquid-fueled rocket. This project was proposed and advised by Jim McKinnon in tandem with the development of systems, ultimately to be implemented in a single-stage-to-orbit (SSTO) reusable launch vehicle. The primary objective of this project consisted of the development of an analytical model for the pressurization system, which allowed extensive user inputs and customization, to solve a fully-transient thermal fluid system. The final program was developed using Microsoft Excel and Visual Basic. The graphical user interface (GUI) allows users to select specific design criteria and set parameters to determine various system outputs over the entire burn time of the rocket, while also calculating the theoretically "optimized" system mass and volume for that set of inputs. To validate the model, we created and tested a simplified test bench of the rocket pressurization system. We selected test bench components based on a small, non-scaled version of an actual system that could potentially be seen in a rocket fuel tank. In lieu of Rocket Propellant -1 (RP-1), we used water, which is both cheaper and safer to handle. Liquid oxygen (LOX) was replaced by liquid nitrogen, also for cost reduction for testing. Based on the test bench data, the model has shown initial promise, accurately predicting the high pressure blow down in the helium tanks. Additionally, when discrepancies in helium temperature into the heat exchanger (HX) are remedied, the heat exchanger analysis appears to be fairly accurate as well; the ullage gas temperature prediction is even better. Regardless, in order to fully anchor the model, especially on the low pressure side, further testing is required with a larger test apparatus to eliminate similitude issues between the model and test bench. Despite the uncertainty in model validity, we were able to make several important observations about the system and implications of actually implementing this revolutionary heat exchanger design.

CHAPTER 1 – INTRODUCTION

Under Pressure (UP) Engineering completed a three-quarter long design process for a helium-fed pressurization system in a liquid fueled rocket. This project was proposed and advised by Jim McKinnon in tandem with the development of systems to be ultimately implemented in a single-stage-to-orbit (SSTO) reusable launch vehicle. The primary objective of the first phase of design consisted of the development of an analytical tool for the pressurization system, which allowed user inputs to solve a steady state model. A full steady state model was then developed, alongside a Graphical User Interface (GUI) implemented in Excel. In the second phase of design, a full transient model was devolved and implemented in Excel, which allows UP Engineering to easily and accurately evaluate potential design solutions. A physical test bench has been designed which will test the analytical model, ultimately verifying or refuting its validity. The final phase of this project consisted of modifying and building the test bench, collecting data to compare to the analytical model, and completing the Excel GUI. The overall project goals, as stated in the project proposal were:

(1) An analytical model of the thermodynamic, fluid, heat transfer, and geometric configurations which will accept user inputs, allowing the system to be optimized for weight, size, and cost.

(2) A physical, scaled model of the system to verify the design created from the analytical model through testing.

OBJECTIVES

The overall objectives of our project were to develop an accurate analytical thermodynamic model for the helium pressurization system and to use this model to test various heat exchanger designs. For each geometric configuration, we used CAD models to judge mechanical integrity and manufacturability. In addition, we developed a physical, experimental model to set a benchmark for our thermodynamic model.

The thermodynamic model consists of an Excel program with a GUI designed in Visual Basic. The model will allow us to change a variety of inputs, including tube lengths, geometry and materials to quickly and accurately test different configurations. Our goal for the model is to be within 5% accuracy as compared to our experimental model. This will allow us to objectively judge each design on characteristics such as weight, durability and heat transfer efficiency. Our full list of initial specifications is shown below.

TABLE 1 – ENGINEERING REQUIREMENTS AND SPECIFICATIONS

<table>
<tr><th>Specification</th><th>Parameter</th><th>Requirement</th><th>Tolerance</th><th>Risk</th><th colspan="2">Compliance</th></tr>
<tr><td>1</td><td>Dry Weight</td><td>1200 kg</td><td>Max.</td><td>High</td><td>A, S</td><td rowspan="9">A = Analysis

S = Similar to Existing Design

T = Test

I = Inspection</td></tr>
<tr><td>2</td><td>Overall Heat Transfer Coefficient</td><td>TBD</td><td>Min.</td><td>Med</td><td>A, T</td></tr>
<tr><td>3</td><td>Cycles to Failure</td><td>100,000</td><td>Min.</td><td>High</td><td>A, S</td></tr>
<tr><td>4</td><td>Reliability</td><td>0.99</td><td>± 0.01</td><td>Low</td><td>A</td></tr>
<tr><td>5</td><td>Fuel Tank Pressure</td><td>2000 psig</td><td>± 500 psig</td><td>Low</td><td>A, S, T</td></tr>
<tr><td>6</td><td>Thermal Stress</td><td>TBD</td><td>Max.</td><td>Med</td><td>A</td></tr>
<tr><td>7</td><td>Unit Cost</td><td>TBD</td><td>Max.</td><td>Low</td><td>A</td></tr>
<tr><td>8</td><td>Heat Exchanger Efficiency</td><td>90.0%</td><td>± 5.0%</td><td>Med</td><td>A, S, T</td></tr>
<tr><td>9</td><td>System Volume</td><td>TBD</td><td>Max.</td><td>Low</td><td>A, I</td></tr>
</table>

It should be noted that this list was never an official set of engineering requirements. Rather, we used these specifications to better understand the important outputs that our system should provide. During the first half of this project, we compared each design using a QFD table, which can be found in Appendix A.

The most difficult specifications to achieve – also, the most important ones – were dry weight system volume. In our designs, the hot side of the exchanger design is not directly in contact with the combustion gases, meaning that we must increase the overall mass of the exchanger, as compared to past designs, to obtain the required helium pressures and temperatures. Many past rocket designs were designed for only one mission, so fatigue life was not important. This design must operate in a system that requires reliability over a large number of missions and have a quick turn-around on the ground. Extreme care was taken to ensure that we addressed as many potential failure modes as possible and minimized them. However, we concede that it is nearly impossible to accurately determine the reliability of this type of system, especially since higher order effects may occur that our model will not be able to account for.

We developed a standard CAD model, based on Frontier Engineering's specifications, for our generic design. This allowed us to spot potential geometric problems that the analytical model could not address. The CAD model was completed in Pro/Engineer (Pro/E) and includes the LOX, RP1 tanks and helium tanks, the heat exchanger and miscellaneous components we deem useful to enhance to realism of this new system. While the CAD model was a useful tool to spot potential mechanical issues, it was not within the scope of our project to complete extensive mechanical design work. Thus, some of the specifications listed in Table 1 are not addressed in this project, as they require additional analysis, such as Finite Element Analysis (FEA), to verify.

MANAGEMENT PLAN

During the Fall quarter, we decided to split up the project into three major sections: physical model, Excel interface, and analytical model. This allows each member of the group to focus on a particular "specialty" while maintaining cohesiveness and teamwork. During the Winter quarter, the focus of the group shifted more heavily towards the analysis of the system model. The primary deliverables that quarter were based on a fully functioning GUI. In order to meet this deadline, UP Engineering reallocated resources to accelerate the analysis process while staying on target for the other deadlines. Spring quarter saw another shift in group focus, this time towards testing and model validation. In this final phase, we encountered the largest delays and setbacks in our progress. Changes to test bench design and the analytical model resulted in a much shorter time spent testing our system and verifying the analytical model. Despite all of the deviations from schedule, we believe that we accomplished our primary objective, and this resulted from distinct contributions from each teammate.

The function of the physical modeler, Joe Marcinkowski, primarily focused on the creation of the CAD model drafted using Pro/Engineer. Joe's enthusiasm and experience with SolidWorks provided us with a comprehensive CAD model of the rocket tanks and preliminary pressurant line geometry that was critical in the mass analysis of this system. Additionally, Joe provided supporting analytical calculations, including basic heat exchanger equations used to check the analytical model. As the project progressed, Joe shifted his attention to test bench design and implementation. Additionally, he oversaw the construction of the actual scale model UP Engineering created to validate our analytical model. Since he is a Cal Poly shop technician, Joe was the best choice to lead the physical build. As the lead for this area of the project, Joe created the test bench budget and a user manual to properly and consistently collect data from the test bench. In the analysis area, Joe developed the initial finite difference model to analyze the heat exchanger into a discreet number of sections.

Sean Green was the primary contributor to the Excel graphical user interface (GUI) we began to develop midway through the first quarter. Through his dedication to learning Visual Basic with Applications (VBA), Sean tied together the physical and analytical models into an easy-to-use Excel application. He continued to update this applet to include more complicated calculations (as they were developed) as well as more output data to the user. Sean continued working on upgrading the Excel GUI through each phase; furthermore, he spent a lot of time troubleshooting errors as they arose. Once the source of the error was determined, he either rewrote the VBA code to circumvent the problem, or installed error protocol to stop the program upon encountering these issues. This work served to increase the robustness of the program for other users in the future.

The steady state analytical model we developed Fall quarter was produced largely from the efforts of Andrew Nahab. With his strong background in analytical tools such as Engineering Equation Solver (EES) and Excel functions, Andrew was the obvious choice for this position. The analytical modeling required to simulate the rocket fuel pressurization system came in two forms: thermal fluid analysis and heat exchanger design. Working with Joe on the heat exchanger configuration, Andrew prepared a system of equations that models the helium properties in various portions of the pressurant system at a single point in time. In the second phase of the project,

Andrew focused his efforts on the development of a transient model of the fuel pressurization system, employing a finite difference model stepping through the full burn time of the rocket. In an attempt to increase functionality and performance, some of the key variables at each time step are iteratively solved in VBA; the other variables are then computed in the Excel workbook. During the final quarter, he aided Sean in troubleshooting the GUI, and made minor changes to the model to correct inconsistencies that arose. Throughout the year, Andrew served as the project lead, coordinating efforts between team members in UP Engineering as well as weekly sponsor meetings with Frontier Engineering. As lead, he was the chairperson for meetings as well as project scheduler. This ensured that UP Engineering achieved results in a timely fashion.

The table below summarizes key deadlines for our project. For a more detailed list of events that occurred over this timespan, see the Management Charts in Appendix I.

TABLE 2 - GENERAL PROJECT SCHEDULE OVERVIEW

Date	Task	Sponsor Communication
10/18/2012	Project Proposal Submitted	Email
11/5/2012	Conceptual Model Complete	Email
12/3/2012	Conceptual Design Review	Email, Phone
2/8/2013	Critical Design Review	In Person
4/30/2013	Manufacturing & Test Review	Email, Phone
5/14/2013	Project Hardware Demo	Email, Phone
5/30/2013	Senior Design Expo	Email
6/6/2013	Final Report Submitted	Email
6/19/2013	Final Presentation	In Person

While the individual assignments allowed each team member to focus on particular facets of this project, everyone remained flexible in order to handle variable workloads. We shifted our responsibilities each quarter to accommodate various issues that arose in more difficult tasks to complete; anytime the transient model or Excel interface hit a snare, we put two members of the group on the task of troubleshooting and correcting the issue. While this slowed down progress of the overall project, UP Engineering determined that it would not sacrifice quality to meet deadlines. However, this put more stress on individual members at times, especially during the later phases in the project. However, by working together as a group, UP Engineering was able to maximize the results of this project.

CHAPTER 2 – BACKGROUND

The majority of our research has centered on previous work done in the area of helium pressurization and heat transfer systems. We have found two significant sources, the American Institute of Aeronautics and Astronautics (AIAA) and the National Aeronautics and Space Administration (NASA), which contain a vast library of information about our topics. The most widely adopted pressurization model for liquid fuel rockets has been a stored-inert-gas system with helium as the pressurant. This is the model we will adapt and optimize for our system.

One area we will be examining is the propellant storage tanks. Two basic shapes have previously been used in many different systems, a sphere and a cylinder with hemispherical ends. The sphere is the strongest shape for a given internal pressure, and on smaller rockets it has been a suitable solution. However, as the size of the rockets increase the use of the cylinder has proved more acceptable. The advantage of the cylinder is that it tends to fit better within the long cylindrical shape of rockets, as can be seen in Figure 1, and this shape allows the tanks to be used as an internal support structure. Another aspect of tank design that we have researched was tank materials. Because of the cryogenic nature of the liquid oxygen and the extreme temperatures associated with spaceflight, traditional tank materials, such as carbon steel, have not worked well. Some materials that have been used in the past are specific aluminum alloys, stainless steels and titanium. Not only do the materials need to stand up to vast temperature swings, the material weight, strength and thermal expansion rates also need to be taken into account.

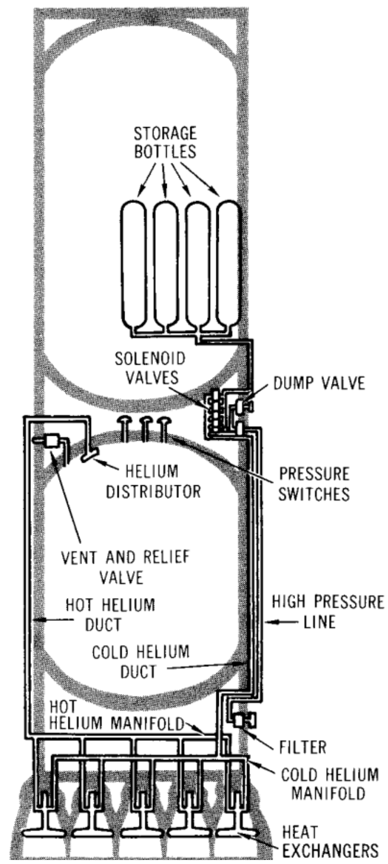


FIGURE 1 - FUEL PRESSURIZATION SYSTEM ON THE FIRST STAGE OF THE SATURN V ROCKET

The fundamental design of fuel pressurization systems used in liquid rockets consists of one or more helium tanks located within the liquid oxygen (LOX) tank. This location allows the helium to be cooled by the LOX to temperatures below -297°F. Since the helium stays in gaseous phase, as the temperature drops, the density increases; thus, less volume is required to hold the necessary mass of pressurant (helium). In order to maintain sufficient pressure in the fuel tank, the cold helium passes through a heat exchanger, which allows the gas to expand and provide sufficient pressure to expel the fuel. Many previous heat exchanger designs have been located in the combustor exhaust. This system configuration provides very high thermal flux, as the sub-zero helium interacts with combustion gases over 3500°F. Once the pressurant has been heated, it passes through pressure control valves and into the fuel tank. Figure 1 shows a diagram of this pressurization system as it was integrated in the Saturn V rocket's first stage.

While the traditional pressurization system is effective, it has a couple drawbacks that limit the potential in new space technology. One of the major problems associated with this configuration is the thermal stress development due to extreme temperature cycling. Over multiple uses, this stress cycling results in thermal cracking, ultimately leading to system failure. Though this

does not appear to be troublesome for single-use rockets, the issue must be resolved to further develop new technologies, such as SSTO flight. Another problem associated with the original design is the tube shear from fretting caused by in-flight vibrations. Since this is very hard to model, tests must be performed to determine the relative success of new designs. SSTO RLV (Reusable launch vehicles), must by designed to minimize weight and allow for simple maintenance. The success of design attempts for these vehicles will rely heavily on the ability to create a robust, lightweight, and easily maintainable vehicle. Evidence of the struggle involved with this endeavor can be seen in the attempts of Space X, Lockheed Martin, the Ansari X Prize, and others, who have, with varying degrees of success, attempted to create a reusable “space plane.”

CHAPTER 3 – MODEL DEVELOPEMENT

The broad method of approach for Cal Poly's mechanical engineering senior projects is "Design, Build, Test". Our project followed this basic structure, but relied heavily upon analytical tools developed in the design phase to develop a successful solution to this problem.

Background research and the development of a solid understanding of the underlying problems was the first step in this approach. This included the study of previous rocket fuel pressurization systems and an analysis of their various successes and failures. From this background research, the fundamental equations for heat transfer, fluid analysis, and thermodynamics were developed for the fuel tank and heat exchanger system involved in the overall pressurization system.

In order to optimize the pressurization system, the equations developed to analyze the heat transfer, fluid, thermodynamic, and materials analysis were integrated into Excel, which will be used to evaluate subsequent designs. This was developed concurrently with a solid model created using Pro/E CAD software in order to allow for the evaluation of mass properties and tank sizing. The final product is a fully functional analytical package that allows user input, and aids in the evaluation of design solutions devised for the heat exchanger and pressurization tank configuration.

In order to anchor the Excel model, a test bench was constructed, and the parameters of this system were entered into the model in order to predict its performance. The construction of this test bench constituted the "build" phase of the senior project. A scale model of the pressurization system was constructed using helium as the pressurant and water as the working fluid. The model was analyzed by applying thermocouples and pressure gages to appropriate areas on the model and comparing the results to those predicted in the theoretical model.

STEADY STATE MODEL DEVELOPMENT

The steady state model developed during the Fall 2012 Quarter identifies seven regions in the entire system (0 – 6) and six state points between the helium tank and fuel tank (A – E). Figure 2 shows the system schematic, with corresponding state points, used in our analysis.

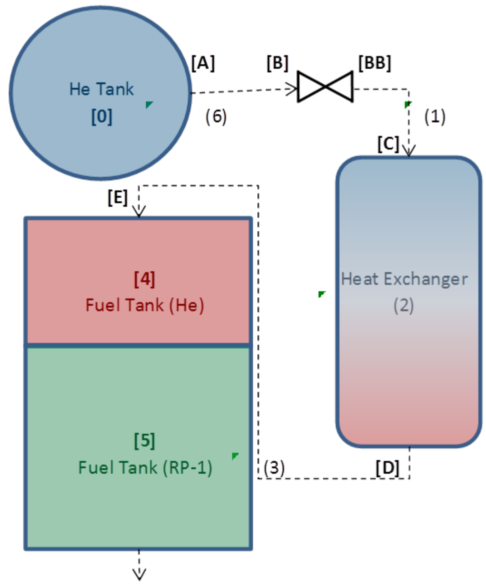


FIGURE 2 – ORIGINAL HELIUM PRESSURANT SYSTEM DIAGRAM

We made several assumptions to simplify our steady state analysis. For instance, we assumed that the helium pressure in the fuel tank (P_4) was only a function of the turbomachinery pumping the RP-1 into the combustion chamber. This was assumed to be a constant 40 psia. Additionally, we neglected heat transfer between the helium-fuel interface in the fuel tank; furthermore, we assumed that there was no RP-1 vapor in the ullage space (designated as Section 4). The helium was assumed to be a perfect gas, both ideal and maintaining constant specific heats throughout the temperature range. Finally, we assumed a heat exchanger efficiency of 95%. During the Fall quarter, we developed a simplified heat transfer model (discussed in a subsequent section). However, we will expand this model when we test specific geometric configurations of various heat exchanger ideas. Thus, we need a heat exchanger efficiency to be specified until that point.

The difficulty of analyzing the helium pressurant system for this SSTO space vehicle is the location of boundary conditions within the model. At time zero – this is the assumed point of our steady state analysis – we know the helium tank pressure and temperature (P_0 & T_0), fuel tank pressure (P_4), and mass flow rate of fuel leaving the fuel tank; this last quantity allows us to solve for the velocity of the helium in the ullage space (v_4). At this point, we note that we have inputs at both the start and end of the helium piping; thus, we need to obtain equations to acquire values for the intermediate state points. In order to obtain a closed-form solution for each state point, we assumed that temperature increases (and decreases) were independent of changes in helium velocity in each section. Thus, we can solve the 1st Law of Thermodynamics twice, first in the thermodynamic form, then in the fluids form. Next, we applied Conservation of Mass to each section to solve for densities at each point. Finally, we used the Ideal Gas Law to determine the pressures corresponding to each density and temperature. The basic analysis for the heat exchanger (Section 2, between points C and D) is summarized below:

1ST LAW OF THERMODYNAMICS

$$\dot{Q}_2 = \dot{m}_{He}\, C_p\, (T_C - T_D)$$

ENERGY EQUATION

$$R\, T_C + 0.5\, V_C^2 = R\, T_D + 0.5\, V_D^2 + f_2\, \frac{L_{CD}}{D_C}\, \frac{V_2^2}{2}$$

CONSERVATION OF MASS

$$\rho_C\, A_C\, V_C = \rho_D\, A_D\, V_D$$

IDEAL GAS LAW

$$P_C = \rho_C\, R\, T_C, \quad P_D = \rho_D\, R\, T_D$$

Our complete analysis, in the form of EES code, was checked to ensure the model's validity. For instance, ΔT, the temperature difference between the fuel and helium in the ullage space, was a positive number, about 10 K. This appeared to be reasonable; we expect that the helium, since it passes through tubing inside the fuel tank, will approach the temperature of the fuel, but should not reach it upon exit into the overhead space. The entropy production in the valve between points B and BB, δs_{valve}, was also positive, as expected by the 1800 psi pressure drop experienced at that location. The last quantity, the total mass of helium required, was merely the steady state mass flow rate of helium over the full rocket burn time. Although that was not an accurate number for the final solution, we obtained a reasonable value nonetheless, which helps support the integrity of the model.

TRANSIENT MODEL DEVELOPMENT

Once we had completed a steady state analysis, we proceeded to derive a fully transient model of our system. Using a finite difference method, which assumes that all system values are constant over an incremental time step, we were able to compute transient variables, such as helium tank temperature and pressure, based on the previous time step values. Intermediate, location-dependent variables, such as the piping velocity, temperature, and pressure, are computed based on the end conditions in the tanks – Sections 0 and 8 in Figure 1 below – for each time step. A new labeling system was adopted to define specific state points (labeled A – F) as well as sections (labeled 0 – 8). Within each incremental time step, an additional finite difference method was applied to evaluate heat transfer across section E. In order to implement this transient model, VBA was employed inside Excel to calculate the finite difference method for the heat exchanger as well as transient variables such as velocity.

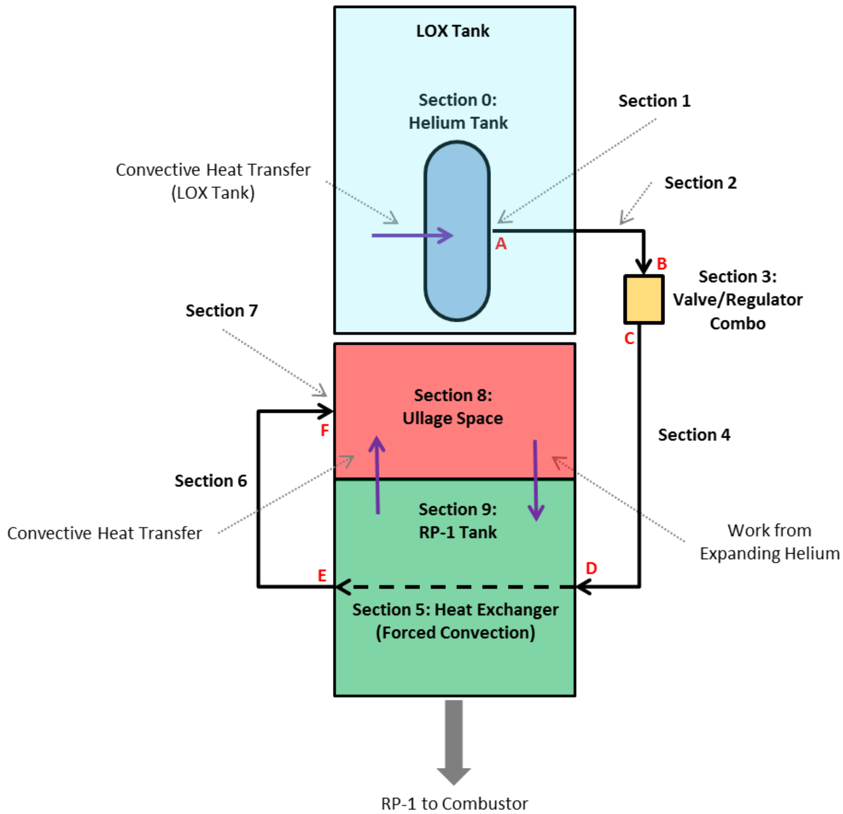


FIGURE 3 – TRANSIENT MODEL SCHEMATIC

HEAT TRANSFER MODEL DEVELOPMENT

The heat transfer equations were divided into three sections, pre heat-exchanger, the heat exchanger and the ullage space. The heat exchanger portion of the model accounts for the greatest potential for heat transfer to occur, however, because we are working to minimize mass on the spacecraft, we are analyzing any area with potential for heat transfer.

Using the steady state schematic, the pre-heat exchanger section consists of the piping downstream of the valve, in section B to C. At this point in the system the fluid starts very cool; however, depending on the piping configuration, the potential for heat transfer is limited by the exterior conditions. If the helium is routed outside of the tanks, the external heat transfer coefficient is low, because it is a gas in natural convection. However, if it is routed through the RP1 the external system will experience similar conditions to the heat exchanger portion. This piping configuration will be determined externally, depending on the tank configuration and space constraints.

In the heat exchanger, we should see favorable heat transfer condition. Within the tubes we will have the helium at cryogenic temperatures that is moving quickly, with Reynolds Numbers over 500,000, meaning we are well into the turbulent flow region. We anticipate the tubes to be relatively thin, because at this point in the system we will be at lower pressures. The exterior of the tubes will have the fuel slowly moving over them. Although the fuel will be in laminar flow, because the mass of fuel is much larger than the mass of helium we should not see a significant drop in the overall fuel temperature, leading to uniform external heat transfer across the length of the tubes.

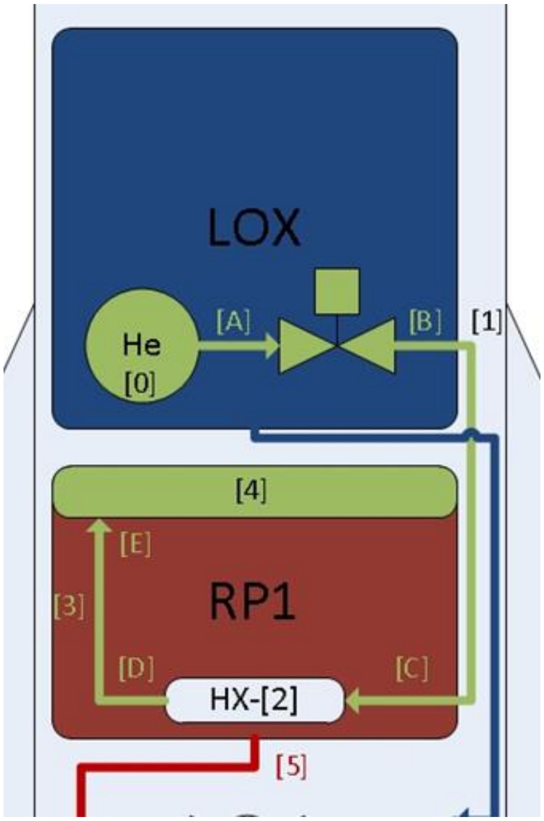


FIGURE 4 - HEAT TRANSFER SCHEMATIC (STEADY STATE)

We anticipate there to be heat transfer across the ullage space; however, we did not include this analysis in our steady state model in an effort to reduce the complexity of the solution. This is included in our transient model to increase the accuracy. This heat transfer is occurring between area 4 and the RP1 in Figure 2, however it will be limited by the temperature of the helium exiting the heat exchanger. To model this heat transfer, the top of the fuel column is assumed to be a horizontal flat plate and the helium in free convection. Because of the large area this will be occurring over, the heat transfer is non-negligible.

In the transient model, to improve the accuracy of the heat transfer model, we have divided the heat exchanger into smaller segments and then numerically solved the heat exchanger system. This allows the program to calculate temperature differences along the heat exchanger, instead of assuming an average temperature difference along the entire system as was done in the steady state model.

CAD DESIGN

We have developed a comprehensive CAD model of the helium pressurization system. This model allows us to spot potential geometric problems that the other model does not address. The model includes the fuel, LOX and helium tanks, the inter-tank piping and the heat exchanger piping. The intention was that for each design that we test using our analytical tool, we would have a corresponding CAD model to allow us to gather accurate pipe lengths. For our most promising thermodynamic design(s) we will develop a more detailed CAD model that will give us more insight into the design. While the CAD models will be useful tools to spot potential mechanical issues, it is not within the scope of our project to complete extensive mechanical design work.

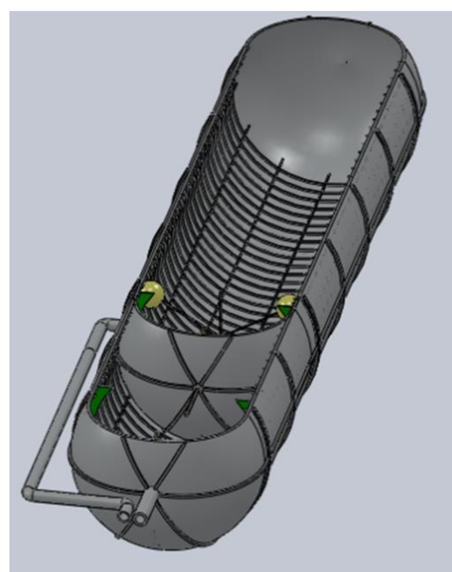


FIGURE 5 - CAD MODEL OVERVIEW

SOFTWARE DESIGN

In order to allow UP Engineering to easily evaluate design ideas after the transient analysis equations are derived, it is necessary to have an application which a user can easily update and use to compare designs side by side. A GUI was developed in Excel to allow a user to adjust inputs in the geometrical, fluids, system, thermodynamic, and heat transfer components of the fuel pressurization model. The final model consists of an input window, output window, system compare window, visual representation of system design, and documentation of system variables, parameters, and assumptions. This GUI contains all of the sophistication of a commercial software application, with Help documentation, and the ability to adjust back-end system parameters.

USER INTERFACE

The input window consists of any adjustable variables that a user needs for iteration in design of the helium fuel pressurization system. This will allow a user to adjust the geometrical parameters in the system design: lengths and diameters of pipes, pipe routing, heat exchanger configuration, and etcetera.

Because the majority of design iterations will consists mainly of geometrical changes, a userform for geometric design was created to allow a user to easily update geometries through a graphical interface. The form allows the user to adjust lengths, diameters, thickness, number of tubes and material for each individual component and section in the pressurization system. The interface gives a visual representation of component weights so that the user can easily see the effects of any adjustments made.

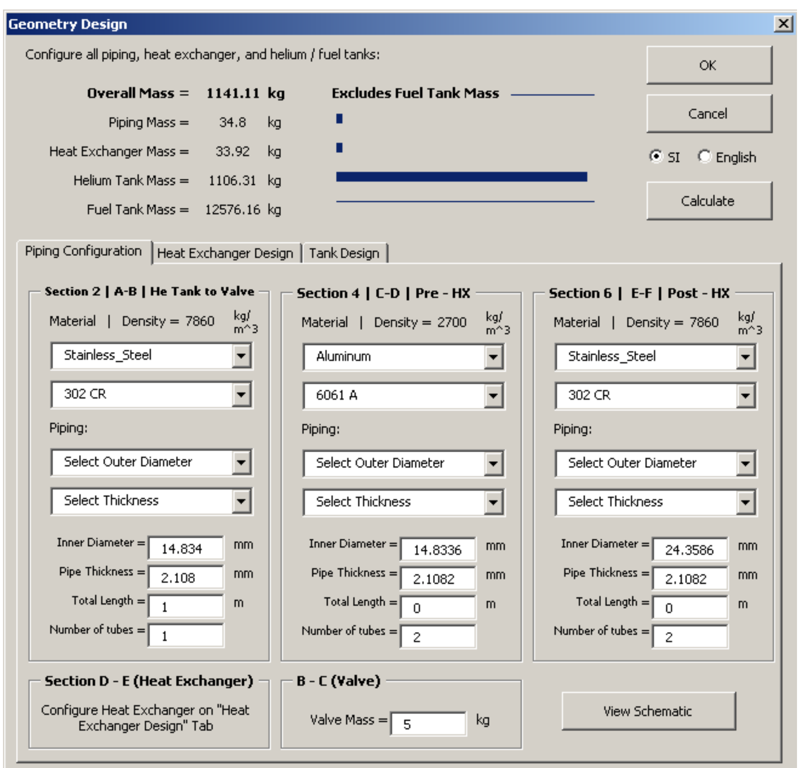


FIGURE 6 - GEOMETRY DESIGN GUI

The output window allows a user to evaluate the performance of potential pressurization system designs. Any system variable can be plotted with time, and compared to previous designs. With material properties input, weight penalties can be evaluated and compared to heat exchanger performance, which will allow for overall system optimization. Additional metrics to display in the output window to aid in design evaluation and optimization were developed during the Spring 2013 Quarter.

The system comparison window concatenates the results of previous system designs onto single charts for viewing. Percent errors, minimums, and maximums of all designs being compared will be displayed to the user. Weighted optimization parameters allow for first-pass evaluations of designs when compared side by side.

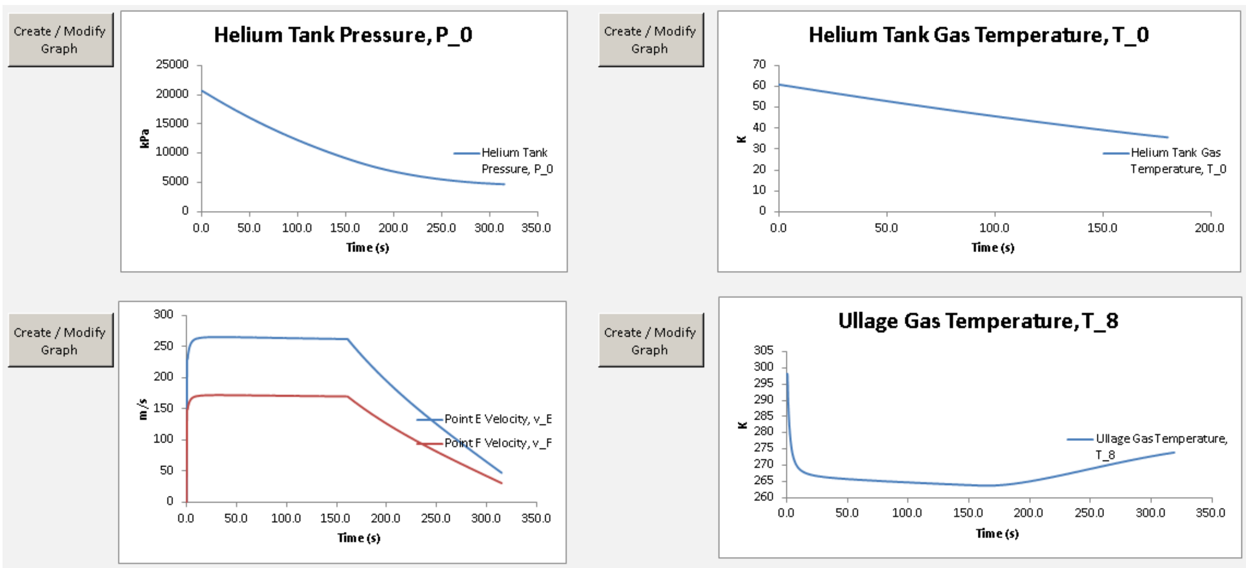


FIGURE 7 - GUI OUTPUT WINDOW

Parameters, variables, assumptions, documentation and help are displayed to the end user, which gives this GUI all the sophistication of software package aiding in the evaluation of the final helium pressurization system design. Variable lists and assumptions are all categorized and sorted based on which variables users are likely to graph. Constants are listed towards the end, with important system design variables (i.e. temperatures and pressures) – ones that determine the success or failure of a design – listed first.

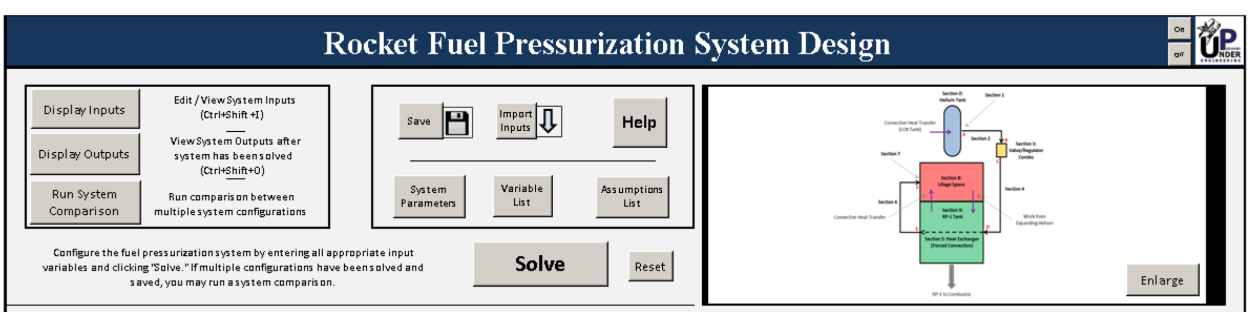


FIGURE 8 - EXCEL GUI PRIMARY USER INTERFACE SCREEN

SOLUTION METHODS WITH VBA

The actual computation of a full transient solution utilizes VBA and in-sheet solving to solve the system through time. Every variable in the system is solved at each time step, and values are recorded on the calculation sheet. The benefit of having every variable recorded at each time step is the ability to plot any variable against time easily and quickly. Additionally, it allows a user to look at how properties at each section change through time – for example, a user could view temperatures at every section, side by side, through time, to see if they were changing appropriately.

To ease the amount of iterations Excel has to do in-sheet, velocities and heat exchanger calculations are iterated upon within VBA, and pasted back in to the sheet, where the values can be appropriately referenced, allowing Excel to reach a stable solution at each time step. Rather than relying on average temperature difference, a finite difference method is implemented in VBA to solve for the final state of the heat exchanger, which gives a higher resolution to the final solution. The final state points are then pasted in to the calculation sheet to allow full system calculation to proceed at that time step.

To calculate fluid properties at each state point, REFPROP, a tool developed by *The National Institute of Science and Technology* (NIST), is implemented in excel. This tool accesses a database of fluid properties, and will assess the specified propertied given the necessary inputs:

Ex. In a cell: =Enthalpy(“helium”, “TP”, “SI”, 300, 14)

This example would calculate the enthalpy of helium using a specified temperature and pressure (TP) of 300 Kelvin and 14 MPa, respectively. The inputs and output are both in SI units.

A user must have the REFPROP database downloaded and appropriately linked to Excel prior to attempting any solutions.

Error checking methods are implemented to guard against a wide variety of possible errors. The main error checks that this system does prior to, and during a solution, are summarized below.

TABLE 3 - SUMMARY OF ERROR CHECKING PROCEDURE IN GUI

Error	Action taken
REFPROP not enabled	Stop solution, warn user
Inputs not defined	Stop solution, tell user which inputs must be given to complete solution
Velocity > (V_limit) m/s Velocity < 0 m/s	Stop solution, warn user
Negative pressure in pipes	Stop solution, warn user
Helium temperature < 10 K	Stop solution, warn user
$\Delta P_{valve} < 0$, indicates no flow out of helium tank	Stop solution, warn user
$\Delta s < 0$	Warn user
#VALUE, #NAME – any Excel based instability	Stop solution, warn user, reset solution
$m_0 \leq 0$ (no more helium)	Stop solution, warn user

Once a solution has been successfully solved, the output window is displayed and the user has the option to save the solution for comparison later, or look at the visual tools in order to gain insight about the particular design.

While dependent largely upon computer speed and performance, the solution procedure outlined about takes approximately 1-2 minutes on a modern high performance computer (i.e. Intel i7 3.2 GHz processor with 8 GB RAM). A progress bar is provided to give a user updates on how many time steps have been solved in order to avoid frustration or confusion. In addition to the full solution, a high speed approximation (< 1 second solution time) is provided on a separate sheet which allows a user to make rough geometry changes and get an idea of the weight penalty involved. These two tools – full solution and quick solution – allow for quick adjustment and evaluation of designs for a helium pressurization system.

CHAPTER 4 –ANALYTICAL MODEL

The final product that Under Pressure Engineering is delivering is an application, anchored through small scale testing, which allows a user to configure and analyze a fuel pressurization system. The application, the development of which is described in Chapter 3, allows a user to change all necessary geometrical, fluid, and thermodynamic inputs, as well as adjust backend parameters such as solving tolerances in order to develop a full transient solution of a pressurization given a thrust profile of a rocket. The model is broken down into three (3) main sections: the input window, the output window, and a system comparison window. For full documentation, please refer to the actual Excel file, and see "Help."

INPUT WINDOW

The input window is the primary window that a user is confronted with upon opening the application. Within this window, all high-level inputs can be entered such that the system will be fully defined. When a system has been completely configured, the user will be able create a transient solution of the system by clicking "Solve." If no errors are detected by the program, the inputs are written to a calculation sheet and pulled in by a VBA procedure which proceeds to calculate a solution at each timestep within a calculated burn time. If any errors occur during the solution of the specified system, the user will be warned and the solution will stop.

A userform (see Figure 6) is provided which allows for an easy and intuitive way to define geometry for all sections of the pressurization system. Contained within this mini-interface is the option to enter geometries in either SI or English unit systems. All inputs are written to the sheet in SI units, however, and the full solution uses SI units to solve.

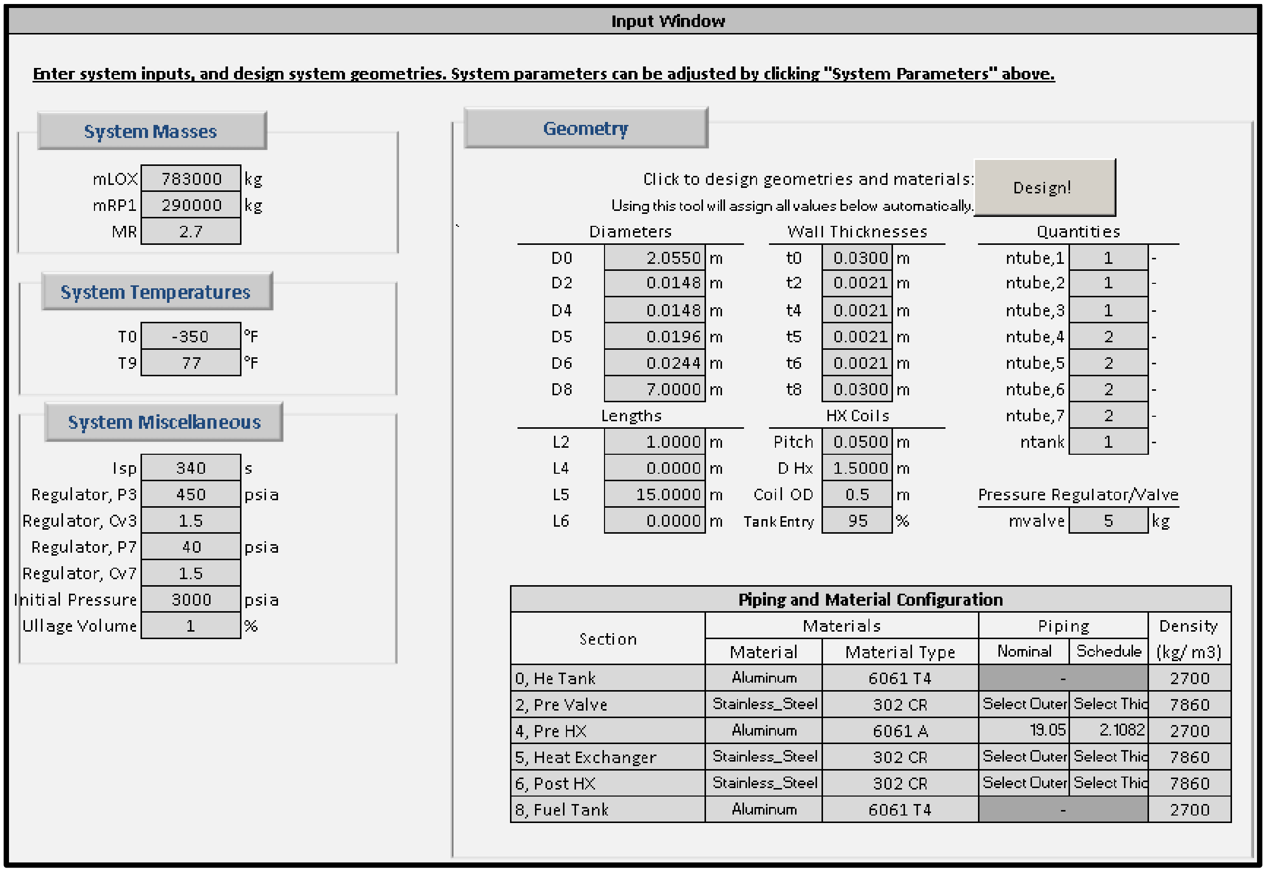


FIGURE 9 – INPUT WINDOW IN GUI

OUTPUT WINDOW

If a successful, or partially successful, transient solution has been completed, the user will be automatically shown the output window. Within this window, there are a number of tools that allow the user to evaluate the success or failure of their design.

Four graphs are displayed to the user and each one can be set to show any of the system variables against time in either SI or English units. A user can also graph multiple variables on one graph for comparison purposes.

A summary table provides the final calculated weight of each system component and the mass of helium used to run the pressurization system. Contained in this table is a summary of the user's inputs for reference as well as the energy calculations for heat within the main heat exchanger.

An additional visual tool allows a user to graphically evaluate the heat exchanger section of their design through a visual display of temperature, pressure, and velocity along the length of the heat exchanger at each time step. The user can click a "Play" button which will show these variables changing through the duration of the burn time.

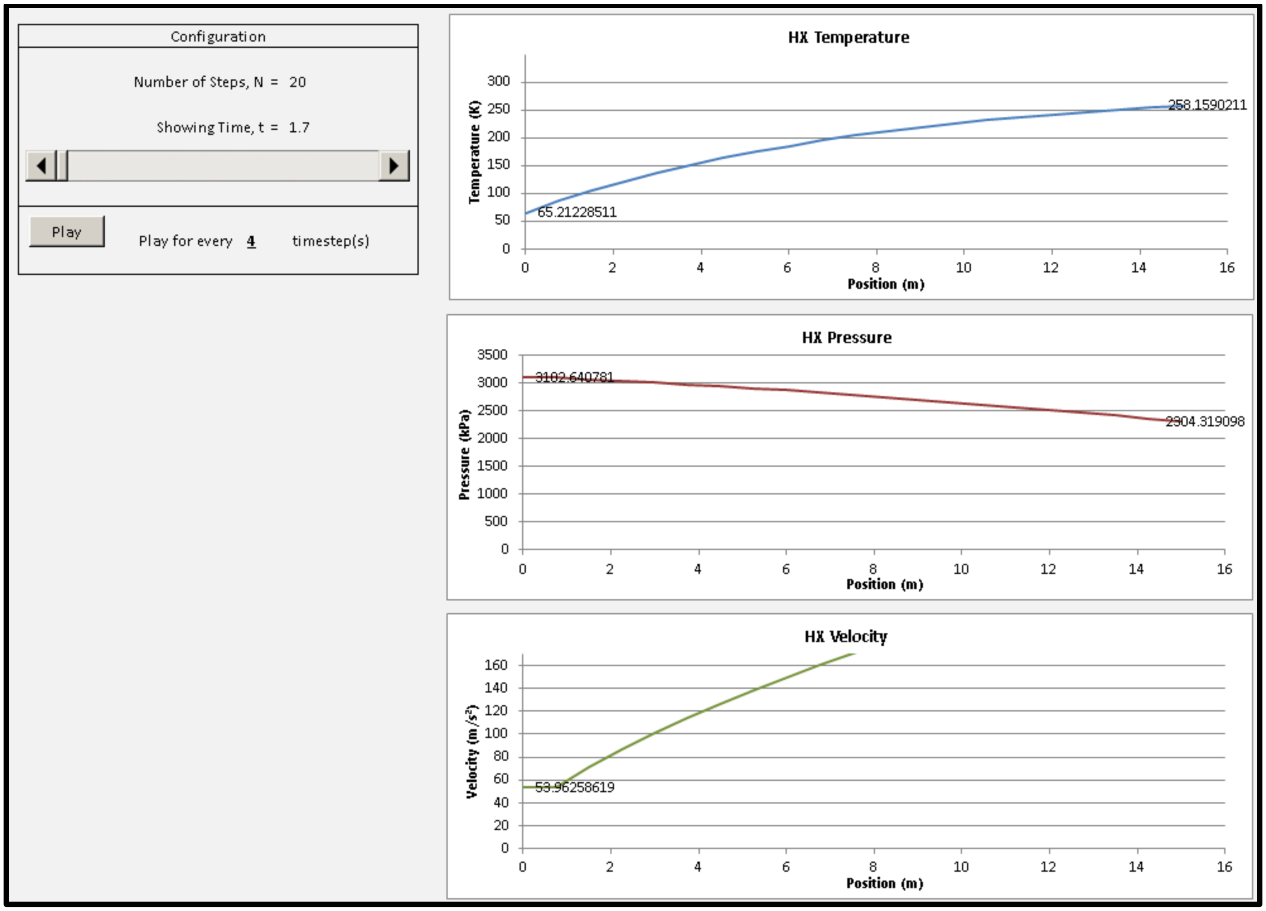


FIGURE 10 – FINITE DIFFERENT HX OUTPUT IN GUI

COMPARISON WINDOW

If two systems have been successfully configured and solved, a user may use a system comparison tool to evaluate the differences between all variables and inputs of the system. Using the "Save" button, a user can save the inputs in a system and also has the option to save any solution that the program has created. These solutions can then be imported in, side by side, and a color coordinated display will present the percent differences for each of the inputs, as well as the mass and heat exchanger energy results. Any system variable can be graphed such that the two systems will be compared alongside one another. This last feature was particularly useful when evaluating the success of the test bench model and comparing it to experimentally captured data.

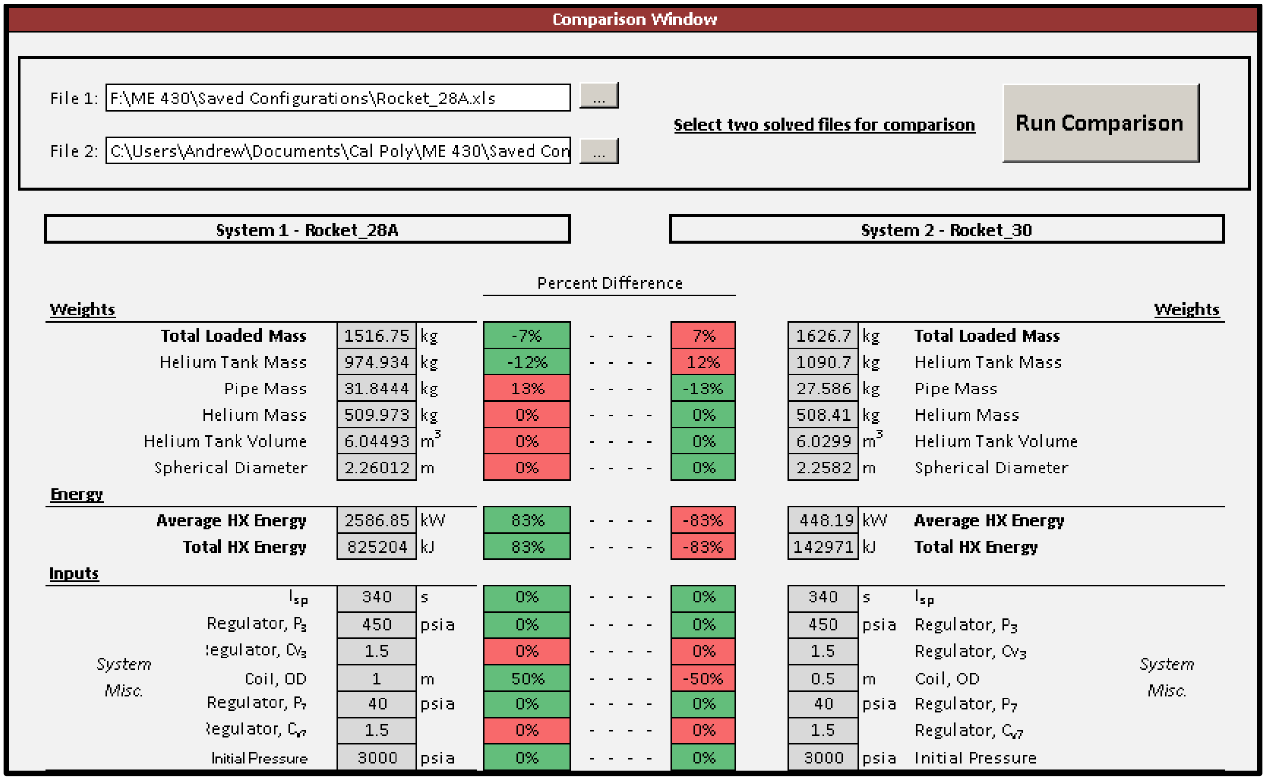


FIGURE 11 – SYSTEM COMPARISON IN GUI

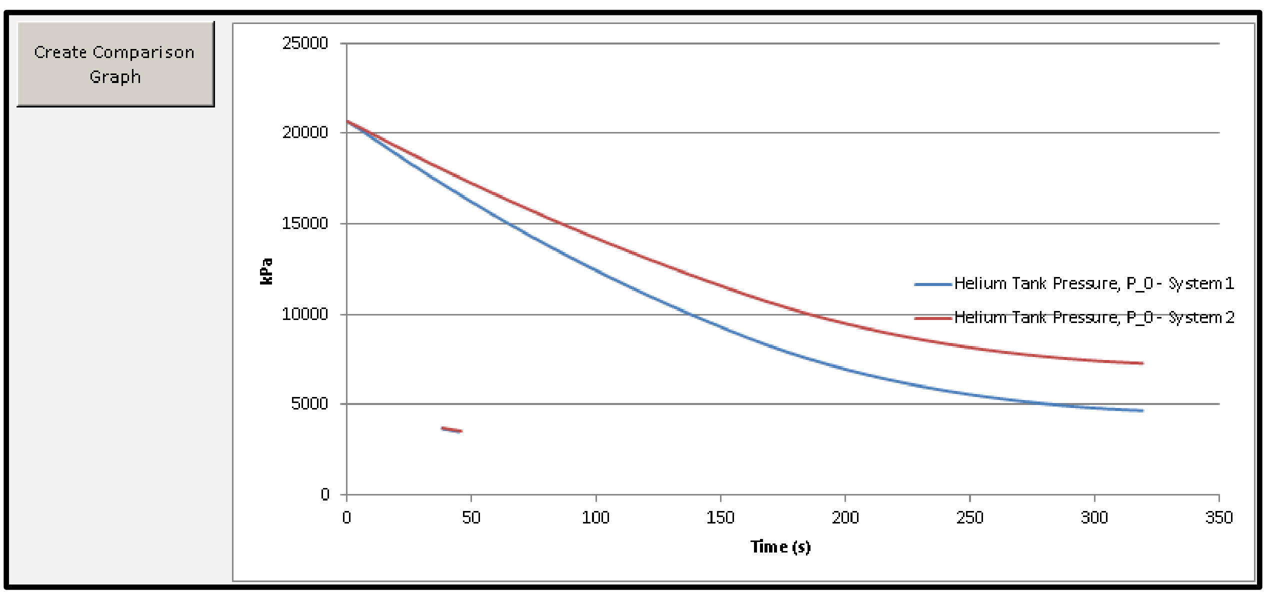


FIGURE 12 – SYSTEM COMPARISON GRAPH

In addition to the inputs that a user configures in the main input window, there is a set of system parameters that a user can configure. These parameters include the type of fuel, pressurant, and coolant used in the system; user defined loss coefficients; solving tolerances; timestep profile; and a thrust profile.

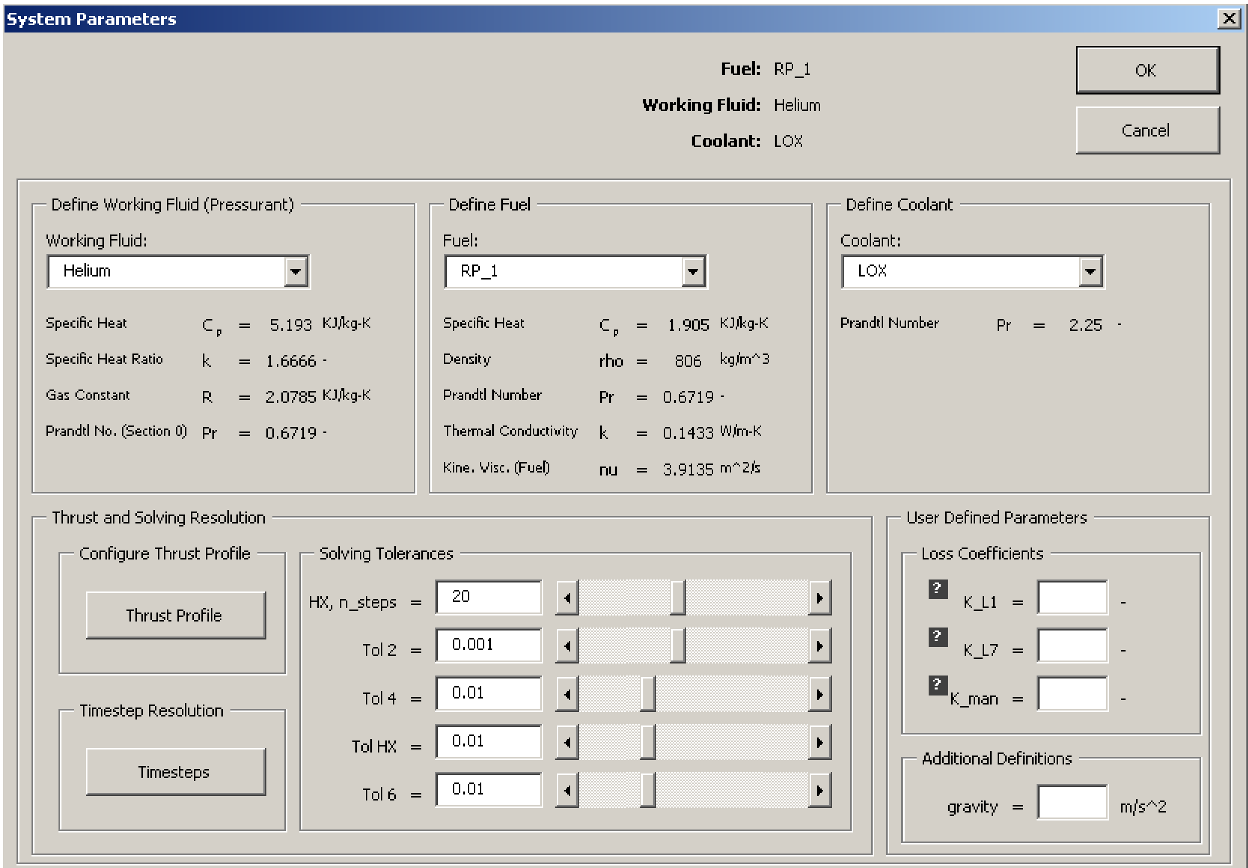


FIGURE 13 – SYSTEM PARAMETERS WINDOW IN GUI

If a user has solved a system and notices unexpected oscillations, or otherwise erratic curves, in their output graphs, they can configure the program such that it will solve using a specific timestep profile (ie. in increments of 0.1s for the first 10 seconds and 0.5s timesteps thereafter) which has been found to relieve this issue. Additionally, solving tolerances can be defined for any of the calculations and each point in the system where iteration takes place.

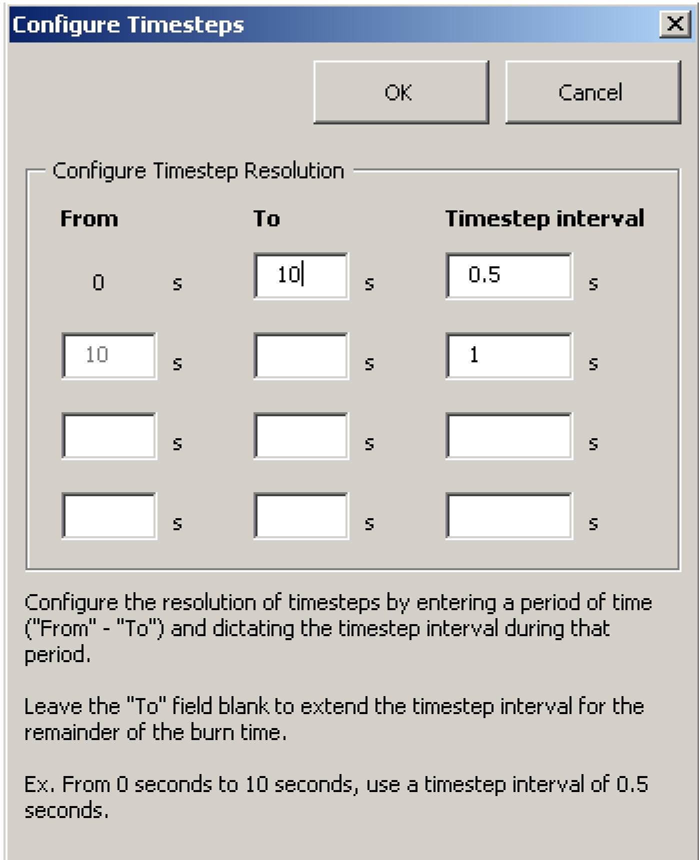


FIGURE 14 – TIMESTEP RESOLUTION WINDOW IN GUI

To calculate a burn time for the system, a user must specify a thrust profile, which they can do in the system parameter window. The thrust profile can be approximated by specifying segments of either constant or linearly decreasing/increasing thrust for specific intervals of time.

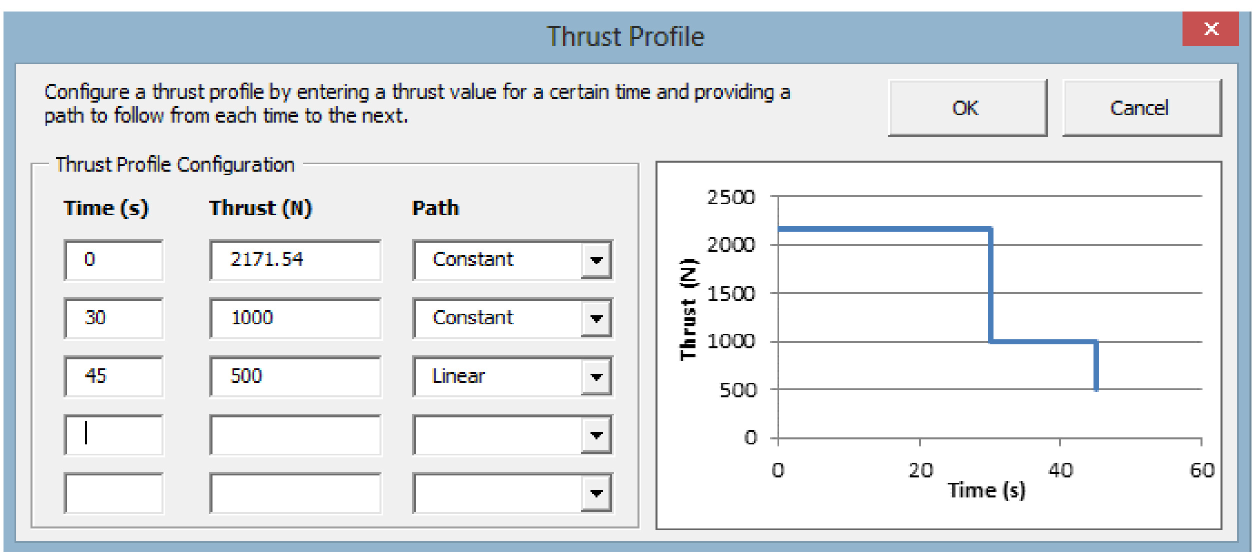


FIGURE 15 – THRUST PROFILE CREATOR IN GUI

In addition to all necessary inputs and parameters used for configuring a pressurization system, this application contains full documentation and trouble-shooting for the most common issues that a user is likely to encounter when using the program. Robustness is built into the application, such that the vast majority of bugs encountered in developing and testing this program have been eliminated. Users will normally be confined to a single window, and will not see the back-end sheets where calculations are performed unless necessary.

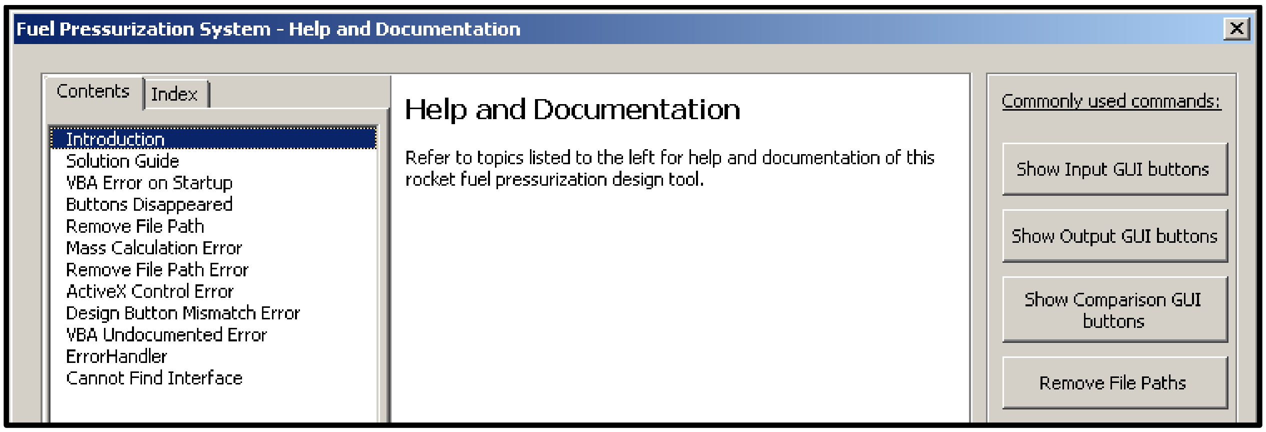


FIGURE 16 – HELP MENU IN GUI

The program is built to be modular, such that if a user wishes to update their assumption list (which is provided), and subsequently change solving methods or equations, they can do so. A user may add or subtract variables and assumptions, and the VBA code is documented thoroughly such that an inclined user could theoretically make necessary changes. If a user changes any backend solution methods, however, the model will have to be re-validated and the testing completed by Under Pressure Engineering no longer be valid.

For additional documentation and program functionality, see the "Help" inside the actual Excel file.

Ideally, the user should be able to obtain a numerical solution for a given set of inputs, or at least obtain a relevant error message suggesting possible fixes to obtain a full solution. Regardless, the interface provides a limited view on the actual complexity of this analytical tool. Much of what happens occurs behind the scenes, and some of these areas are the focus of this section. See Appendix E for a more detailed analysis of key equations used in the model.

"CALCULATIONS" TAB

While many of the equations were calculated in VBA (see Appendix F for sample code), a wide range of variables were computed directly in an Excel sheet called "Calculations". Originally thought to be able to contain all the necessary equations to solve the transient model, the worksheet became too unstable due to countless iterative loops and dependencies. To properly solve the system, some of the variables were transferred to VBA, and those values are then pasted as constants in the respective cells. However, there are over 170 variables in this worksheet, and more than half of them are calculated without assistance from Visual Basic.

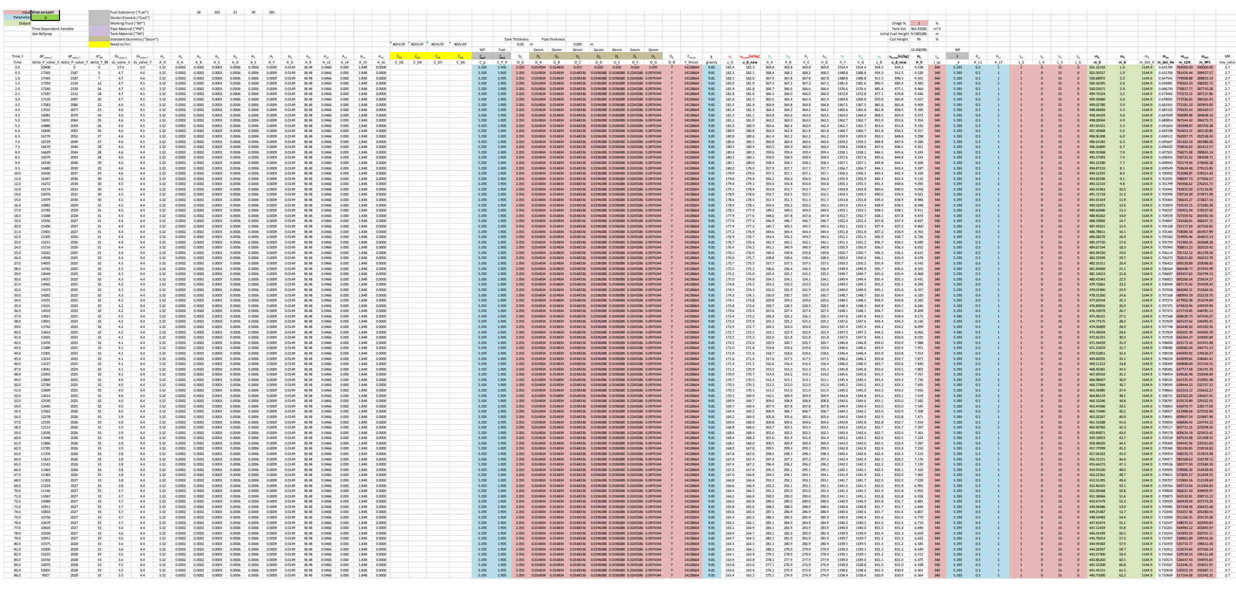


FIGURE 17 – WIDE AREA OF "CALCULATIONS" SHEET

The figure above shows a large section of this sheet. Individual variables are assigned a particular column, and individual time steps correspond to a full row. Thus, any cell represents a particular variable at a given time. This is more clearly demonstrated in Figure 18. (Note that color codes correspond to a particular type of variable and are not arbitrarily assigned.)

											Ullage %	1	%	
											Tank Vol	363.43585	m^3	
											Initial Fuel Height	9.5381286	m	
											Coil Height	95	%	
												15.036785		WF
F_{thrust}	g	u_0	**$u_{0,new}$(kJ/kg)**	h_A	h_B	h_C	h_D	h_F	h_G	u_8	**$u_{8,new}$(kJ/kg)**	**H_9**	I_{sp}	k
F_thrust	gravity	u_0	**u_0_new**	h_A	h_B	h_C	h_D	h_F	h_G	u_8	**u_8_new**	**H_9**	I_sp	_k
14128664	9.81	182.4	182.3	369.8	369.8	369.8	369.8	1554.4	1554.4	934.3	934.3	9.538	340	5.193
14128664	9.81	182.3	182.1	368.4	368.2	368.2	368.2	1388.8	1388.8	934.3	911.5	9.520	340	5.193
14128664	9.81	182.1	182.0	367.9	367.8	367.8	367.8	1388.8	1388.8	911.5	896.5	9.501	340	5.193
14128664	9.81	182.0	181.9	367.3	367.2	367.2	367.2	1381.6	1381.6	896.5	885.4	9.483	340	5.193
14128664	9.81	181.9	181.8	366.7	366.6	366.6	366.6	1376.6	1376.6	885.4	877.1	9.464	340	5.193
14128664	9.81	181.8	181.6	366.1	366.0	366.0	366.0	1372.8	1372.8	877.1	870.8	9.446	340	5.193
14128664	9.81	181.6	181.5	365.5	365.4	365.4	365.4	1369.8	1369.8	870.8	865.8	9.427	340	5.193
14128664	9.81	181.5	181.4	364.9	364.8	364.8	364.8	1367.5	1367.5	865.8	861.8	9.409	340	5.193
14128664	9.81	181.4	181.3	364.3	364.2	364.2	364.2	1365.6	1365.6	861.8	858.5	9.390	340	5.193
14128664	9.81	181.3	181.1	363.8	363.6	363.6	363.6	1364.0	1364.0	858.5	855.9	9.372	340	5.193
14128664	9.81	181.1	181.0	363.2	363.0	363.0	363.0	1362.7	1362.7	855.9	853.6	9.354	340	5.193
14128664	9.81	181.0	180.9	362.6	362.4	362.4	362.4	1361.7	1361.7	853.6	851.8	9.335	340	5.193
14128664	9.81	180.9	180.8	362.0	361.8	361.8	361.8	1360.7	1360.7	851.8	850.2	9.317	340	5.193
14128664	9.81	180.8	180.6	361.4	361.2	361.2	361.2	1359.9	1359.9	850.2	848.8	9.298	340	5.193
14128664	9.81	180.6	180.5	360.8	360.6	360.6	360.6	1359.2	1359.2	848.8	847.6	9.280	340	5.193
14128664	9.81	180.5	180.4	360.2	360.0	360.0	360.0	1358.6	1358.6	847.6	846.5	9.261	340	5.193
14128664	9.81	180.4	180.3	359.6	359.4	359.4	359.4	1358.1	1358.1	846.5	845.6	9.243	340	5.193
14128664	9.81	180.3	180.1	359.0	358.9	358.9	358.9	1357.6	1357.6	845.6	844.8	9.224	340	5.193
14128664	9.81	180.1	180.0	358.4	358.3	358.3	358.3	1357.1	1357.1	844.8	844.1	9.206	340	5.193
14128664	9.81	180.0	179.9	357.9	357.7	357.7	357.7	1356.7	1356.7	844.1	843.4	9.187	340	5.193
14128664	9.81	179.9	179.6	357.3	357.1	357.1	357.1	1356.3	1356.3	843.4	842.3	9.169	340	5.193
14128664	9.81	179.6	179.4	356.2	356.0	356.0	356.0	1355.9	1355.9	842.3	841.4	9.132	340	5.193
14128664	9.81	179.4	179.1	355.0	354.8	354.8	354.8	1355.3	1355.3	841.4	840.6	9.095	340	5.193
14128664	9.81	179.1	178.9	353.9	353.7	353.7	353.7	1354.8	1354.8	840.6	840.0	9.058	340	5.193
14128664	9.81	178.9	178.6	352.7	352.5	352.5	352.5	1354.3	1354.3	840.0	839.4	9.021	340	5.193
14128664	9.81	178.6	178.4	351.5	351.3	351.3	351.3	1353.8	1353.8	839.4	838.9	8.984	340	5.193

FIGURE 18 – LOCAL AREA IN "CALCULATIONS" SHEET

"QUICK MODEL" TAB

Though our model provides a thorough, transient solution for a helium pressurant system, our sponsor, Frontier Engineering, has asked us to develop a shortcut method for calculating the optimized heat exchanger length to minimize pressure system total mass. To accomplish this task, we created the "Quick Model" tab – actually two tabs – which compute the theoretical minimum helium tank diameter for a set of inputs. Due to the general nature of this calculation, the answer is based on an empirical factor, which remains the same as long as the inputs are constant. Thus, the effect of changing the heat exchanger tube length, which does not affect this factor, can be seen as long as other parameters (i.e. geometry, thrust profile, etc.) are unaltered. Due to the experimental nature of these factors, users are cautioned to oversize the tank when the quick model suggests a size considerably smaller than the current input. The raw calculation tab associated with this quick model is shown below.

Start P	20684	kPa					
Start T	60.93	K					
Ideal P	4653.96	kPa					
Ideal T	37.97	K					
m_start orig	501.321						
	Original	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6
Volume:	4.54	4.54	4.54	4.54	4.54	4.54	4.54
New m_final	236.8	236.7	236.7	236.6	236.6	236.6	236.6
delta_m	84.7	84.8	84.8	84.8	84.9	84.9	84.9
Factor	1.203	1.203	1.203	1.203	1.203	1.203	1.203
new m_start	501.2	501.1	501.0	501.0	501.0	501.0	501.0
new vol	4.54	4.54	4.54	4.54	4.54	4.54	4.54
new dia	2.055	2.055	2.055	2.055	2.055	2.055	2.055

FIGURE 19 – "QUICK MODEL" SHEET SETUP

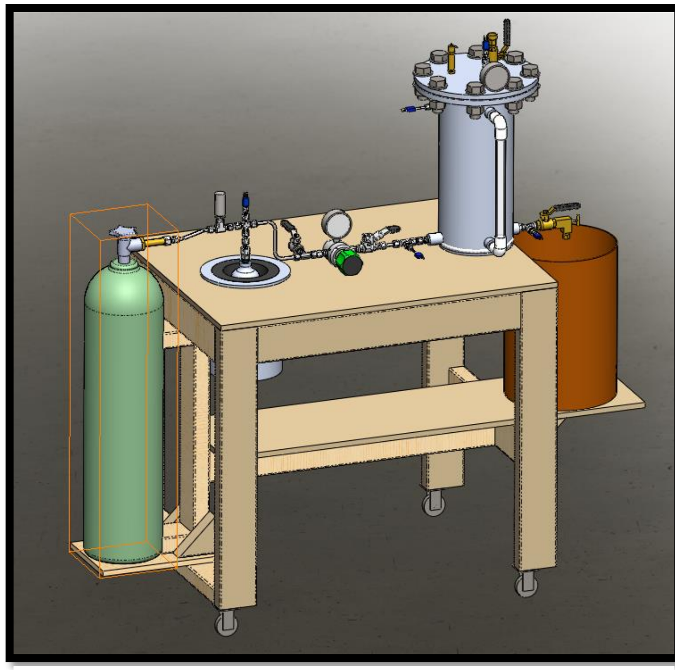


FIGURE 20 – TEST BENCH MODEL

To benchmark our analytical model, we built a small, simplified model of the pressurization system. This system consisted of a similar setup to the SSTO launch vehicle; however there will be some small changes to make the experiment safer and more viable in a laboratory environment. Instead of using rocket fuel we substituted water, which has similar thermal conductivity properties. Also, instead of using liquid oxygen as our coolant used liquid nitrogen, which has a similar melting point (16 ^{0}F colder, -321 ^{0}F), and is readily available on the Cal Poly campus.

The model consisted of five areas: a helium tank, an auxiliary helium tank cooled in liquid nitrogen, a regulator, a coiled heat exchanger and a water reservoir. When a valve is opened on the helium tank, pressurized helium moves into the auxiliary tank until it has reached equilibrium. At this point, we shut in the auxiliary tank, and cool the tank to -321 ^{0}F while maintaining the same pressure, lowering the density of the helium. After cooling, a valve on the outlet of the tank is opened, allowing the regulator to maintain a constant, lower pressure downstream as the helium flows through the heat exchanger. Following the heat exchanger, the helium moves into the fuel tank, where pressurizes the water to a designated pressure, pushing the water through a needle valve into a catch bucket. Throughout the system, we monitored the pressure and temperature using a combination of two pressure gauges, a pressure transducer and four Type T thermocouples. In addition, we will measure the water flow by using a clear, graduated cylinder. The sensors were run through a Data Acquisition System, allowing us to accurately monitor and analyze the transient variables in the experiment.

This experimental model allowed us to test our analytical tool. The goal of the experiment was not to recreate the internal working of the launch vehicle, but rather to input all of conditions of the physical experiment into the analytical model and have it output similar results.

The test bench was designed with safety in mind. On the high pressure side, prior to the regulator, we should not see more than 1900 psi, the fill pressure of the helium tank, and we have sized the system to accommodate at least 2000 psi. If we were to see more than that we have an emergency relief valve located on the auxiliary tank that allowed us to dump pressure from the system. The low pressure side of the system is controlled by a regulator that regulates pressure from 0-100 psi. This side of the system has been pressure rated to at least 150 psi, and in the event that our regulator stops functioning properly and sends high pressure downstream, we have a high flow, relief valve set to open at 100 psi to protect the operators and equipment. All welding done was completed by a professional welder to ensure operator safety. A full procedure has been drafted to warn the operators of any potential dangers they could run into if the test bench is not properly handled. This document can be found in Appendix G.

The test bench uses a variety of different pipe fittings to connect. Wherever possible, the bench will use *Swagelok* fittings, however to connect in to the valves and regulator, pipe connections will be used. To ensure that the gauges will be in the correct orientation JIC swivel fittings will be used where needed. See Appendix B for drawings and P&IDs.

FIGURE 21 – FULL TEST BENCH CONSTRUCTION SETUP

CHAPTER 6 – MODEL VERIFICATION

TEST BENCH: LOW PRESSURE SIDE

One of the biggest problems that we faced in the construction and testing of the test setup was that helium leaks occurred across a few of the pipe joints. Initially, we experienced leaking across the gasket at the top of the fuel tank at pressures over 20 psig. To eliminate this problem, the fiber gasket was replaced by a rubber gasket, and we increased the torque setting on the flange bolts to 150 ft-lb. Throughout testing, this leaking was especially noticeable at the connection coming out of the auxiliary helium bottle; because of this, we were not able to test the high pressure side of the system above 1,100 psi. Additionally, many of the fittings could not be fully sealed when exposed to cryogenic temperatures. Different coefficients of thermal expansion resulted in increased clearances, and the fittings could not be tightened after the threads iced over. However, even with the helium seepage, we were able to maintain a sufficient pressure in the helium bottle to run successful tests. In the future it is recommended to eliminate any pipe connections if possible, use rubber gaskets and O-rings and to ensure that all pipe connections are properly taped to reduce the occurrence of consistent leaks.

We used an *MCC USB-2408* data acquisition system to capture the data from the test bench onto a strip chart running on a laptop. While we were able to attain a maximum sampling rate of 11 Hz, we chose a 10 Hz sample rate, because of the clean decimals and exact match with our model resolution (also 10 Hz). After the first round of testing, we discovered that the system, primarily two thermocouples, appeared to be shorting when the pressure transducer was drawing 5V power from the DAQ board. To circumvent this problem, we used a dedicated power supply to power the transducer in the final round of tests. Our team suspects that this issue likely stemmed from a wire that shorted in one of the thermocouples; however, we were not able to isolate the issue, and changing the power source kept it from affecting our results.

One area we had trouble characterizing throughout the entire project was the fluid behavior across the valve. This held true in the test bench as well, as helium was flowing out of the valve at a significantly higher temperature than our model initially predicted. This led to the heat exchanger inlet temperature being higher than expected, providing us with less meaningful data to analyze on the outlet of the heat exchanger. In an attempt to reduce the heat transfer from the helium bottle exit to the heat exchanger inlet, we poured liquid nitrogen on the connecting tube to reduce the surface temperature. Though we decreased the temperature well, below ambient, the plot below reveals that we were still very far off from our theoretical model (~150 K).

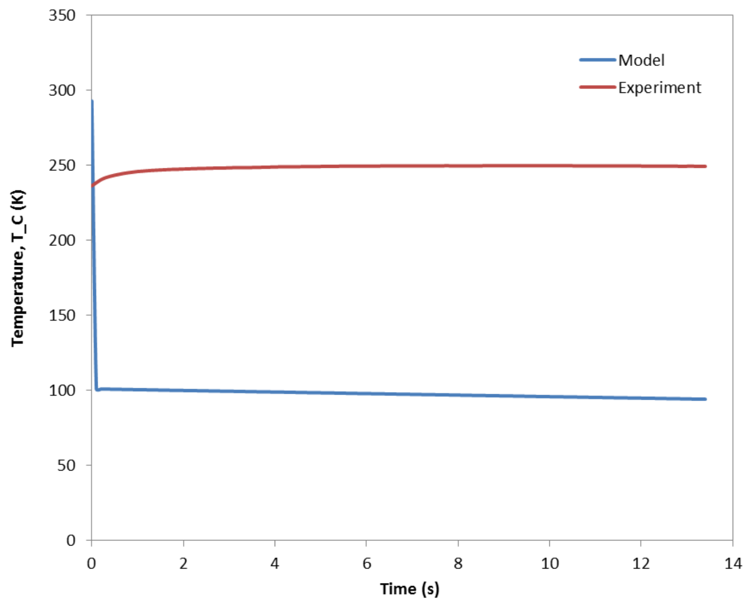


FIGURE 22 – ORIGINAL HX INLET TEMPERATURE DATA (RUN 009)

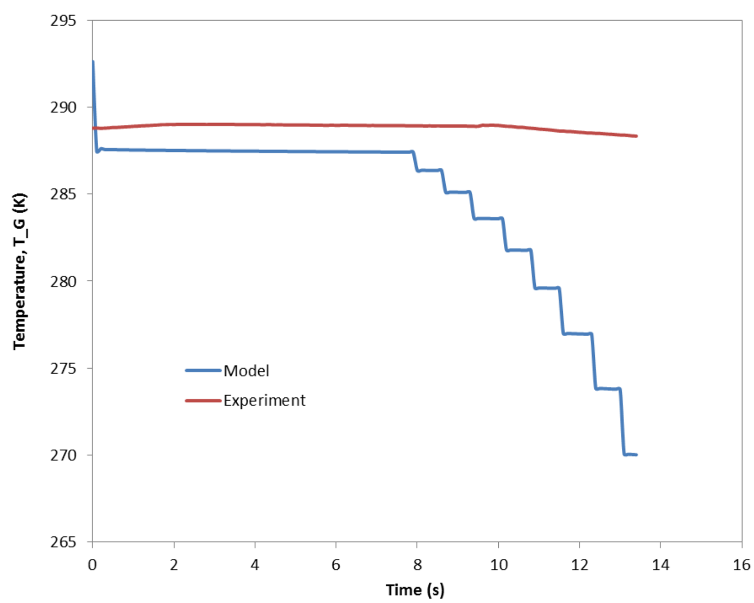


FIGURE 23 – ORIGINAL HX INLET TEMPERATURE DATA (RUN 009)

As expected, the large discrepancy between our model and experimental inlet temperatures resulted in a large error between the outlet temperatures as well (see Figure 23 above). This, in turn, affected the ullage gas temperature, and we observe a predicted temperature below actual data.

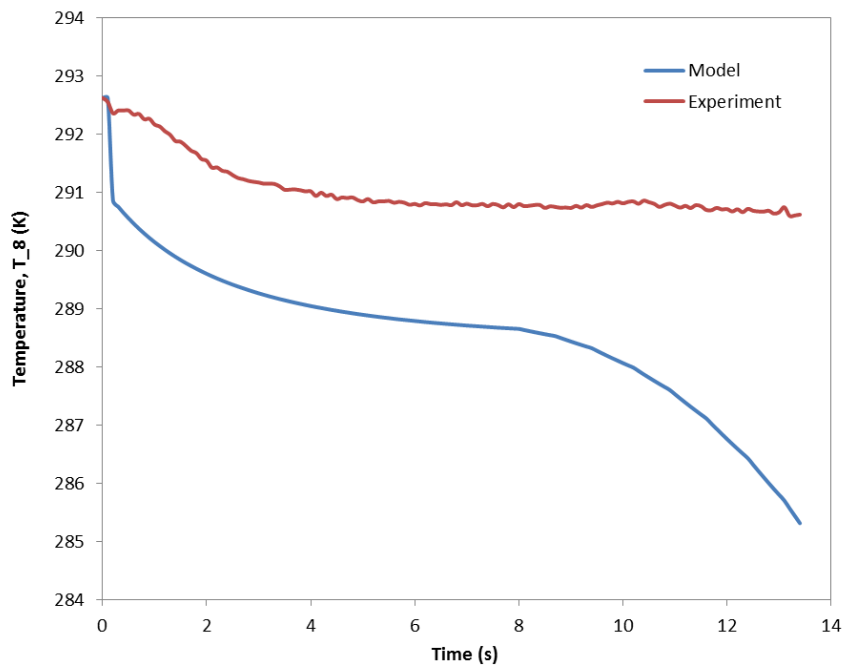


FIGURE 24 – ORIGINAL ULLAGE GAS TEMPERATURE DATA (RUN 009)

A cursory glance at the results above would lead to the assumption that our analytical model developed for the project is flawed. While we cannot say with absolute certainty that it is perfectly sound, we decided to modify the model parameters to produce heat exchanger inlet temperatures that more closely resembled the actual data taken from this high flowrate run. This allows us to directly compare the heat exchanger model with our physical system. Modification of the helium tank temperature created the necessary inlet temperature, and enlarging the helium tank diameter in the model allowed us to decrease the change in inlet temperature associated with a properly sized model.

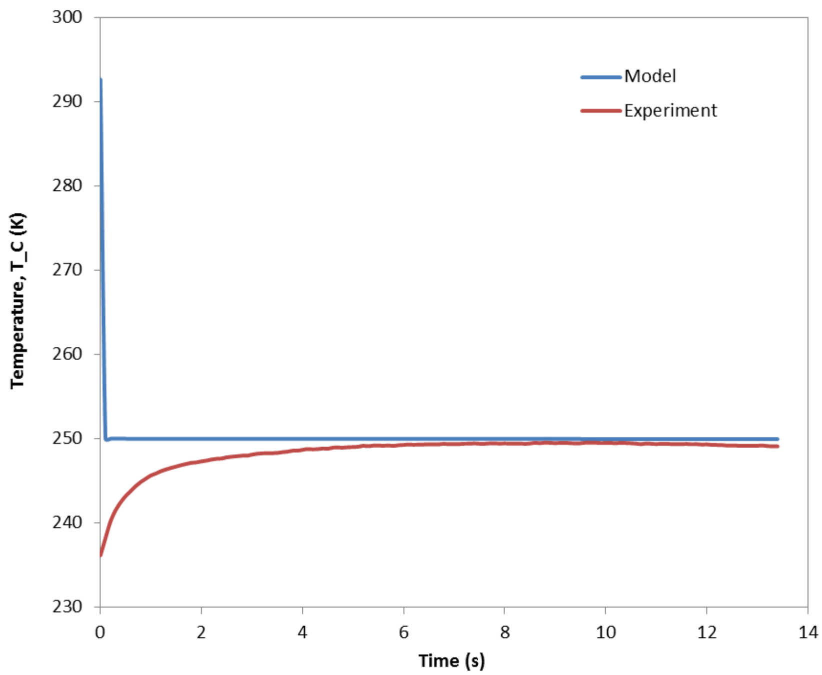


FIGURE 25 – MODIFIED HX INLET TEMPERATURE DATA (RUN 009)

Now that the model deviates by a maximum of 10 K, we can directly compare the outlet temperatures to verify the analytical model. This is shown in the plot below.

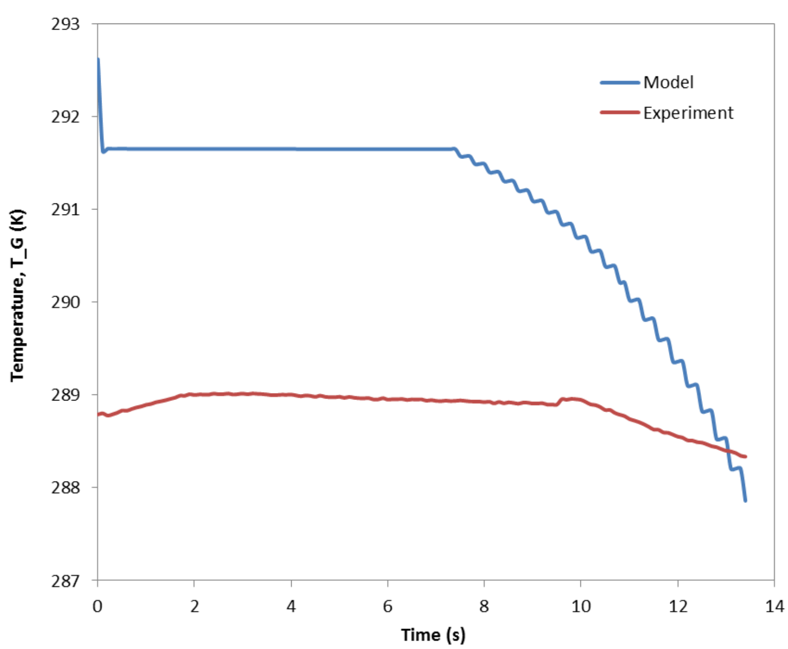


FIGURE 26 – MODIFIED HX OUTLET TEMPERATURE DATA (RUN 009)

As Figure 26 reveals, our heat exchanger model is quite accurate, with a steady state error of around +2.7 K and a steeper drop off as the coil is exposed to ullage gas due to the receding water level in the tank. While it appears large in the figure, the steady state error is relatively small, and the slightly high prediction can be attributed to the slightly high inlet temperatures that the model created in the modified analysis. The steep drop in the model towards the end is caused by the elimination of heat transfer we assumed once the given heat exchanger segment is exposed to the ullage gas. Although some heat transfer will occur, the energy gained in the moving helium comes from the energy lost in the ullage space; thus, the net transfer is zero. To illustrate this point, note the close proximity between the anticipated and actual ullage gas temperature data.

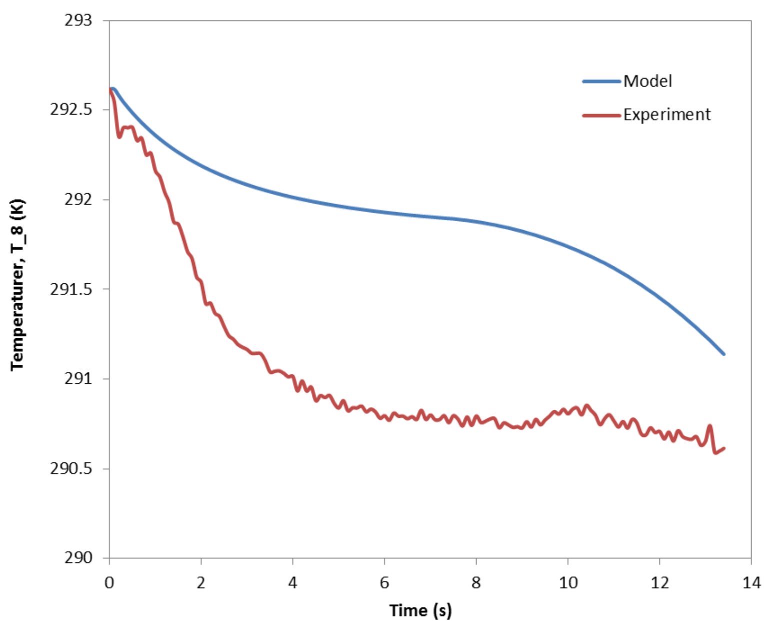


FIGURE 27 – MODIFIED ULLAGE GAS TEMPERATURE DATA (RUN 009)

As before, the plot is misleading. While the gap between our two data sets appears to be large, the difference is less than 1.5 K. Furthermore, the model trends similarly to the actual data. Thus, we believe that the tests we were able to conduct give additional credibility to our model, though we admit that some areas could be improved in the future.

However, despite our relatively accurate comparison, we are force to conclude that this test bench setup is simply too small to fully validate the low pressure side of the system. Even at the fastest flowrates and highest water tank pressures possible, the helium in the tube is greatly affected by the thermal mass present in the piping and tanks. While this will still be present in a full-size model, the ratio of pipe/tank mass to helium mass will be orders of magnitude lower than in the test bench.

In addition, the Reynolds numbers that are expected in a full-size model will be much greater than anything that can be achieved in the small tubes we were using for this bench; we are limited by a velocity threshold that cannot be exceeded – Mach 0.3 – to assume no particular compressibility effects occur. The non-scaled geometry of the heat exchanger coil could also affect

results. Since the critical transition Reynolds number is modulated by coil geometry, the laminar region may expand or contract, depending on the configuration used. As a result, the heat transfer correlations we are using for the full rocket simulation required alteration from turbulent to laminar or mixed flow. Though we added several laminar correlations to handle the test bench analysis, we may have overlooked some, perhaps even contradicting a fundamental assumption we hold for our model. Thus, even if we were able to attain the predicted heat transfer and temperature values around the heat exchanger, it would not give us conclusive evidence to verify the analytical model. While it is very difficult to predict the effects of thermal mass on the helium, we believe that a fuel tank approximately the size of a large air compressor tank would be able to give sufficient results to accurately represent the full size model. A tank this large would allow us to achieve fully developed turbulent flow in the heat exchanger, minimizing the impact of thermal mass in the tubing, and can give a better representation of the actual regulator valve we would be planning to use. Table 4 summarizes this point.

TABLE 4 – REYNOLDS NUMBER SYSTEM CHARACTERIZATION

System	Critical Re	Actual Re
Test Bench	5700	9800
Rocket	3800	1540000

TEST BENCH: HIGH PRESSURE SIDE

While the low pressure side of the test bench does not provide very strong data to anchor our model to, we found that the high pressure side correlates very well with our experimental data.

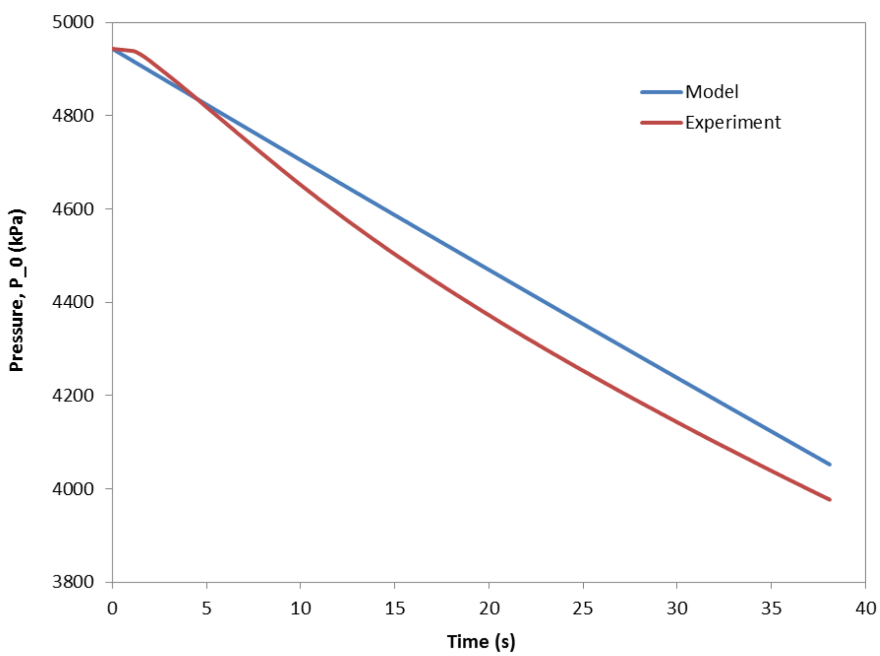


FIGURE 28 – HELIUM TANK PRESSURE VERIFICATION (RUN 007 – LOW FLOWRATE)

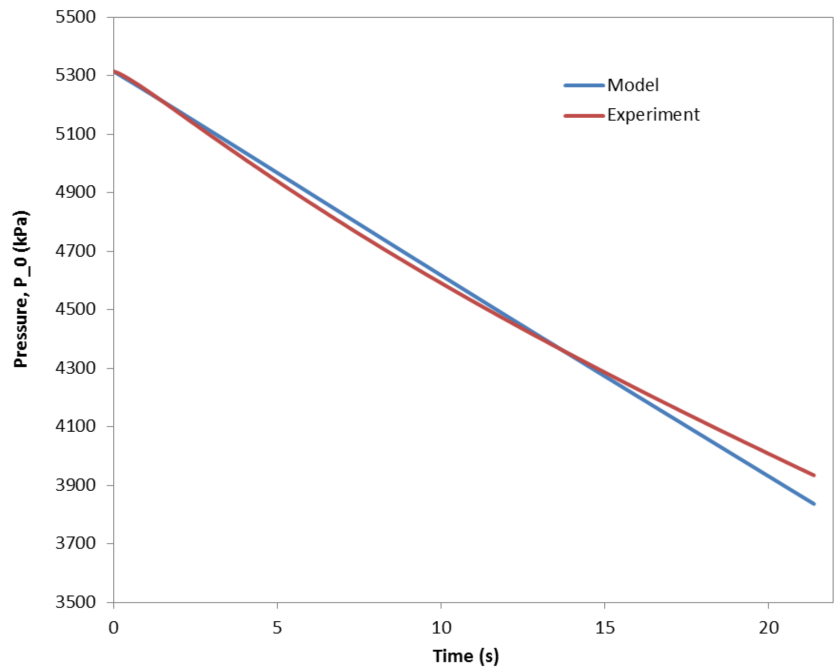


FIGURE 29 – HELIUM TANK PRESSURE VERIFICATION (RUN 008 – MEDIUM FLOWRATE)

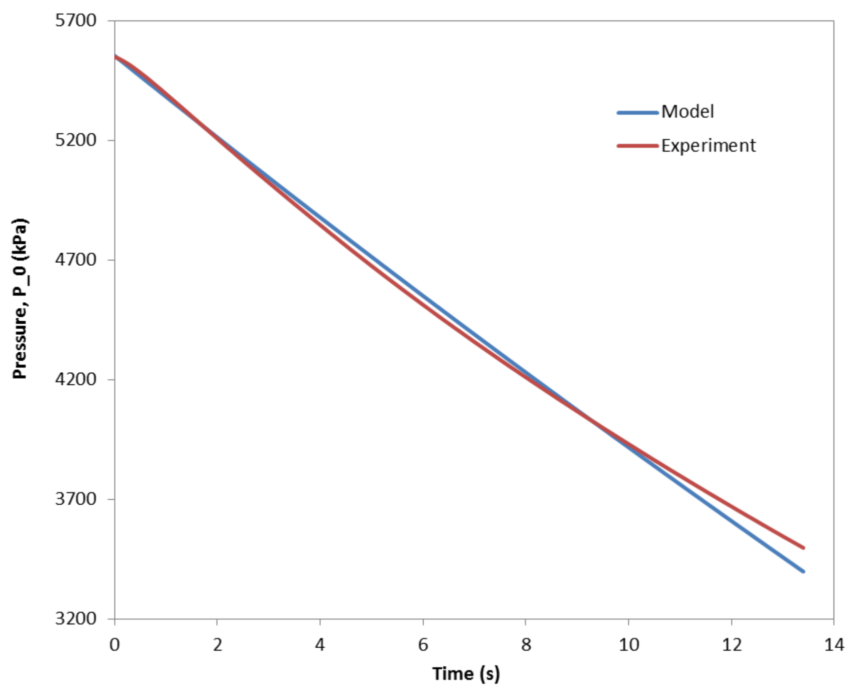


FIGURE 30 – HELIUM TANK PRESSURE VERIFICATION (RUN 009 – HIGH FLOWRATE)

The three figures above show the helium tank pressure curves for our model and test bench data collected during Runs 007 – 009. These three runs correspond to the widest range of flowrates we obtained during our tests. Key parameters for each of these data runs is shown below.

TABLE 5 – DATA RUN SUMMARY AT VARIOUS FLOWRATES

Run	Regulator Outlet P_3 (psia)	Water Height Drop (in)	Drop Time Δt (s)	Mass Flow Rate (kg/s)	Equivalent Thrust F_t (N)
007	36.7	8.0	33.0	0.1144	763
008	54.7	8.0	18.5	0.2041	1362
009	88.7	8.0	11.6	0.3255	2172

Careful observation will reveal that at all three flowrates, the model-experiment comparison is quite precise. Though the margin in Figure 28 appears to be larger than the subsequent plots, we can see that the y-axes are not of equal scale. To summarize the error margins in both the pressure and temperature graphs – temperature plots are shown in Appendix H – see the following table.

TABLE 6 – HELIUM TANK PRESSURE & TEMPERATURE ERROR

Run	Average Pressure Deviation (%)	Average Temp Deviation (%)	Max Pressure Error (%)	Max Temp Error (%)
007	1.65	2.55	2.35	3.91
008	0.64	3.54	1.70	6.21
009	0.72	4.12	2.84	9.62

It is evident that our temperature plots were not nearly as precise as our pressure graphs. Sources of the error can be attributed primarily to the helium tank cooling region. As specified in the test bench drawings, the helium bottle was placed in an insulated aluminum container, which was capped by a piece of foam to eliminate excessive boil off of the liquid nitrogen. However, the liquid nitrogen reacted so violently to the top of the aluminum container that we could only fill up about half of the cavity with liquid nitrogen at any given time. Therefore, we believe that the helium bottle contained an adverse temperature gradient, where the warmer helium stayed in the upper portion of the bottom and the cold helium was immersed in liquid nitrogen towards the bottom. Figure 31 shows evidence for this supposition.

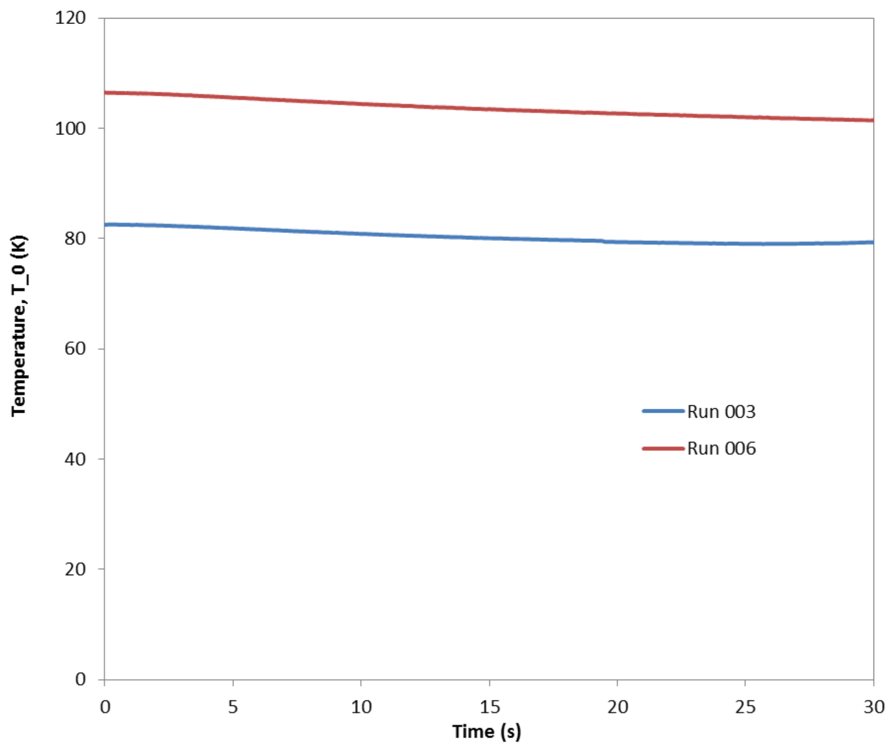


FIGURE 31 – HELIUM TANK TEMPERATURE COMPARISON

This temperature data was taken during two different runs, which occurred on different days of testing. During the initial phase of testing (Run 003), we placed the helium tank thermocouple towards the bottom of the helium bottle. We were quite pleased to find that the liquid nitrogen cooled the helium down to cryogenic levels, but we did not suspect a temperature gradient at this point. Due to the inconsistent data obtained during the first night (Runs 001-005), we decided to make some modifications to the test bench. One such change was locating this temperature thermocouple towards the top of the helium bottle. During the second round of tests (Run 006), we found a 20 K jump in the helium bottom temperature, which lends itself to the theory presented in this section.

Identifying the problem was easy compared to constructing a useful solution. Unfortunately, our helium tank container was too shallow to properly immerse the tank in liquid nitrogen. The resulting temperature gradient in the bottle may very well account for our discrepancies between the experiment and model, especially since the experimental temperature data seems to unexplainably fall below the model's prediction as the run progresses. Applying the proposed gradient theory, we can reason that the warm helium evacuated the tank in the initial section of the run, which left cold helium below to now fill the tank and, as far as the thermocouple sensed, lower the gas temperature in the bottle.

CHAPTER 7 – RECOMMENDATIONS & CONCLUSION

RECOMMENDATIONS

After performing the validation testing, we recommend that further testing be completed using a larger-scale test setup. The small setup that we used was useful to determine the general trends and overall validity of our system; however, we were not able to achieve the maximum 5% average deviation for every variable tested that we were hoping for between the model and the bench. This is due to a variety of reasons, which are discussed in depth in Chapter 6. In short, the test bench was too small to fully represent many of the finer details in the full size system, and the disproportional scaling between tubes, tanks, and helium mass resulted in unanticipated effects. If testing is continued, it is recommended that the system is resized with a much larger fuel tank which will reduce the effects of ambient heat on the helium and would allow the flow to become fully turbulent. Furthermore, fully submerging the helium tank in the liquid nitrogen would benefit data collection and verification on the high pressure side of the system.

We have found several errors with our test bench design, and thus, we cannot fully verify the analytical model. However, assuming that the model UP Engineering has developed is accurate, there are a few important takeaways we get from applying our model to the SSTO rocket feasibility study. First, there is an upper limit on the effective length of a heat exchanger. Once the helium gas reaches ambient (fuel tank) temperature, there is no need to add additional length to the heat exchanger. Furthermore, the marginal benefit obtained from added length to the heat exchanger diminishes as the coil gets longer. For instance, the benefit of increasing the coil from 5m to 15m is very noticeable; increasing from 15m to 25m may be useful as well; but the jump from 25m to 35m may not be worth the added weight.

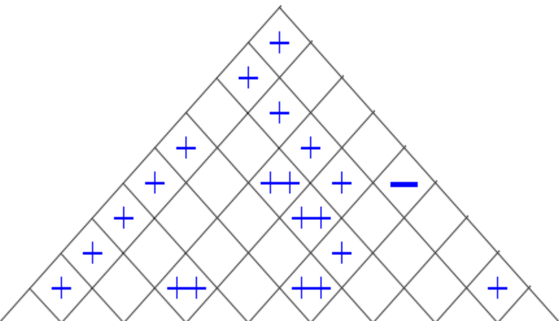
The second observation is that the helium tank mass is the primary contributor to the pressurant system weight. Therefore, if there is any way to decrease wall thickness or diameter of the tank, it is generally worthwhile to do so. This can be achieved through various aspects of the system design. For instance, the wall thickness can be decreased by changing the tank material. The overall diameter can be decreased by increasing the heat exchanger length. The helium tank volume can be reduced by sub-cooling the LOX to -350°F, which produces a very large reduction in tank mass compared to the initial system at -300°F. Considering each of these options will help users, such as Frontier Engineering, to better optimize their fuel pressurant systems.

CONCLUSION

During the three quarters spent on this senior project, UP Engineering was able to develop a fully-functioning, transient GUI to analytically model a fuel pressurant system. Initially, we created a steady state model that was implemented in a basic Excel GUI. This model was then upgraded to a fully-functioning transient analytical model during the first part of winter quarter. Moving forward, UP Engineering built a physical bench for testing and verification of the pressurization system and supporting analysis. Testing of this bench occurred in spring, and the preliminary results look promising. The models and conclusions derived therein will be handed off to Jim McKinnon of Frontier Engineering for use and aid in the design of a single-stage-to-orbit reusable launch vehicle. Ideally, the designs and analysis constructed through this project will provide a solid foundation that will aid Frontier Engineering in their goal to construct a reusable launch vehicle.

APPENDIX A – QUALITY FUNCTION DEPLOYMENT

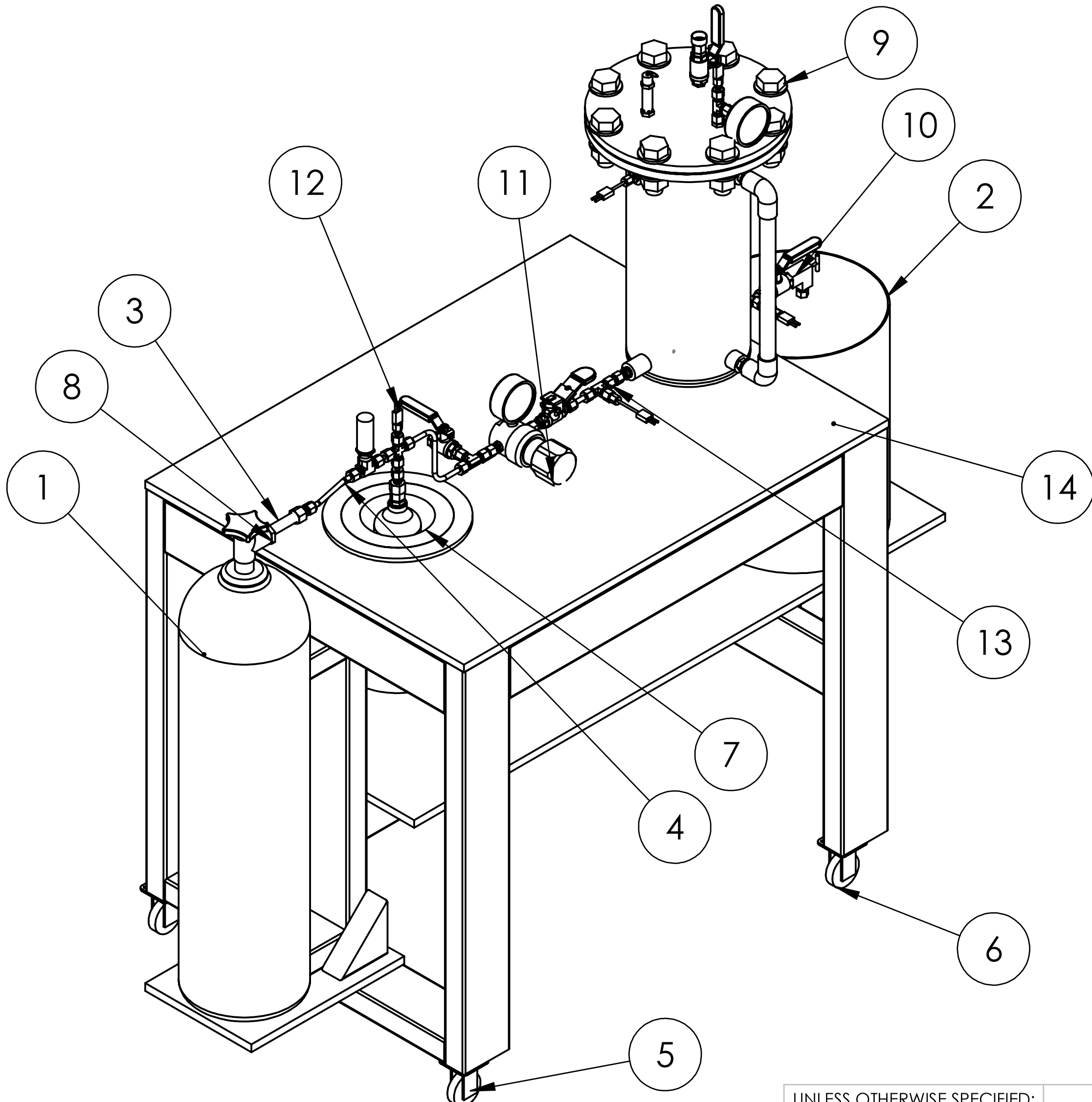
Legend		
◎	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▲	▲	x	x	x	x	▼	▲
				Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Dry Weight	Overall Heat Transfer Coefficient	Cycles to Failure	Reliability	System Volume	Fuel Tank Pressure	Maximum Thermal Stress	Unit Cost	Heat Exchanger Efficiency
1	9	20.0	5.0	Lightweight	◎		○	○	○	○		◎	▲
2	9	20.0	5.0	High Number of Cycles to Failure	○		◎	○		▲	◎	○	
3	9	4.0	1.0	Low Cost	○	▲	▲	○	▲	▲	▲	◎	○
4	9	16.0	4.0	High Heat Transfer		◎	▲	▲	○		▲	▲	◎
5	3	12.0	3.0	Low Vibration	▲		○						
6	9	12.0	3.0	Compatible Materials		○	▲	○	▲	○	◎	▲	▲
7	3	8.0	2.0	No Fuel Freezing		○		▲		▲			▲
8	3	8.0	2.0	Manufacturability	▲	▲	▲	▲	▲			○	○
				Target or Limit Value									
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)									
				Max Relationship Value in Column	9	9	9	3	3	3	9	9	9
				Weight / Importance	272.0	216.0	316.0	200.0	132.0	128.0	308.0	328.0	220.0
				Relative Weight	12.8	10.2	14.9	9.4	6.2	6.0	14.5	15.5	10.4

FIGURE A1 – HOUSE OF QUALITY FOR FUEL PRESSURIZATION SYSTEM.

APPENDIX B – TEST BENCH COMPONENT DRAWINGS



ITEM NO.	PART NUMBER	QTY.
1	Helium Tank	1
2	Bucket	1
3	MC 79215A665	1
4	TB002	1
5	MC 2406T19	2
6	MC 2406T61	2
7	TB005	1
8	MC 79215A664	1
9	WR000	1
10	WO000	1
11	RA000	1
12	AT000	1
13	$\varnothing$0.25" x 2" SS Tube	1
14	TA000	1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

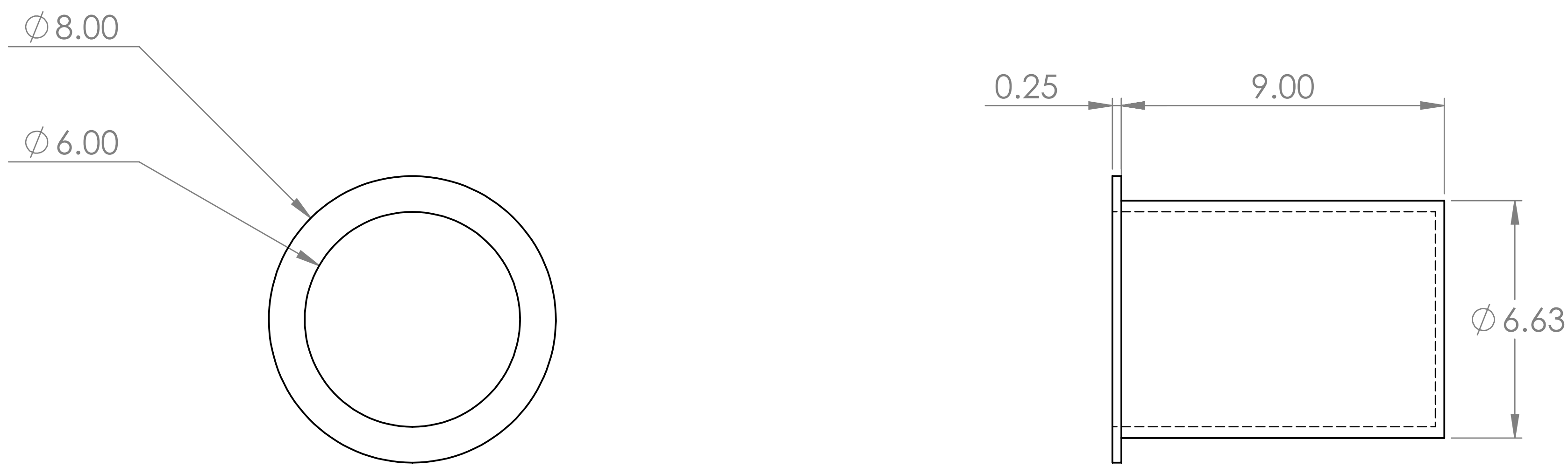
UNDER PRESSURE ENGINEERING

TITLE: Test Bench Overview

SIZE A | DWG. NO. TB000 | REV

SCALE:1:10 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005	
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	AL 6061
FINISH	
DO NOT SCALE DRAWING	

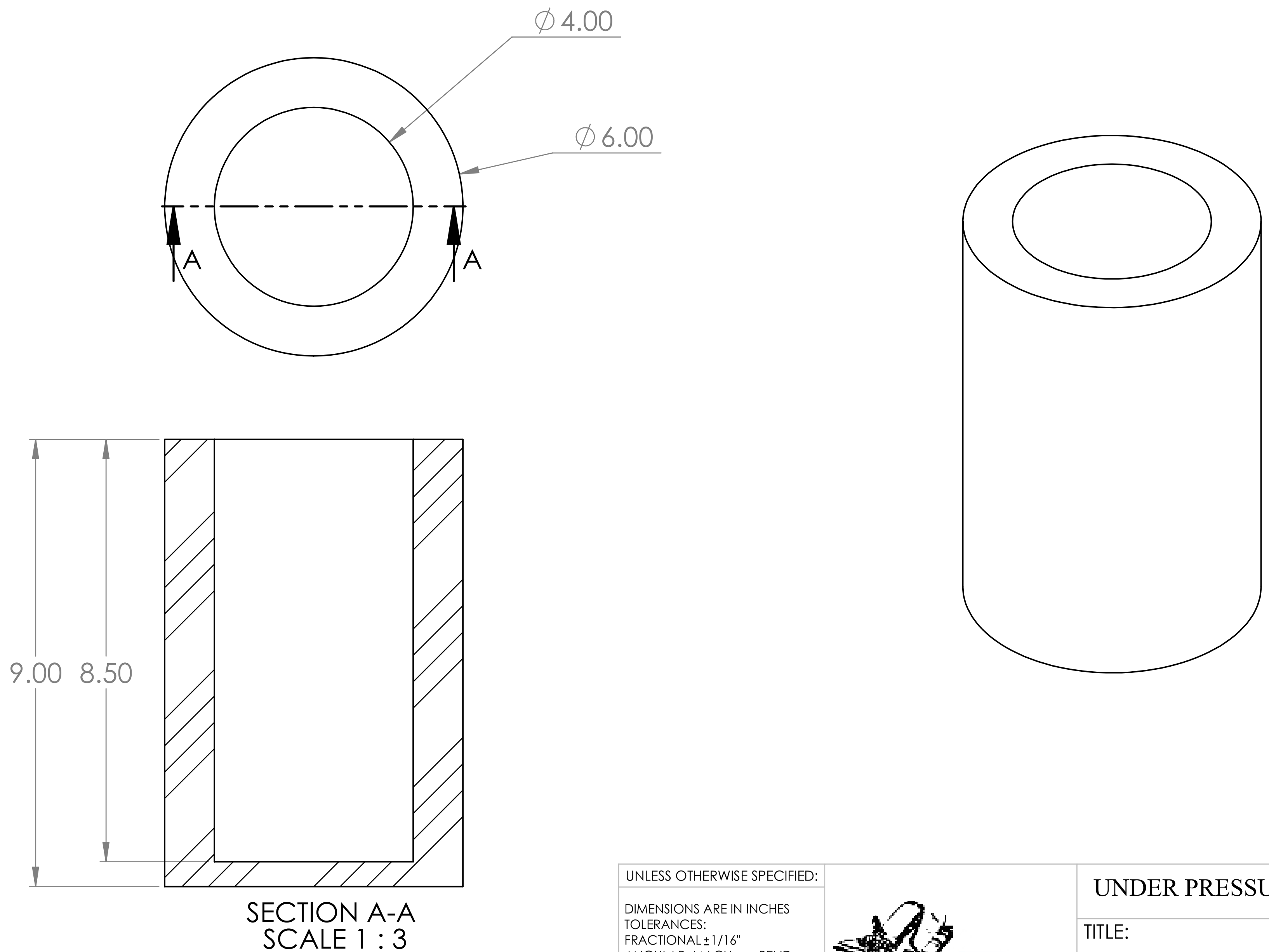
UNDER PRESSURE ENGINEERING

TITLE: Aux Helium Tank Bucket

SIZE	DWG. NO.	REV
A	TB002	

SCALE:1:5	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	PVC Foam
FINISH	
DO NOT SCALE DRAWING	

UNDER PRESSURE ENGINEERING

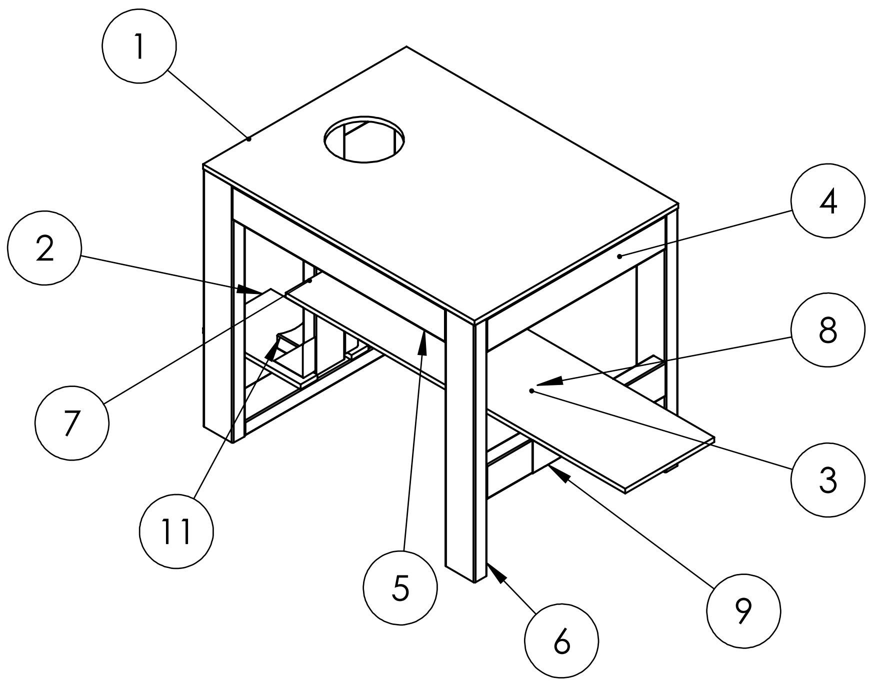
TITLE:

Foam Insulation

SIZE	DWG. NO.	REV
A	TB005	
SCALE:1:3	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1

ITEM NO.	PART NUMBER	Size	QTY.
1	Table Top	.5"x24"x32"	1
2	Helium Tank Base	See Drawing	1
3	Bucket Support	0.5"x12.5"x11.5"	1
4	Cross Beams	2"x4"x21"	4
5	Long Beams	2"x4"x25"	2
6	Table Leg	2"x4"x26.25"	4
7	Vertical Support	2"x4"x24.75"	1
8	Long Support	2"x4"x27.5"	1
9	Angled Support	See Drawing	4
10	Steel Bracket	-	1
11	Helium Tank Support	See Drawing	2



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
AL 6061

FINISH

DO NOT SCALE DRAWING

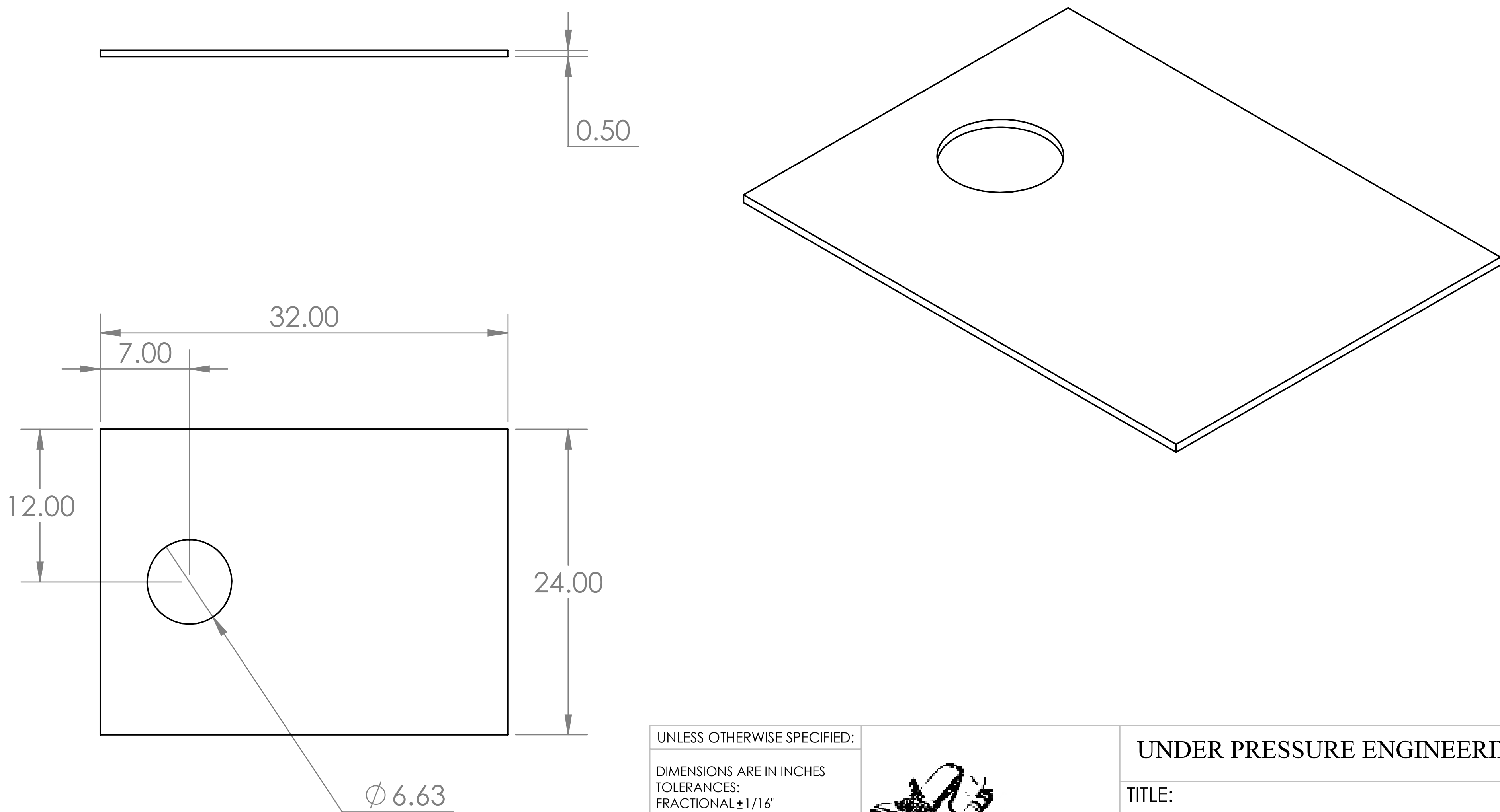
UNDER PRESSURE ENGINEERING

TITLE:
Table Assembly

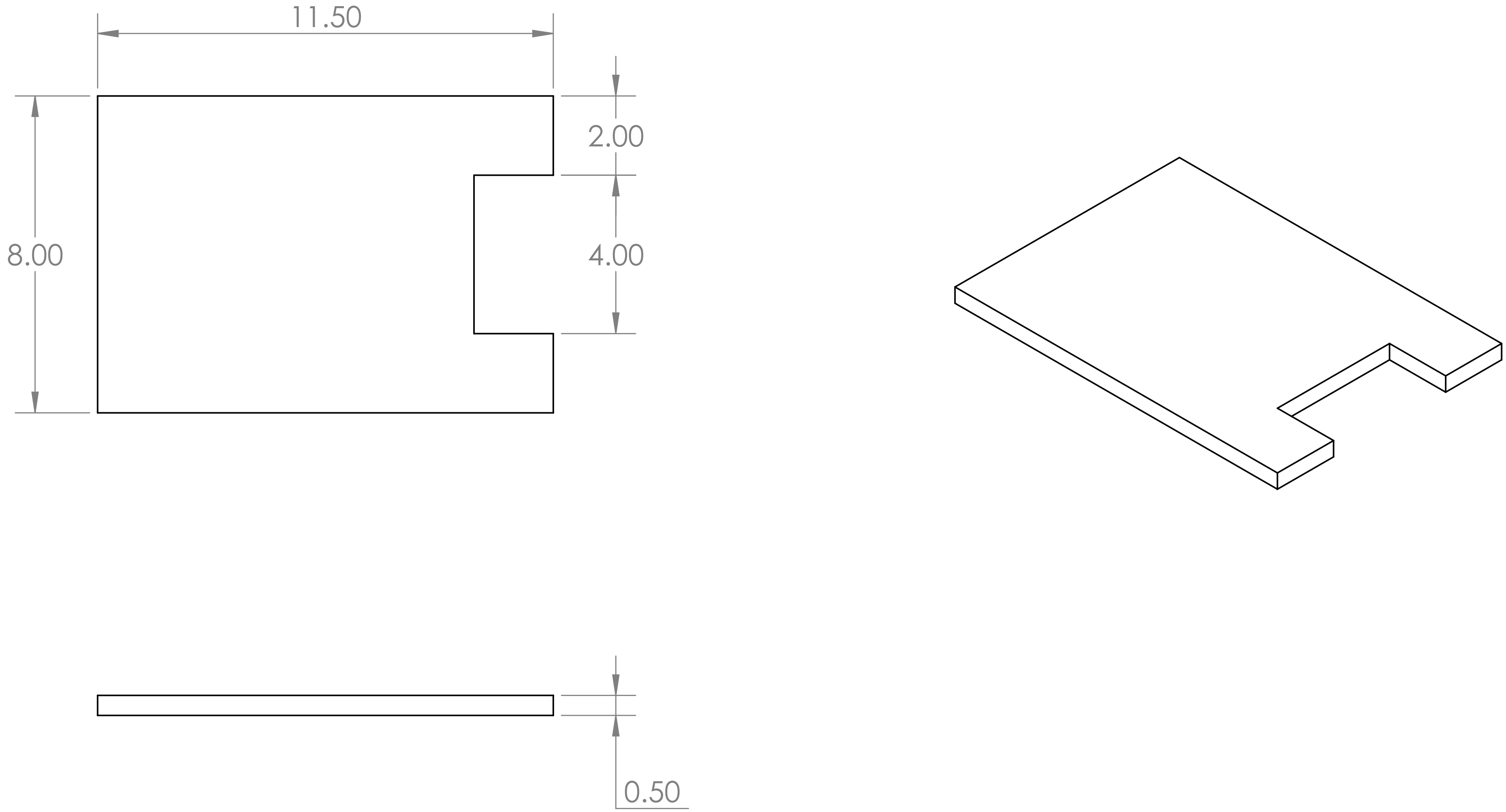
SIZE A | DWG. NO. TA000 | REV

SCALE:1:16 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

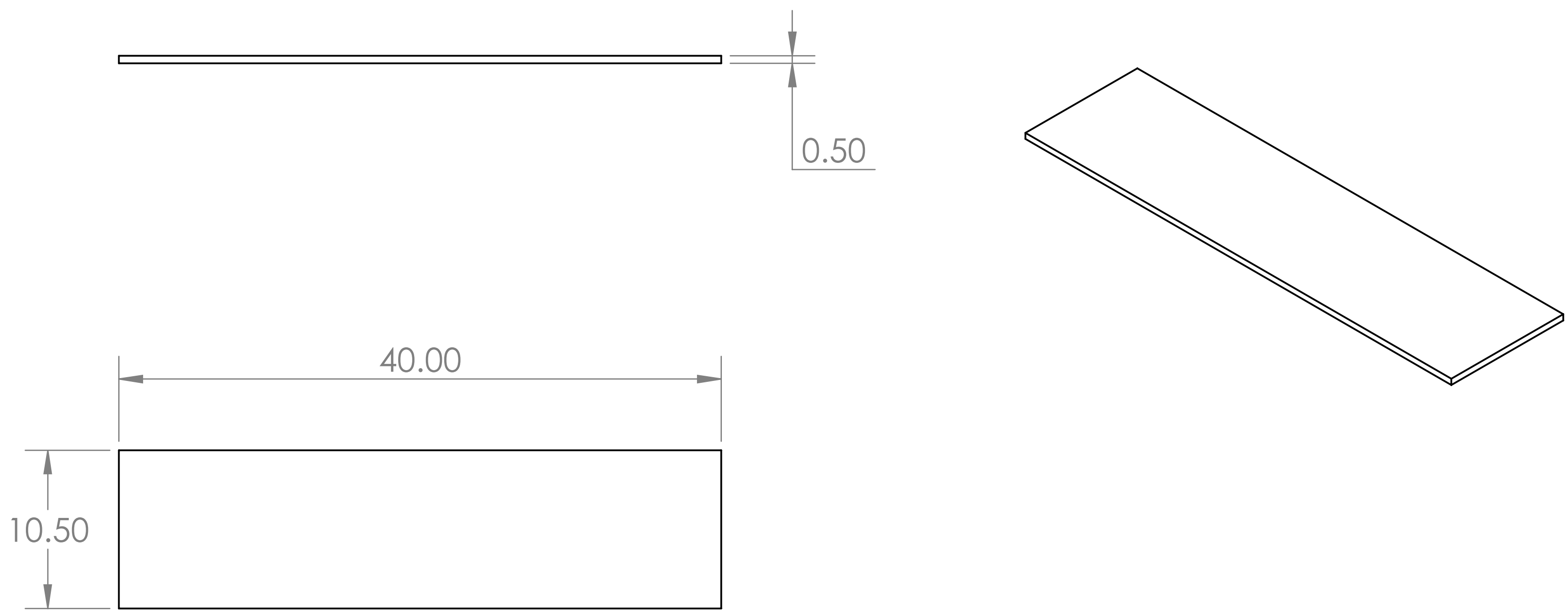


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005	UNDER PRESSURE ENGINEERING	
INTERPRET GEOMETRIC TOLERANCING PER:	TITLE: Table Top	
MATERIAL PLYWOOD	SIZE A DWG. NO. TA001	REV
FINISH DO NOT SCALE DRAWING	SCALE:1:12 WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005 INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL PLYWOOD FINISH DO NOT SCALE DRAWING	UNDER PRESSURE ENGINEERING (logo)	UNDER PRESSURE ENGINEERING TITLE: Helium Tank Base SIZE A DWG. NO. TA002 REV SCALE:1:4 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: PLYWOOD

FINISH:

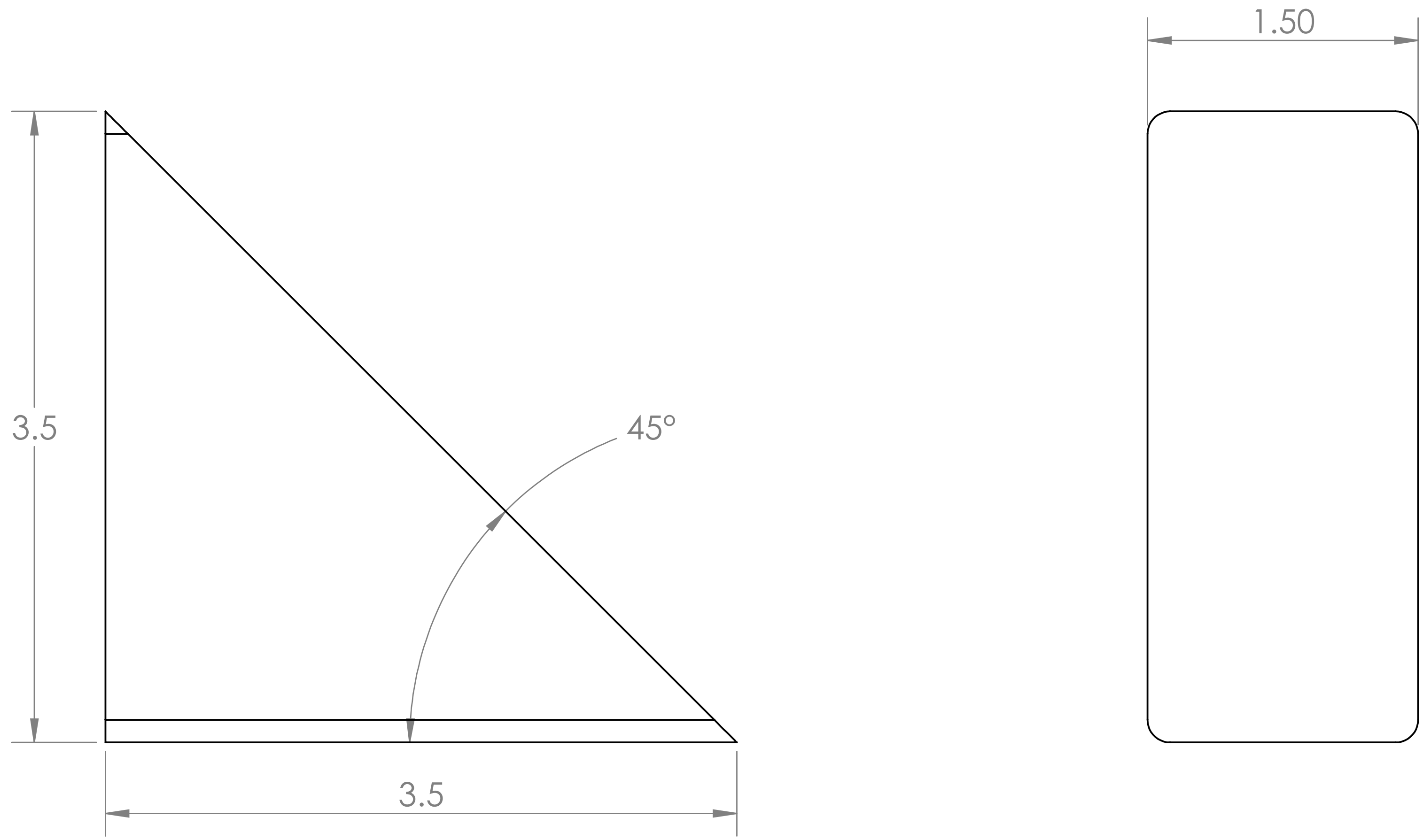
DO NOT SCALE DRAWING

UNDER PRESSURE ENGINEERING

TITLE: Lower Shelf

SIZE	DWG. NO.	REV
A	TA003	

SCALE:1:12 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Wood

FINISH

DO NOT SCALE DRAWING

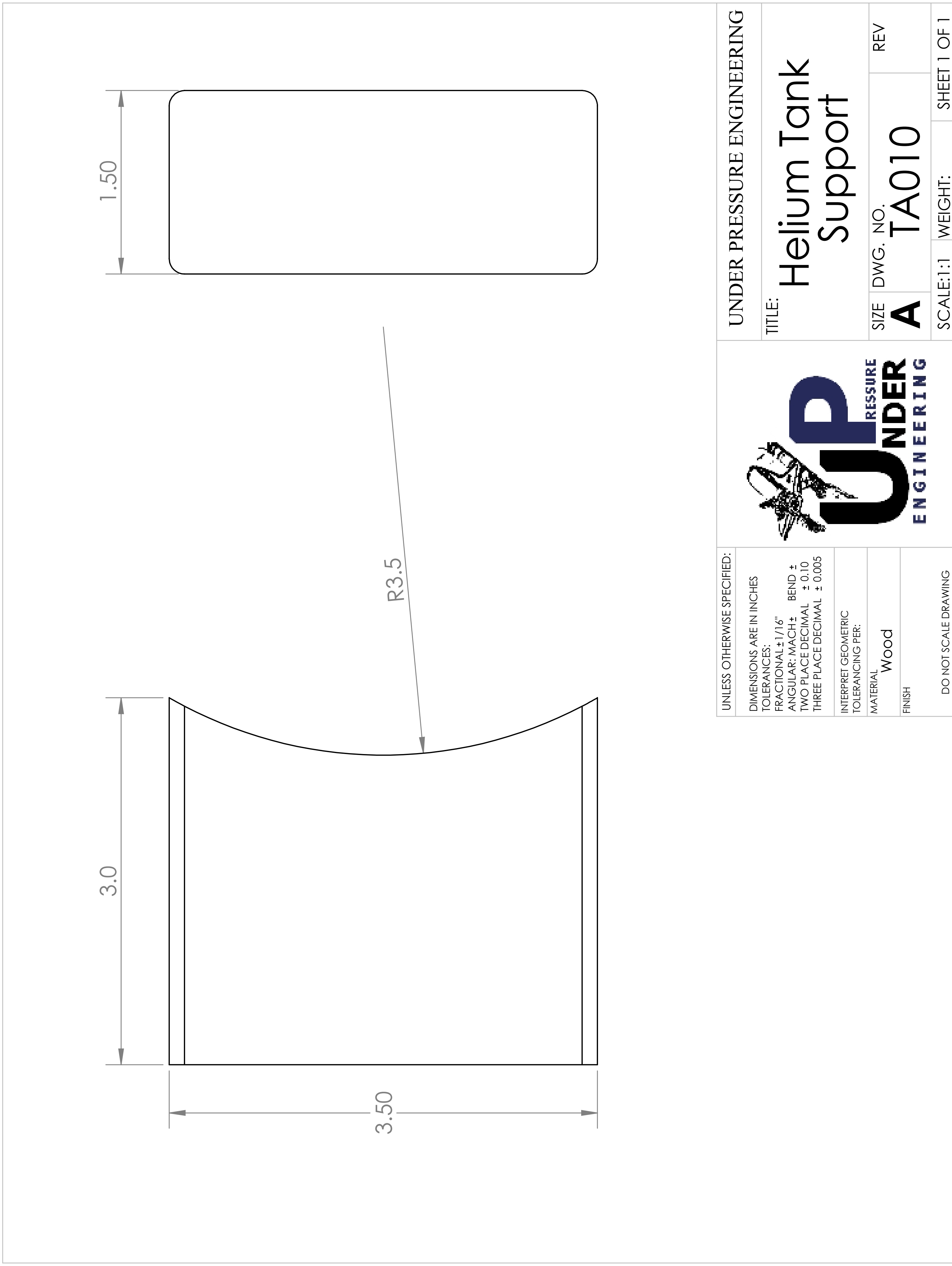
UNDER PRESSURE ENGINEERING

TITLE: Angled Wood Support

SIZE	DWG. NO.	REV
A	TA009	

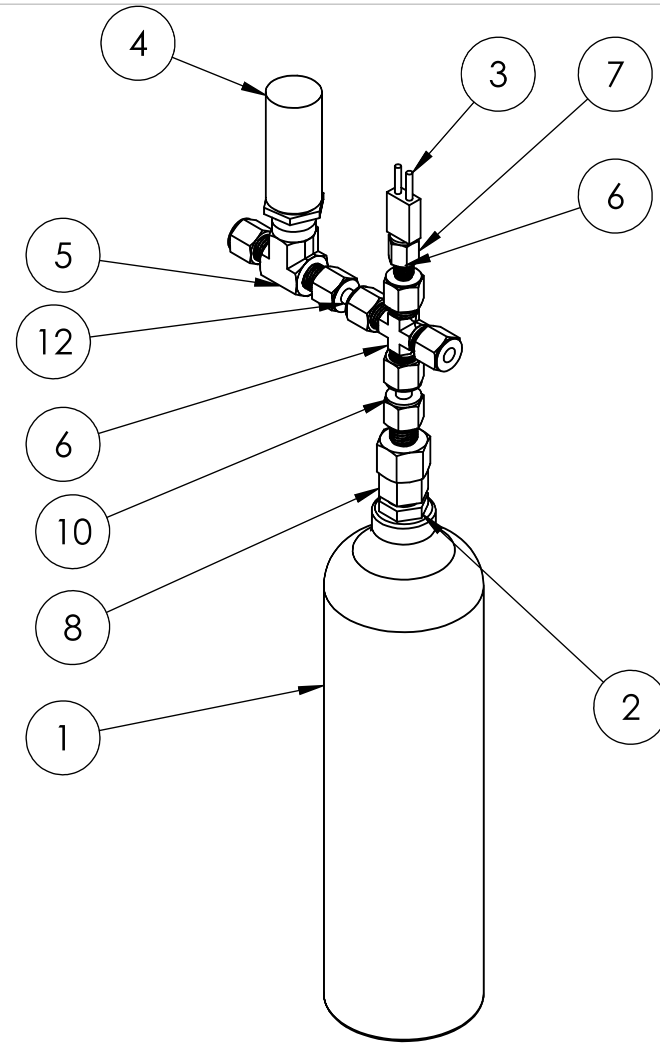
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



1.50
R3.5
3.0
3.50
UNDER PRESSURE ENGINEERING
TITLE:
Helium Tank Support
SIZE
A
DWG. NO.
TA010
REV
SCALE:1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Wood
FINISH
DO NOT SCALE DRAWING
1
2
3
4
5

ITEM NO.	PART NUMBER	QTY.
1	Paintball Tank	1
3	OMEGA TQSS-18E-12	1
4	OMEGA PX309-2KGV	1
5	MC 4040T61	1
12	∅0.25"x1" SS Tube	2



ITEM NO.	PART NUMBER	Type 1	Size 1	Type 2	Size 2	QTY.
2	SR ear-991947erl	MJIC	0.375	UNF	5/8-18	1
5	SL SS-400-3-4TTF	2xFSL	0.25	FNPT	0.25	1
6	SL SS-400-4	4x FSL	0.25	-	-	1
7	SL SS-200-R-4	MSL	0.25	FSL	0.125	1
8	MC 5482K76	Tube Nut	0.375	-	-	1
9	DHH SS-2407-06-04	FJIC	0.375	MJIC	0.25	1
10	SL SS-400-A-4ANF	FJIC	0.25	MSL	0.25	1

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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

UNDER PRESSURE ENGINEERING

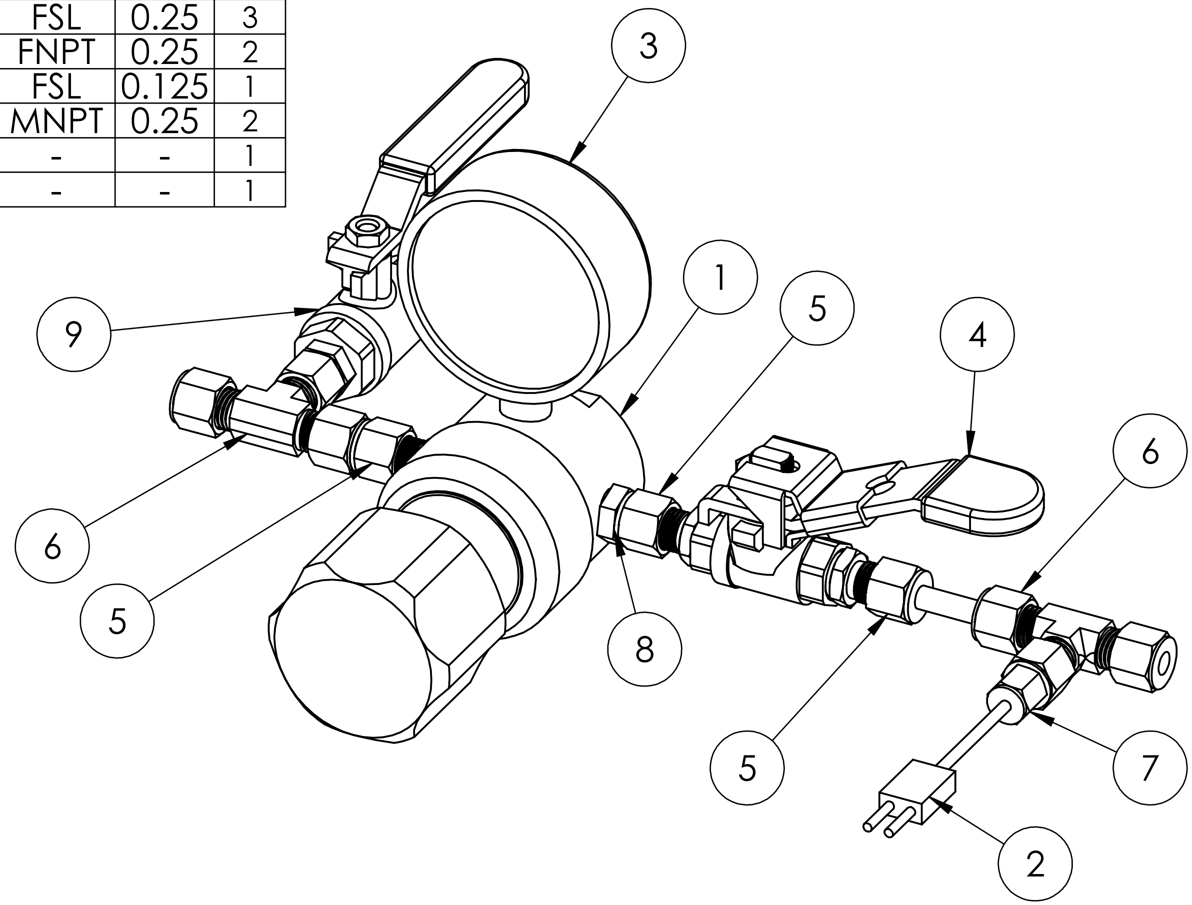
TITLE: Auxilary Tank Assembly

SIZE A | DWG. NO. AT000 | REV

SCALE:1:3 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

ITEM NO.	PART NUMBER	Type 1	Size 1	Type 2	Size 2	QTY.
1	SL KPR1FRB422A20000	-	-	-	-	1
2	Omega TQSS-18E-2	-	-	-	-	1
3	MC 4066K41	-	-	-	-	1
4	MC 46325K26	-	-	-	-	1
5	SL SS-400-1-4	MNPT	0.25	FSL	0.25	3
6	SL SS-400-3	2x FSL	0.25	FNPT	0.25	2
7	SL SS-200-R-4	MSL	0.25	FSL	0.125	1
8	SL SS-4-TA-1-4	MSL	0.25	MNPT	0.25	2
9	MC 4040T61	-	-	-	-	1
10	∅0.25"x1" SS Tube	-	-	-	-	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

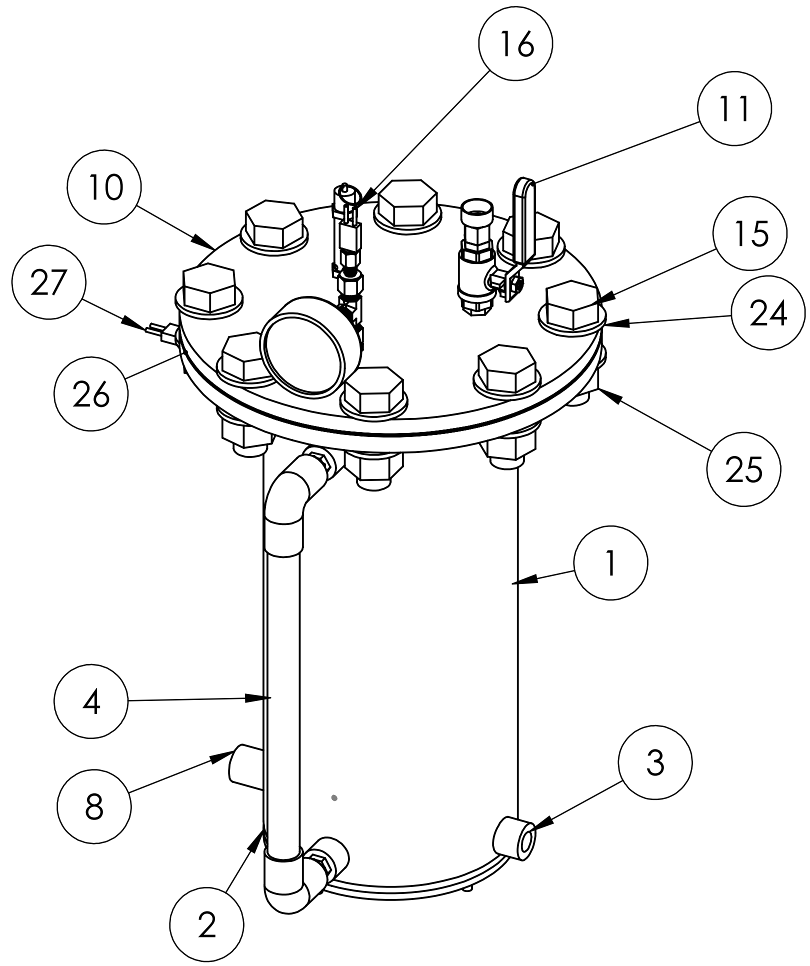
UNDER PRESSURE ENGINEERING

TITLE: Regulator Assembly

SIZE A | DWG. NO. RA000 | REV

SCALE:1:2 | WEIGHT: | SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	WR001	1
2	WR002	1
3	WR004	4
4	WR006	1
8	WR005	1
9	WR007	1
10	WR003	1
11	MC 47865K21	1
14	MC 9889K25	1
15	Hex Bolt- 7/8"x2.5"	8
16	OMEGA TQSS-18E-12	1
17	MC 4066K51	1
23	MC 93306A543	3
24	7/8" Washer	16
25	7/8" Nut	8
26	MC 9472K52	1
27	Omega TQSS-18E-3	1



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

UNDER PRESSURE ENGINEERING

TITLE: Water Resevior Overview

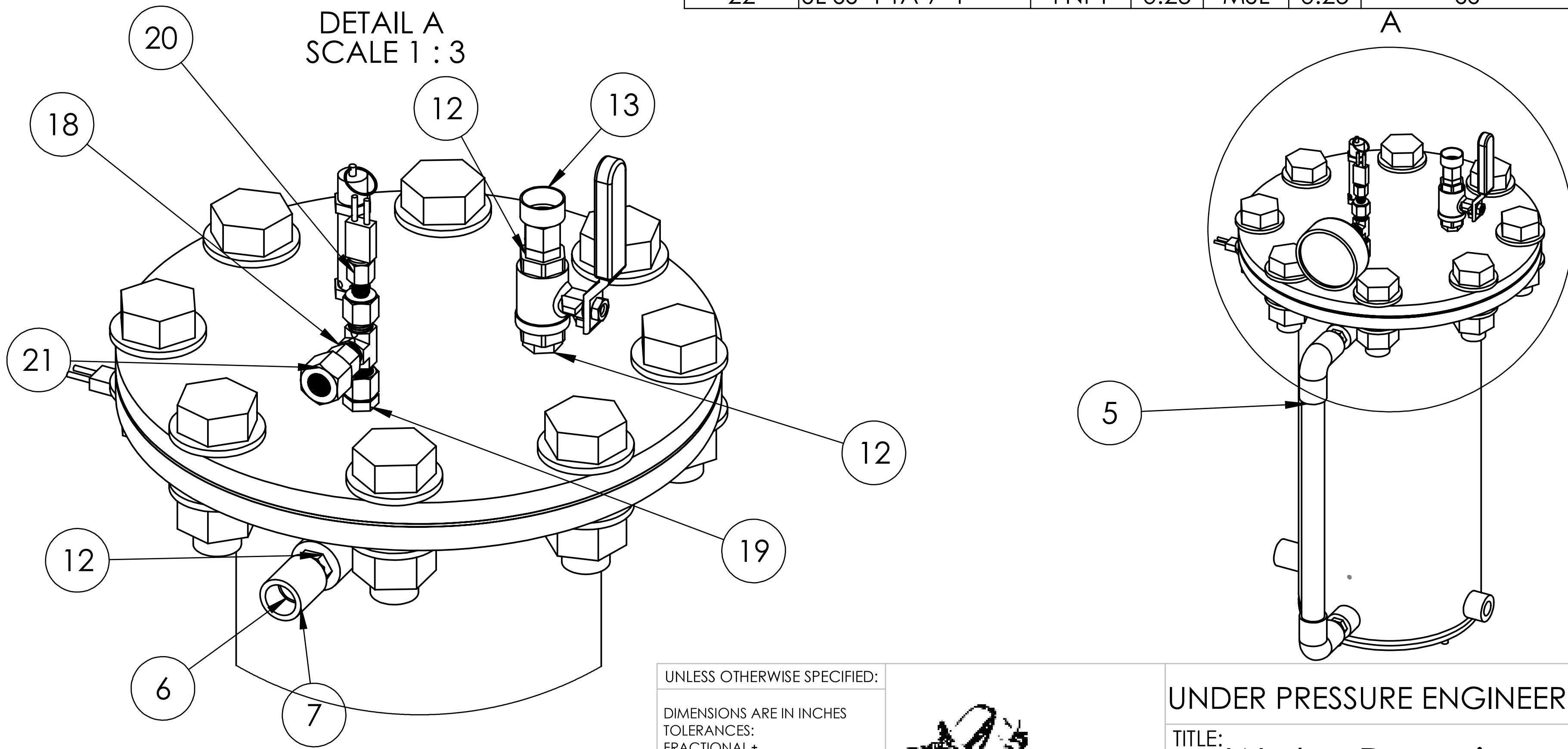
SIZE A | DWG. NO. WR000 | REV

SCALE:1:5 | WEIGHT: | SHEET 1 OF 2

5 4 3 2 1

ITEM NO.	PART NUMBER	Type 1	Size 1	Type 2	Size 2	Material	QTY.
5	MC 9161K21	Slip	.5	Slip	.5	Clear PVC Elbow	2
6	MC 4880K199	Slip	.5	FNPT	.25	White PVC	2
7	WR008	Pipe	0.5	Pipe	0.5	Clear PVC	2
12	MC 5485K22	MNPT	.25	MNPT	.25	Brass	4
13	MC 73605T65	FNPT	0.25	GH	0.75	Brass	1
14	SL SS-200-1-4	MNPT	0.25	SL	.125	SS	2
19	SL SS-400-3	3x FSL	0.25	-	-	SS	1
20	SL SS-4-TA-1-4	MSL	0.25	MNPT	0.25	SS	1
21	SL SS-200-R-4	MSL	0.25	FSL	0.125	SS	1
22	SL SS-4-TA-7-4	FNPT	0.25	MSL	0.25	SS	1

NOTE: ITEM NO. 14 IS INSIDE WATER RESERVIOR



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

UNDER PRESSURE ENGINEERING

TITLE: Water Resevior Fittings

SIZE A | DWG. NO. WR000A | REV

SCALE:1:5 | WEIGHT: | SHEET 2 OF 2

5 4 3 2 1

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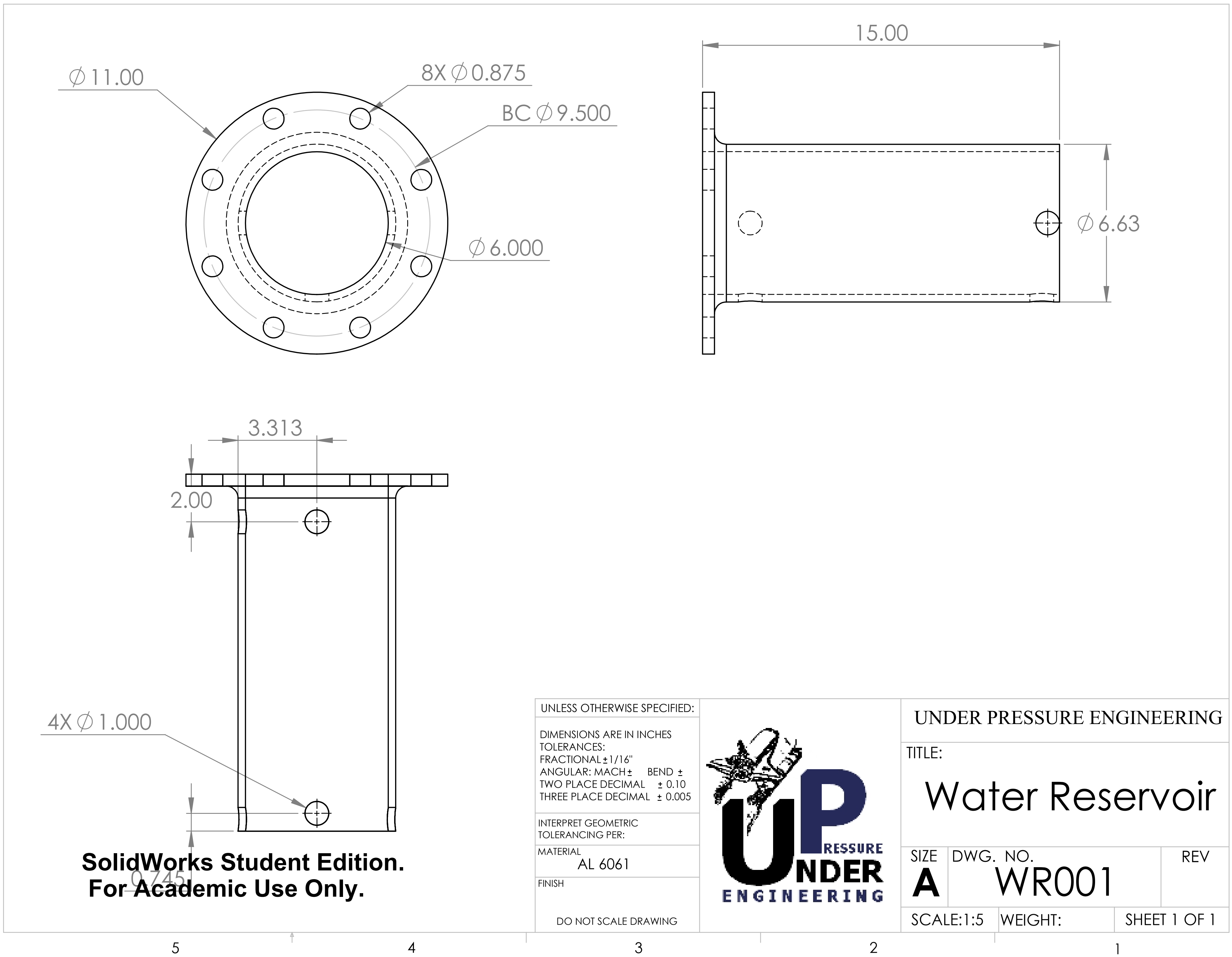
Ø11.00
8X Ø0.875
BC Ø9.500
Ø6.000
15.00
Ø6.63
3.313
2.00
4X Ø1.000
0.745
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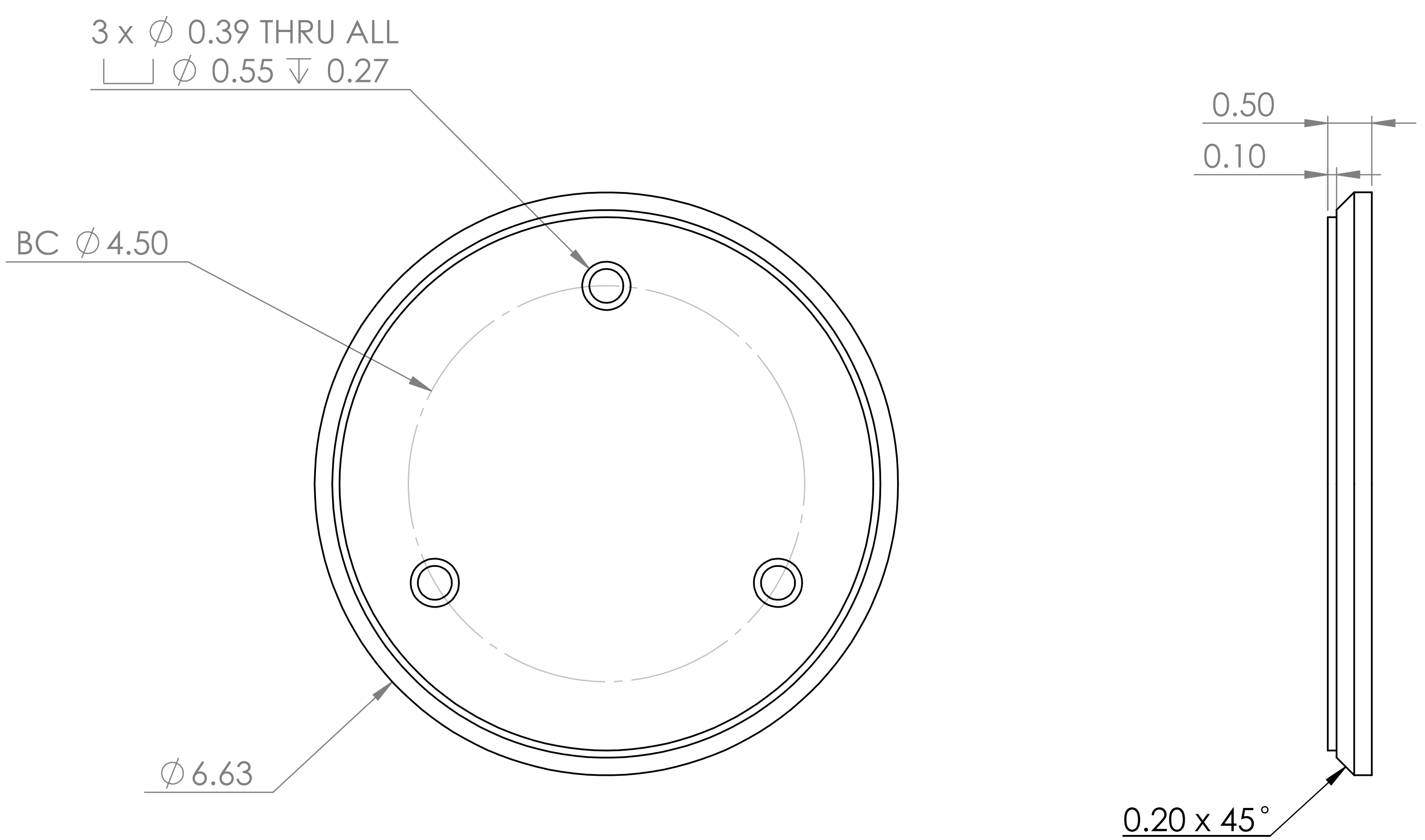
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061
FINISH
DO NOT SCALE DRAWING
UNDER PRESSURE ENGINEERING
TITLE:
Water Reservoir
SIZE
A
DWG. NO.
WR001
REV
SCALE:1:5
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



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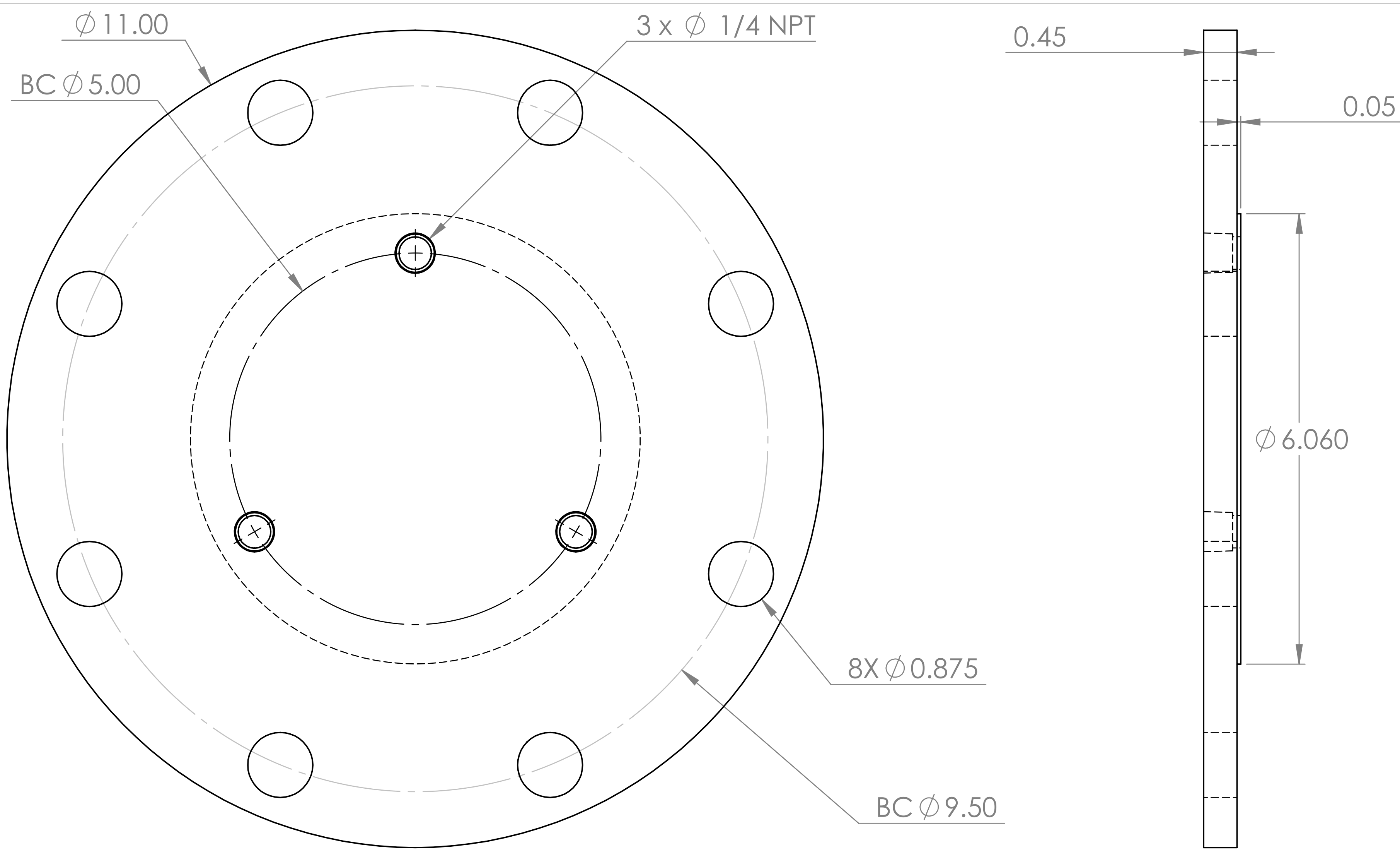
UNLESS OTHERWISE SPECIFIED:		UNDER PRESSURE ENGINEERING
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005		TITLE: Water Reservoir Bottom
INTERPRET GEOMETRIC TOLERANCING PER:		
MATERIAL AL 6061		SIZE A / DWG. NO. WR002 / REV
FINISH		
DO NOT SCALE DRAWING		SCALE:1:2 / WEIGHT: / SHEET 1 OF 1

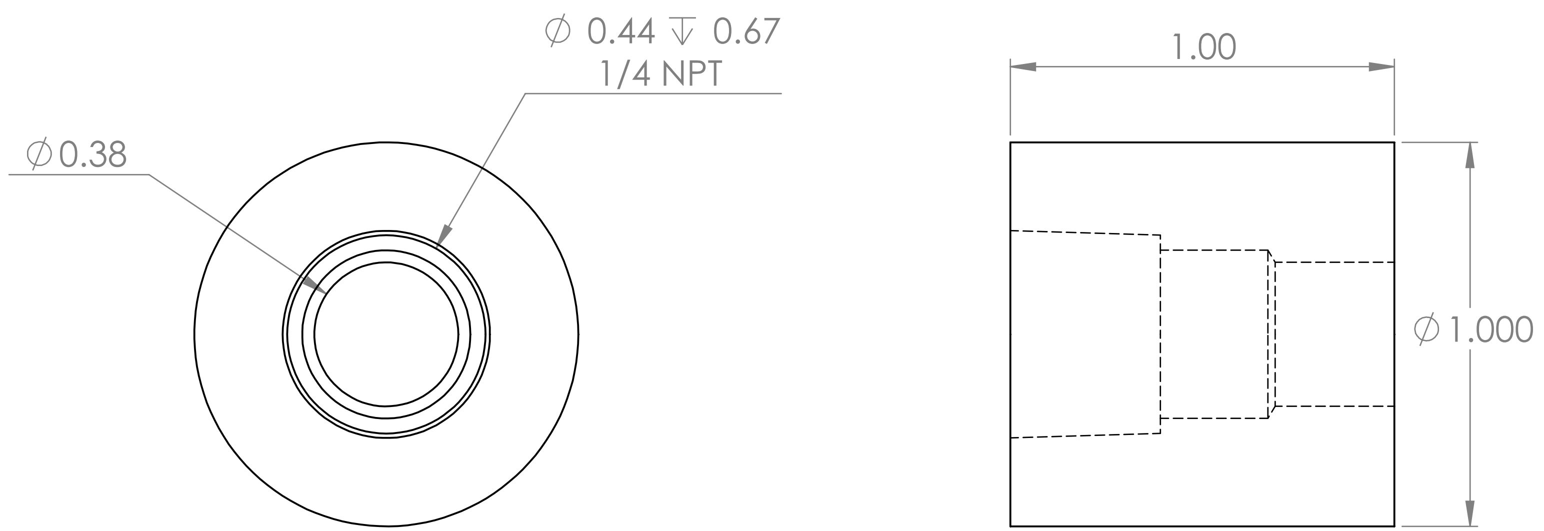
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:	UNDER PRESSURE ENGINEERING
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005	TITLE: Water Reservoir Cap
INTERPRET GEOMETRIC TOLERANCING PER:	SIZE A
MATERIAL AL 6061	DWG. NO. WR003
FINISH	REV
DO NOT SCALE DRAWING	SCALE:1:2 WEIGHT: SHEET 1 OF 1

UNDER PRESSURE ENGINEERING

5 4 3 2 1



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TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: AL 6061

FINISH

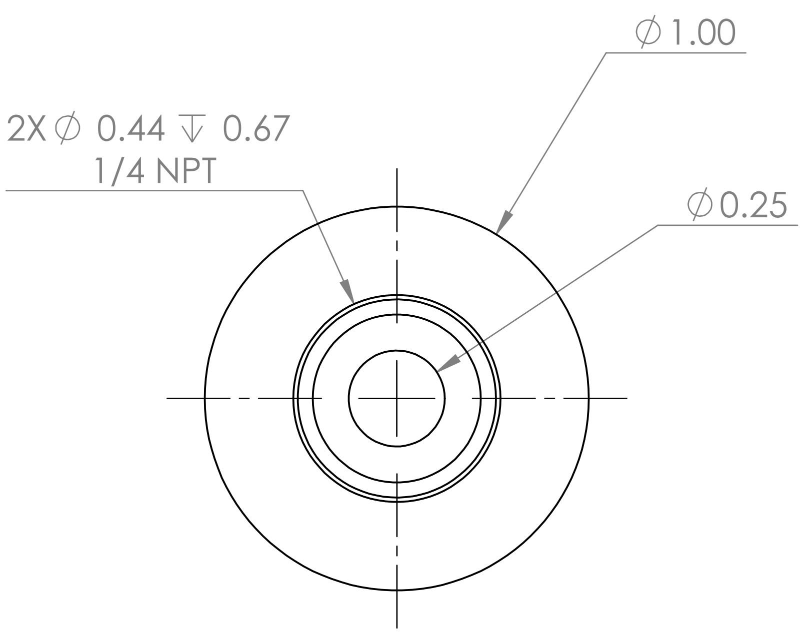
DO NOT SCALE DRAWING

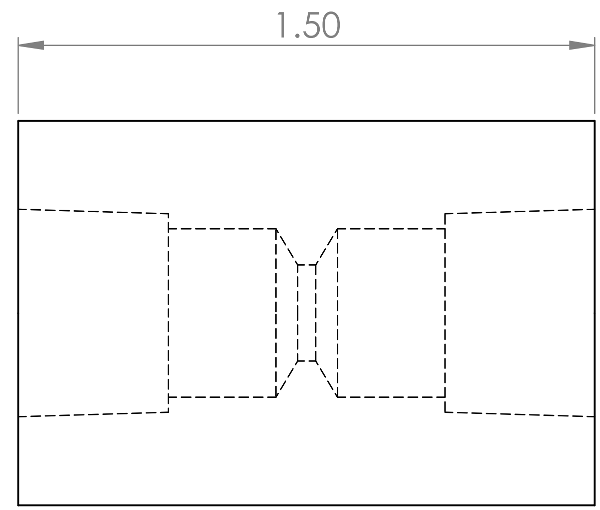
UNDER PRESSURE ENGINEERING

TITLE: Tank Inlet- 1 Side Tapped

SIZE	DWG. NO.	REV
A	WR004	

SCALE:2:1 | WEIGHT: | SHEET 1 OF 1





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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
AL 6061

FINISH

DO NOT SCALE DRAWING

UNDER PRESSURE ENGINEERING

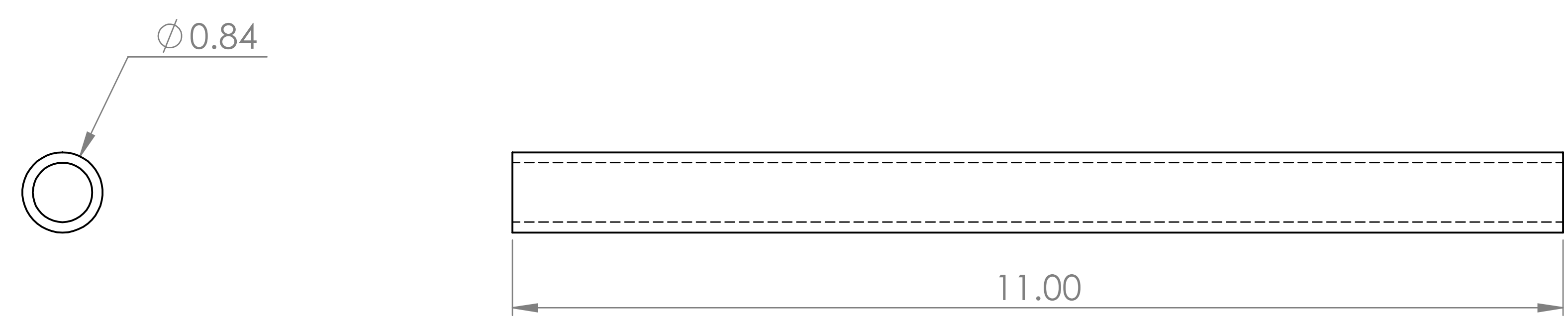
TITLE:

Water Resevior Fitting
Two Taps

SIZE	DWG. NO.	REV
A	WR005	

SCALE:2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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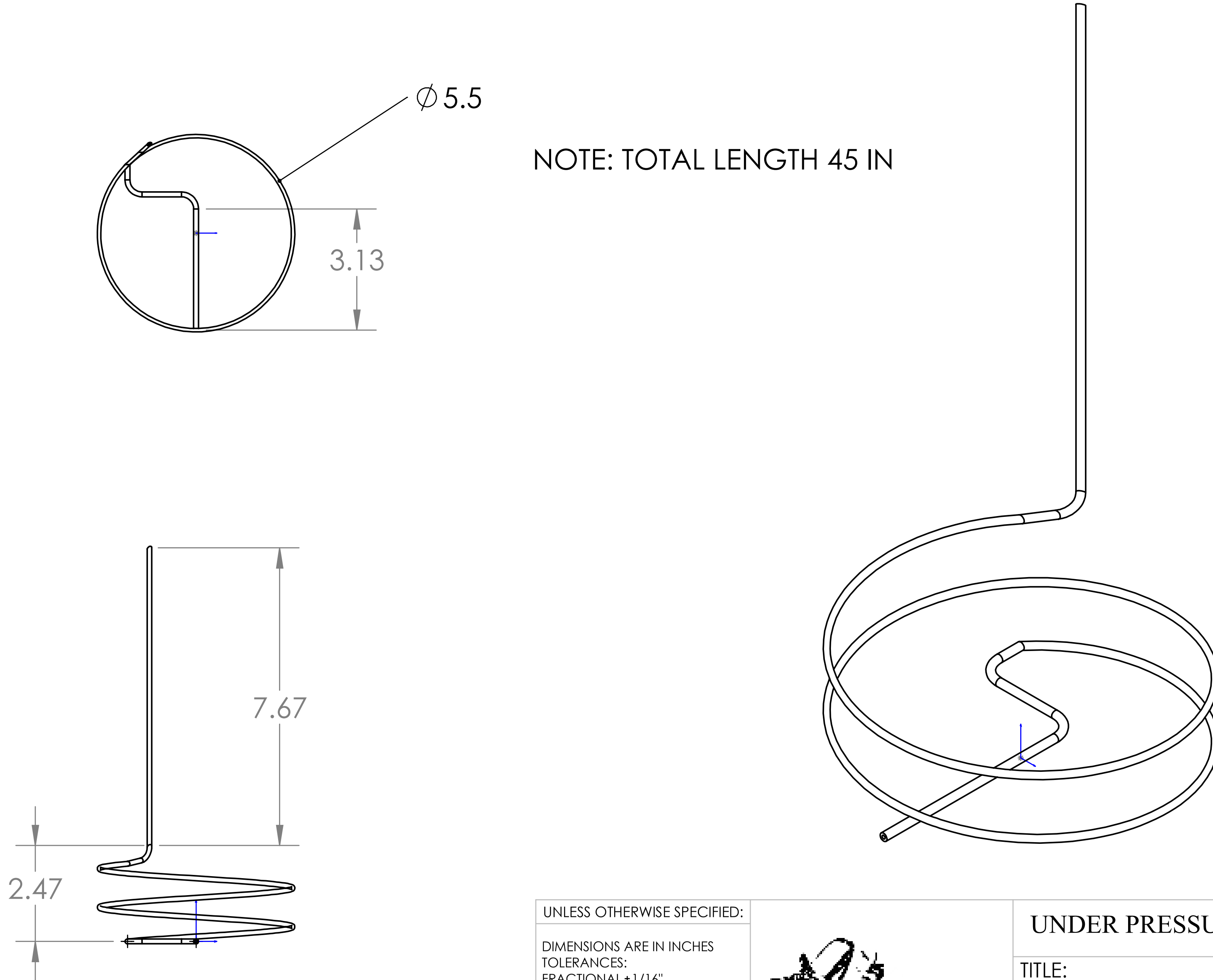
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/16" ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.10 THREE PLACE DECIMAL ± 0.005	UNDER PRESSURE ENGINEERING	
INTERPRET GEOMETRIC TOLERANCING PER:	TITLE: Level Gauge	
MATERIAL Clear PVC	SIZE A DWG. NO. WR006	REV
FINISH DO NOT SCALE DRAWING	SCALE:1:2 WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: AL 6061

FINISH

DO NOT SCALE DRAWING

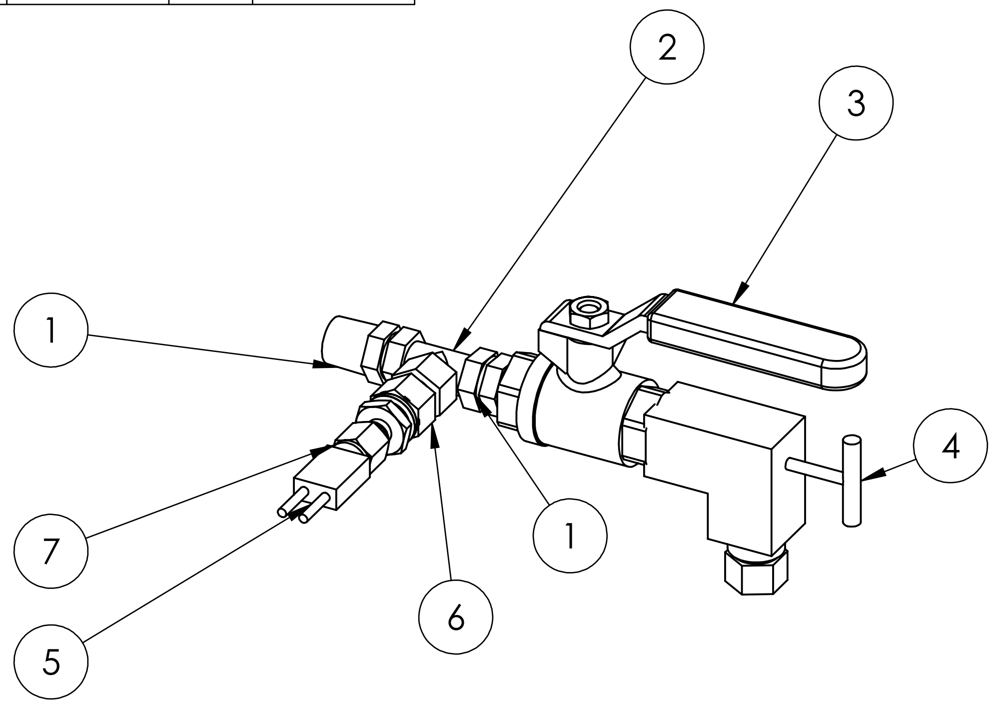
UNDER PRESSURE ENGINEERING

TITLE: Heat Exchanger Coils

SIZE	DWG. NO.	REV
A	WR007	

SCALE:1:4	WEIGHT:	SHEET 1 OF 1

ITEM NO.	PART NUMBER	Type 1	Size 1	Type 2	Size 2	QTY.
1	DHH 6505-04-04	FJIC	0.25	MNPT	0.25	2
2	DHH 2603-04-04-04	3x MJIC	0.25	-	-	1
3	MC 47865K21	-	-	-	-	1
4	MC 5049K9	-	-	-	-	1
5	OMEGA TQSS-18G-2	-	-	-	-	1
6	DHH 6565-04-04	FJIC	0.25	FJIC	0.25	1
7	SL SS-200-1-4	MNPT	0.25	FSL	0.125	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16"
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.10
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

UNDER PRESSURE ENGINEERING

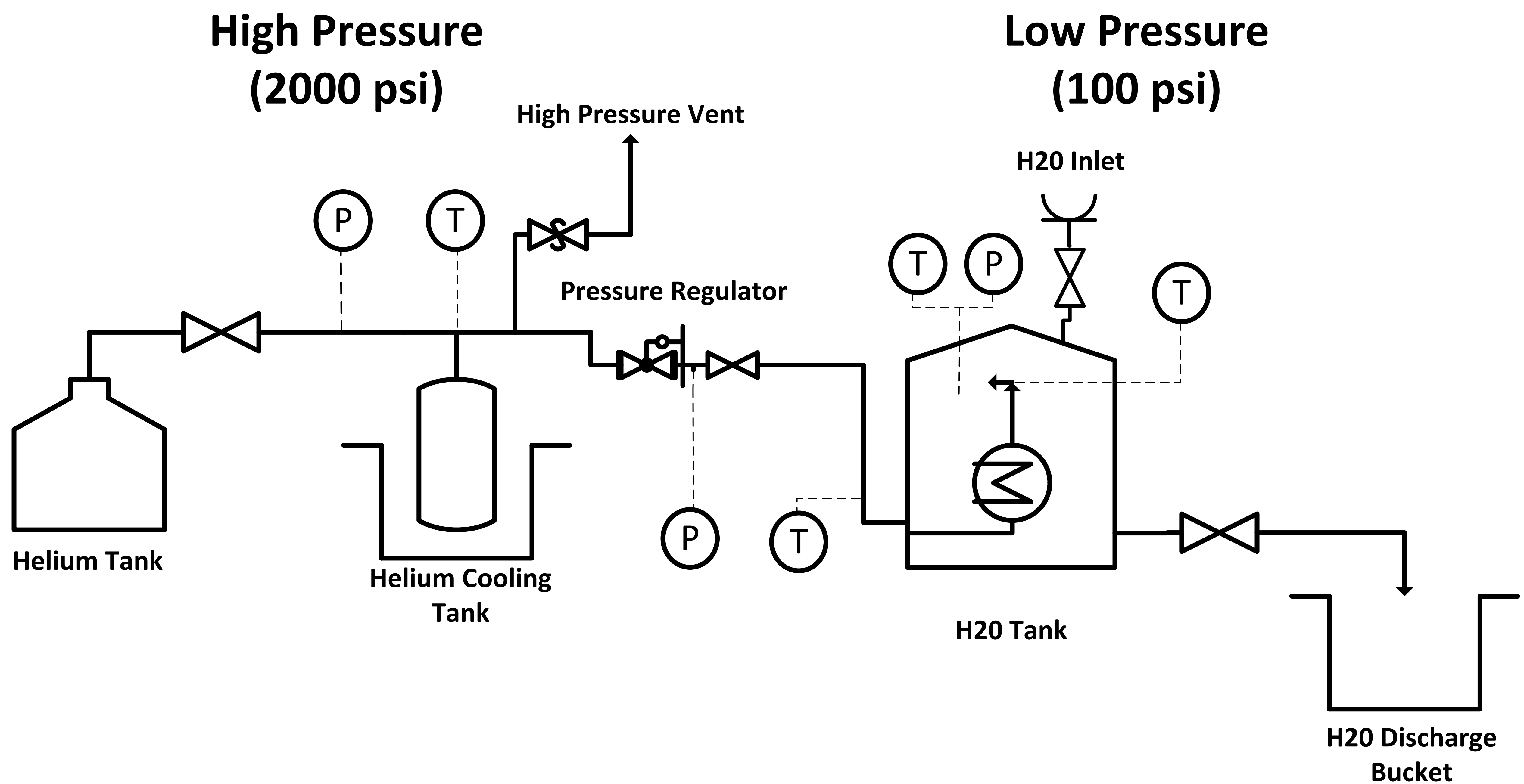
TITLE:

Water Outlet Assembly

SIZE	DWG. NO.	REV
A	WO000	

SCALE:1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



PRESSURE UNDER ENGINEERING

Rocket Fuel Pressurization
Test Bench
Piping and Instrument
Diagram

APPENDIX C – TEST BENCH COMPONENT BOM

TABLE C1- BILL OF MATERIALS AND CORRESPONDING SUPPLIERS FOR TEST BENCH CONSTRUCTION.

Test Bench Budget					
Category	Item	Description	Quantity	Unit Cost	Total Cost
Helium Tank	Helium Tank Rental	AirGas Size 60(960 in^3)	3	$63.59	$190.77
	Helium Tank Nut	CGA #580	1	$3.69	$3.69
	Helium Tank Nipple	CGA #580- 1/4" NPT	1	$3.23	$3.23
Auxilary Tank	Auxilary Tank	12 oz Paintball Tank	1	$29.99	$29.99
	End Cap	8"x8"x.25" Al 6061 Plate	1	$9.18	$9.18
	Relief Valve	Ball Valve (2000 psi SS)	1	$47.81	$47.81
	Regulator	Swagelock (0-100 psi outlet)	1	$293.23	$293.23
	Outlet Valve	Ball Valve	1	$21.00	$21.00
	Check Valve	SL SS-4C-1	1	$47.61	$47.61
	Liquid N2 Container	Insulated Foam Container	1	$40.70	$40.70
	Additional Insultation	Closed Cel Foam	1	$30.98	$30.98
Piping	Stainless Tubing	1/4" Stainless Tubing x 6'	1	$10.87	$10.87
	Stainless Tubing	1/8" Stainless Tubing x 6'	2	$9.91	$19.82
Test Apparatus	Tube	6"x24" AL 6061 Sch 40 Pipe	1	$81.03	$81.03
	Ends	12" x 36" x 0.5" Al 6061 Plate	1	$101.10	$101.10
	Garden Hose Fitting	1/4" F NPT - Garden Hose	1	$4.55	$4.55
	Alumnium Rod	1" x 1 ft	1	$8.31	$8.31
	Clear PVC Pipe	0.5" x 4'	1	$9.08	$9.08
	H20 Flow Control	1/4" NPT Needle Valve	1	$7.23	$7.23
	Low Pressure Relief Valve	High Flow 100 psi Pop	1	$29.81	$29.81
	Gasket	6"x 1/16" Buna-N Gasket	1	$10.54	$10.54
	Additional Gasket	6" Rubber Gasket	1	$2.27	$2.27
	Cap Bolts	7/8"-9 x 2.5"	8	$1.13	$9.04
	Cap Nut	7/8"-9 x 2.5" Pkg: 10	1	$7.00	$7.00
	Washers	7/8" Pkg: 16	1	$3.27	$3.27
	Lock Washers	7/8" Pkg: 10	1	$8.13	$8.13
	H20 Ball Valve	1/4" NPT FF	2	$8.58	$17.16
Measurements	Thermocouple Long	Type T(-350 F- Amb)	2	$26.00	$52.00
	Thermocouple Short Exposed	Type T(-350 F- Amb)	2	$26.00	$52.00
	Thermocouple Short Grounded	Type T(-350 F- Amb)	1	$26.00	$26.00
	Thermocouple Connectors	Type T F Glass	4	$4.10	$16.40
	Thermocouple Wire	Type T 50'	1	$36.00	$36.00
	High Pressure Transducer	0-2000 psi SS, Bottom Mount	1	$175.00	$175.00
	Low Pressure Gauge	0-100 psi Brass, Bottom Mount	1	$9.84	$9.84
	Low Pressure Gauge	0-100 psi SS, Back Mount	1	$47.75	$47.75
	Low Pressure Gauge	0-100 psi SS, Bottom Mount	1	$41.47	$41.47
Fittings	FNPT- Swagelok	SL SS-400-7-4	1	$11.72	$11.72
	Aux Tank Fitting	5/8"-18 - -6 JIC Aluminum	1	$5.95	$5.95
	Swagelok Run Tee	SL SS-400-3-4TTF	2	$32.68	$65.36
	Swagelok Cross	SL SS-400-4	1	$41.20	$41.20
	MNPT- 1/4" Swagelok	SL SS-400-1-4	4	$7.11	$28.44
	Swagelok Tee	SL SS-400-3	2	$22.65	$45.30
	MNPT- 1/8" Swagelok	SL SS-200-1-4	1	$8.42	$8.42
	0.25 Swagelok Adapter- FJIC	SL SS-400-A-4ANF	1	$10.52	$10.52
	0.25 Swagelok Adapter- 1/8 Swagelok	SL SS-200-R-4	3	$9.22	$27.66
	0.25 Swagelok Adapter- MNPT	SL SS-4-TA-1-4	4	$6.11	$24.44
	0.25 Swagelok Adapter- MNPT	SL SS-4-TA-7-4	1	$9.82	$9.82
	0.375 Tube Nut	MC 5482K76	1	$3.53	$3.53
	0.375 FJIC- 0.25 MJIC Adapter	DHH SS-2407-06-04	1	$8.30	$8.30
	F JIC- M Pipe	DHH 6505-04-04	2	$1.38	$2.76
	MMM JIC	DHH 2603-04-04-04	2	$1.75	$3.50
	F JIC- F JIC	DHH 6565-04-04	1	$9.79	$9.79
	F JIC- F Pipe	DHH 6506-04-04	2	$2.34	$4.68
	Clear PVC Elbow	MC 9161K21	2	$6.11	$12.22
	PVC Bushing	MC 4880K199	2	$0.65	$1.30
	M NPT - M NPT Brass	MC 5485K22	4	$2.30	$9.20
Miscellaneous	Hardware	Piping Mounts	1	$9.89	$9.89
	Bucket	Hardware Store 5 Gallon Bucket	1	$5.00	$5.00
	Swivel Casters	2" Swivel Caster with Brake	2	$10.90	$21.80
	Rigid Casters	2" Rigid Caster	2	$4.08	$8.16
	Aluminum Bolts	0.25"x1.25" PKG: 25	1	$11.44	$11.44
	Cart	Wood for Cart	1	$50.00	$50.00
Total					$1,944.26

APPENDIX D – TEST BENCH COMPONENT SPECIFICATIONS

Swagelok Regulator .... SL KPR1FRB22A20000

McMaster High Flow Relief Valve .... MC 9889K25

Omega Type T Thermocouples .... OMEGA TQSS-18*

Omega Pressure Transducer .... OMEGA PX309-2KGV

MCC Data Acquisition System .... MCC USB-2408

General-Purpose

Part No.

KPR1FRB411A20000

Part Description:

SS PR Regulator, 0 to 100 psig (6.8 bar), 3600 psig (248 bar) inlet, B Config, PCTFE Seat, 1/4 in. FNPT, 0.02 Cv

Product Specifications

General	
Body Material	316 Stainless Steel
Cap Assembly	Standard
Cleaning Process	Standard Cleaning and Packaging (SC-10)
eClass (4.1)	37011108
eClass (6.0)	37-01-11-08
Maximum Inlet Pressure	3600 psig (248 bar)
Outlet Range	0 to 100 psig (6.8 bar)
Port Configuration	Left Inlet/Right Outlet; Top Outlet Gauge Port {B}
Port Type	1/4 in. Female NPT
UNSPSC (11.0501)	41112404
UNSPSC (4.03)	41112404
UNSPSC (SWG01)	41112404

! The complete catalog contents must be reviewed to ensure that the system designer and user make a safe product selection. When selecting products, the total system design must be considered to ensure safe, trouble-free performance. Function, material compatibility, adequate ratings, proper installation, operation, and maintenance are the responsibilities of the system designer and user.

Caution: Do not mix or interchange valve components with those of other manufacturers.

Air Flow Capacities for
ASME-Code Brass Pop-Safety Valves

(A) Valves with Test Ring

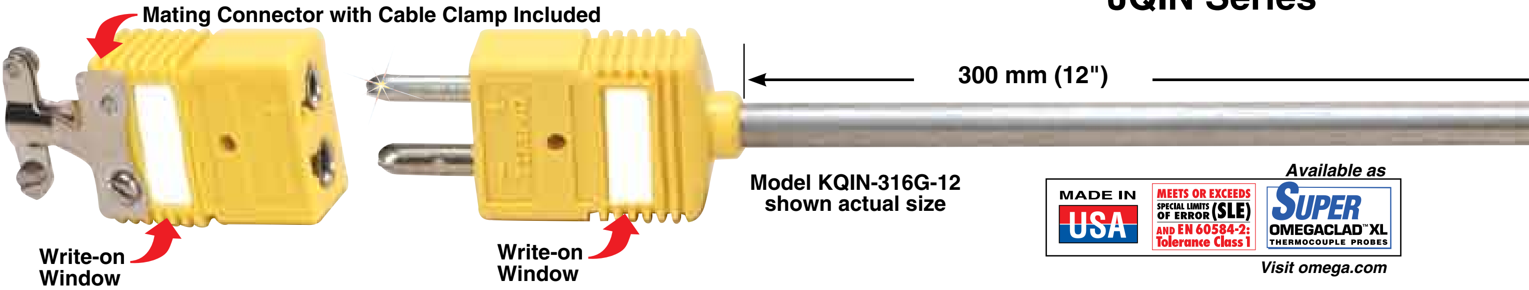
A

Set Pressure, psi	Air Flow Capacity, Standard Cubic Feet per Minute (SCFM)								
	Medium Flow				High Flow				
	9889K15	9889K19	9889K29	9889K39	9889K25	9889K35	9889K45	9889K49	9889K59
25	—	22	22	33	45	65	65	155	155
30	—	24	24	37	51	73	73	175	175
35	—	27	27	41	57	82	82	195	195
40	—	30	30	46	63	90	90	215	215
45	—	33	33	50	69	99	99	236	236
50	50	36	36	54	75	107	107	256	256
55	54	38	38	59	80	116	116	276	276
60	58	41	41	63	86	124	124	296	296
65	62	44	44	67	92	133	133	316	316
70	66	47	47	72	98	141	141	336	336
75	70	50	50	76	104	150	150	357	357
80	74	52	52	80	110	158	158	377	377
85	77	55	55	84	116	167	167	397	397
90	81	58	58	89	122	175	175	417	417
95	85	61	61	93	128	184	184	437	437
100	89	64	64	97	133	192	192	458	458
105	93	66	66	102	139	201	201	478	478
110	97	69	69	106	145	209	209	498	498
115	101	72	72	110	151	217	217	518	518
120	105	75	75	114	157	226	226	538	538
125	109	78	78	119	163	234	234	559	559
130	113	80	80	123	169	243	243	579	579
135	117	83	83	127	175	251	251	599	599
140	121	86	86	132	181	260	260	619	619
145	125	89	89	136	186	268	268	639	639
150	129	92	92	140	192	277	277	659	659
175	148	106	106	162	222	319	319	760	760
200	168	120	120	183	251	361	361	861	861
225	188	134	134	205	281	404	404	962	962
250	207	148	148	226	310	446	446	1,063	1,063
275	—	162	162	247	339	488	488	1,164	1,164
300	—	176	176	269	369	531	531	1,265	1,265

Quick Disconnect Thermocouples

with Low Cost Standard Size Connector Molded to Probe Sheath—Metric and Standard Dimensions

JQIN Series



Model KQIN-316G-12 shown actual size

Available as

MADE IN USA | MEETS OR EXCEEDS SPECIAL LIMITS OF ERROR (SLE) AND EN 60584-2: Tolerance Class 1 | SUPER OMEGACLAD™ XL THERMOCOUPLE PROBES

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- Male Connector Permanently Molded to Probe Sheath
- Standard Size, Color-Coded Connector Body
- Choice of 304, 310, 316, 321 SS Inconel® or Super OMEGACLAD® XL Sheath
- LCP and Ceramic Connectors Available
- Withstands Vibration, High Temperature and High Pressure
- Connector Body Rated to 220°C (425°F)

Metric Dimension - Standard Quick Disconnect Probes

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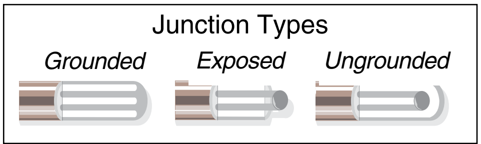
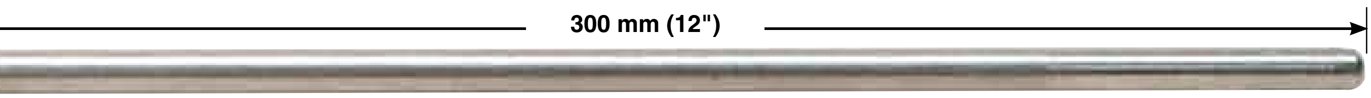
Alloy/ANSI Color Code	Sheath Dia. mm	Model No. 300 mm Length	Model No. 450 mm Length	Model No. 600 mm Length
Iron- Constantan Inconel Sheath J	1.5 3.0 4.5 6.0	JQIN-M15(*)-300 JQIN-M30(*)-300 JQIN-M45(*)-300 JQIN-M60(*)-300	JQIN-M15(*)-450 JQIN-M30(*)-450 JQIN-M45(*)-450 JQIN-M60(*)-450	JQIN-M15(*)-600 JQIN-M30(*)-600 JQIN-M45(*)-600 JQIN-M60(*)-600
Iron- Constantan 304 SS Sheath J	1.5 3.0 4.5 6.0	JQSS-M15(*)-300 JQSS-M30(*)-300 JQSS-M45(*)-300 JQSS-M60(*)-300	JQSS-M15(*)-450 JQSS-M30(*)-450 JQSS-M45(*)-450 JQSS-M60(*)-450	JQSS-M15(*)-600 JQSS-M30(*)-600 JQSS-M45(*)-600 JQSS-M60(*)-600
CHROMEGA®-ALOMEGA® Inconel Sheath K	1.5 3.0 4.5 6.0	KQIN-M15(*)-300 KQIN-M30(*)-300 KQIN-M45(*)-300 KQIN-M60(*)-300	KQIN-M15(*)-450 KQIN-M30(*)-450 KQIN-M45(*)-450 KQIN-M60(*)-450	KQIN-M15(*)-600 KQIN-M30(*)-600 KQIN-M45(*)-600 KQIN-M60(*)-600
CHROMEGA®- ALOMEGA® 304 SS Sheath K	1.5 3.0 4.5 6.0	KQSS-M15(*)-300 KQSS-M30(*)-300 KQSS-M45(*)-300 KQSS-M60(*)-300	KQSS-M15(*)-450 KQSS-M30(*)-450 KQSS-M45(*)-450 KQSS-M60(*)-450	KQSS-M15(*)-600 KQSS-M30(*)-600 KQSS-M45(*)-600 KQSS-M60(*)-600
CHROMEGA®-ALOMEGA® Super OMEGACLAD® XL Sheath K	1.5 3.0 4.5 6.0	KQXL-M15(*)-300 KQXL-M30(*)-300 KQXL-M45(*)-300 KQXL-M60(*)-300	KQXL-M15(*)-450 KQXL-M30(*)-450 KQXL-M45(*)-450 KQXL-M60(*)-450	KQXL-M15(*)-600 KQXL-M30(*)-600 KQXL-M45(*)-600 KQXL-M60(*)-600
OMEGA-P®-OMEGA-N® Super OMEGACLAD® XL Sheath N	1.5 3.0 4.5 6.0	NQXL-M15(*)-300 NQXL-M30(*)-300 NQXL-M45(*)-300 NQXL-M60(*)-300	NQXL-M15(*)-450 NQXL-M30(*)-450 NQXL-M45(*)-450 NQXL-M60(*)-450	NQXL-M15(*)-600 NQXL-M30(*)-600 NQXL-M45(*)-600 NQXL-M60(*)-600
CHROMEGA®- Constantan Inconel Sheath E	1.5 3.0 4.5 6.0	EQIN-M15(*)-300 EQIN-M30(*)-300 EQIN-M45(*)-300 EQIN-M60(*)-300	EQIN-M15(*)-450 EQIN-M30(*)-450 EQIN-M45(*)-450 EQIN-M60(*)-450	EQIN-M15(*)-600 EQIN-M30(*)-600 EQIN-M45(*)-600 EQIN-M60(*)-600
CHROMEGA®- Constantan 304 SS Sheath E	1.5 3.0 4.5 6.0	EQSS-M15(*)-300 EQSS-M30(*)-300 EQSS-M45(*)-300 EQSS-M60(*)-300	EQSS-M15(*)-450 EQSS-M30(*)-450 EQSS-M45(*)-450 EQSS-M60(*)-450	EQSS-M15(*)-600 EQSS-M30(*)-600 EQSS-M45(*)-600 EQSS-M60(*)-600
Copper- Constantan Inconel Sheath T	1.5 3.0 4.5 6.0	TQIN-M15(*)-300 TQIN-M30(*)-300 TQIN-M45(*)-300 TQIN-M60(*)-300	TQIN-M15(*)-450 TQIN-M30(*)-450 TQIN-M45(*)-450 TQIN-M60(*)-450	TQIN-M15(*)-600 TQIN-M30(*)-600 TQIN-M45(*)-600 TQIN-M60(*)-600
Copper- Constantan 304 SS Sheath T	1.5 3.0 4.5 6.0	TQSS-M15(*)-300 TQSS-M30(*)-300 TQSS-M45(*)-300 TQSS-M60(*)-300	TQSS-M15(*)-450 TQSS-M30(*)-450 TQSS-M45(*)-450 TQSS-M60(*)-450	TQSS-M15(*)-600 TQSS-M30(*)-600 TQSS-M45(*)-600 TQSS-M60(*)-600

** Specify junction type: **G** (Grounded), **E** (Exposed), **U** (Ungrounded). **To order with 310 SS, 316 SS or 321 SS sheath**, change "**SS**" in model number to "**310SS**", "**316SS**" or "**321SS**" respectively. Consult Sales for lengths between 50 and 300 mm or for lengths over 600 mm.*
***Type N Inconel Sheathing is available, Contact Sales for model numbers.** No additional charge.*
***Ordering Example: KQSS-M30U-300**, molded junction quick disconnect probe, Type K (CHROMEGA®-ALOMEGA®), 304SS sheath, 3 mm OD, ungrounded junction, 300 mm length.*



Discount Schedule	
1-10	Net
11-24	10%
25-49	15%
50 and over	Consult Sales



The OMEGA® quick disconnect molded thermocouple assemblies are available with sheath diameters of 1.5, 3, 4.5 and 6 mm (1⁄16, 1⁄8, 3⁄16 and 1⁄4") in standard 300, 450 and 600 mm (12, 18 and 24") nominal lengths. Custom lengths are also available, consult sales for details.

Made from Special Limits of Error OMEGACLAD® wire. Probes can be bent to between 2 and 3 times the diameter

Standard Dimension - Standard Quick Disconnect Probes

To Order ***Visit omega.com/jqin for Pricing and Details***

Alloy/ANSI Color Code	Sheath Dia. in.	Model No. 12" Length	Model No. 18" Length	Model No. 24" Length
Iron- Constantan Inconel Sheath J	1⁄16	JQIN-116(*)-12	JQIN-116(*)-18	JQIN-116(*)-24
	1⁄8	JQIN-18(*)-12	JQIN-18(*)-18	JQIN-18(*)-24
	3⁄16	JQIN-316(*)-12	JQIN-316(*)-18	JQIN-316(*)-24
	1⁄4	JQIN-14(*)-12	JQIN-14(*)-18	JQIN-14(*)-24
Iron- Constantan 304 SS Sheath J	1⁄16	JQSS-116(*)-12	JQSS-116(*)-18	JQSS-116(*)-24
	1⁄8	JQSS-18(*)-12	JQSS-18(*)-18	JQSS-18(*)-24
	3⁄16	JQSS-316(*)-12	JQSS-316(*)-18	JQSS-316(*)-24
	1⁄4	JQSS-14(*)-12	JQSS-14(*)-18	JQSS-14(*)-24
CHROMEGA®-ALOMEGA® Inconel Sheath K	1⁄16	KQIN-116(*)-12	KQIN-116(*)-18	KQIN-116(*)-24
	1⁄8	KQIN-18(*)-12	KQIN-18(*)-18	KQIN-18(*)-24
	3⁄16	KQIN-316(*)-12	KQIN-316(*)-18	KQIN-316(*)-24
	1⁄4	KQIN-14(*)-12	KQIN-14(*)-18	KQIN-14(*)-24
CHROMEGA®- ALOMEGA® 304 SS Sheath K	1⁄16	KQSS-116(*)-12	KQSS-116(*)-18	KQSS-116(*)-24
	1⁄8	KQSS-18(*)-12	KQSS-18(*)-18	KQSS-18(*)-24
	3⁄16	KQSS-316(*)-12	KQSS-316(*)-18	KQSS-316(*)-24
	1⁄4	KQSS-14(*)-12	KQSS-14(*)-18	KQSS-14(*)-24
CHROMEGA®-ALOMEGA® Super OMEGACLAD® XL Sheath K	1⁄16	KQXL-116(*)-12	KQXL-116(*)-18	KQXL-116(*)-24
	1⁄8	KQXL-18(*)-12	KQXL-18(*)-18	KQXL-18(*)-24
	3⁄16	KQXL-316(*)-12	KQXL-316(*)-18	KQXL-316(*)-24
	1⁄4	KQXL-14(*)-12	KQXL-14(*)-18	KQXL-14(*)-24
OMEGA-P®-OMEGA-N® Super OMEGACLAD® XL Sheath N	1⁄16	NQXL-116(*)-12	NQXL-116(*)-18	NQXL-116(*)-24
	1⁄8	NQXL-18(*)-12	NQXL-18(*)-18	NQXL-18(*)-24
	3⁄16	NQXL-316(*)-12	NQXL-316(*)-18	NQXL-316(*)-24
	1⁄4	NQXL-14(*)-12	NQXL-14(*)-18	NQXL-14(*)-24
CHROMEGA®- Constantan Inconel Sheath E	1⁄16	EQIN-116(*)-12	EQIN-116(*)-18	EQIN-116(*)-24
	1⁄8	EQIN-18(*)-12	EQIN-18(*)-18	EQIN-18(*)-24
	3⁄16	EQIN-316(*)-12	EQIN-316(*)-18	EQIN-316(*)-24
	1⁄4	EQIN-14(*)-12	EQIN-14(*)-18	EQIN-14(*)-24
CHROMEGA®- Constantan 304 SS Sheath E	1⁄16	EQSS-116(*)-12	EQSS-116(*)-18	EQSS-116(*)-24
	1⁄8	EQSS-18(*)-12	EQSS-18(*)-18	EQSS-18(*)-24
	3⁄16	EQSS-316(*)-12	EQSS-316(*)-18	EQSS-316(*)-24
	1⁄4	EQSS-14(*)-12	EQSS-14(*)-18	EQSS-14(*)-24
Copper- Constantan Inconel Sheath T	1⁄16	TQIN-116(*)-12	TQIN-116(*)-18	TQIN-116(*)-24
	1⁄8	TQIN-18(*)-12	TQIN-18(*)-18	TQIN-18(*)-24
	3⁄16	TQIN-316(*)-12	TQIN-316(*)-18	TQIN-316(*)-24
	1⁄4	TQIN-14(*)-12	TQIN-14(*)-18	TQIN-14(*)-24
Copper- Constantan 304 SS Sheath T	1⁄16	TQSS-116(*)-12	TQSS-116(*)-18	TQSS-116(*)-24
	1⁄8	TQSS-18(*)-12	TQSS-18(*)-18	TQSS-18(*)-24
	3⁄16	TQSS-316(*)-12	TQSS-316(*)-18	TQSS-316(*)-24
	1⁄4	TQSS-14(*)-12	TQSS-14(*)-18	TQSS-14(*)-24

** Specify junction type: **G** (Grounded), **E** (Exposed), **U** (Ungrounded).*

To order with 310, 316 or 321 SS sheath**, change "**SS**" in model number to "**310SS**", "**316SS**" or "**321SS**" respectively; no additional charge. Consult Sales for lengths between 2 to 12", or for lengths over 24". **Type N Inconel Sheathing is available, Contact Sales for part numbers.
***Ordering Example: KQSS-18U-12**, molded junction quick disconnect probe, type K (CHROMEGA®-ALOMEGA®), 304SS sheath, 1⁄8" OD, ungrounded junction, 12" length.*

RUGGED, GENERAL PURPOSE TRANSDUCER
COMMON SPECIFICATIONS

mV Output Wiring

Wiring	Cable	mini DIN	Twist-Lock
Excitation (+)	Red	Pin 1	Pin A
Output (+)	White	Pin 3	Pin C
Output (-)	Green	Pin 4	Pin D
Excitation (-)	Black	Pin 2	Pin B
Spare			Pin E
Vent			Pin F

5 Vdc Output Wiring

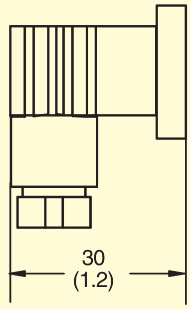
Wiring	Cable	mini DIN	Twist-Lock
Excitation (+)	Red	Pin 1	Pin A
Excitation (-)	Black	Pin 2	Pin B
Output (+)	White	Pin 3	Pin C
N/C†		Pin 4	Pin D
Spare			Pin E
Vent			Pin F

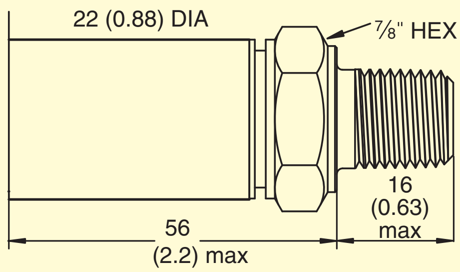
mA Output Wiring

Wiring	Cable	mini DIN	Twist-Lock
Supply (+)	Red	Pin 1	Pin A
Supply (-)	Black	Pin 2	Pin B
N/C†		Pin 3	Pin C
N/C†		Pin 4	Pin D
Spare			Pin E
Vent			Pin F

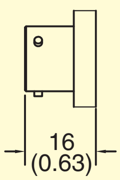
† N/C: Do not connect any wires to this pin.

mini DIN

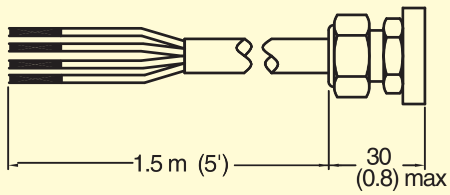




Twist-Lock



CABLE



COMMON SPECIFICATIONS

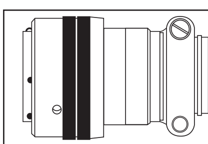
OMEGA's PX309 Series models below 100 psi use a high-accuracy silicon sensor protected by an oil-filled stainless steel diaphragm. Units 100 psi and above use silicon strain gages molecularly bonded to the stainless steel diaphragm

Long-Term Stability (1 Year): ±0.25% typical
Typical Life: 10 million cycles typical
Operating Temperature: -40 to 85°C (-40 to 185°F)
Proof Pressure:
All psia and ≤50 psig Ranges: 3x capacity or 20 psi, whichever is greater
100 psig Ranges: 2x capacity
Burst Pressure: 500% of capacity or 25 psi, whichever is greater
Response Time: <1 ms
Shock: 50 g, 11 ms half-sine
Vibration: ±20 g
Protection Class: IP 65
Wetted Parts:
316 SS for all psia and 1 to 50 psig ranges; 17-4 PH stainless steel for ranges 100 to 10,000 psig
Pressure Port: ¼-18 MNPT
Electrical Connections:
PX309: 1.5 m (5') 2-, 3-, or 4-conductor cable (mA, 5V, mV outputs, respectively)
PX319: mini DIN connector with mating connector included

Compatible Meters/Controllers for PX309 Series Pressure Transducers

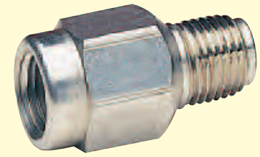
Starting at $150, the iSeries is available in 1/32, 1/16, and 1/8 DIN programmable process controllers with serial and embedded Internet/Ethernet communications (Order EI Option CNi16D). The iSeries features programmable color displays, free software and ActiveX Controls, selectable full autotune PID control, and NEMA 4 (IP65) rated front bezel. Ordering Examples: DPiS8, strain/process (monitor only), 1/8 DIN, $300; CNiS8, strain/process controller with 2 control outputs, $370. See pages D-7 thru D-21 for the complete selection.

PX329: Twist-lock connector, vented mating connector sold separately (PT06V-10-6S)
Weight:
PX309: 154 g (5.4 oz)
PX319: 100 g (3.5 oz)
PX329: 100 g (3.5 oz)



PX329 Mating Connector PT06V-10-6S $26.50

Order a snubber to protect your pressure transducer!



PS-4G, $12.75, shown actual size.

Snubbers protect sensors from fluid hammers/spikes.

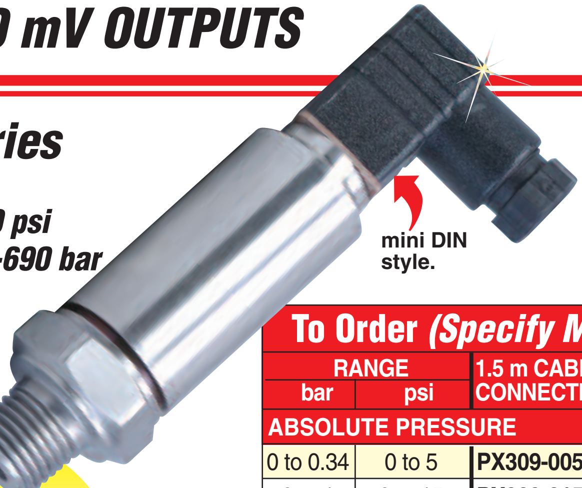
HOW TO ORDER PX309 SERIES

RUGGED, GENERAL PURPOSE TRANSDUCERS WITH 100 mV OUTPUTS

See Section Y for a Selection of Scientific, Technical, and Reference Books Available from omega.com

PX309 Series

100 mV Output
0-1 to 0-10,000 psi
0-70 mbar to 0-690 bar



PX319-050GV, $175, mini DIN connector included, shown smaller than actual size.

Metric thread adaptors available, see section C.

Starts at $175

NIST Standard

- Gage or Absolute Pressure
- Low Pressure to 1 psig
- Rugged Solid State Design
- All Stainless Steel Construction
- High Stability, Low Drift
- 0.25% Accuracy

100 mV Output Specifications

Excitation:
0 to 50 psig and All psia Ranges: 10 Vdc (ratiometric), (5 to 12 Vdc limits)
100 to 10,000 psig Ranges: 5 Vdc (ratiometric), (3 to 10 Vdc limits)
Output: 0 to 100 mV, except 2 psi = 40 mV and 1 psi = 20 mV
Accuracy: ±0.25% FS BSL at 25°C; includes linearity, hysteresis and repeatability
Zero Offset: ±2% FSO; ±4% for 1 and 2 psi ranges
Span Setting: ±2% FSO; ±4% for 1 and 2 psi ranges
Compensated Temperature: 0 to 50°C (32 to 122°F)
Thermal Zero and Span Effects (Over Compensated Range):
15 to 10,000 psi Ranges: ±2% FSO
5 psi Range: ±3% FSO
2 psi Range: ±4% FSO
1 psi Range: ±5% FSO

LOW-PRESSURE RANGES HIGHLIGHTED

To Order *(Specify Model Number)*

RANGE bar	RANGE psi	1.5 m CABLE CONNECTION	PRICE	MINI DIN CONNECTION	PRICE	TWIST-LOCK CONNECTION	PRICE
ABSOLUTE PRESSURE							
0 to 0.34	0 to 5	PX309-005AV	$300	PX319-005AV	$300	PX329-005AV	$300
0 to 1	0 to 15	PX309-015AV	195	PX319-015AV	215	PX329-015AV	235
0 to 2.1	0 to 30	PX309-030AV	195	PX319-030AV	215	PX329-030AV	235
0 to 3.4	0 to 50	PX309-050AV	195	PX319-050AV	215	PX329-050AV	235
0 to 6.9	0 to 100	PX309-100AV	195	PX319-100AV	215	PX329-100AV	235
0 to 14	0 to 200	PX309-200AV	195	PX319-200AV	215	PX329-200AV	235
0 to 21	0 to 300	PX309-300AV	195	PX319-300AV	215	PX329-300AV	235
GAGE PRESSURE							
0 to 0.07	0 to 1	PX309-001GV	$300	PX319-001GV	$300	PX329-001GV	$300
0 to 0.14	0 to 2	PX309-002GV	300	PX319-002GV	300	PX329-002GV	300
0 to 0.34	0 to 5	PX309-005GV	300	PX319-005GV	300	PX329-005GV	300
0 to 1	0 to 15	PX309-015GV	175	PX319-015GV	175	PX329-015GV	215
0 to 2.1	0 to 30	PX309-030GV	175	PX319-030GV	175	PX329-030GV	215
0 to 3.4	0 to 50	PX309-050GV	175	PX319-050GV	175	PX329-050GV	215
0 to 6.9	0 to 100	PX309-100GV	175	PX319-100GV	175	PX329-100GV	215
0 to 10	0 to 150	PX309-150GV	175	PX319-150GV	175	PX329-150GV	215
0 to 14	0 to 200	PX309-200GV	175	PX319-200GV	175	PX329-200GV	215
0 to 21	0 to 300	PX309-300GV	175	PX319-300GV	175	PX329-300GV	215
0 to 34	0 to 500	PX309-500GV	175	PX319-500GV	175	PX329-500GV	215
0 to 69	0 to 1000	PX309-1KGV	175	PX319-1KGV	175	PX329-1KGV	215
0 to 138	0 to 2000	PX309-2KGV	175	PX319-2KGV	175	PX329-2KGV	215
0 to 207	0 to 3000	PX309-3KGV	175	PX319-3KGV	175	PX329-3KGV	215
0 to 345	0 to 5000	PX309-5KGV	175	PX319-5KGV	175	PX329-5KGV	215
0 to 517	0 to 7500	PX309-7.5KGV	175	PX319-7.5KGV	175	PX329-7.5KGV	215
0 to 690	0 to 10,000	PX309-10KGV	175	PX319-10KGV	175	PX329-10KGV	215

Comes complete with 5-point NIST-traceable calibration.

Notes: *1. Units 100 psig and above may be subjected to vacuum on the pressure port without damage. 2. For alternative performance specifications to suit your application, contact Engineering.*

Ordering Examples: PX309-100GV, *100 psi gage pressure transducer with 100 mV output at 5 Vdc excitation and 1.5 m cable termination,* ***$175. PX319-015AV,*** *15 psi absolute pressure transducer with 100 mV output @ 10 Vdc excitation and mini DIN termination,* ***$215.***

PX329-3KGV, *3000 psi gage pressure transducer with 100 mV output @ 5 Vdc excitation and twist-lock termination,* ***$215.*** *Mating connector sold separately, order* ***PT06V-10-6S, $26.50.*** *Consult Sales for OEM pricing.*

ACCESSORIES

MODEL NO.	PRICE	DESCRIPTION
CAL-3	$150.00	Recalibration: 5-point NIST traceable
PT06V-10-6S	26.50	Mating connector for PX329
CA-39-4PC22-5	90.00	4-conductor mating twist-lock connector with 1.5 m (5') cable for PX329
CX5302	15.00	Extra mini DIN connector for PX319

USB-2408 Series

24-Bit Multifunction Temperature & Voltage Devices

MEASUREMENT COMPUTING

Features

- Measure thermocouples (TCs) or voltage
- Up to 16 analog inputs
- 24-bit resolution
- Up to 1 kS/s sampling
- 8 digital I/O
- Two counters
- Up to 2 analog outputs
- 500 VDC isolation between field wiring and the USB interface

Software

- TracerDAQ® software included for acquiring and displaying data and generating signals
- Universal Library includes support for Visual Studio® and Visual Studio®.NET, including examples for Visual C++®, Visual C#®, Visual Basic®, and Visual Basic® .NET
- DAQFlex open-source software framework; compatible with Windows® 32/64, Linux®, and Mac® platforms
- Comprehensive drivers for DASYLab® and NI LabVIEW™
- InstaCal software utility for installing, calibrating, and testing

USB-2408 Series devices offer high-resolution voltage or thermocouple measurements along with digital I/O and counter inputs. The USB-2408-2AO (shown here) includes analog output functionality.

USB-2408 Series Selection Chart

Model	Analog Inputs	Throughput Rate	Analog Outputs	Digital I/O	Counters
USB-2408	16 SE/8 DIFF	Up to 1 kS/s	—	8	2
USB-2408-2AO	16 SE/8 DIFF	Up to 1 kS/s	2	8	2

Overview

The USB-2408 Series are multifunction DAQ devices designed for highly-accurate voltage or temperature measurements. Each device features up to 16 single-ended (SE)/8 differential (DIFF) analog inputs. Each device includes 8 digital I/O and two counter inputs. The USB-2408-2AO also features two analog outputs. Each device in the series offers 24-bit resolution for ultra-accurate voltage or TC measurements.

Analog Input

Each device includes 16 SE/8 DIFF analog inputs which you can configure for voltage or TC input on a per-channel basis. Eight software-selectable voltage input ranges are provided. You can configure these ranges on a per-channel basis from ±10 V to ±0.078 V. When measuring TCs, configure analog inputs in DIFF mode. All devices also include open TC detection to identify improperly working thermocouples.

Sample Rate

USB-2408 Series devices can sample analog input channels at up to a 1 kS/s.*

Digital I/O

Eight digital I/O channels are included with each USB-2408 Series device, and you can read from or write to each individual bit.

Counters

Two 32-bit counters are included with USB-2408 Series devices. The TTL level inputs are capable of read/write rates of up to 500 Hz and an input frequency of up to 1 MHz.

Analog Output (USB-2408-2AO only)

The USB-2408-2AO includes two 16-bit analog outputs. Each output has a ±10 V range. Both outputs can be updated at a rate of up to 500 S/s per channel; one output can be updated at a rate of 1 kS/s.

Software

Each USB-2408 Series device includes TracerDAQ, an out-of-the-box application that generates, acquires, analyzes, displays, and exports data within seconds of installing Measurement Computing data acquisition hardware. TracerDAQ includes a Strip Chart, Oscilloscope, Function Generator, and Rate Generator, all of which are accessed through a common, easy-to-use menu page.

Driver support and detailed example programs are included for Universal Library programming libraries for Microsoft® Visual Studio® programming languages, and other languages, including DASYLab®, and ULx for NI LabVIEW®.

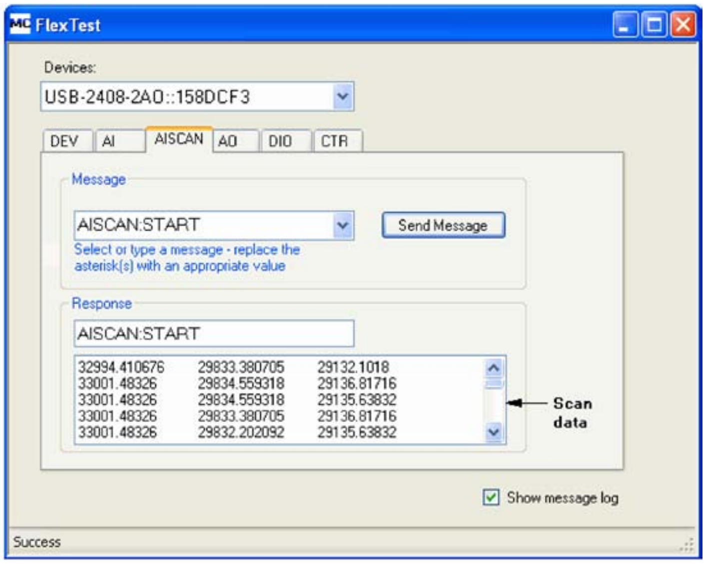
* Refer to the section, *Noise filtering, data rate, and throughput rate*, in the *USB-2408 Series User's Guide* to learn how the USB-2408 Series noise filtering feature affects the throughput rate for analog inputs.

USB-2408 Series

General Information & Specifications

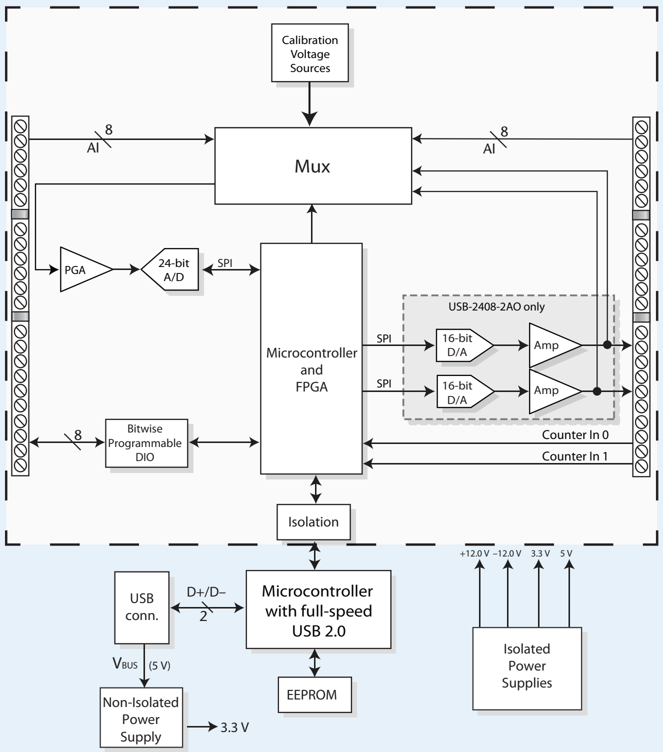
DAQFlex

For DAQ programming in virtually any OS, USB-2408 Series devices include DAQFlex, a framework that combines a small footprint driver with a message-based command protocol. The simplicity of the driver is enabled with a message-based protocol that offers an efficient yet powerful interface to DAQ devices and a common command set that simplifies application development.



FlexTest is an interactive GUI-based utility that demonstrates how to communicate with a device using the DAQFlex communication protocol and software.

USB-2408 Series Block Diagram



Specifications

All specifications are subject to change without notice.
Typical for 25 °C unless otherwise specified.
All specifications apply to all temperature and voltage input channels unless otherwise specified.

Analog Input

A/D Converter Type: ADS1256, 24-bit Sigma Delta
A/D Data Rates: 3750 S/s, 2000 S/s, 1000 S/s, 500 S/s, 100 S/s, 60 S/s, 50 S/s, 25 S/s, 10 S/s, 5 S/s, 2.5 S/s
Throughput (Software-Selectable for Single Channel and Multiple Channels)
  Single Channel: 2.5 S/s to 1102.94 S/s
  Multiple Channels: 0.16 Hz to 1102.94 Hz
Number of Channels: Up to 16 channels individually software-selectable as SE or DIFF; TCs require differential mode; for each channel configured as differential, you lose one single-ended channel
Input Isolation: 500 VDC min between field wiring and USB interface
Channel Configurations: Temperature sensor input, software-selectable to match sensor type; voltage input
Input Voltage Range
  Thermocouple Mode: ±0.078125 V
  Voltage Mode* (Software-Selectable): ±10 V, ±5 V, ±2.5 V, ±1.25 V, ±0.625 V, ±0.3125 V, ±0.15625 V, ±0.078125 V
Absolute Maximum Input Voltage
  CxH-CxL relative to GND: ±22 V max (power on), ±10 V max (power off)
Input Impedance: 10 MΩ (power on), 390 Ω (power off)
Input Leakage Current
  ±20 nA
  Input Voltage >±22 V (Power On/Off): ±1 µA max
Input Capacitance: 590 pf
Maximum Working Voltage (Signal + Common Mode)
  Voltage Mode: ±10.25 V max
Common Mode Rejection Ratio
  Thermocouple Mode (f_{IN} = 60 Hz): 110 dB
  Voltage Mode (f_{IN} = 60 Hz, all input ranges): 90 dB
ADC Resolution: 24 bits
Crosstalk: Adjacent channels,100 dB
Input Coupling: DC
Channel Gain Queue: Up to 64 elements, software-selectable channel and range
Warm-Up Time: 45 minutes min
Open Thermocouple Detect: Software-selectable for each channel
CJC Sensor Accuracy
  15 °C to 35 °C: ±0.5 °C typ
  0 °C to 55 °C: ±1.0 °C max

USB-2408 Series

Specifications

Channel Configurations

CxH/CxL

Thermocouple: 8 DIFF channels

Voltage: 16 individually configurable channels that can be configured as either 16 SE or 8 DIFF

Compatible Sensors (Thermocouple)

J: –210 °C to 1200 °C
R: –50 °C to 1768 °C
T: –270 °C to 400 °C
E: –270 °C to 1000 °C
K: –270 °C to 1372 °C
S: –50 °C to 1768 °C
N: –270 °C to 1300 °C
B: 0 °C to 1820 °C

Thermocouple Accuracy Specifications*
Includes CJC Measurement Error and Polynomial Linearization Error
Specifications Valid for One Year or 3000 Operating Hours, Whichever Comes First

Thermocouple	Sensor temperature range	Accuracy error, maximum	Accuracy error,typical	Tempco (°C/°C)
J	–210 °C	±2.572 °C	±1.416 °C	±0.022
	0 °C	±0.935 °C	±0.469 °C	
	1200 °C	±1.869 °C	±1.456 °C	
K	–210 °C	±2.917 °C	±1.699 °C	±0.029
	0 °C	±1.017 °C	±0.526 °C	
	1372 °C	±2.478 °C	±2.022 °C	
N	–200 °C	±3.480°C	±2.030 °C	±0.029
	0 °C	±1.201 °C	±0.659 °C	
	1300 °C	±1.991 °C	±1.600 °C	
R	–50 °C	±4.826 °C	±3.133 °C	±0.082
	250 °C	±2.117 °C	±1.424 °C	
	1768 °C	±2.842 °C	±2.347 °C	
S	–50 °C	±4.510 °C	±2.930 °C	±0.089
	250 °C	±2.165 °C	±1.468 °C	
	1768 °C	±3.187 °C	±2.597 °C	
B	250 °C	±5.489 °C	±3.956 °C	±0.14
	700 °C	±2.283 °C	±1.743 °C	
	1820 °C	±2.202 °C	±1.842 °C	
E	–200 °C	±2.413 °C	±1.352 °C	±0.017
	0 °C	±1.069 °C	±0.551 °C	
	1000 °C	±1.575 °C	±1.211 °C	
T	–200 °C	±2.821 °C	±1.676 °C	±0.027
	0 °C	±1.050 °C	±0.558 °C	
	400 °C	±0.957 °C	±0.595 °C	

* Each terminal block has a CJC sensor. The accuracy listed above assumes the screw terminals are at the same temperature as the CJC sensor.
The accuracy errors do not include the inherent accuracy error of the TC sensor. Ask your TC supplier about the actual TC sensor accuracy limitations.
Connect TCs to the USB-2408 Series device so that they float with respect to AGND .
When configuring TC sensors, keep any stray capacitance relative to AGND as small as possible to avoid settling time and accuracy errors.
AGND and DGND pins are isolated from earth ground. To connect TC sensors to voltages referenced to earth ground, maintain isolation between the AGND/DGND pins and earth ground.
To achieve the TC accuracies listed above, warm up the USB-2408 Series device for 45 minutes after the initial power on. The accuracies listed above are only guaranteed if the device is housed in the plastic enclosure.

USB-2408 Series

Specifications

Analog Input DC Voltage Measurement Accuracy						
Range	Gain error (% of reading)	Offset error	INL error (% of range)	Absolute accuracy	Gain temperature coefficient (% reading/°C)	Offset temperature coefficient (µV/°C)
±10 V	±0.0037	50 µV	±0.0008	500 µV	±0.0006	3
±5 V	±0.0047	25 µV	±0.0008	300 µV	±0.0006	2
±2.5 V	±0.0059	20 µV	±0.0008	200 µV	±0.0006	1
±1.25 V	±0.0056	20 µV	±0.0008	100 µV	±0.0006	1
±0.625 V	±0.0068	15 µV	±0.0005	60 µV	±0.0006	1
±0.3125 V	±0.0104	15 µV	±0.0006	50 µV	±0.0006	1
±0.15625 V	±0.0184	10 µV	±0.0005	40 µV	±0.0006	1
±0.078125 V	±0.0384	10 µV	±0.0009	40 µV	±0.0006	1

Input Bandwidth	
A/D Data Rate	–3 db Bandwidth (Hz)
3750 S/s	1615
2000 S/s	878
1000 S/s	441
500 S/s	221
100 S/s	44.2
60 S/s	26.5
50 S/s	22.1
25 S/s	11.1
10 S/s	4.42
5 S/s	2.21
2.5 S/s	1.1

Noise Performance

Refer to the *USB-2408 Series User's Guide* for noise performance specifications

Channel Switching Error

Refer to the *USB-2408 Series User's Guide* for channel switching error specifications

Throughput Rate

The maximum throughput of a USB-2408 Series device is 1.1 kS/s aggregate. The USB-2408 provides the ability to set conversion rates on a per-channel basis. This feature gives the user flexibility and control over noise averaging on a for each channel.

Refer to the *USB-2408 Series User's Guide* for tables and formulas that explain the many options for single- and multichannel throughputs.

Analog Voltage Output (USB-2408-2A0 only)

Unused AOUTx output channels should be left disconnected.

The USB-2408-2AO output voltage level defaults to 0 V whenever the host PC is reset, shut down or suspended, or if a reset command is issued to the device.

The duration of the output transient depends highly on the enumeration process of the host computer. Typically, the output of the USB-2408-2AO is stable after two seconds.

Digital to Analog Converter: DAC8552
Number of Channels: 2
Resolution: 16 bits
Output Ranges
  Calibrated: ±10 V
  Uncalibrated: ±10.05 V, software-selectable
Output Transient
  Host computer is reset, powered on, suspended or a reset command is issued to device
    Duration: 2 s
    Amplitude: 2 V p-p
  Initial Power On
    Duration: 50 ms
    Amplitude: 5 V peak
Differential Non Linearity: ±0.25 LSB typ, ±1 LSB max
Output Current: AOUTx pins, ±5.0 mA max
Output Short-Circuit Protection
  AOUTx connected to AGND: Unlimited duration
Output Coupling: DC
Power on and Reset State: DACs cleared to zero-scale, 0 V, ±50 mV
Output Noise: 60 µVrms (BW=1.5 KHz)
Settling Time: To rated accuracy, 10 V step, 75 µs
Slew Rate: 1.0 V/µs
Throughput
  Single-Channel: 1000 S/s max, system-dependent
  Multi-Channel: 1000 S/s /#ch max, system-dependent
Calibrated Absolute Accuracy
  Range: ±10 V
  Accuracy (±LSB): 16.0
Calibrated Absolute Accuracy Components
  Range: ±10 V
  % of Reading: ±0.0183
  Offset: ±1.831 **mV**
  Temp Drift (%/°C): 0.00055
  Absolute Accuracy at FS: ±3.661 mV
Relative Accuracy
  Range: ±10 V
  Relative Accuracy: ±4.0 LSB typ

Analog Input/Output Calibration

Warm-Up Time: 45 minutes min
Calibration: Firmware calibration
Calibration Interval: 1 year
AI Calibration Reference: 10.000 V, ±5 mV max
    Actual measured values stored in EEPROM
  Tempco: 5 ppm/°C max
  Long Term Stability: 30 ppm/1000 hours
AO Calibration Procedure (USB-2408-2AO Only): The analog output pin is internally routed to the analog input pin.
AOUTx Readback (USB-2408-2AO Only, Software-Selectable): Each AOUTx output can be independently measured by the onboard A/D converter

USB-2408 Series

Specifications & Ordering Information

Digital Input/Output

Digital Input

Number of I/O: 8 channels
Configuration: Each DIO bit can be independently read from (DIN) or written to (DOUT). DIN bits can be read at any time whether the DOUT is active or tri-stated.
Input Voltage Range: 0 to 15 V
Input Type: CMOS (Schmitt trigger)
Input Characteristics: 47 kΩ pull-up/pull-down resistor, 28 kΩ series resistor
Maximum Input Voltage Range: 0 V to 20 V max (power on/off, relative to DGND
Pull-Up/Pull-Down Configuration: All pins pulled up to 5 V through individual 47 kΩ resistors (the J6 shorting block default position is pins 1 and 2)
Pull-down capability is available by placing the J6 shorting block across pins 2 and 3
Transfer Rate (Software Paced): 500 port reads or single bit reads per second typ
Input High Voltage: 1.3 V to 2.2 V
Input Low Voltage: 1.5 V to 0.6 V
Schmitt Trigger Hysteresis: 0.4 V to 1.2

Digital Output

Number of I/O: 8 channels
Configuration: Each DIO bit can be independently read from (DIN) or written to (DOUT). DIN bits can be read at any time whether the DOUT is active or tri-stated.
Output Characteristics: 47 kΩ pull-up, open drain (DMOS transistor)
Each DMOS transistor source pin is internally connected to DGND
Pull-Up Configuration: All pins pulled up to 5 V through individual 47 kΩ resistors (the J6 shorting block default position is pins 1 and 2).
Transfer Rate (Software Paced)
Digital Output: 500 port writes or single bit writes per second typ
Output Voltage Range: 0 V to 5 V (no external pull up resistor, internal 47 kΩ pull-up resistors connected to 5 V by default); 0 V to 15 V max
Drain to Source Breakdown Voltage: 50 V min
Off State Leakage Current: 1.0 µA
Sink Current Capability: 150 mA max (continuous) per output pin
150 mA max (continuous) for all eight channels
DMOS Transistor On-Resistance (Drain to Source): 4 Ω

Counter

Pin Names: CTR0, CTR1
Number of Channels: 2 channels
Resolution: 32-bits
Counter Type: Event counter
Input Type: Schmitt trigger, rising edge triggered
Input Source: CTR0 (pin 44), CTR1 (pin 42)
Counter Read/Writes Rates (Software Paced)
Counter Read: System-dependent, 500 reads per second.
Counter Write: System-dependent, 500 writes per second.
Input Characteristics: Each CTRx input pin has 562 kΩ resistor pulled up to 5 V and a 10 kΩ series resistor
Input Voltage Range: ±15 V max
Maximum Input Voltage Range: CTR0,CTR1 relative to GND and DGND, ±20 V max (power on/off)
Input High Voltage: 1.3 V to 2.2 V
Input Low Voltage: 1.5 V to 0.6 V
Schmitt Trigger Hysteresis: 0.4 V to 1.2
Input Bandwidth (-3 dB): 1 MHz
Input Capacitance: 25 pf
Input Leakage Current: ±120 nA @5 V, ±1.6 mA @±15 V
Input Frequency: 1 MHz, max
High Pulse Width: 500 ns, min
Low Pulse Width: 500 ns, min

Memory

EEPROM: 4096 bytes isolated micro reserved for sensor configuration, 256 bytes USB micro for external application use

Microcontroller

Type: One high-performance 8-bit RISC microcontroller with USB interface (non-isolated)
One high-performance 16-bit RISC microcontroller for measurements (isolated)

Power

Supply Current: Quiescent current, 275 mA
This is the total quiescent current requirement for the USB-2408 Series which includes up to 10 mA for the status LED. This does not include any potential loading of the digital I/O bits, +5 V user terminal or the AOUTx outputs.
Voltage Supervisor Limits: 4.5 V > V_{ext} or V_{ext} > 5.5 V, PWR LED = Off, (power fault)
4.5 V < V_{ext} < 5.5 V, PWR LED = On
5 V User Output Voltage Range: Available at terminal block pin 40, 4.75 V to 5.25 V
+5 V User Output Current: Available at terminal block pin 40, 10 mA max
Isolation: Measurement system to computer, 500 VDC min

USB Specifications

USB Device Type: USB 2.0 (full-speed)
Device Compatibility: USB 1.1, USB 2.0
USB Cable Type: A-B cable, UL type AWM 2527 or equivalent (min 24 AWG VBUS/GND, min 28 AWG D+/D–)
USB Cable Length: 3 meters max

Environmental

Operating Temperature Range: 0 °C to 50 °C
Storage Temperature Range: -40 °C to 85 °C
Humidity: 0% to 90% non-condensing

Mechanical

Dimensions (L × W × H): 127 × 89.9 × 35.6 mm (5.00 × 3.53 × 1.40 in.)
User Connection Length: 3 meters max

Screw Terminal Connector

Connector Type: Fixed screw terminal
Wire Gauge Range: 16 AWG to 30 AWG

Ordering Information

Description	Part No.
USB-based 24-bit, isolated, multifunction DAQ device with USB cable	USB-2408
USB-based 24-bit, isolated, multifunction DAQ device with two analog outputs and USB cable	USB-2408-2AO

Accessories

E-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 1 m	745690-E001
E-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 2 m	745690-E002
J-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 1 m	745690-J001
J-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 2 m	745690-J002
K-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 1 m	745690-K001
K-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 2 m	745690-K002
T-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 1 m	745690-T001
T-type thermocouples wire, fiberglass (0 °C to 482 °C , 32 °F to 900 °F), 2 m	745690-T002

Software

Icon-based data acquisition, graphics, control, and analysis software	DASYLab
Out-of-the-box virtual instrument suite with strip chart, oscilloscope, function generator, and rate generator – professional version	TracerDAQ Pro

USB-2408-Series.indd
Document Revision 2, February, 2012

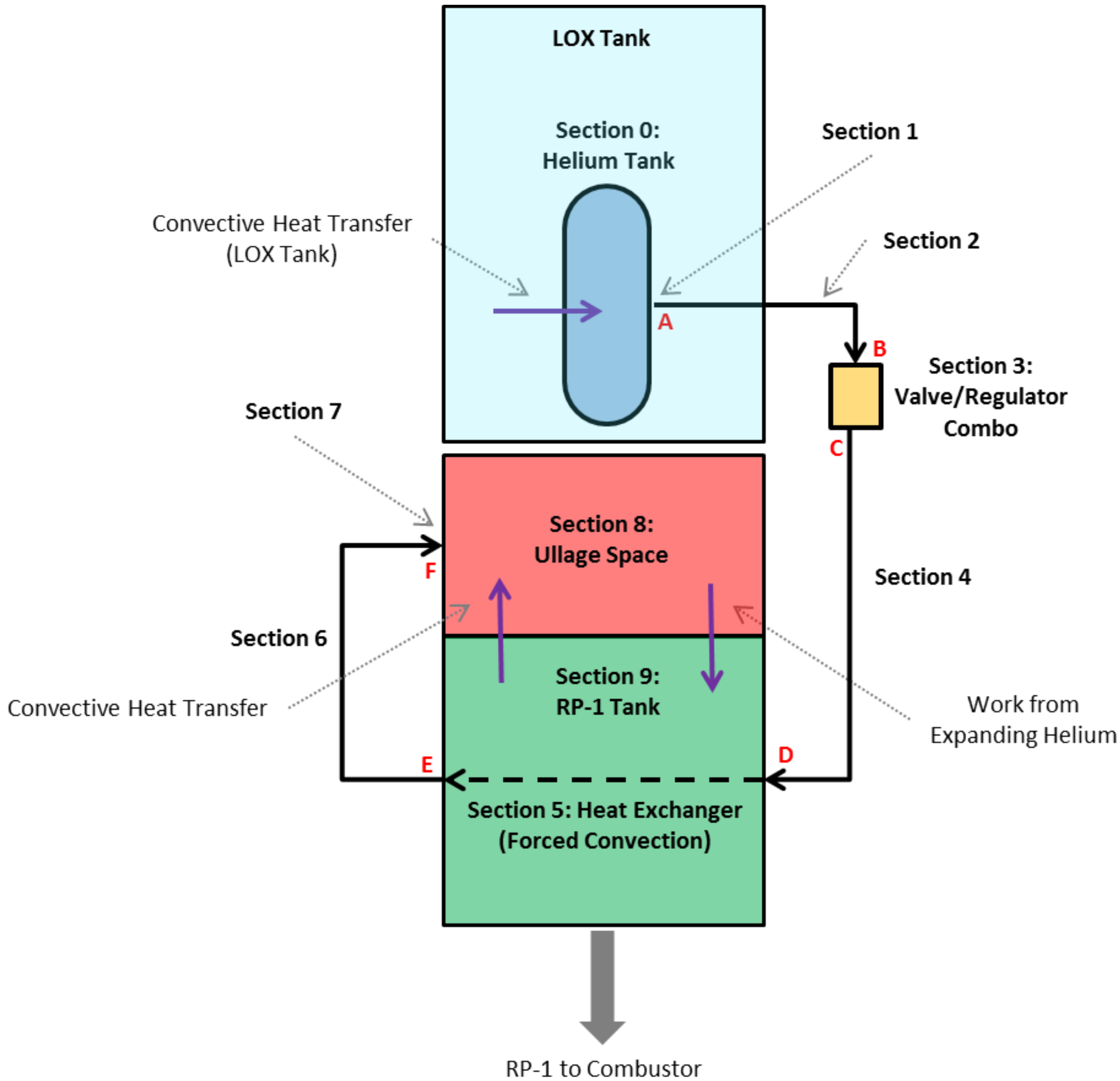


FIGURE E1 – INITIAL STATE POINT DIAGRAM OF HELIUM PRESSURANT SYSTEM. KEY ENERGY TRANSFERS ARE INDICATED WITH A PURPLE ARROW. SCHEMATIC NOT TO SCALE.

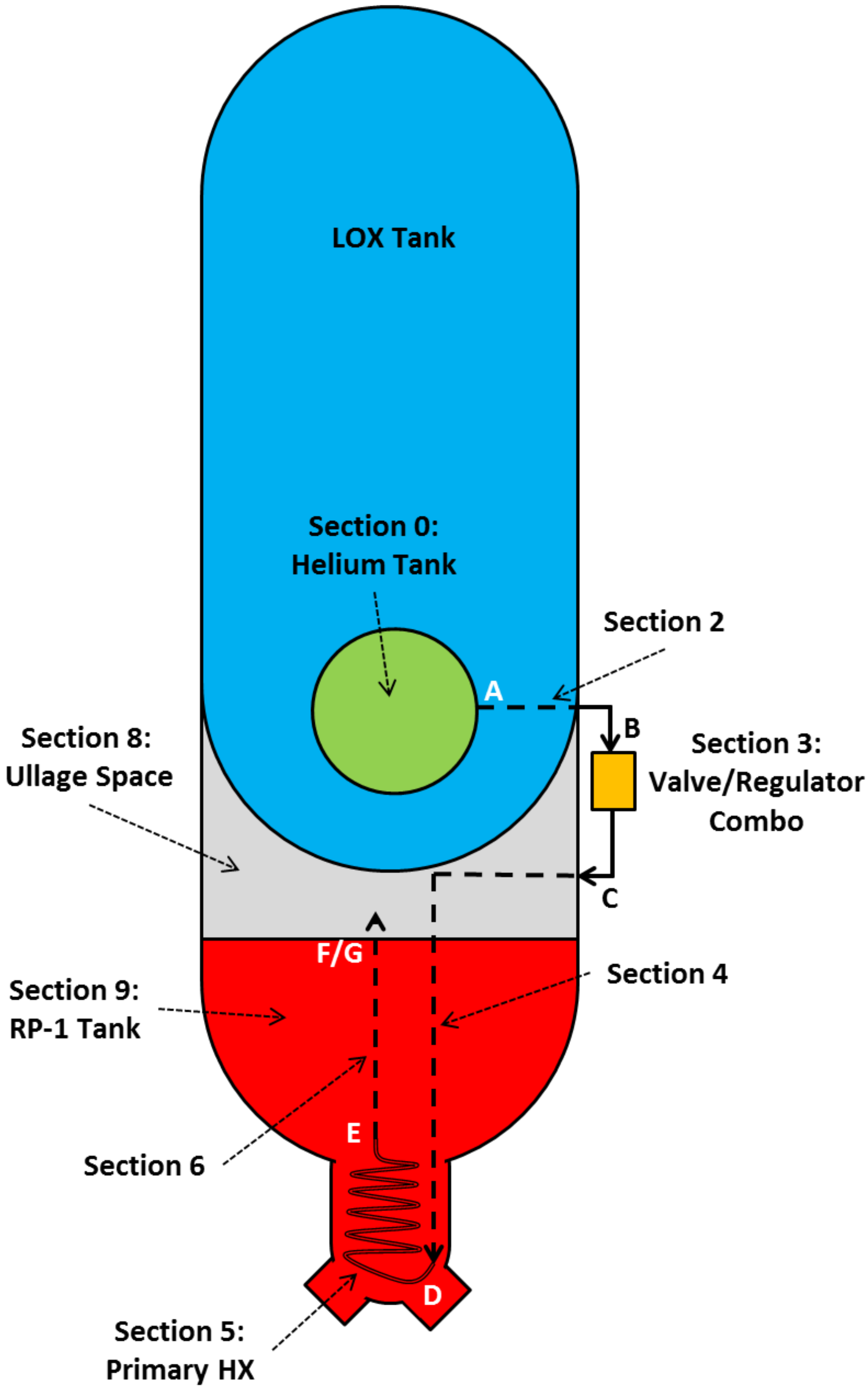


FIGURE E2 – FINAL STATE POINT DIAGRAM OF HELIUM PRESSURANT SYSTEM. SCHEMATIC NOT TO SCALE.

Many of the common equations used in our program are derived from a few fundamental thermodynamic principles. In this section, we will present the derivation of some equations common to various sections of our pressurant system.

The Conservation of Mass equation has the general form:

$$\frac{d}{dt}\int_{CV} \rho \, dV + \int_{CS} \rho \, \vec{v} \cdot d\vec{A} = 0$$

For pipe flow, we make the following assumptions:

Steady (single instance in time)

Density does not vary in given cross section

While the density does change between state points, we use the finite different method to assume that the incremental density does not change, but that change occurs instantaneously at the border of the next incremental section of pipe. This is a good approximation if our increments are small enough (i.e. high resolution).

The continuity equation then reduces as follows:

$$\int_{CS} \rho \, \vec{v} \cdot d\vec{A} = 0$$

$$-\int \rho_A \, v_A \, dA + \int \rho_B \, v_B \, dA \; = 0$$

$$\rho_A \, v_A \, A_A = \; \rho_B \, v_B \, A_B = \dot{m}_{He}$$

$$\boldsymbol{\rho_B = \; \rho_A \frac{v_A}{v_B} \frac{A_A}{A_B}}$$

The next equation we will consider is the 1st Law of Thermodynamics:

$$\frac{d}{dt}\int_{CV}\left(e+\frac{P}{\rho}\right)\rho\, dV + \int_{CS}\left(e+\frac{P}{\rho}\right)\rho\, \vec{v}\cdot d\vec{A} = \dot{Q} - \dot{W}$$

Where:

$$e = u + \frac{v^2}{2} + gz$$

For pipe flow, we will assume the following:

Steady (single instance in time)

Density and energy do not vary in given cross section

Negligible change in potential energy

No work done on fluid

Perfect gas (ideal gas + constant specific heats)

This equation is then simplified:

$$\int_{CS}\left(e+\frac{P}{\rho}\right)\rho\, \vec{v}\cdot d\vec{A} = \dot{Q}$$

$$-\int\left(h_A+\frac{{v_A}^2}{2}\right)\rho_A\, v_A\, dA + \int\left(h_B+\frac{{v_B}^2}{2}\right)\rho_B\, v_B\, dA\ = \dot{Q}$$

$$\dot{Q} = -\rho_A\, v_A\, A_A\left(h_A+\frac{{v_A}^2}{2}\right) + \rho_B\, v_B\, A_B\left(h_B+\frac{{v_B}^2}{2}\right)$$

From continuity, however, we find that the mass flow rates are equal between each state point. Thus:

$$\dot{Q} = -\dot{m}_{He}\left(h_A+\frac{{v_A}^2}{2}\right) + \dot{m}_{He}\left(h_B+\frac{{v_B}^2}{2}\right)$$

$$\dot{Q} = \dot{m}_{He}\left(c_p(T_B - T_A) + \frac{{v_B}^2 - {v_A}^2}{2}\right)$$

$$q = c_p(T_B - T_A) + \frac{{v_B}^2 - {v_A}^2}{2}$$

$$\boldsymbol{T_B = T_A + \frac{1}{c_p}\left(q - \frac{{v_B}^2 - {v_A}^2}{2}\right)}$$

The third important general equation we will investigate is the Momentum equation:

$$\frac{d}{dt}\int_{CV} v\,\rho\,dV + \int_{CS} v\,\rho\,\vec{v}\cdot d\vec{A} = \sum \vec{F}$$

Still analyzing pipe flow, we use the following assumptions to simplify:

Steady (single instance in time)

Density does not vary in given volume or cross section

Inviscid in differential volume (v = constant)

One-dimensional flow

Internal compressible pipe flow modeled as flow over a flat plate

The equation above now reduces:

$$\int_{CS} v\,\rho\,\vec{v}\cdot d\vec{A} = \sum \vec{F}$$

Where:

$$\sum \vec{F} = P_B A_B - P_A A_A + F_f$$

$$F_f = \frac{1}{2}\rho_{AB}\,A_s\,C_d\,{v_{AB}}^2$$

$$F_f = \frac{1}{16}(\rho_A + \rho_B)\,A_s\,C_d\,(v_A + v_B)^2$$

Thus:

$$\dot{m}_{He}(v_B - v_A) = P_B A_B - P_A A_A + \frac{1}{16}(\rho_A + \rho_B)\, A_s\, C_d\, (v_A + v_B)^2$$

$$\boldsymbol{P_B = \frac{A_A}{A_B} P_A - \frac{\rho_A}{16 A_B}\left(1 + \frac{A_A v_A}{A_B v_B}\right)(v_A + v_B)^2 A_s C_d - \frac{\dot{m}_{He}}{A_B}(v_B - v_A)}$$

We will now use these 3 equations in Excel to iteratively solve for the appropriate new velocity into the next pipe section.

SECTION 0: HELIUM TANK (LOCATED IN LOX TANK)

Internal Energy & Temperature (time-dependent)

Specific energy (e) and density (ρ) are not a function of volume (V)

Negligible potential energy and kinetic energy in tank

Specific energy = internal energy (i.e. e=u)

No work done on helium in tank

Finite difference model applies

Q_{lox} = constant

h_A = constant

m_{He} = constant

$$\boldsymbol{u_0(1) = \frac{u_0(0) m_0(0) + \dot{Q}_{LOX}\Delta t - \dot{m}_{He} h_A \Delta t}{m_0(1)}}$$

Ideal gas

Small change in helium tank mass between time steps

Thermal mass of helium tank added to helium mass when computing temperature drop

$$\boldsymbol{T_0(1) = T_0(0) + \frac{\dot{Q}_{LOX}\Delta t - \dot{m}_{He} h_A \Delta t}{C_v\left[m(0) + m_{tank,eq} - \frac{\dot{m}_{He}}{2}\Delta t\right]}}, \qquad \boldsymbol{C_v = C_p - R}$$

$$\boldsymbol{m_{tank,eq} = \frac{c_{Al}}{c_{v,He}}\, m_{tank}}$$

Pressure (time-dependent)

$$\boldsymbol{P_0 = \frac{Z_0\, m_0\, R\, T_0}{n_{tank}\, V_0}}$$

Density (time-dependent)

$$\boldsymbol{\rho_0 = \frac{m_0}{n_{tank}\, V_0}}$$

Heat Transfer (time-dependent)

Turbulent flow, tank modeled as internal pipe flow of diameter D_0

Forced convection HT

LOX at constant temperature

Helium tank is spherical

$$\boldsymbol{\dot{Q}_{LOX} = U_{LOX}\, A_{s0}\, (T_0 - T_{LOX})}$$

$$\boldsymbol{A_{s0} = \pi {D_0}^2}$$

$$\boldsymbol{U_{LOX} = \left[\frac{t_{wall}}{k_{wall}} + \frac{1}{h_{in}}\right]^{-1}}$$

$$\boldsymbol{h_{in} = \frac{Nu_{in} k_{in}}{D_0}}$$

$$\boldsymbol{Nu_{in} = 0.0243 {Re_{LOX}}^{0.8}\, Pr^{0.4}}$$

$$\boldsymbol{Re_{LOX} = \frac{v_0 D_0}{\nu_0}}$$

SECTION 1: HELIUM TANK TO PIPE ENTRANCE

Velocity, Pressure, Temperature, Density (location-dependent)

Given: P_0, T_0, ρ_0

Minor loss, $K_{L1} = 0.5$

Negligible heat transfer

$$\boldsymbol{V_A = \frac{\dot{m}_{He}}{A_A\, \rho_A}}$$

$$\boldsymbol{P_A = P_0 - \frac{\rho_A K_{L1}}{16}\left(1 + \frac{A_0 V_0}{A_A V_A}\right)(V_0 + V_A)^2 - \frac{\dot{m}_{He} V_A}{A_A}}$$

$$\boldsymbol{T_A = T_0 - \frac{V_A^2}{2 c_p}}$$

$$\boldsymbol{\rho_A = \frac{P_A}{Z_A\, R\, T_A}}$$

[Iterate through calculations until v_A converges…]

SECTION 2: PIPING FROM HELIUM TANK TO REGULATOR

Velocity, Pressure, Temperature, Density (location-dependent)

Given: P_A, T_A, ρ_A

Constant coefficient of drag ($C_{D1} = 0.003$)

$$\boldsymbol{V_B = \frac{\dot{m}_{He}}{A_B\,\rho_B}}$$

$$\boldsymbol{P_B = \frac{A_A P_A}{A_B} - \frac{\rho_A A_{s2} C_{d2}}{16 A_B}\left(1 + \frac{A_A V_A}{A_B V_B}\right)(V_A + V_B)^2 - \frac{\dot{m}_{He}(V_B - V_A)}{A_B}}$$

$$\boldsymbol{T_B = T_A + \frac{1}{c_p}\left(q_2 - \frac{V_B^2 - V_A^2}{2}\right)}$$

$$\boldsymbol{\rho_B = \frac{P_B}{Z_B\,R\,T_B}}$$

[Iterate through calculations until v_B converges…]

Heat Transfer

Negligible heat transfer ($L_2 \approx 0$ □ $\Delta t \approx 0$)

Constant specific heat (c_p)

$$\boldsymbol{q_2 = U_2 A_{s2}(\Delta T_{LM}) = \dot{m}_{He} c_p (T_B - T_A) = 0}$$

SECTION 3: REGULATOR

Enthalpy (location-dependent)

Valve is isenthalpic

$$\boldsymbol{h_C = h_B}$$

Velocity, Pressure, Temperature, Density (location-dependent)

Regulator outlet pressure constant (set by user)

$$\boldsymbol{V_C = \frac{\dot{m}_{He}}{A_C\,\rho_C}}$$

$$\boldsymbol{P_C = 450\ psia}$$

$$\boldsymbol{T_C = (\text{"helium"}, \text{"HP"}, \text{"SI"}, h_C, P_C)}$$

$$\rho_C = \frac{P_C}{Z_C\, R\, T_C}$$

SECTION 4: PIPING FROM REGULATOR TO PRIMARY HX

Finite difference model: Section 4 broken up into m equal pieces

Velocity, Pressure, Temperature, Density (location-dependent)

Given: P_C, T_C, ρ_C

Constant coefficient of drag (C_{D4} = 0.002)

$$V_D = \frac{\dot{m}_{He}}{A_D\, \rho_D}$$

$$P_D = \frac{A_C P_C}{A_D} - \frac{\rho_C A_{s4} C_{d4}}{16 A_D}\left(1 + \frac{A_C V_C}{A_D V_D}\right)(V_C + V_D)^2 - \frac{\dot{m}_{He}(V_D - V_C)}{A_D}$$

$$T_D = T_C + \frac{1}{c_p}\left(q_4 - \frac{V_D^2 - V_C^2}{2}\right)$$

$$\rho_D = \frac{P_D}{Z_D\, R\, T_D}$$

[Iterate through calculations until v_D converges…]

Heat Transfer

Cylinder in cross flow

Constant specific heat (c_p)

Pr = 0.7 for helium (constant)

$$q_X = \frac{U_X \frac{A_{s4}}{n}(\mathrm{T}_9 - T_{DX})}{\dot{m}_{He}}$$

$$U_X = \left[\frac{1}{h_{out}} + \frac{t_{wall}}{k_{wall}} + \frac{1}{h_{in}}\right]^{-1}$$

$$h_{in} = f_{enhance} \frac{Nu_{in} k_{in}}{ID_4}$$

$$f_{enhance} = \left(Re_{in}\left(\frac{ID_4 + OD_4}{ID_{4,coil} + OD_{4,coil}}\right)^2\right)^{0.05}$$

$$Nu_{in} = \frac{f_i}{8} \frac{(Re_{in} - 1000)\, Pr_{in}}{1 + 12.7\left(\frac{f_i}{8}\right)^{0.5}\left(Pr_{in}^{\frac{2}{3}} - 1\right)}$$

$$f_i = (0.79\, log(Re_{in}) - 1.64)^{-2}$$

$$Re_{in} = \frac{v_{DX}\, ID_4}{\nu_{in}}$$

$$h_{out} = \frac{Nu_{out} k_{out}}{OD_4}$$

$$Nu_{out} = 0.3 + \frac{0.62 Re_{out}^{0.5}\ \ Pr_{out}^{\frac{1}{3}}}{\left(1 + \left(\frac{0.4}{Pr_{out}}\right)^{\frac{2}{3}}\right)^{0.25}}\left(1 + \left(\frac{Re_{out}}{282000}\right)^{0.625}\right)^{0.8}$$

$$Re_{out} = \frac{v_8 D_8}{\nu_{out}}$$

SECTION 5: PRIMARY HX

Finite difference model: Section 5 broken up into n equal pieces

Velocity, Pressure, Temperature, Density (location-dependent)

Given: P_D, T_D, ρ_D

Constant coefficient of drag (C_{D5} = 0.002)

$$V_{EX} = \frac{\dot{m}_{He}}{A_E\, \rho_E}$$

$$P_{EX} = \frac{A_D P_D}{A_E} - \frac{\rho_D A_{s5} C_{d5}}{16000 A_E}\left(1 + \frac{A_D V_D}{A_E V_E}\right)(V_D + V_{EX})^2 - \frac{\dot{m}_{He}(V_{EX} - V_D)}{1000 A_E}$$

$$T_{EX} = T_D + \frac{1}{c_p}\left(q_X - \frac{V_{EX}^2 - V_D^2}{2000}\right)$$

$$\rho_{EX} = \frac{P_{EX}}{Z_E\, R\, T_{EX}}$$

[Iterate through calculations until v_E converges…]

Heat Transfer

Cylinder in cross flow

Constant specific heat (c_p)

Pr = 0.7 for helium (constant)

$$q_X = \frac{U_X \frac{A_{s5}}{n} (T_9 - T_{EX})}{\dot{m}_{He}}$$

$$U_X = \left[\frac{1}{h_{out}} + \frac{t_{wall}}{k_{wall}} + \frac{1}{h_{in}}\right]^{-1}$$

$$h_{in} = f_{enhance} \frac{Nu_{in} k_{in}}{ID_5}$$

$$f_{enhance} = \left(Re_{in} \left(\frac{ID_5 + OD_5}{ID_{5,coil} + OD_{5,coil}}\right)^2\right)^{0.05}$$

$$Nu_{in} = \frac{f_i}{8} \frac{(Re_{in} - 1000)\, Pr_{in}}{1 + 12.7 \left(\frac{f_i}{8}\right)^{0.5} \left(Pr_{in}^{\frac{2}{3}} - 1\right)}$$

$$f_i = (0.79\, log(Re_{in}) - 1.64)^{-2}$$

$$Re_{in} = \frac{v_{EX}\, ID_5}{\nu_{in}}$$

$$h_{out} = \frac{Nu_{out} k_{out}}{OD_5}$$

$$Nu_{out} = 0.3 + \frac{0.62 Re_{out}^{0.5}\ Pr_{out}^{\frac{1}{3}}}{\left(1 + \left(\frac{0.4}{Pr_{out}}\right)^{\frac{2}{3}}\right)^{0.25}} \left(1 + \left(\frac{Re_{out}}{282000}\right)^{0.625}\right)^{0.8}$$

$$Re_{out} = \frac{v_8 D_8}{\nu_{out}}$$

SECTION 6: PIPING FROM PRIMARY HX TO PIPE EXIT

Finite difference model: Section 6 broken up into o equal pieces

Velocity, Pressure, Temperature, Density (location-dependent)

Given: P_F, T_F, ρ_F

Constant coefficient of drag (C_{D6} = 0.002)

$$V_F = \frac{\dot{m}_{He}}{A_F\, \rho_F}$$

$$P_F = \frac{A_E P_E}{A_F} - \frac{\rho_E A_{s6} C_{d6}}{16000 A_F}\left(1 + \frac{A_E V_E}{A_F V_F}\right)(V_E + V_F)^2 - \frac{\dot{m}_{He}(V_F - V_E)}{1000 A_F}$$

$$T_F = T_E + \frac{1}{c_p}\left(q_6 - \frac{V_F^2 - V_E^2}{2000}\right)$$

$$\rho_F = \frac{P_F}{Z_F\, R\, T_F}$$

[Iterate through calculations until v_F converges…]

Heat Transfer

Cylinder in cross flow

Constant specific heat (c_p)

Pr = 0.7 for helium (constant)

$$q_X = \frac{U_X \frac{A_{s6}}{n}(T_9 - T_{FX})}{\dot{m}_{He}}$$

$$U_X = \left[\frac{1}{h_{out}} + \frac{t_{wall}}{k_{wall}} + \frac{1}{h_{in}}\right]^{-1}$$

$$h_{in} = f_{enhance} \frac{Nu_{in} k_{in}}{ID_6}$$

$$f_{enhance} = \left(Re_{in}\left(\frac{ID_6 + OD_6}{ID_{6,coil} + OD_{6,coil}}\right)^2\right)^{0.05}$$

$$Nu_{in} = \frac{f_i}{8}\,\frac{(Re_{in} - 1000)\, Pr_{in}}{1 + 12.7\left(\frac{f_i}{8}\right)^{0.5}\left(Pr_{in}^{\frac{2}{3}} - 1\right)}$$

$$f_i = (0.79\, log(Re_{in}) - 1.64)^{-2}$$

$$Re_{in} = \frac{v_{FX}\, ID_6}{\nu_{in}}$$

$$h_{out} = \frac{Nu_{out} k_{out}}{OD_6}$$

$$Nu_{out} = 0.3 + \frac{0.62 Re_{out}^{0.5}\ Pr_{out}^{\frac{1}{3}}}{\left(1 + \left(\frac{0.4}{Pr_{out}}\right)^{\frac{2}{3}}\right)^{0.25}}\left(1 + \left(\frac{Re_{out}}{282000}\right)^{0.625}\right)^{0.8}$$

$$Re_{out} = \frac{v_8 D_8}{\nu_{out}}$$

SECTION 7: PIPE EXIT INTO ULLAGE

Enthalpy (location-dependent)

Exit holes from pipe into fuel tank modeled as isenthalpic valve

$$h_G = h_F$$

Velocity, Pressure, Temperature, Density (location-dependent)

Regulator outlet pressure constant (set by user)

$$V_G = \frac{\dot{m}_{He}}{A_G\,\rho_G}$$

$$P_G = 40\,psia$$

$$T_G = (\text{"helium"}, \text{"HP"}, \text{"SI"}, h_G, P_G)$$

$$\rho_G = \frac{P_G}{Z_G\,R\,T_G}$$

SECTION 8: ULLAGE VOLUME

Internal Energy & Temperature (time-dependent)

Specific energy (e) and density (ρ) are not a function of volume (V)

Negligible potential energy and kinetic energy in tank

Specific energy = internal energy (i.e. e=u)

Finite difference model applies

P_8 = *constant*

Q_{conv} = *constant*

V_8 = *constant*

h_F = *constant*

m_{He} = *constant*

v_F = *constant*

$$u_8(1) = \frac{u_8(0)m_8(0) + \dot{Q}_{conv}\Delta t - P_8 A_8 V_8 \Delta t + \dot{m}_{He}\left(h_F + \frac{v_F^2}{2000}\right)\Delta t}{m_8(1)}$$

$$T_8(1) = ("helium", "EP", "SI", u_8(1), P_8(1))$$

Pressure (time-dependent)

Minor loss, K_{L7} = 1.0 neglected

$$P_8 = P_G$$

Density (time-dependent)

$$\rho_8 = \frac{m_8}{V_8}$$

Heat Transfer (time-dependent)

Turbulent flow

Free convection HT b/n helium-RP1 boundary

Forced convection HT b/n helium at fuel tank wall

RP-1 at constant ambient temperature

Fuel tank wall at constant ambient temperature

Properties evaluated at film temperature: $T_F = 0.5(T_8 + T_9)$

Pr = 8.0 for RP-1 (constant)

$$\dot{Q}_{RP1} = h_{RP1}\, A_8\, (T_9 - T_8) + h_{tank}\, A_{s,tank}\, (T_9 - T_8)$$

$$h_{RP1} = \frac{Nu_{RP1}\, k_{RP1}}{D_8}$$

$$Nu_{RP1} = 0.15 Ra_{RP1}{}^{\frac{1}{3}}$$

$$Ra_{RP1} = \frac{g\, \beta\, (T_9 - T_8)\, D^3}{\nu_{RP1}\, \alpha_{RP1}}\ , \qquad \beta = \frac{1}{T_f}$$

$$h_{tank} = \frac{Nu_{tank} k_{tank}}{D_8}$$

$$Nu_{tank} = 0.0243 Re_{tank}{}^{0.8}\, Pr^{0.4}$$

$$Re_{tank} = \frac{v_8 D_8}{\nu_{RP1}}$$

$$A_{s,tank} = \pi L_8 D_8 \,, \qquad L_8 = \frac{V_8}{A_8}$$

$$V_8(1) = V_8(0) + \dot{V}_8 \,\Delta t$$

SYSTEM

Pipe/Tank Cross Section Area

Constant geometry (cross section & number of tubes) between state points

$$A_D = \frac{\pi}{4} D_D{}^2 n_{tube,4}$$

Pipe/Tank Cross Section Area

Constant geometry (cross section & number of tubes) between state points

$$A_{S,5} = \pi D_E{}^2 n_{tube,5}$$

Fuel Mass Flow Rate (constant)

Constant thrust profile

Constant specific impulse

Constant gravitational constant

$$\dot{m}_9 = \frac{F_{thrust}}{I_{sp} g}$$

Fuel Tank Volumetric Flow Rate (constant)

Constant fuel mass flow rate

Constant fuel density

$$\dot{V}_9 = \frac{\dot{m}_9}{\rho_9}$$

Fuel Tank Helium Velocity (constant)

Constant fuel tank volumetric flow rate

Constant fuel tank cross-sectional area

$$v_8 = \frac{\dot{V}_8}{A_8} \,, \qquad \dot{V}_8 = \dot{V}_9$$

Helium Mass Flow Rate (time-dependent)

Constant across entire system at any time step

$$\dot{m}_{He} = \rho_8\, A_8\, v_8$$

Helium Properties (constant)

Constant specific heats

Ideal gas

$$C_p = 5.193 \frac{kJ}{kg \cdot K}$$

$$k = \frac{5}{3}$$

MASS CALCULATION

Helium Tank Volume

Given: $V_{0,guess}$, $P_{0,start}$, $T_{0,start}$, $m_{0,start}$, $m_{0,final}$

No helium loss from system

Empirical factor: f = 1.203

$$m_{0,final,ideal} = \frac{P_{0,ideal}\, V_0}{Z_{0,ideal}\, R\, T_{0,ideal}}$$

$$\Delta m_0 = m_{0,final} - m_{0,final,ideal}$$

$$m'_{0,start} = (m_{0,start} - \Delta m_0)\, f$$

$$V'_0 = \frac{m'_{0,start}\, Z_{0,start}\, R\, T_{0,start}}{P_{0,start}}$$

$$V_0 = V'_0$$

[Iterate through calculations until V_0 converges…]

Helium Mass

Negligible helium mass in piping

2% surplus of helium

$$m_{He} = 1.02\,(V_0\, \rho_0 + V_8\, \rho_8)$$

Pipe Mass

Given: t_{wall}, D_{inner}, n_{pipe}, L

*Material: 2095 Aluminum, ρ = 2700 kg/m^3^*

$$m_{pipe} = \frac{\pi\, L\, n_{pipe}}{4}\left[(D_i + 2t)^2 - D_i^2\right]\rho_{Al}$$

Helium Tank Mass (constant)

Spherical tank

Minimum wall thickness based on hoop stress

Material: 7075-T6 Aluminum

$n_{tank} = 1$

Factor of Safety: 1.05

$$m_{tank} = \frac{4}{3}\pi\left[\left(\frac{D_0}{2} + t\right)^3 - \left(\frac{D_0}{2}\right)^3\right]\rho_{Al}$$

$$t = \frac{P_0 D_0}{4\sigma_Y} FS_{tank}$$

Total System Mass (constant)

$$m_{tot} = m_{tank} + m_{He} + \sum m_{pipe}$$

APPENDIX F – SAMPLE VBA CODE

EXCERPTS FROM VBA CODE FOR SYSTEM SOLUTION

```
Private Sub SystemSolve_Click()

' DESCRIPTION:
  ' This routine takes user inputs from the Interface and runs a full transient solution. Each
  ' time step is solved and pasted to the Calculation tab. Methods implemented in this routine:
    ' Finite difference method of solving for the heat exchanger
    ' Iterative solutions of velocities
    ' Error checking and handling
    ' Writing variables to calculation sheet at each time step
  ' Trigger: Will run when a user clicks the SOLVE button on the Interface tab

' Error handling
On Error GoTo errHandler
```

USER INPUTS ARE WRITTEN TO CALCULATION SHEET

```
' Write user inputs to calculation sheet
  'm_LOX
        Sheets("Calculations").Range("m_LOX")(FirstVarRow).Value = Sheets("Interface").Range("m_LOX_input").Value

  'm_RP1
        Sheets("Calculations").Range("m_RP1")(FirstVarRow).Value = Sheets("Interface").Range("m_RP1_input").Value
```

ERROR CHECKING IS SET UP TO TAKE PLACE DURING THE SOLVING OF EACH TIME STEP

```
' Check for solving instabilities like #VALUE or #NAME in cells
  For Each PossibleError In Sheets("Calculations").Range("A" & FirstVarRow & ":HH" & FirstVarRow)

    If IsError(PossibleError) = True Then
      ErrorMessage = "Initial timestep unsolvable at:" & PossibleError.Address & ". Check input
                  values and re-solve."
      GoTo errHandler
    End If

  Next PossibleError

  ' Define counter to prevent infinite while loops when iterating
    Dim WhileCount As Integer
    WhileCount = 0
  ' Number of times to let while loop iterate before exiting
    Dim LoopLimit As Integer
    LoopLimit = 500
  ' Define upper limit for velocities (m/s) before generating and error
    Dim v_limit As Integer
    v_limit = 100
  ' Define lower limit for temperatures (K) for error generation
    Dim Temp_limit As Integer
    Temp_limit = 10
```

EXCERPT OF VELOCITY AT SECTION E BEING SOLVED. FINITE DIFFERENCE METHOD FOR HEAT EXCHANGER IS SHOWN BELOW.

```
For Timestep = 1 to NumberOfTimesteps

    'Solve Point E
        ' Write 0th row for HX_array (items for point D)
        HX_array(0, 1) = time_step     ' Time
        HX_array(0, 2) = 0             ' HX Step
        HX_array(0, 3) = 0             ' Position
        HX_array(0, 4) = t_d           ' Temperature
        HX_array(0, 5) = p_d           ' Pressure
        HX_array(0, 6) = v_d           ' Velocity


     'Increase number of HX steps until stable solution obtained
        n_increase = 0
        hx_mult = 1     'HX multiplier to index HX array
Adjust_n_1:
        If n_increase = 1 Then
          n_steps = n_steps * 2
          n_increase = 0
          hx_mult = hx_mult * 2   'HX multiplier re-indexes HX array upon increase in n_steps
        End If

        If n_steps > 1000 Then
        ErrorMessage = "Infinite regression occurring. Consider altering parameters to accomodate."
        GoTo errHandler
        End If

        v_ex = v_d
        v_e_prev = v_d
        p_e_prev = p_d
        t_e_prev = t_d
        p_ex = p_d
        t_ex = t_d
        rho_ex = rho_d
        rho_e_prev = rho_d
        A_e_prev = A_d
        delta_v = 1
        q_5 = 0
        q_x = 0
        n_count = 0
        q_last = 1
        t_s_5 = t_9

        'Critical Re based on coil flow
        Re_crit_i = 2300 * (1 + 12 * ((A_e * 4 / 3.14159 / n_tube_5) ^ 0.5 / (0.95 * D_8)) ^ 0.5)

        Pr_i = Sheets("Calculations").Range("Pr_5_inner")(FirstVarRow + Time).Value    'Prandtl #
        Pr_o = Sheets("Calculations").Range("Pr_5_outer")(FirstVarRow + Time).Value
        k_x_o = Sheets("Calculations").Range("k_5_outer")(FirstVarRow + Time).Value
        k_5_wall = Sheets("Calculations").Range("k_5_wall")(FirstVarRow + Time).Value

        If X_hx > L_4 Then
          X_hx = X_hx - dx
          dx = (A_d / A_e * v_d) * dt
          X_hx = X_hx + dx
        End If
```

```
If n_steps = 0 Then
   v_ex = A_d / A_e * v_d
End If

For x = 1 To n_steps
   If ((x - 1) * L_5 / n_steps) > (X_hx - L_4) Then  'Compares begining of HX segment to IC boundary
      t_ex = t_9
      q_x = 0
      p_ex = A_e_prev / A_e * p_e_prev - A_s5 / A_e / n_steps * C_D5 * rho_e_prev / 16000 * _
      (1 + A_d * v_e_prev / A_e / v_ex) * (v_e_prev + v_ex) ^ 2 - m_dot_he * (v_ex - v_e_prev) / A_e / 1000
      rho_ex = REFPROP.Density("Helium", "TP", "SI", t_ex, p_ex / 1000)
      v_ex = v_e_prev
   ElseIf A_d <> A_e And x = 1 Then
      If A_d < A_e Then   'Sudden expanding pipe
         K_5 = (1 - A_d / A_e) ^ 2
      Else              'Sudden contracting pipe
         K_5 = 0.5 * Cos(3.14159 / 2 * A_e / A_d)
      End If
      If n_tube_4 <> n_tube_5 Then
         K_5 = K_5 + K_man
      End If
      p_ex = p_d - 0.5 * rho_d * K_5 * v_d ^ 2 / 1000
      v_ex = A_d / A_e * v_d
      h_ex = REFPROP.Enthalpy("Helium", "TP", "SI", t_d, p_d / 1000)
      t_ex = REFPROP.Temperature("Helium", "HP", "SI", h_ex, p_ex / 1000)
   Else
      Do While delta_v > Tol_5 And A_s5 <> 0
         p_ex = A_e_prev / A_e * p_e_prev - A_s5 / A_e / n_steps * C_D5 * rho_e_prev / 16000 * _
         (1 + A_e_prev * v_e_prev / A_e / v_ex) * (v_e_prev + v_ex) ^ 2 - m_dot_he * (v_ex - v_e_prev) / A_e / 1000
         t_ex = t_e_prev + (q_x - (v_ex ^ 2 - v_e_prev ^ 2) / 2000) / C_p

         ' Check for extreme temperature and kick back if required
         If t_ex > t_9 Or t_ex < 0 Then
         n_increase = 1
         GoTo Adjust_n_1
         End If

         ' Check for extreme pressure and kick back if required
         If p_ex < 0 Then
         n_increase = 1
         GoTo Adjust_n_1
         End If

         v_ex_prime = m_dot_he / A_e / rho_e_prev

         ' Inside wall HT
            ' Get new viscosity (inner)
            nu_x_i = REFPROP.Viscosity("helium", "TP", "SI", (t_e_prev + t_ex + 2 * t_9) / 4, p_ex / 1000) * _
            0.000001 / rho_e_prev

            ' Get new thermal conductivity (inner)
            k_x_i = REFPROP.ThermalConductivity("helium", "TP", "SI", (t_e_prev + t_ex + 2 * t_9) / 4, p_ex / 1000) / _
            1000

            Re_x_i = v_ex_prime * (A_e * 4 / 3.14159 / n_tube_5) ^ 0.5 / nu_x_i

            ' Set proper correlation based on laminar or turbulent flow
            If Re_x_i < Re_crit_i Then
               f_i = 64 / Re_x_i
               Nus_x_i = 48 / 11
```

```
        Else
          f_i = (0.79 * Log(Re_x_i) - 1.64) ^ (-2)
          Nus_x_i = f_i / 8 * (Re_x_i - 1000) * Pr_i / (1 + 12.7 * (f_i / 8) ^ 0.5 * (Pr_i ^ (2 / 3) - 1))
        End If

        'Heat transfer enhancement
        f_enhance = (Re_x_i * ((ID_5_tube + OD_5_tube) / (ID_5_coil + OD_5_coil)) ^ 2) ^ 0.05

        h_x_i = f_enhance * Nus_x_i * k_x_i / D_e

      'Outside wall HT
        ' Heat exchanger RP-1 velocity
        A_8_HX = 3.14159 / 4 * (D_8_HX) ^ 2
        v_8_HX = A_8 / A_8_HX * v_8

        Re_x_o = v_8_HX * D_8_HX / nu_x_o

        Nus_x_o = 0.3 + 0.62 * Re_x_o ^ 0.5 * Pr_o ^ (1 / 3) / (1 + (0.4 / Pr_o) ^ (2 / 3)) ^ 0.25 * _
        (1 + (Re_x_o / 282000) ^ (5 / 8)) ^ 0.8

        h_x_o = Nus_x_o * k_x_o / D_e

      U_x = 1 / (1 / h_x_i + t_5_wall / k_5_wall + 1 / h_x_o)
      q_x = U_x * A_s5 / n_steps * (t_9 - t_ex) / 1000 / m_dot_he

      delta_v = ((v_ex_prime - v_ex) ^ 2) ^ 0.5
      v_ex = v_ex_prime

      ' Check for heat transfer instability (oscillation) and kick back if required
      If q_x <> 0 Then
        If (q_x / Abs(q_x)) / (q_last / Abs(q_last)) = -1 Then
        n_increase = 1
        n_count = n_count + 1
        End If
        If Abs(q_x / q_last) > 2 And WhileCount > 10 Then
        n_increase = 1
        n_count = n_count + 1
        End If
        If n_count > 1 Then
        GoTo Adjust_n_1
        End If
      End If

      ' Error check for infinite looping
      If WhileCount > LoopLimit Then
        ErrorMessage = "Iteration timeout when calculating v_e. Timestep = " & time_step
        GoTo errHandler
      End If

      WhileCount = WhileCount + 1

      q_last = q_x
    Loop
    WhileCount = 0

    ' Final Pressure & Temperature calculation in HX segment
    p_ex = A_e_prev / A_e * p_e_prev - A_s5 / A_e / n_steps * C_D5 * rho_e_prev / 16000 * _
    (1 + A_d * v_e_prev / A_e / v_ex) * (v_e_prev + v_ex) ^ 2 - m_dot_he * (v_ex - v_e_prev) / A_e / 1000
    t_ex = t_e_prev + (q_x - (v_ex ^ 2 - v_e_prev ^ 2) / 2000) / C_p
  End If
  rho_ex = REFPROP.Density("Helium", "TP", "SI", t_ex, p_ex / 1000)
```

```
            p_e_prev = p_ex
            t_e_prev = t_ex
            rho_e_prev = rho_ex
            v_e_prev = v_ex
            A_e_prev = A_e

            q_5 = q_5 + q_x

            delta_v = 1

            ' Write to HX Array
            If (x - 1) Mod hx_mult = 0 Then
                HX_array(((x - 1) / hx_mult + 1), 1) = time_step            ' Time
                HX_array(((x - 1) / hx_mult + 1), 2) = x                 ' HX Step
                HX_array(((x - 1) / hx_mult + 1), 3) = L_5 / n_steps * x     ' Position
                HX_array(((x - 1) / hx_mult + 1), 4) = t_ex               ' Temperature
                HX_array(((x - 1) / hx_mult + 1), 5) = p_ex               ' Pressure
                HX_array(((x - 1) / hx_mult + 1), 6) = v_ex               ' Velocity
            End If

            'Check for high velocity
            If v_ex > v_limit_hx Then
                ErrorMessage = "Velocity exceeds " & v_limit_hx & " m/s in heat exchanger portion " & x & "/" & n_steps & "."
                GoTo errHandler
            End If

            ' Calculate minimum tube surface temp in hx
            If q_x <> 0 Then
                If t_9 - 1000 * q_x * m_dot_he / (h_x_o * A_s5 / n_steps) < t_s_5 Then
                    t_s_5 = t_9 - 1000 * q_x * m_dot_he / (h_x_o * A_s5 / n_steps)
                End If
            End If

        Next x

        v_e = v_ex
        p_e = p_ex
        t_e = t_ex
        rho_e = rho_ex

    'Paste values to sheet
    Sheets("Calculations").Range("v_e")(FirstVarRow + Time).Value = v_e
    Sheets("Calculations").Range("t_e")(FirstVarRow + Time).Value = t_e
    Sheets("Calculations").Range("p_e")(FirstVarRow + Time).Value = p_e
    Sheets("Calculations").Range("rho_e")(FirstVarRow + Time).Value = rho_e
    Sheets("Calculations").Range("q_5")(FirstVarRow + Time).Value = q_5
    Sheets("Calculations").Range("t_s_5")(FirstVarRow + Time).Value = t_s_5

    ' Paste HX Array to sheet
    For x = 0 To n_steps / hx_mult
        Sheets("HX_Calc").Range("HX_Temp_Time")(HX_Array_Row + x + 2).Value = HX_array(x, 1)
        Sheets("HX_Calc").Range("HX_Temp_Step")(HX_Array_Row + x + 2).Value = HX_array(x, 2)
        Sheets("HX_Calc").Range("HX_Temp_Position")(HX_Array_Row + x + 2).Value = HX_array(x, 3)
        Sheets("HX_Calc").Range("HX_Temp_T")(HX_Array_Row + x + 2).Value = HX_array(x, 4)
        Sheets("HX_Calc").Range("HX_Temp_P")(HX_Array_Row + x + 2).Value = HX_array(x, 5)
        Sheets("HX_Calc").Range("HX_Temp_V")(HX_Array_Row + x + 2).Value = HX_array(x, 6)
    Next x
    HX_Array_Row = HX_Array_Row + (n_steps / hx_mult + 1) '* (Time + 1) + 1

Next Timestep
```

EXCERT OF ERROR HANDLING PROCEDURE

```
' Error Handler procedure
errHandler:

  MsgBox ErrorMessage, vbOKOnly, "Error"

  ' Paste solved code from ErrorHandler tab into Calculations tab to reset. Do for any error for redundancy
      Sheets("ErrorHandle").Select
        ActiveSheet.Range("A4:HH12").Select
      Selection.Copy

      Sheets("Calculations").Select
        ActiveSheet.Range("A4").Select
      ActiveSheet.Paste
      ActiveSheet.Range("E4").Select

  ShowInput = True

  Resume exitHere

End Sub
```

APPENDIX G – TEST BENCH PROCEDURE

This document will outline the safety information, initial setup, experimental procedure and data monitoring procedures for running the Helium Pressurization Test Bench. Please read the entire document before working with any of the equipment.

Safety:

- Safety glasses, long pants and closed toed shoes must be worn at all times when near the equipment.
- Before the regulator the system is pressure rated to everywhere to 2000 psi. Do not run the system if pressures go above this pressure and release helium through the auxiliary tank relief valve.
- Whenever moving the table, disconnect the helium tank and cap it.
- Lock casters when not in use.
- Before the cap can be removed from the helium tank ensure that the tank has been strapped or chained in.
- Before introducing helium into the system ensure that the auxiliary tank relief valve and regulator valve are closed.
- When filling the water tank take care not to overfill that system and flood the heat exchanger coil.
- When working with liquid nitrogen ensure that all appropriate protective equipment is being used properly.
- After liquid nitrogen has been introduced into the system treat everything as if it has been exposed to the cold temperatures. Take care not to touch any piping or equipment with bare hands.
- Do not store any unnecessary equipment on the table. This could pose a hazard if a relief valve needed to be opened.
- Do not lean, sit or stand on the table.
- Do not stand behind the table when it has been pressurized. In case of emergency the relief valves vent towards the read of the table.
- The auxiliary tank relief valve is for emergency use only. If venting the auxiliary tank, do so through the regulator and water fill port.

Initial Setup:

This section will cover the setup of the table and the preparations required to effectively run the experiment. Before proceeding please see the Piping and Instrument Diagram to familiarize yourself with the terms used. Please note that the word vent is used when referring to removing gas from the system and drain is referring to removing liquid.

Tools Required

- 1 1/8” Wrench
- 9/16” Wrench
- Tank Strap or Chain
- Stop watch
- Garden Hose

Table Setup

1. Ensure that the table is in a position where the vent ports will not damage anything and that the water fill hose can reach a spigot. Lock all casters when the table is in position.
2. With cap on, carefully lift the helium tank into position and strap it to the vertical wooden post directly behind the tank mount. Only after the tank has been strapped in and you are ready to proceed can the tank cap be removed. Place the tank cap underneath the table for storage.
3. Connect the helium tank nut and nipple to the helium tank. Tighten the nut using the 1 1/8” wrench. Do not over tighten the nut as this could cause damage to the nut or nipple.
4. If necessary, using the 9/16” wrench connect the auxiliary tank inlet line to the helium tank outlet elbow.
5. Ensure that the auxiliary tank relief valve, regulator ball valve, water tank fill valve and water tank outlet valve are all closed.
6. Ensure that all fittings are tight and that either the upper or lower heat exchanger port is capped depending on test configuration.
7. Introduce helium into the system by slowly opening the helium tank. When the auxiliary tank pressure has reached equilibrium close the helium tank.
8. Slowly open the regulator ball valve and while watching the pressure in the water tank, set the regulator pressure such that the pressure in the water tank is 40 psig. Vent the water tank slightly through the water outlet port to ensure that the system remains steady at 40 psig. Close the outlet port when finished.
9. Close the regulator ball valve and carefully vent the water tank until no pressure remains in the water tank.
10. Introduce water into the water tank by hooking up a garden hose to the water tank fill port. Fill the tank 3/4 of the way, stopping below the max fill line. Take caution not to overfill the system and get water into the heat exchanger coils. If

this does happen, push all water out of the coils using warm helium to prevent interior pipe freezing.

11. Drain the water using the water tank drain port and set the flow control valve so that the entire tank is drained in about 60 seconds. This will form the basis for the mass flow rate calculations.
12. Close the drain port and refill the water tank. Close the fill port and remove hose when finished.
13. Slowly open the regulator ball valve to introduce helium into the water tank. Monitor water tank pressure to ensure that is at 40 psi. If it is not adjust regulator accordingly. If the tank pressurizes higher than 60 psi then vent the system through the water tank fill port.
14. Drain the water tank through the water tank drain port while monitoring water flow rate and helium tank pressure. The tank pressure should maintain a constant 40 psi and the water should drain in about 60 seconds. Adjust the regulator and flow control valve to maintain this pressure and flow rate if needed.
15. Once pressure and flow rates are set, close the helium regulator ball valve, drain the water tank and vent any leftover helium in the water tank. If you are to begin testing it is not necessary to vent to auxiliary tank, however if testing is complete then vent all pressure from the system through the heat exchanger, not the auxiliary tank relief valve.

Software Required

- Instacal (provided online from MC website)
- TracerDAQ (provided online from MC website)

Data Acquisition Setup

This section will be cover the setup and operation of the DAQ system used with our experiment. Obtain the *MCC USB-2408* or similar product before proceeding.

1. Connect thermocouples and pressure transducers into analog signal input ports. (Note: Powering the pressure transducer(s) with the available 5V supply through the DAQ may result in thermocouple shorting. Use an additional constant 5V source if possible.)
2. Connect USB to laptop. The DAQ should now show 1 or 2 green lights on the side of the unit.
3. Once the board is powered up, open *Instacal* program. If the computer is properly reading the DAQ, the system ID code will appear as a subsection of “PC Board List” in the main window.

4. In order to assign proper signal analysis through the input ports, the DAQ system must be calibrated. Select "Configure…" under the "Install" tab. The menu will now allow you to control input readings, selecting thermocouple or voltage settings. For additional information regarding calibration, see MCC website.
5. (Optional: To check if the DAQ is correctly receiving signal, you can open a low resolution strip chart by selecting "Test" tab, "Analog". This step is only for your benefit and does not affect the system.)
6. To calibrate the new configuration, select "A/D" under the "Calibration" tab. This process may take a few minutes, depending on the computer and USB cable speed.
7. Open *TracerDAQ*, and select "Strip Chart" from the opening menu. Click "Run".
8. The program will now open up a blank strip chart. To configure input channel settings, select "Channel Settings…" under the "Edit" tab. Select the number of desired input channels, and define channel names and units, if desired.
9. Once this is complete, go to "Edit" → "DAQ Hardware Settings…". This menu will allow you to match the physical analog channel on the DAQ with the channel names in the strip chart.
10. To change the sample rate and data acquisition time, select "Scan Rate/Trigger Settings" under the "Edit" tab. This window allows users to change the Scan rate and/or sampling time length. (Note: Increasing the number of input channels decreases the maximum sample rate possible. Additionally, the DAQ can record a limited number of data points per run, so higher sample rates result in less total time allowed for recording.)
11. Once the system has been fully configured from the steps above, you can run the strip chart by clicking the play (triangle) button in the upper left corner of the main window. Recordings stop when the stop (square) button is pressed, or when the maximum recording limit has been reached.
12. Once the data run is complete, you can save the data as a .sch, .csv, or .txt file. Select "Save As" under the "File" tab.
13. Hardware setups can be saved for future runs by saving the configuration ("File" → "Save Configuration").
14. When finished testing, close both *TracerDAQ* and *Instacal*.

Experiment Procedure

This section will cover how to run the experiment. Please ensure that the initial setup has been completed and familiarize yourself with all safety items before proceeding.

1. Ensure that the auxiliary tank relief valve, regulator ball valve, water tank fill valve and water tank outlet valve are all closed.
2. Fill the water tank to the max fill line.
3. Slowly introduce helium into the auxiliary helium tank by opening the helium tank and monitoring pressure in the auxiliary tank. Do not proceed until this pressure has reached equilibrium.

4. With warm helium, pressurize the helium tank to 40 psi. Close the regulator ball valve when complete.
5. Carefully introduce liquid nitrogen into the helium cooling bucket, taking care not to spill liquid nitrogen onto the table. Cover the cooling bucket when liquid nitrogen is not being added to limit the amount of nitrogen lost to the atmosphere.
6. Monitor the helium temperature and pressure until the temperature has reached -315 F and the pressure has equalized.
7. Close the helium tank.
8. Slowly open the helium regulator ball valve while opening the water drain valve.
9. Monitor pressures, temperatures and water flow rate as the water drains from the system.
10. When the water is drained, close the regulator ball valve and vent the water tank.
11. If testing is complete, vent the auxiliary helium tank by opening the regulator ball valve and the water fill port.

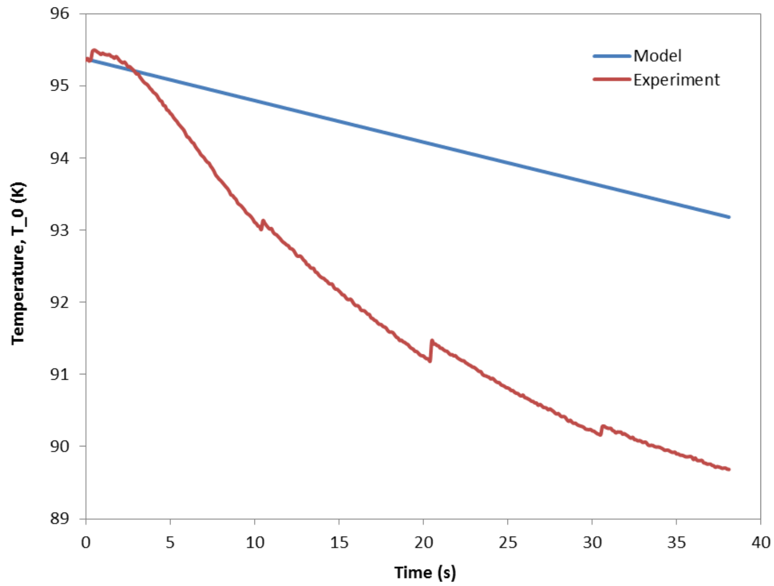


FIGURE H1 – HELIUM TANK TEMPERATURE VERIFICATION (RUN 007 – LOW FLOWRATE)

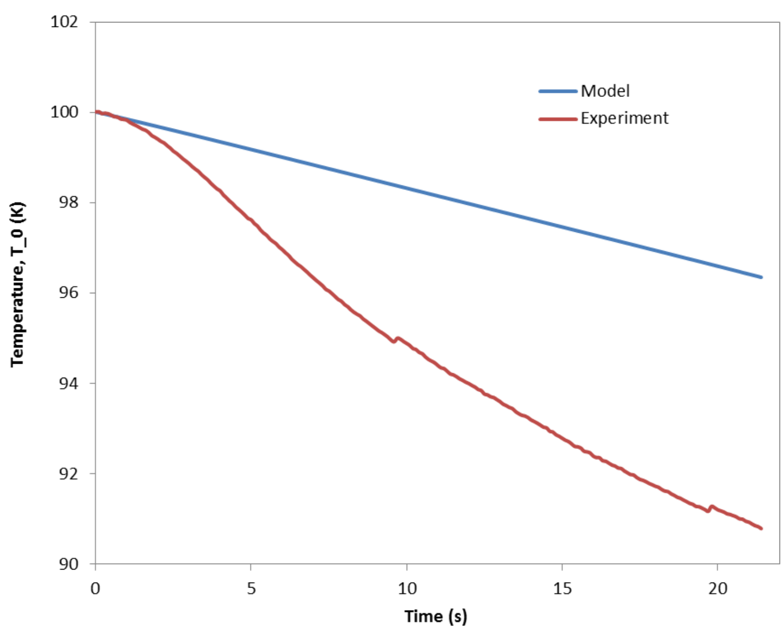


FIGURE H2 – HELIUM TANK TEMPERATURE VERIFICATION (RUN 008 – MEDIUM FLOWRATE)

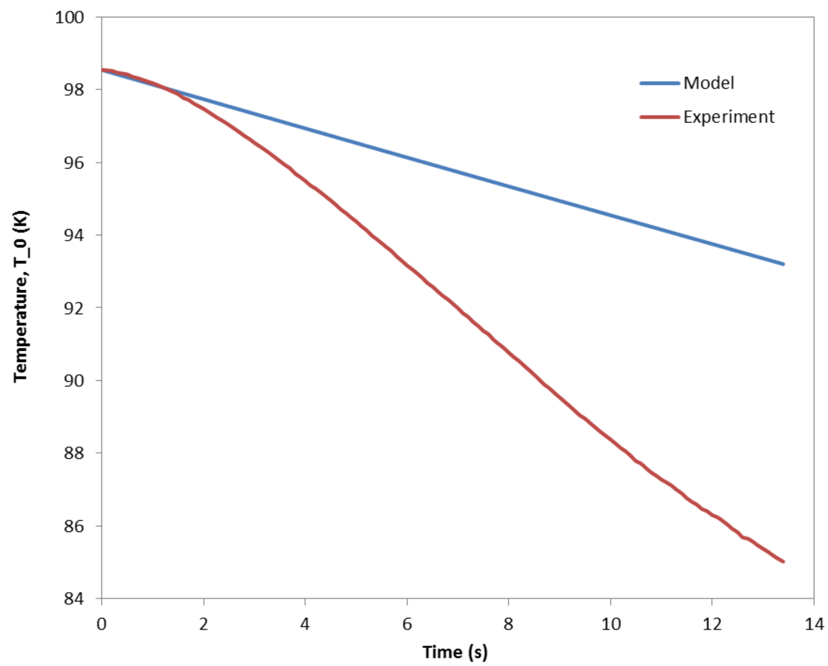


FIGURE H3 – HELIUM TANK TEMPERATURE VERIFICATION (RUN 009 – HIGH FLOWRATE)

APPENDIX I – MANAGEMENT CHARTS

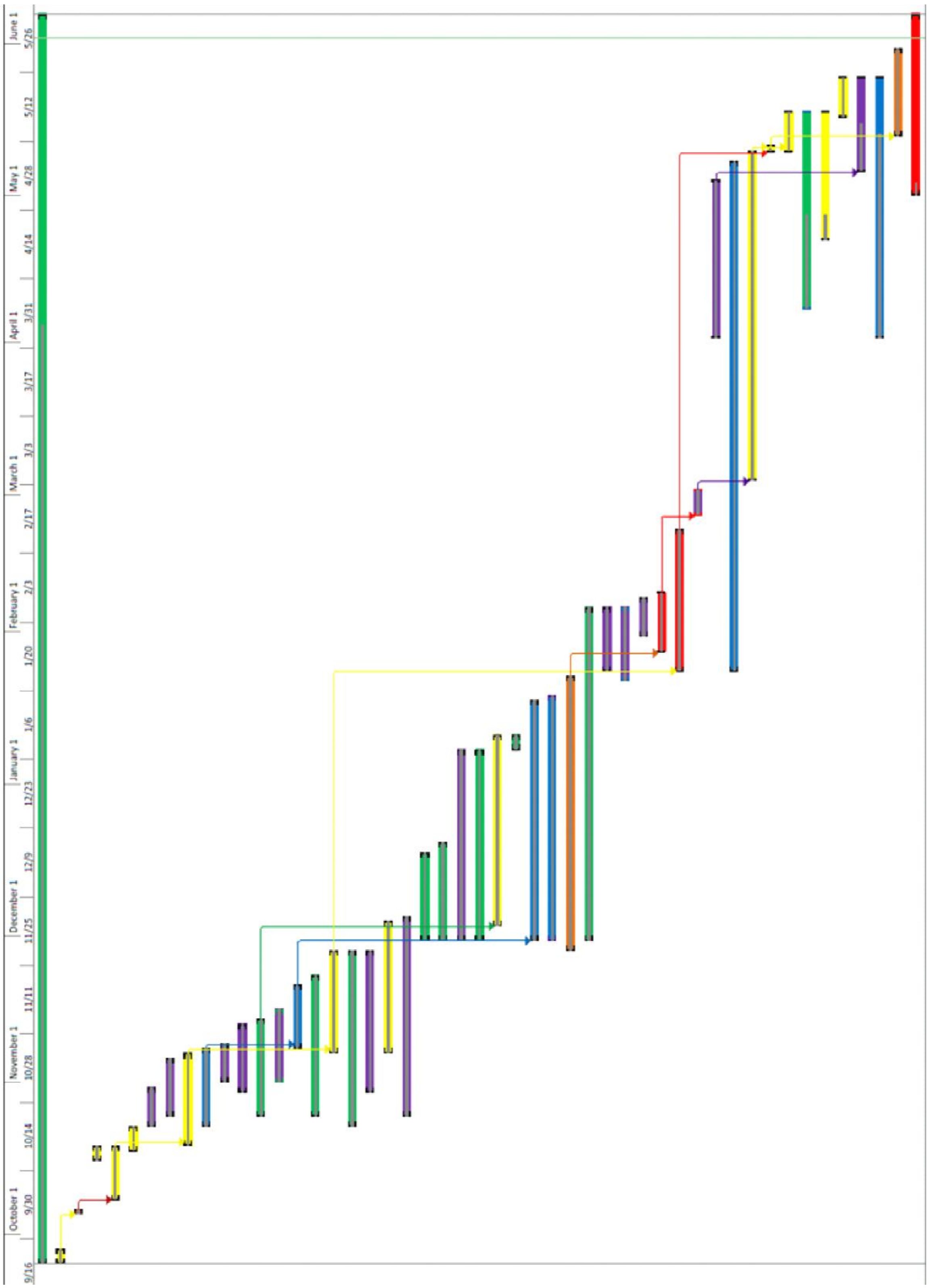


FIGURE I1 – GANTT CHART OF SENIOR PROJECT TIMELINE

TABLE I1 – SENIOR PROJECT TASKS COMPLETED

ID	Indicators	Task Mode	Task Name	Participants	% Complete	Duration	Start	Finish	Predecessors
1			Project Scheduling	Andrew	75%	183 days	Tue 9/25/12	Thu 6/6/13	
2	✓		Letter of Introduction	All	100%	3 days	Tue 9/25/12	Thu 9/27/12	
3	✓		First Sponsor Meeting	All + LoCascio + McKinnon	100%	1 day	Fri 10/5/12	Fri 10/5/12	2
4	✓		Individual Task Assignment	All	100%	3 days	Tue 10/16/12	Thu 10/18/12	
6	✓		Project Proposal	All	100%	9 days	Mon 10/8/12	Thu 10/18/12	3
5	✓		Blackbox Model	All	100%	3 days	Thu 10/18/12	Mon 10/22/12	
7	✓		Material Tables	Joe	100%	6 days	Tue 10/23/12	Tue 10/30/12	
12	✓		Blackbox CAD Model	Joe	100%	8 days	Thu 10/25/12	Mon 11/5/12	
8	✓		Conceptual Model	All	100%	13 days	Fri 10/19/12	Tue 11/6/12	6
20	✓		Excel Visual Framework	Sean	100%	12 days	Tue 10/23/12	Wed 11/7/12	
13	✓		System Schematic	Joe	100%	6 days	Thu 11/1/12	Thu 11/8/12	
14	✓		CAD Tanks	Joe	100%	10 days	Tue 10/30/12	Mon 11/12/12	
17	✓		Steady State Model	Andrew	100%	14 days	Thu 10/25/12	Tue 11/13/12	
19	✓		SS Heat Transfer Model	Joe, Andrew	100%	11 days	Thu 11/1/12	Thu 11/15/12	
18	✓		Excel SS Function Framewor	Sean	100%	9 days	Thu 11/8/12	Tue 11/20/12	20
21	✓		SS Model Assumptions	Andrew	100%	21 days	Thu 10/25/12	Thu 11/22/12	
9	✓		Conceptual Design Review	All	100%	15 days	Wed 11/7/12	Tue 11/27/12	8
22	✓		Model Variables	Andrew	100%	26 days	Tue 10/23/12	Tue 11/27/12	
23	✓		Prelim. CAD Piping	Joe	100%	21 days	Tue 10/30/12	Tue 11/27/12	
15	✓		Conceptual Design Report	All	100%	19 days	Wed 11/7/12	Mon 12/3/12	
16	✓		VBA Support (A/N)	Joe	100%	29 days	Thu 10/25/12	Tue 12/4/12	
35	✓		Variables	Andrew	100%	12 days	Fri 11/30/12	Mon 12/17/12	
32	✓		Continuity Equations	Andrew	100%	14 days	Fri 11/30/12	Wed 12/19/12	
33	✓		1st Law Equations	Joe	100%	27 days	Fri 11/30/12	Mon 1/7/13	
34	✓		2nd Law Equations	Andrew	100%	27 days	Fri 11/30/12	Mon 1/7/13	
24	✓		Transient Model	All	100%	29 days	Mon 12/3/12	Thu 1/10/13	17
36	✓		Momentum Equations	Andrew	100%	3 days	Tue 1/8/13	Thu 1/10/13	
25	✓		Final Excel GUI	Sean	100%	35 days	Fri 11/30/12	Thu 1/17/13	18
26	✓		Mass Equations	Sean, Joe	100%	36 days	Fri 11/30/12	Fri 1/18/13	
10	✓		Critical Design Review Preser	All + LoCascio	100%	40 days	Wed 11/28/12	Tue 1/22/13	
28	✓		Assumptions & Equations Di	Andrew	100%	48 days	Fri 11/30/12	Tue 2/5/13	
29	✓		Test Bench Budget	Joe	100%	9 days	Thu 1/24/13	Tue 2/5/13	
30	✓		Finite Diffence HX Model	Joe, Sean	100%	11 days	Tue 1/22/13	Tue 2/5/13	
31	✓		Test Bench P&ID, Detailed D	Joe	100%	6 days	Thu 1/31/13	Thu 2/7/13	
11	✓		Critical Design Presentation	All + McKinnon	100%	10 days	Mon 1/28/13	Fri 2/8/13	10
27	✓		Critical Design Report	All + LoCascio + McKinnon	100%	21 days	Thu 1/24/13	Thu 2/21/13	9
37	✓		Order Materials	Joe + McKinnon	100%	5 days	Mon 2/25/13	Fri 3/1/13	11
43	✓		Pro/E Training	Joe	100%	24 days	Tue 4/2/13	Fri 5/3/13	
38	✓		GUI Upgrades	Sean	100%	74 days	Thu 1/24/13	Tue 5/7/13	
39	✓		Test Bench Construction	All	100%	49 days	Mon 3/4/13	Thu 5/9/13	37
48	✓		Mfg & Test Review	All	100%	1 day	Fri 5/10/13	Fri 5/10/13	27,39
42	✓		Test Bench Testing	All	100%	6 days	Fri 5/10/13	Fri 5/17/13	39
46			Model Validation	Andrew, Sean	50%	30 days	Mon 4/8/13	Fri 5/17/13	
47			Design Iteration	All	25%	20 days	Mon 4/22/13	Fri 5/17/13	
40	✓		Expo Poster	All	100%	6 days	Fri 5/17/13	Fri 5/24/13	
44			Final Pro/E CAD Model	Joe	50%	15 days	Mon 5/6/13	Fri 5/24/13	43
49			Final GUI	Sean	75%	39 days	Tue 4/2/13	Fri 5/24/13	
41	✓		Senior Design Expo	All + LoCascio	100%	14 days	Mon 5/13/13	Thu 5/30/13	48
45			Final Project Report	All + LoCascio + McKinnon	10%	27 days	Wed 5/1/13	Thu 6/6/13	

APPENDIX J – REFERENCES

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