Port Flow Test System

By

PREFLOW SYSTEMS

Daniel Chairez
Chelsea E. Crawford
Daniel S. Welch

Sponsored

By

Solar Turbines
A Caterpillar Company

Advisor: Dr. Thomas Mackin
Mechanical Engineering Department
California Polytechnic University
San Luis Obispo, California

June 2011

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Table of Contents

List of Figures

List of Tables

Executive Summary

Solar Turbines Gas Compressor Engineering Division of San Diego, California called upon the mechanical engineering students of California Polytechnic University, San Luis Obispo to provide recommendations for optimization of compressor end cap port design. Various sizes of compressors have end caps with numerous ports that exchange fluids between the inside and outside of the working fluid pressure vessel. Because so many ports must exist on the end caps, unusual flow paths are created to supply the appropriate location within the compressor. These flow paths commonly consist of a drilled inlet hole which intersects with a sudden expansion. The sudden expansion is deemed the “fly cut” because of its semicircular shape.

Sudden expansions in general cause very high energy losses in fluid flow. This is one of the primary concerns when designing the compressor end cap port layout. Due to the unusual nature of the fly cuts found in Solar Turbines’ end caps, published information on the pressure losses for this particular flow path do not exist. For this reason, Solar Turbines were required to base their port design on the best information available, including: historical compressor design methods, conservative design analysis estimates, and computational fluid mechanics software. Of these options, the computational method could provide the best estimate but only if validated experimentally. In response to this problem, PreFlow Systems was formed and investigated the solution of designing, building, and testing a scaled experimental test apparatus.

This report outlines the details involved in every aspect of the project, including: technical specifications and objectives, design conceptualization, engineering analysis, manufacturing, testing, and results. Each of these phases was crucial in creating the final flow test apparatus which simulated the gas port flow of Solar Turbines’ compressor end caps. This apparatus ultimately provided an experimental basis for concluding that computation fluid mechanics software is a reasonable aide in end cap port design.

Chapter 1: Introduction

Solar Turbines Incorporated, a subsidiary of Caterpillar Incorporated, is a major manufacturer of industrial gas turbines and associated multi-stage compressors for the oil and gas industry. Such compressors are used in both pipeline transport and direct production applications. In particular, the Solar Turbines Gas Compressor Engineering Division needs a better method of sizing supply gas and oil ports to feed the internal components of their multi-stage compressors. Calculating accurate pressure losses with conventional fluid mechanics analysis and industry standardhead loss coefficients is not possible due to the unique geometries of the ports. In order to optimize their compressors' end-cap design, Solar Turbines has asked PreFlow Systems to determine the pressure loss coefficients occurring in the ports. PreFlow Systems will do so by designing a test apparatus which will simulate the port flow so that the pressure loss coefficients may be determined experimentally.

Background

A multi-stage compressor's function is to take in external air or gas to pressurize it through a series of rotating impellers. The compressor's major parts include a rotor shaft with shrouded impeller(s), dry gas seals (journal bearings/compressor seals), balance piston, and compressor housing. Located at both ends of the compressor housing are end-caps, which fully enclose the compressor housing. With end-caps installed, the compressor housing is essentially a very large pressure vessel. Figure 1 below depicts a typical multi-stage compressor.

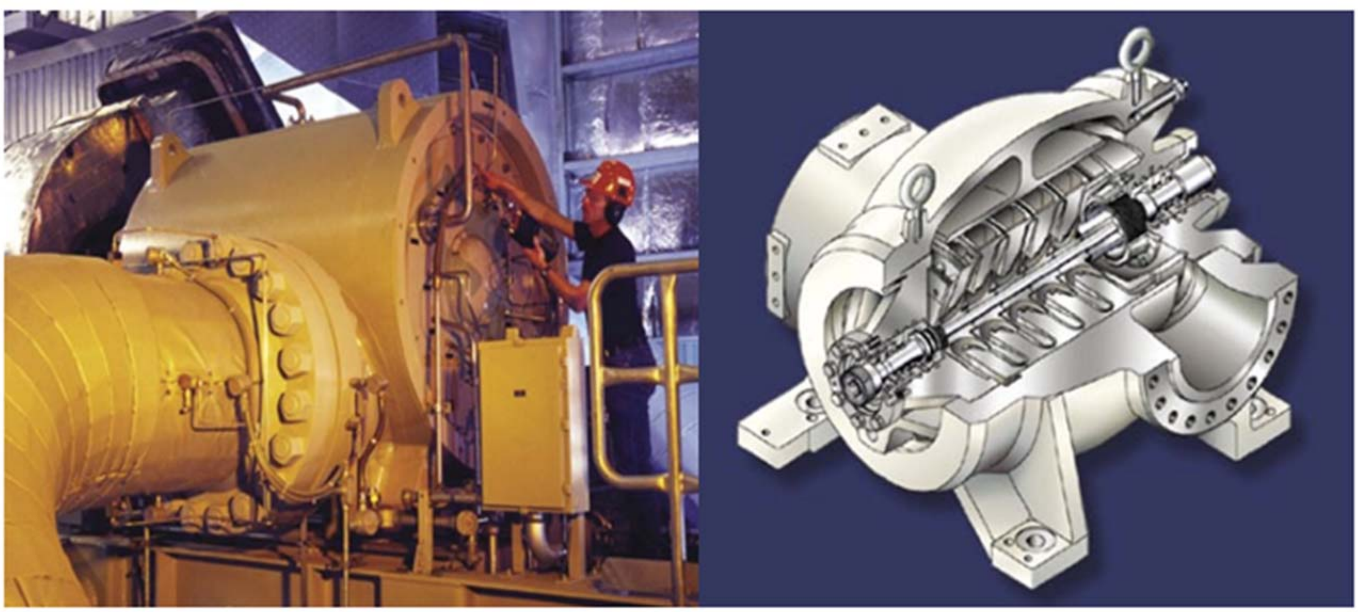


Figure 1. Multi-Stage Compressor

Compressor Major Parts and Operation

The rotor shaft is made up of stacked impeller sections, which are secured together by a tension rod running the length of the compressor rotor through each section's center. This method of constructing the compressor's shaft is particular to Solar Turbines and highly regarded because of its durability and ease of customizability. The impeller is the most important part on the compressor because this is the mechanism that transfers work to the fluid. A shrouded impeller is typical for multi-stage compressors and their size determines the compressor's performance. The shape and layout of the shrouded impellers is shown in the compressor section views of Figure 2.

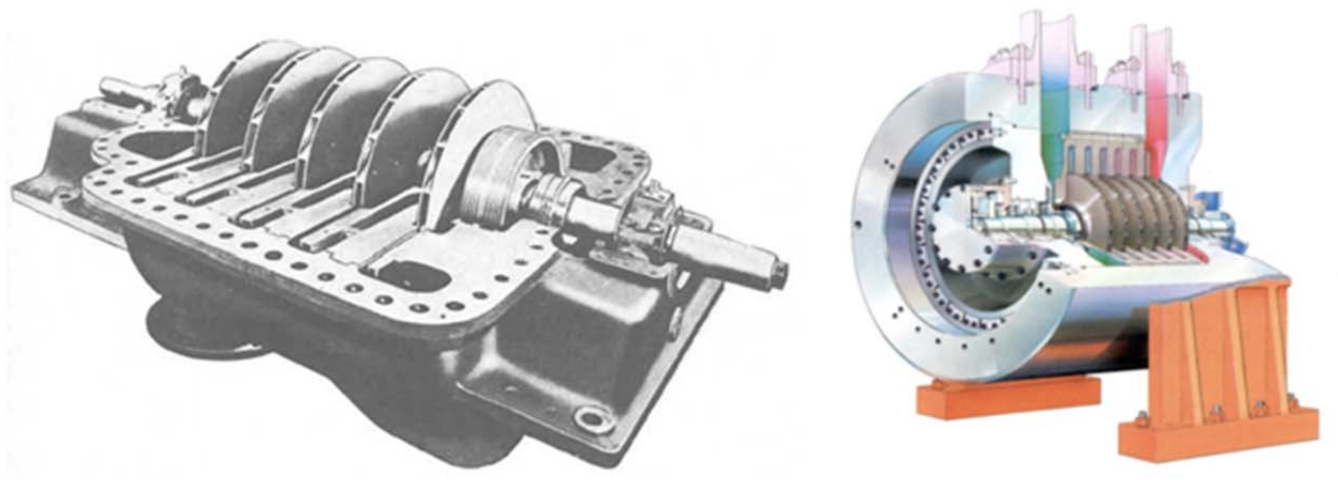


Figure 2. Section views of a multi-stage compressor with shrouded impellers

In addition to the impellers, the rotor shaft also consists of a balance piston, and dry gas seals. The balance piston is used for rotor balance and to reduce thrust-bearing loads, which control the axial motion of the shaft. In addition to the balance piston, dry gas seals act as journal bearings and gaskets.

The dry gas seals are essential to the proper function of a gas compressor. These seals act primarily as journal bearings for the rotor shaft by utilizing a working fluid of gas at a higher pressure than the gas in the impellers. The high pressure gas, of the dry gas seals, acts as a barrier to prevent compressor leakage while still supporting the rotor bearing loads. Multiple dry gas seals are included at each end of the rotor shaft for failure prevention.

As mentioned previously, the end-caps and compressor cylinder enclose the rotor shaft components to create a working pressure vessel. To supply and drain the appropriate fluids to the internal mechanisms of the compressor, both the suction and discharge end-caps have various inlet and outlet ports. These supply ports play a vital role in the operation of the compressor. The ports can supply either oil for the journal bearing or provide gas for the dry gas seal. End-caps come in a variety of sizes depending on the proportions of the compressor; therefore, the supply and drain ports can also vary.

In order to accommodate the wide array of ports required to reach the inside face of the end-cap, the geometry of any given port can be quite complicated. These ports are usually stepped and angled to intersect with the correct inlet location of its respective component. Figures 3 and 4, on the following page, provide various views of how these ports are typically located on the end-caps.

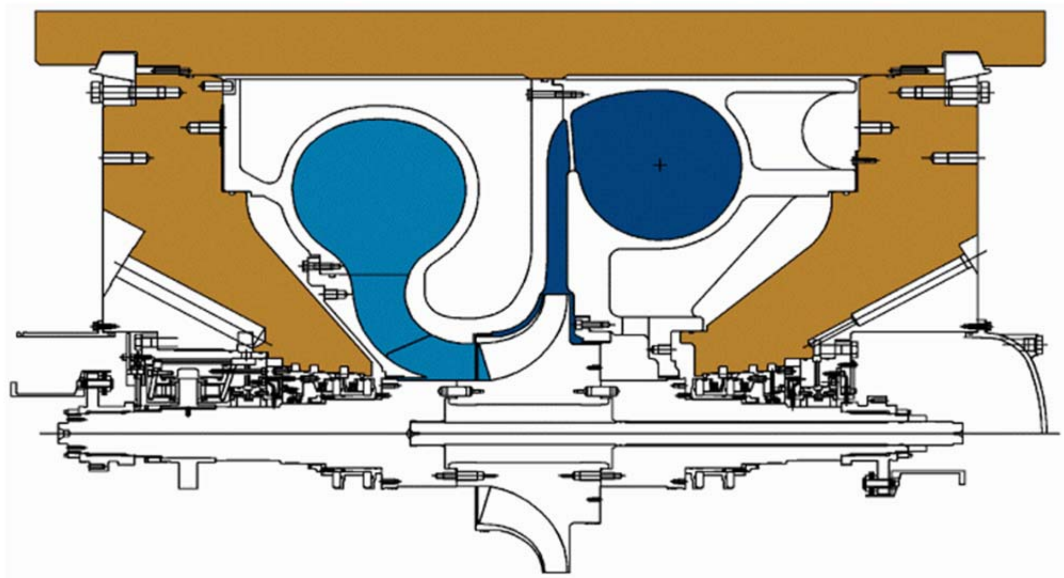


Figure 3. Quarter section view of a single stage centrifugal compressor. Credit Solar Turbines

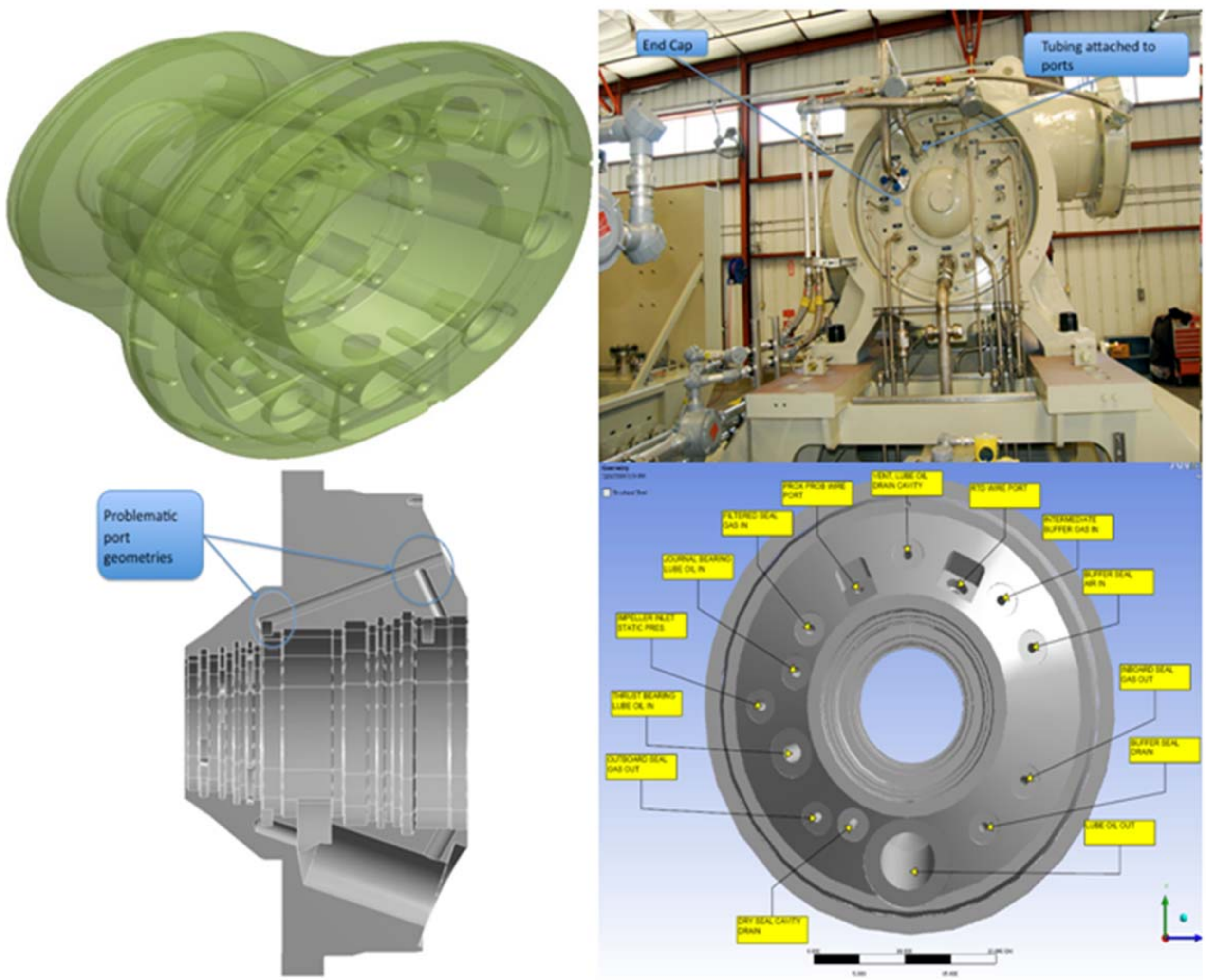


Figure 4. End Cap figures include transparent, actual, cross-sectional, and front view.

Solar Turbines currently determines the end-cap port layout and sizing based upon conservative estimates and previous standards. Frequently, the ports were made as large as possible to achieve the pressure and flow rates needed for the internal components of the compressor. The unknown flow characteristics and losses of the ports ultimately lead to limitations on end cap geometry. Therefore, fully understanding port losses is necessary to optimize the end-caps' port geometry.

The end-caps shown in the proposal's figures are of a very large scale. Large end-caps can usually support multiple ports without interference with neighboring ports. However, as the proportions of the compressor are reduced, risk of interference becomes more likely. End-cap space for ports then becomes limited and the necessity to optimize port geometry becomes essential. Optimization of these ports would involve reducing their size while still being able to maintain their necessary operating and boundary conditions. This study could also lead to reducing certain losses within the ports and can lead to a reduction in the workload of the feed pumps. The ability to provide the required conditions to the internal components of the compressor at an increased efficiency would reduce operating costs.

Examples of Testing Methods

Testing to find loss coefficients for certain geometries is something that has been accomplished various times. In an introductory fluid mechanics textbook, there is a list of tables with head loss coefficients for some commonly used geometries. Therefore, when researching how to experimentally find head loss coefficients, we examined previous research papers which investigated their very own unique geometries.

Blake P. Tullis' research paper, "Flow Testing 24-inch DUROMAXX HDPE Pipe" determined the hydraulic roughness and characteristics to include losses of the ContechDuromaxx HDPE drainage pipe. The research study was conducted at Utah State Universities Water Research Laboratory. A depiction of this experiment's setup can be found in Appendix A.

The pressure taps in Figure 5were used to measure the change in hydraulic head across the length of the test pipe. The pressure taps were strategically placed in the steel pipe upstream of the test sections. At each pressure location there were two pressure taps installed on opposite sides of the steel pipe and then connected together. Then differential pressure transmitters were used in order to measure pressure differentials across the test pipe. The figure above also shows the location of the pressure taps before and after the test pipe. Flow rates within the pipe were determined using existing equipment at the Utah Water Research Laboratory.

A research paper called "Irrecoverable Pressure Loss Coefficients for a short radius of curvature piping elbow at high Reynold's number" by Bettis Atomic Power Laboratory evaluated the pressure drop characteristics of a short radius-piping elbow for high Reynold's numbers. The unique geometry in this case was a very tight radius elbow. The test apparatus of this study can be found in Appendix B.

However, because of the smaller size of this apparatus, flow straighteners are used before the fluid reaches the test section. Pressure taps are located at the inlet and outlet of the test sections. Flow rate testing in this experiment was conducted by using the differential pressure readings. Then they were verified using venturi flow rate meters with known venturi flow rate coefficients.

Both research papers demonstrated the fundamental testing equipment needed to test for losses in internal flow. The flow should be straight prior to entering the test section and pressure readings are taken at the test sections inlets and outlets. The flow rate within the test apparatus is also calculated experimentally and checked with instrumentation to ensure accurate results. Both of these research papers will be taken into consideration when Pre-Flow Systems designs and tests the apparatus.

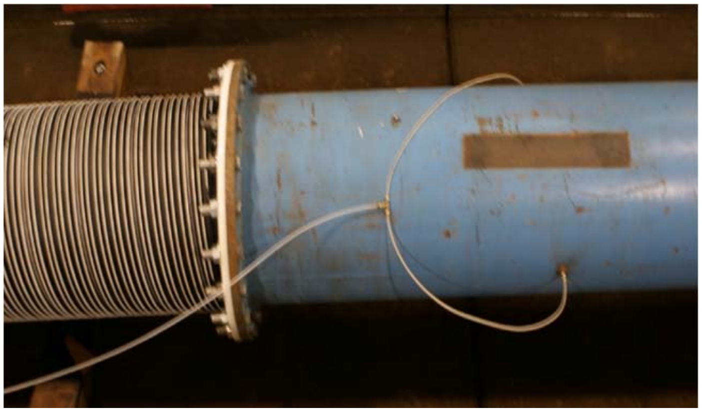


Figure 5. Fluid experiment setup with pressure taps

Chapter 2: Objectives

The ultimate goal of this project is to optimize the geometry of Solar Turbines' compressor end-cap ports. Pressure losses within different ports will be determined through calculation, computer modeling, and experimentation. In particular, PreFlow Systems is most concerned with determining the head loss coefficients and overall flow characteristics of unusual port configurations that do not have existing industry information. Analysis of this project's results will provide a basis for suggesting optimized port configurations to Solar Turbines.

In order to yield valuable information for the end-cap optimization, PreFlow Systems defines the following as the project's primary objectives:

- Design and build a scaled experimental test apparatus that simulates the flow through compressor end cap ports, which have complicated geometries
- Predict experimental results through calculations and computer modeling of various port configurations
- Calibrate and ensure accuracy of the test apparatus by conducting first stage of testing with a common flow path that has known head loss coefficients
- Collect sufficient data from multiple test runs in the second stage of testing for a variety of port dimensions
- Generate design curves for port configurations from experimental data
- Analysis of the ports with normal operating conditions versus emergency failure scenarios with head loss coefficient information acquired through testing
- Provide suggestions for ways to improve port geometry as based upon acquired head loss coefficient data
- If time permits, conduct third experimental testing stage with new flow paths to prove validity of suggested alterations to port geometries

The test apparatus is the primary project deliverable. The majority of the project objectives are highly dependent upon the success of its functionality. Most importantly, it should be noted that the experimental device will be utilized for validation by Solar Turbines even after PreFlow Systems has fulfilled the aforementioned objectives. Throughout all phases of the design process, the project objectives must be regarded. The design phase of the project is initiated by defining the test apparatus' technical specifications.

Technical Specifications

The specifications of the device were determined by the Quality Function Deployment (QFD) matrix in Appendix C. The QFD method correlates the customer requirements to PreFlow Systems' design requirements. In making these correlations, design conceptualization will be efficiently directed to the project objectives.

The primary technical specifications listed in Table 1 focus on meeting appropriate parameters. As shown in the QFD matrix, the primary purpose for dimension limits is for mobility of the test apparatus. Furthermore, the limitations on test pressure and precision of the experiment device are of especially high concern. Inherent to any design for experimentation, the validity of a test is dependent upon acquiring precise measurements. Also, as described in the *Design Development* section of this report, the pressure limit was determined by the limits of the fluid supply.

A specification's risk factor is directly related to how much not meeting a parameter could influence the overall success of the design. The table categorizes such risk into categories of high (H), medium (M), or low (L).

The degree to which the specifications are satisfied is determined through the compliance methods. Throughout the progress of the test apparatus design, PreFlow Systems will verify if the specifications are met through methods of inspection (I), analysis (A), testing (T), or comparison of the its similarity to existing designs (S).

Table 1. Experimental Test Apparatus Technical Specification

Specification No.	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Weight	100 lbs	MAX	M	I
2	Length	7 ft	MAX	M	I
2	Width	5ft	MAX	M	I
3	Height	4ft	MAX	L	I
4	Test Pressure	90 psi	MAX	H	A, I, T, S
5	Precision	Nominal Value	±10%	H	A, I, T, S

Furthermore, throughout the project's progress, the QFD matrix will be regarded in conjunction with the primary technical specifications. This is to ensure that PreFlow Systems delivers valuable experimental findings from a functional test apparatus to Solar Turbines.

Chapter 3: Design Development

As defined by the objectives, PreFlow Systems has defined this project to include phases of research, apparatus concept generation, engineering analysis, building and testing of the apparatus, and analysis of experimental results. This chapter in particular documents the test apparatus' progression from an initial concept to its final design and involves the first three project phases. These initial phases first involved determining the basic requirements of the test apparatus as based upon the project objectives and technical specifications.

Device Sub-Functions

Inspiration for the apparatus stems from the common test practices discovered in research and mentioned in this report's project background. In order to act on this inspiration, it was required to understand the requirements of the PreFlow Systems test apparatus in particular. By categorizing the apparatus into sub-function groups, the generation of technical specifications and design conceptualization becomes more manageable. The primary sub-functions of the test apparatus are:

- Fluid supply
- Flow Control
- Measurement
- Simulate Ports
- House Components

A discussion of each of these sub-functions introduces how the test apparatus has evolved from a general idea to a detailed device with specified components. In-depth engineering analysis was required to properly fulfill the device sub-functions and is documented primarily in this chapter.

Fluid Supply

As the name implies, this sub-function involves any component dealing with fluid source and transport. The first important consideration was determining the overall test media. According to our background research, water is the most commonly used test fluid for determining loss coefficients experimentally. The primary reasons for this are that water is inexpensive, indicates leaks in the system well, and is incompressible. PreFlow Systems initially adopted water as the primary test media under the same justifications, and because the scope of the project was then believed to include oil ports.

However, as the overall design concept evolved, feedback from fluid experts at Solar Turbines and Cal Poly suggested that the primary fluid media should be air. This recommendation was found to be very applicable to the project for the following reasons:

- No mess if leakage occurs
- Lighter weight
- More readily available sources i.e. shop air, air tank, or compressor
- Better simulates actual scope of project i.e. analysis of gas ports of concern

The primary worry associated with using air as the test media is that leaks in the system would be difficult to detect. PreFlow Systems plans to prevent this issue by playing close attention to the assembly of the fittings on the test rig. That is, the probes places into the static taps will be carefully inserted and secured with epoxy. Then upon completion of their assembly, a vacuum test, as suggested by Cal Poly fluids expert, Dr. Westphal, will be conducted to check for leakage at the static probe/tap interface.

Upon Solar Turbines' approval to select air as the test fluid, consideration of the appropriate source was then necessary. In order for the test fluid to be at an adequate flow rate within the apparatus, the supply would be required to provide a consistent source of pressurized air. In order to obtain this, three primary source options were applicable to the project:

- Shop Air
- Air Tank
- Compressor

To select the proper source for the PreFlow Systems test apparatus, many considerations of how the supply would affect experimental results were made. In particular, density is an important factor for gathering accurate data mainly due to the fact that air is a compressible medium. Influences of changes in density include molecular make-up of the fluid, temperature, and pressure. Accuracy and precision are of highest concern for the PreFlow Systems project and thus any variables influencing uncertainty or error must be taken into account. Temperature and pressure are relatively easy parameters to measure while the molecular make-up of the air is not. Thus, it is very important that the moisture and particulate content of the air be controlled.

Compressors and shop air (essentially an "infinitely" large compressor source) often have variations in moisture and particulate conditions due to the fact that their intake air is from atmosphere. In addition, the engines providing work to the compressor also have influence on the quality of resulting pressurized air. In contrast, tanks have a controlled closed supply of air at known and consistent conditions. Due to the known test apparatus requirement of clean air, the compressor and shop air options were considered with the addition of filter/dryer components. A Pugh Matrix, which considered factors based upon the specifications in the QFD, was compiled to aide in the decision making process for the apparatus' air source.

Table 2. Air Source Pugh Matrix

	Air Tank	Compressor with Dryer/Filter	Shop Air with Dryer/Filter
Air Quality	+	S	S
Flow Rate Consistency	S	-	+
Moisture Content	+	S	-
Pressure Range	S	+	-
Safety	-	+	+
Availability	-	S	+
Portability	-	+	S
Noise	+	-	S
Temperature	+	-	S
Cost	S	-	+
∑+	4	3	4
∑-	3	4	2
∑S	3	3	4

Flow Control

Flow Control is important to the PreFlow System test apparatus because our method of experimentation requires varying the Reynolds number to generate appropriate design plots. The dimensionless parameter depends upon the pipe diameter, fluid properties (density and kinematic viscosity), and the velocity of the fluid flow. Under the law of conservation of energy, it becomes clear that changes in system dynamic pressures results in a change in the fluid velocity. These parameters are inversely proportional. A clearer indication of this relationship can be found in Bernoulli's equation, which is derived from the energy equation.

$$\frac{v^2}{2} + gz + \frac{P}{\rho} = constant$$

The law of conservation of energy, as represented by the Bernoulli's equation, provides a reasonable explanation for the basis of the design considerations made within the Flow Control sub-function. However, as it will be explained later in this report, for purposes of particular analysis of the PreFlow Systems test apparatus, the Bernoulli's equation will be invalid.

In order to adjust the inlet and outlet pressures, as well hold the pressures steady for a particular setting, a pressure regulator is required. At the inlet, a pressure regulator will control the supply pressure and at the end of the test apparatus, another regulator will provide a back-pressure. As explained superficially in the Bernoulli's equation, altering these pressures will allow for a change in fluid velocity.

In addition to the pressure regulation requirement, a method of creating fully developed flow is required for the measurement devices upstream of the test section. As revealed in the background research, flow conditioning is a standard requirement for such test devices. Further details on how the *Flow Control* sub-function will be fulfilled are included in the *Major Components* section of this report.

Measurement

The overall success of the project is dependent upon the results obtained from experimentation conducted on the test apparatus. Accuracy and precision is of the highest concern and required for more measurements than just that of the pressures upstream and downstream of the test section.

The basis for selection of the instrumentation lies in the ultimate project objective. PreFlow Systems commits to providing end caps design suggestions by conducting analysis on various ports' pressure los coefficients. The pressure loss coefficients are determined with several measurements acquired from the test apparatus. Understanding of how to analytically determine the pressure loss coefficient is critical to attaining the appropriate measurements.

As shown in PreFlow System's background research of standard flow test systems analysis, the pressure loss coefficient is defined as follows:

$$Loss\ Coefficient = \frac{Total\ Pressure\ Loss}{Upstream\ Dynamic\ Pressure}$$

A more detailed derivation of this concept in Appendix D depicts the total pressure loss occurring between two fixed points in a fluid system. In particular, the terms of this loss coefficient relation are interconnected by the fundamental fluid mechanics relation that total pressure is equal to the sum of static pressure and dynamic pressure. In symbolic form, this is written as:

$$P_t = P_s + \frac{1}{2}\rho V^2$$

Then, by incorporating the symbolic notation into the fundamental pressure loss coefficient relation, the equation governing PreFlow System's project becomes:

$$Loss\ Coefficient = \frac{\left(P_1 + \frac{1}{2}\rho {V_1}^2\right) - \left(P_2 + \frac{1}{2}\rho {V_2}^2\right)}{\frac{1}{2}\rho {V_1}^2}$$

Of noticeable concern is the fact that the loss coefficient is actually highly dependent on upon fluid density, ρ, and velocity, V, which has been incorporated by the dynamic pressure. Clearly, as shown in the brief derivation, it is required that the test apparatus measures total pressure, static pressure, and the fluid characteristics of density and velocity.

Density is very important to this project for more reasons than just its presence in the pressure loss coefficient parameter. Because the test media is air, an incompressible fluid, the density of the system will change with alterations in the apparatus' operating pressures. Furthermore, because density cannot be measured directly, it must be obtained by another standard analytical method.

Again, stemming from fluid mechanics fundamentals, it is safe to assume that air behaves as an ideal gas at relatively low flow speeds. This is the relation that allows calculation of the air density in the test apparatus. The Mach number, a dimensionless ratio of an object's relative velocity to the speed of sound in a given fluid, is the standard parameter for the ideal gas assumption. At Mach numbers less than 0.3, it is safe to assume air is an ideal gas. Therefore, to determine the fluid density, it is calculated from the ideal gas relation as follows:

$$\rho = \frac{P}{RT}$$

To reiterate, density, *ρ,* is equal to the fluid pressure divided by the ideal gas constant, *R*, and fluid temperature, *T*. The ideal gas constant is a value particular to the fluid molecular composition.

Finally, as shown in the previous governing equations, the test apparatus must be able to measure:

- total pressure
- static pressure
- air velocity
- air density
- air temperature

The specific methods of measuring such values are described in *Major Components*.

Simulate Ports

An important consideration for fulfilling the project objectives is to determine a method of simulating the complicated geometries of the various gas ports that occur in the Solar Turbines end caps. These problematic geometries are important to the project because the pressure losses associated with such configurations are not already documented.

In order to determine which particular port configurations should be analyzed, PreFlow Systems reviewed the multiple end-cap drawings and models provided by Solar Turbines. As described in *Port*

Characterization, such findings are documented in a general library as well as in graphs. Statistical analysis of the information gathered from the drawings is what ultimately determines the method in which the ports are best simulated.

Furthermore, PreFlow Systems will attempt to make predictions about the unknown flow conditions in the complicated ports as based upon boundary conditions provided by Solar Turbines. By conducting analysis on the ports' inlet pressures and flow rates, for example, predictions can be made for the appropriate test apparatus operating conditions.

House Components

Finally, another important factor to the overall design of the apparatus is its housing. As presented in the technical specifications, the device should be a reasonable size and weight. This is primarily for considerations of storage, mobility, and user interface. The extensive testing requirements of the project could be cumbersome if not recognized when designing the device mount.

Port Characterization

To define the problematic geometries of the ports, PreFlow Systems reviewed drawings of the discharge and suction end caps for eleven gas compressor models. The eleven models are denoted as C28, C31, C33, C41, C45, C51, C61, C65, C85, C160, andC401. Review of each of these compressors yielded a list totaling 140 gas ports. The most common problematic geometry occurring within this group is shown in Figure 6.

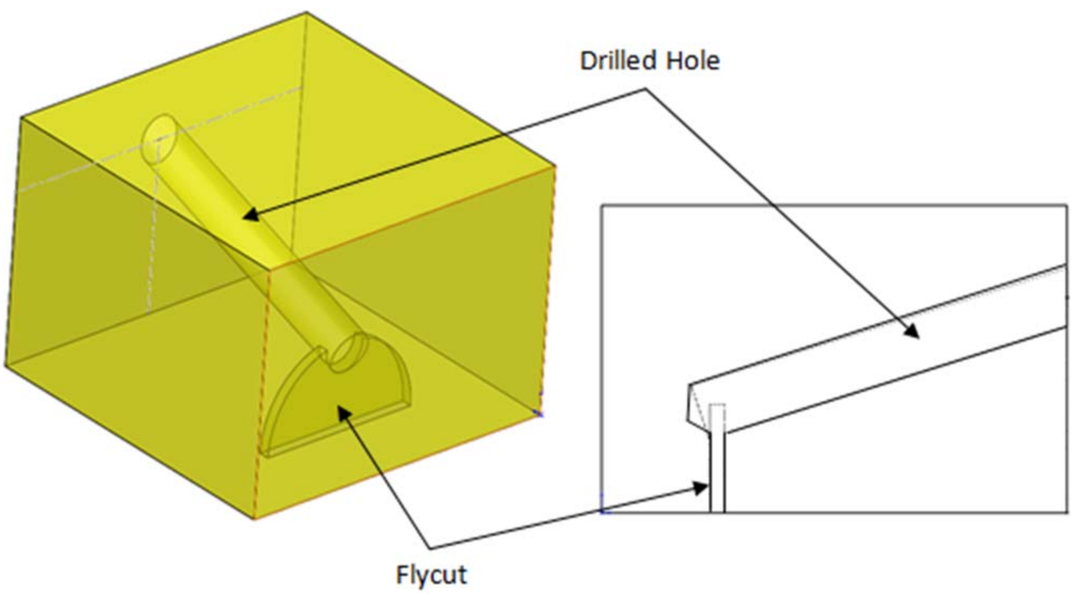


Figure 6. Most common problematic geometry in the gas ports of the endcaps

As shown in Figure 6, the geometry consists of two main parts: drilled hole and flycut. For this given gas port configuration, a variety of dimensions and angles were found. This is what determined the necessity to document these dimensions in an excel file, named as the Port Library. Within the library, each port is characterized by the following:

- diameter of the drilled hole
- flycut width
- angle between the drilled hole and flycut centerlines
- horizontal offset between the flycut and the end of the drilled hole
- fly-cut radius

Figures 7 and 8 indicate where the dimensions are located on the most common problematic configuration.

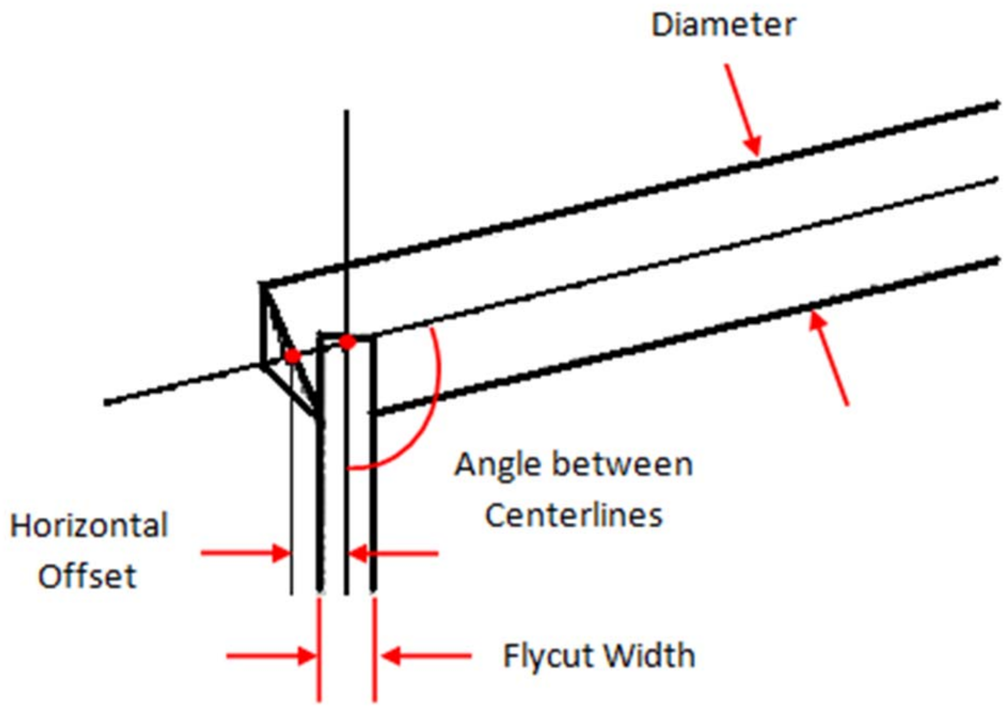


Figure 7. Dimensions and angles characterized in the port library

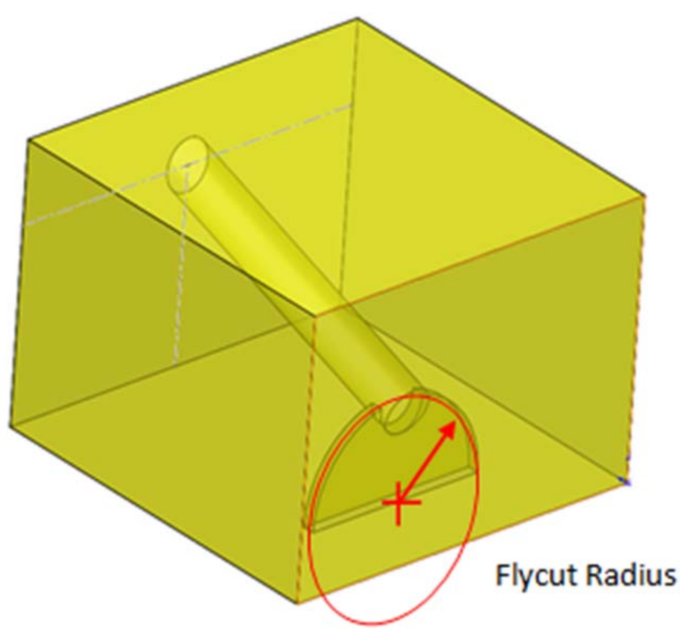


Figure 8. Flycut radius of the geometry

Selected Dimensions and Test Plan

The decision of which dimensions to use in the test section block was made based upon the analysis presented in Appendix D, as well as in consideration of amount of test section blocks needed for certain testing plans. If it was desired to test every possible combination of port dimensions (diameter, flycut width, angle, horizontal offset and flycut radius) with the commonly occurring dimensions, then 375 test section blocks would be required. This plan is very unrealistic to perform with the time and resources available. Testing with only the combinations of the most common dimensions would require 81 test section blocks. This alternative is still too unrealistic for the project schedule. Therefore, a plan that uses only nine test blocks to analyze the effects of each variable is appropriate.

The first test section block will consist of the most common dimensions and angles from the port library. Table 3 summarizes these values. This test section block will be considered the standard control block.

Table 3. Common dimensions and angles for gas ports

Diameter (in)	1
Angle (degrees)	110
Flycut Width (in)	0.5
Horizontal Offset (in)	0.45
Flycut Radius (in)	2.5

This configuration will be tested with varying velocities and pressures of the air to generate graphs of pressure loss coefficients compared to Reynolds Number. The resulting data will represent the loss coefficient for a typical gas port.

Then, two test section blocks with identical dimensions as the control block, except for one dimension being different, will be machined. This will be done for each dimension except the drilled hole diameter. With two blocks for each of the four dimensions, eight additional test section blocks will be required. Using the values indicated in red on each figure of Appendix D, an analysis on the effects of changing each dimension will occur by holding all the other dimensions constant. This will aide in understanding how much of an effect each variable has on the loss coefficient. Once this testing is finished, then it will be determined if more testing is needed for certain dimensions that have a significant effect. Table 4 summarizes the additional eight test sections with their dimensions. The extreme values for the flycut radius were changed into 2 and 5.5 inches for easy of machinability.

Table 4. Dimensions and angles for the eight additional test section blocks

	Lower Value	Higher Value
Angle (degrees)	90	140
Flycut Width (in)	0.25	1
Horizontal Offset (in)	-0.05	0.9
Flycut Radius (in)	2	5.5

Model Predictions

In order to design the apparatus to best simulate the actual operation of the end-caps ports, it is necessary to make predictions based upon information already known by Solar Turbines. PreFlow Systems was able to conduct preliminary analysis following completion of the port library and upon receiving a memo from Solar Turbines which provided the boundary conditions of the ports.

By using the drilled hole dimensions of the Port Library and the supply flow rates provided in the Solar Turbines Boundary Conditions memo, the estimated fluid velocities were found. These values, and estimated fluid properties for air, (density, ρ, and kinematic viscosity, μ) were then used to predict Reynolds number.

$$Re = \frac{\rho V D}{\mu}$$

The port numbers on the horizontal axis of Figure 9 only correspond with a limited selection of the ports, the buffer seals, because clarification is required on which conditions apply to the other ports. Although the distribution does not include all of the ports that PreFlow Systems is really concerned about, it still is useful in providing the first indication of the appropriate testing range. The bulk of the values are above 4000, which indicates turbulent flow exists within the ports.

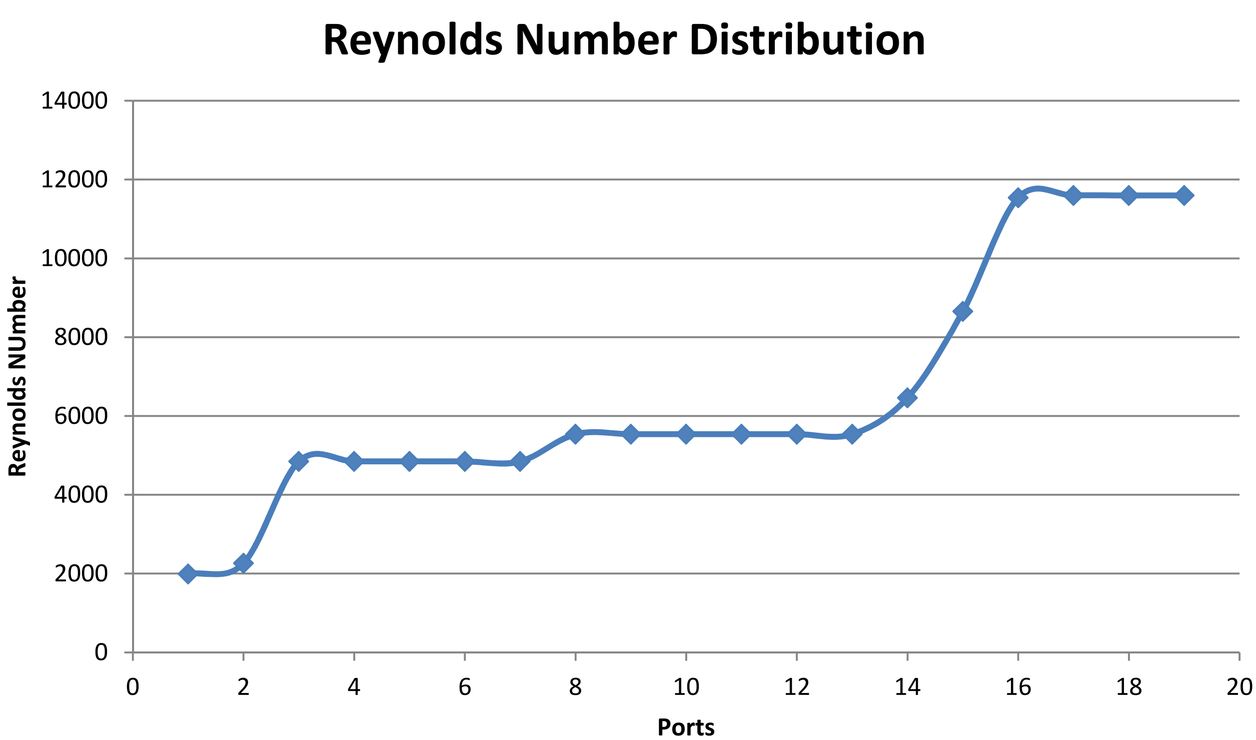


Figure 9. Distribution of expected Reynolds numbers determined from boundary conditions

Another important prediction made as based upon the boundary conditions is the operating range of the pressure measurement devices. In order to specify a pressure transducer with the appropriate resolution, the operating range must be known. Appendix E explains how the maximum pressure loss within the test section can be no greater than the dynamic pressure of the system.

$$Largest\ \|P_1 - P_2\| = \frac{1}{2}\rho {V_1}^2 \rightarrow Differential\ Pressure\ Transducer\ Range\ 0\ to\ \frac{1}{2}\rho {V_1}^2$$

By using the same information as the calculation of Reynolds number, the absolute maximum pressure reading for buffer gas seal ports would be no larger than 0.025 psi. As shown in the graph of Figure 10, the majority of these pressure values are actually much lower, at no greater than 0.005 psi.

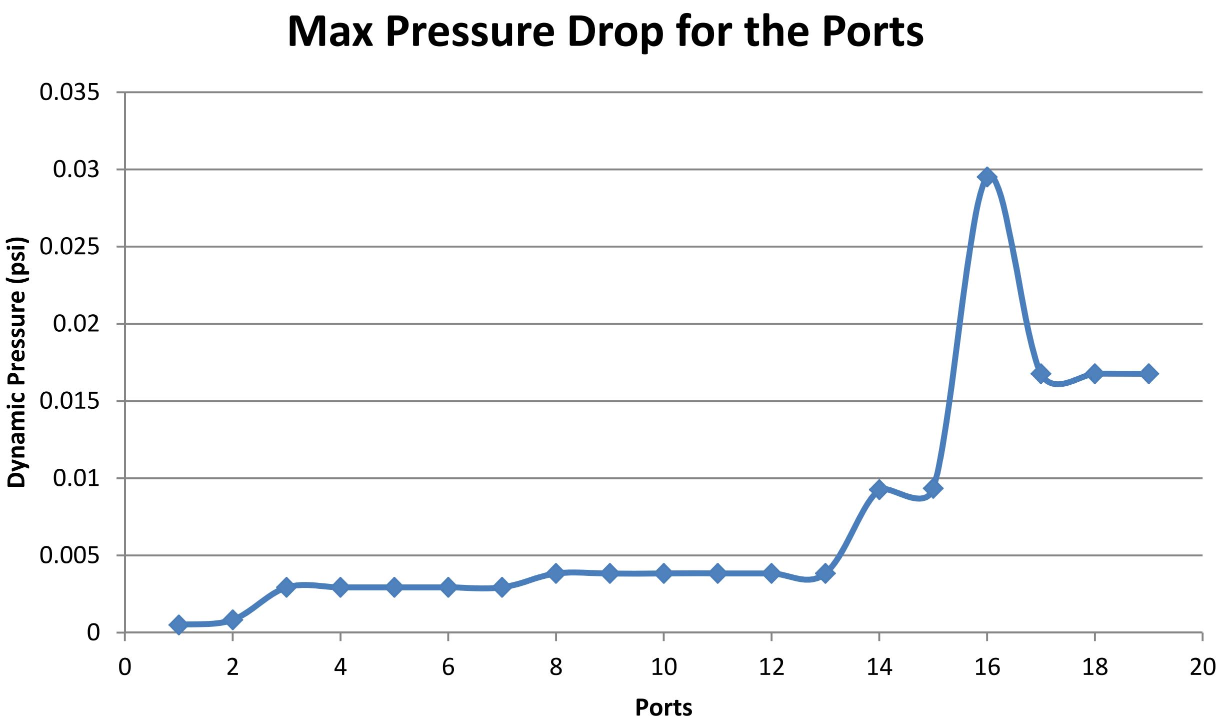


Figure 10. Distribution of max pressure drop expected for the test apparatus

The dynamic pressures estimated for the simulated ports were used in consideration of specifying necessary components in the preliminary test apparatus concept design. Further, in-depth, analysis of the operating conditions is considered to validate the following design and described in the sections following the concept designs.

Conceptual Designs

One primary design consideration for the test apparatus is the geometry occurring at the end of the test section block. In order to determine the loss coefficient, it is necessary to measure the total pressure after the air flows through the flycut. This can be found experimentally in several ways. After many hours of idea generation and engineering analysis, the design was narrowed to three concepts.

The first concept is the "Long Duct" design shown in Figure 11. This design would consist of a long duct, or vent, that has the same dimensions as the rectangular gap from the exit of the flycut. Near the bottom of the duct, a total pressure probe would be positioned in the center to measure the total pressure of the air.

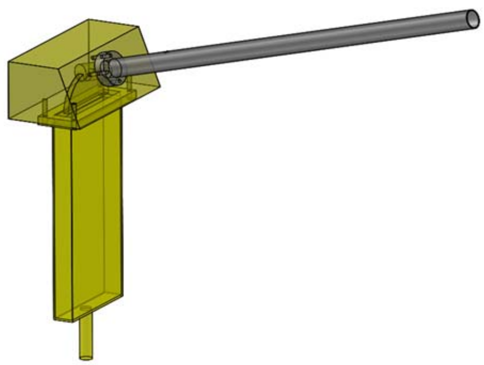


Figure 11. Long Duct Design

The limitations of this design are that it would be very expensive because every flycut width and radius change in a test section block would require a custom duct built for that exact size. In addition, each duct would need its own pressure measuring device because changing swapping probes between ducts would be a hassle and also introduce more uncertainties into the measured data. Another concern is the questionable length required for the duct so the air flow can reach fully developed flow after the flycut. In contrast, the total pressure measurement would be directly after the flycut so no correction would be needed.

The second out flow design is the "Chamber Vent" design shown in Figure 12. The chamber vent design would consist of a wide vent attached to the exit of the flycut. This vent would be designed to simulate the volumetric expansion from the flycut to the ring area of the compressor chamber.

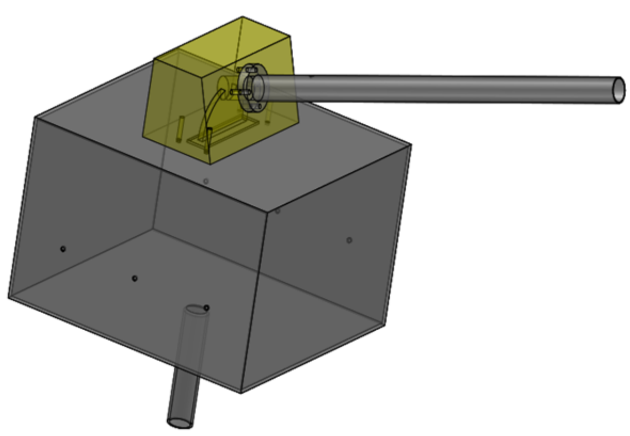


Figure 12. Chamber Vent Design

The design would be less expensive compared to the long duct design because only one vent would be needed for all the experiments. Also, if the flycut width or radius were to change with the next test section block testing, then the same vent could still be used. This would also reduce the amount of pressure probes needed because static taps could determine the total pressure. This is under the assumption that with a wide expansion, the velocity of the air in the vent as well as the dynamic pressure will drop to zero. This results in the total pressure equaling the static pressure. Overall, the problem associated with this design involves determining a volume for the chamber vent that realistically models the conditions in the compressor.

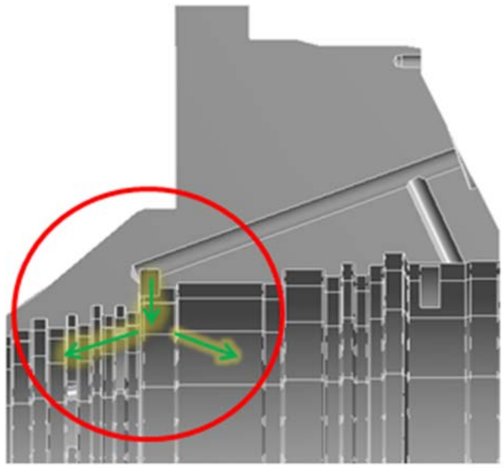


Figure 13. Complex internal layout of the Compressor Chamber

In Figure 13, the complex internals occupy the compressor chamber that the gases from the ports flow into (green arrows). The gases are then focused to the outside of the chamber by the gases going through the compressor (red arrows). Trying to model the volume that the gases from the ports expand into is difficult with such complex internals and forces from other gases. In addition, the gases that enter the compressor chamber also spread out in all directions as shown in Figure 14 which adds to the complexity.

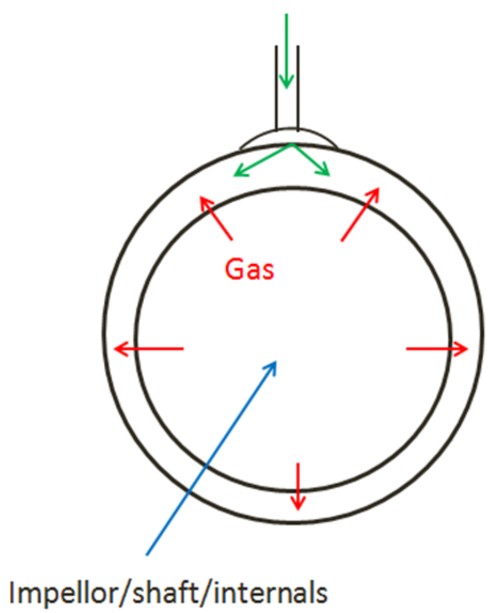


Figure 14. Port Gases spread out in all directions

The last concept for the out flow design is the Corrected Expansion. This design uses a similar chamber vent except the vent is not designed to simulate the compressor chamber but rather to produce an appropriate sudden expansion to force the air flow's velocity to zero. This will reduce the dynamic pressure in the vent to zero and make the static pressure equal to the total pressure. Like the chamber vent design, static tabs will measure the static pressure of the air flow through the vent. With this pressure measurement, we can determine the loss coefficient from the inlet tube to the vent. Then, we would experimentally find the loss coefficient from the inlet tube into the vent as shown on the right side of Figure 15. By subtracting the first loss coefficient from just the vent loss coefficient, we can determine the loss coefficient of just the problematic geometry. This option is less expansive then the long duct for the same reason as the chamber vent design. We would be using the same vent with different test section blocks and with the connector to the inlet tube.

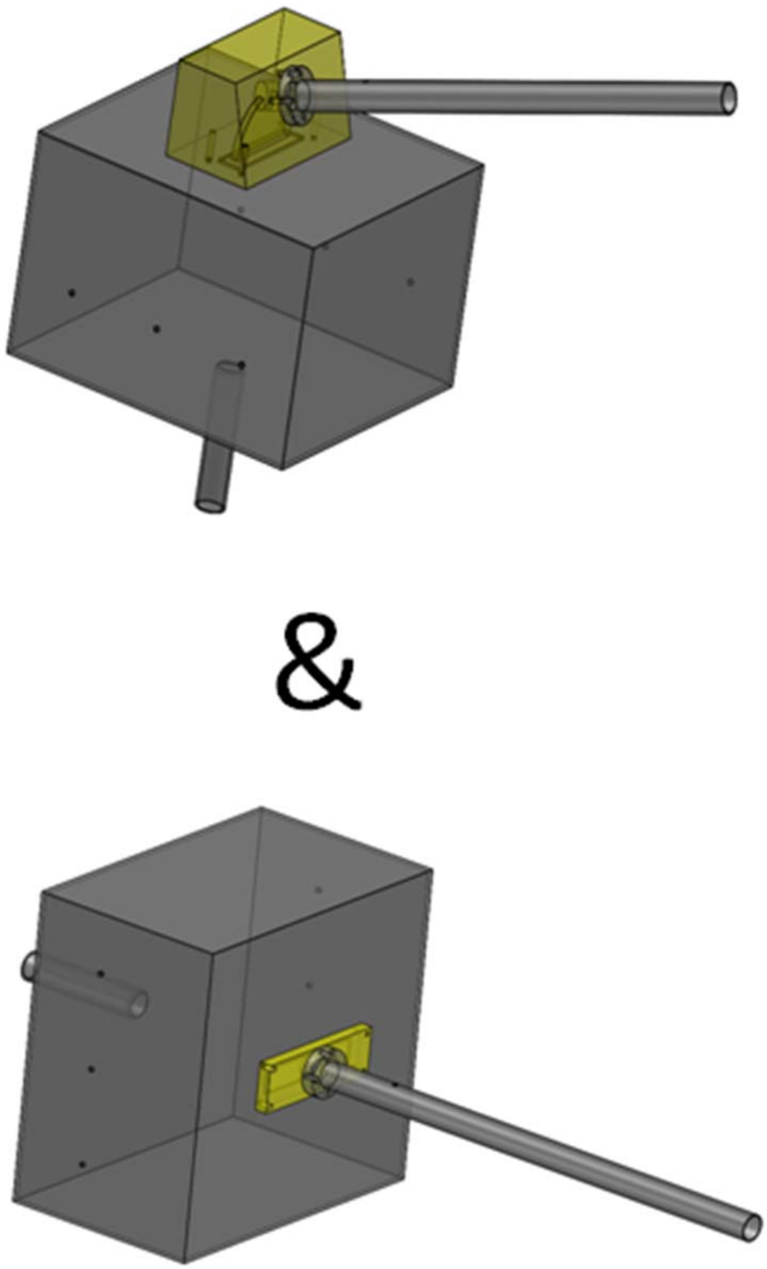


Figure 15. Corrected Expansion Design

To help us compare these designs, we formed a Pugh matrix. Refer to Table 5 below. With the uncertainty of when the flow would be developed in the long duct, we rated the long duct lower in accuracy, precision, and how well it could simulate the actual conditions. We rated the chamber vent high in the simulation category because if the analysis on the complex conditions were modeled correctly then it would yield the best loss coefficient from the whole air path. Unfortunately, this high complexity means that if we calculated the volume expansion with our skills and technology, we might not model the volume correctly so we rated the chamber design as having a lot of uncertainty in the analysis. Overall, the corrected expansion design seems the best because of its cost, accuracy and our certainty that experimental subtraction of loss coefficients should work correctly.

Table 5. Pugh Matrix on for primary design concepts

	Long Duct	Chamber Vent	Corrected Expansion
Accuracy	-	S	+
Simulation	-	+	S
Precision	-	+	+
Uncertainty Analysis	S	-	+
Cost	-	+	S
∑+	0	3	3
∑-	4	1	0
∑S	1	1	2

As a result of this analysis, we selected the corrected expansion to be our conceptual out flow design for this project.

Preliminary Concept Design

The preliminary concept test apparatus we have designed to fulfill the needs of our sponsor Solar Turbines is presented in the schematic shown in Figure 16. The most significant part of the system is the "Test Section" which will yield the loss coefficients. However, there are other support components that also play a vital role in our system to ensure accurate results. Ensuring accurate test results requires the air be conditioned before entering the test section. The air used by our system will need to be dry, clean and not contain distorted or swirling flow. The key measurements we need to record are air flow rates, temperature, total pressure inlet, and static pressure outlet of the test section. These parameters will be manipulated to acquire multiple pressure loss coefficients and Reynolds numbers.

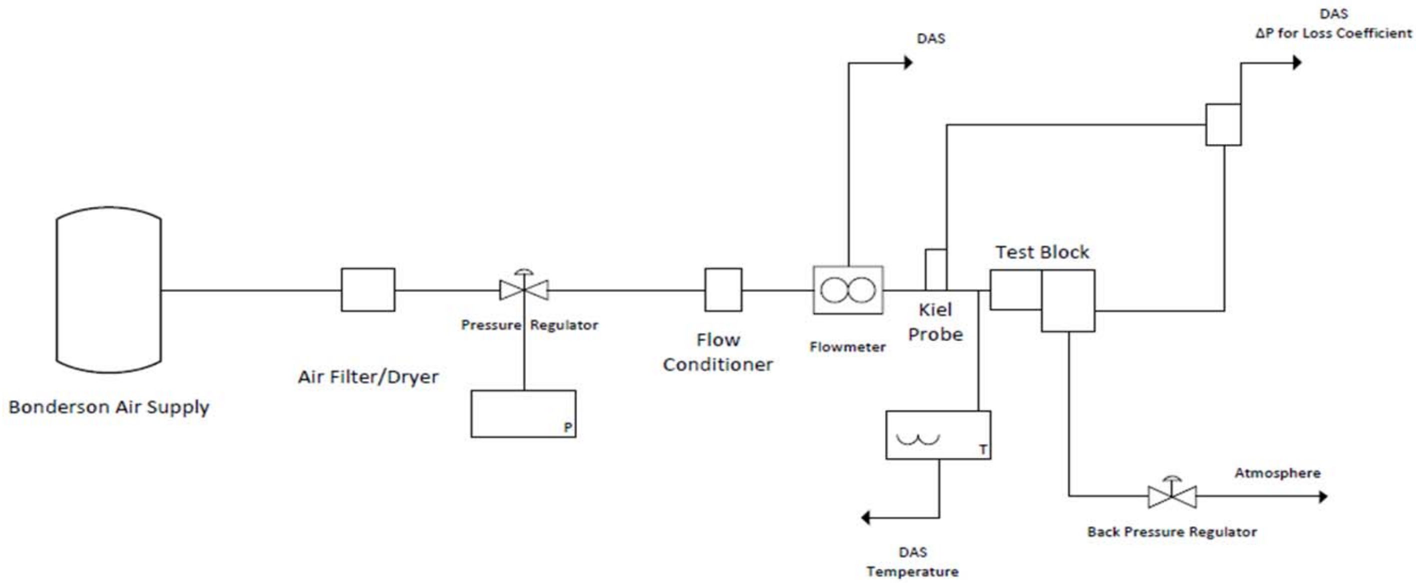


Figure 16. Concept Diagram of Test Apparatus

The air for the test apparatus will be supplied by Bonderson's Engineering Projects Center's shop air located on the Cal Poly campus. The shop air is maintained between 90-120 psi and contains an inline dryer to supply dry air, but there is no data regarding moisture content within the system. Therefore to ensure dryness and cleanliness there will be an additional dryer and filter system in place. A pressure regulator will control test section inlet pressure while the back pressure regulator will control the systems flow rates. The flow conditioner will ensure straightened flowing air within our system before entering the test block.

To measure our system flow rates there will be an inline flow meter after the pressure regulator. A Kiel probe and a thermocouple will be placed before the test section inlet to measure total pressure and temperature to determine air properties. After the test section there will be static ports measuring pressure. The Kiel probe and static ports will be connected to a differential pressure transducer to measure differential pressure.

A data acquisition system will be used to collect temperature, differential pressure, and flow rates. After the data has been collected we will calculate pressure loss coefficients and Reynolds numbers then plot them with the pressure loss coefficient on the ordinate axis and the Reynolds numbers on abscissa axis.

Major Components

Test Section

The test block section of our test apparatus is the most important part our system because this is where the losses occur. The inlet pipe will be mounted to the test block with a gasket and flange to ensure no leaking at the connection. The sudden expansion duct after the fly cut will allow for interchangeability between different test blocks with different fly cut dimensions. The sudden expansion duct will have a total of six static taps to measure duct static pressure. Six static taps will be used as taking static pressure at different test points of the duct will produce the average static pressure inside the duct. Refer to Figure 17 for a visual.

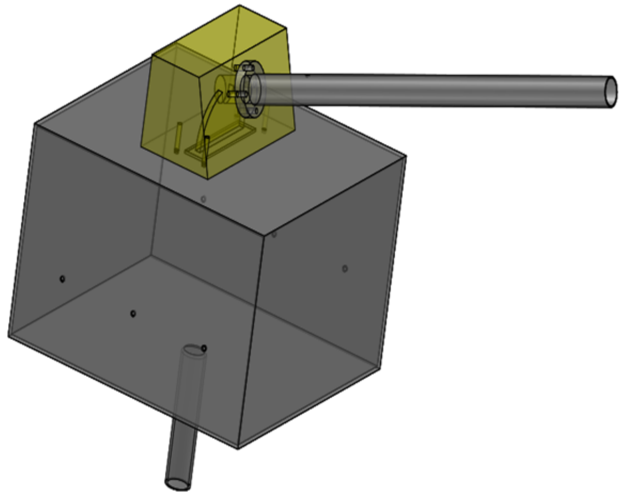


Figure 17. Test Section

Inline Disposable Desiccant Air Dryer

The main purpose of the air filter dryer is to remove any particulates and moisture from our air supply. Loss coefficients are dependent on fluid densities therefore if we had moisture in our air supply it would introduce error in our calculations. The inline disposable desiccant air dryer which will be used in our system contains disposable desiccant air dryers. When the desiccant needs changing there is a color changes from orange to green to inform you of replacement being required. There is a transparent bowl as part of the housing which allows you to see the color of the desiccant without having to disassemble the system. The desiccant material in the air dryer is a silica gel which also includes a 40-micron pre-filter. The air dryer can be installed either horizontally or vertically allowing for different configurations. The maximum operating pressure of the air filter dryer is 125 psi. The inlet connection is to the air dryer is an NPT female which exits to the outlet connection of an NPT male. Refer to Figure 18 for a visual of the air filter.

Figure 18. Air Filter/Dryer

Pressure Regulator

The main purpose of the pressure regulator is to set the inlet pressure before entering the test block. The pressure regulator or air regulator we will use in our system is a high-flow regulator with an attached pressure gauge. The pressure regulator contains a relieving feature which reduces downstream pressure through a vent port when there is a blockage in our system and air pressure rises. The inlet connection is to both the air regulator inlet and outlet ports are NPT. Air pressure is adjusted with a T-handle and accuracy of the air regulator is ±3 psi. The air regulator specifications are 1" Pipe Size, 360 Max SCFM, 5 to 125 PSI Range and the housing is made of aluminum. Refer to Figure 19 for a visual of the pressure regulator inlet.

Figure 19. Pressure Regulator for inlet pressure

Back Pressure Regulator

The back pressure regulator will be used to alter the back pressure and change the pressure differential which drives the fluid velocity within our system. The regulator will have an aluminum adjustable pressure-maintaining relief valve. This type of back pressure regulators maintain the adjusted pressure set at inlet without any regard for the outlet pressure which in our case will be atmospheric pressure. If the pre-set pressure at the inlet is exceeded the regulator will vent the excess air to maintain the set pressure. These types of regulators are commonly used with compressor systems to control air pressure instruments. The backpressure regulator is adjusted with a phenolic adjustment knob and regulator specifications are 1/2" Pipe Size, pressure range 0-150 psi, maximum pressure is 250 psi, NPT female side inlet and outlet and vented side relief port. Refer to Figure 20 for a visual of the back pressure regulator.

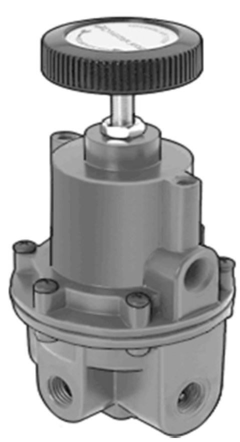


Figure 20. Back Pressure Regulator for flow rate manipulation

Flow Conditioner

The VORTAB® VIS Insertion Sleeve Flow Conditioner will straighten out the air flow and remove any distortion and swirling flow before entering the test block. The result will be more accurate and consistent measurements in our system. The application for this flow conditioner is for systems where the piping does not contain sufficient straight pipe to ensure straightened flow. The insertion sleeve can be customer specified with an inside diameter from 0.87 to 48 inches and made out of 316L stainless steel. The insertion sleeve also requires at least 3 diameters in length before providing straight fully developed flow. Refer to Figure 21 for a visual of the flow conditioner.

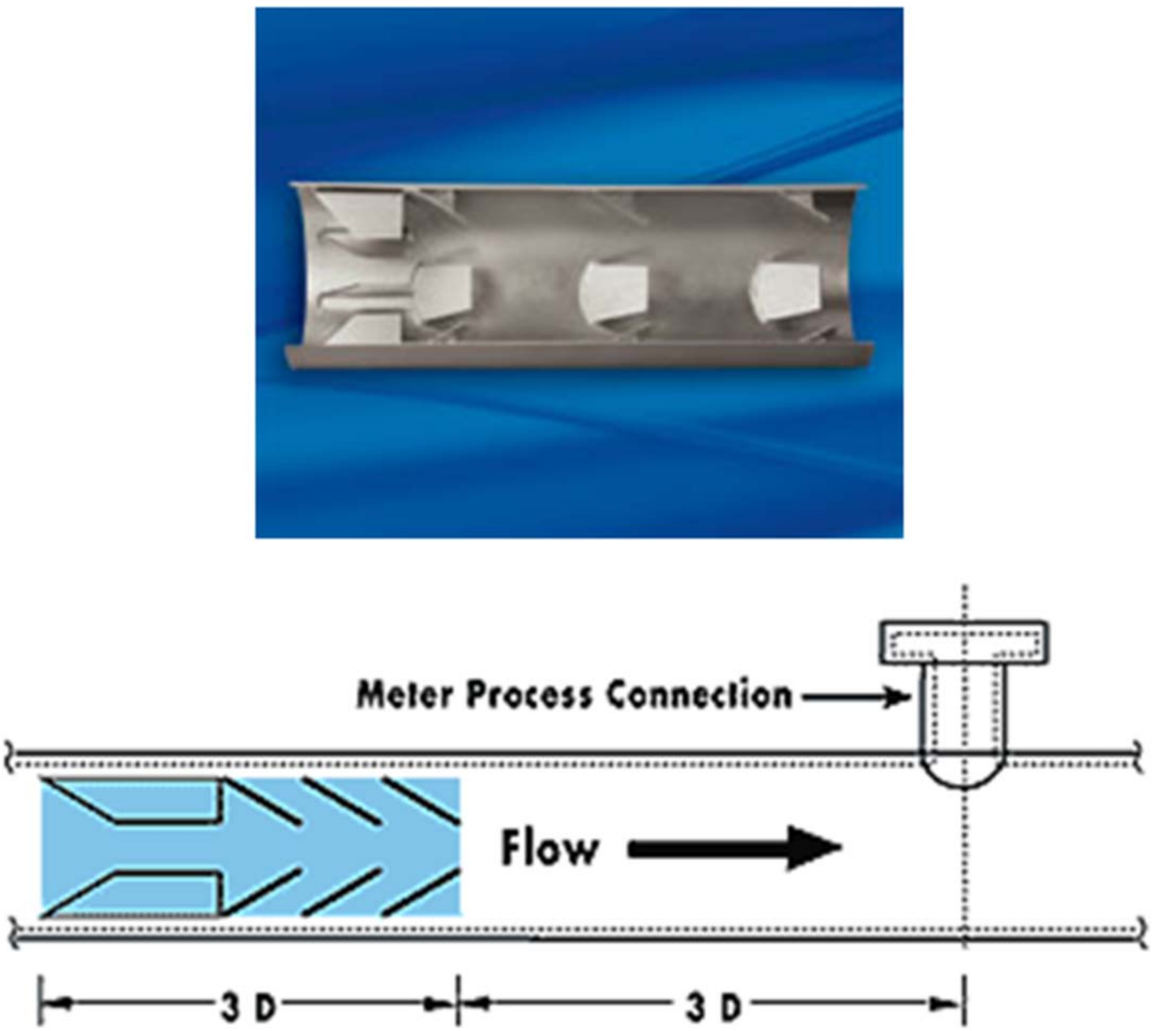


Figure 21. Insertion Sleeve Flow Conditioner

Kiel Probe

Kiel probes are used to measure the total pressure in a fluid stream. The inlet pressure will have both static and dynamic pressure, which makes using a Kiel probe valuable in our test apparatus. Kiel probes also have the advantage of operating where the direction of flow is unknown and can vary throughout its operating conditions with some limitations. Refer to Figure 22 for a visual of the Kiel probe.

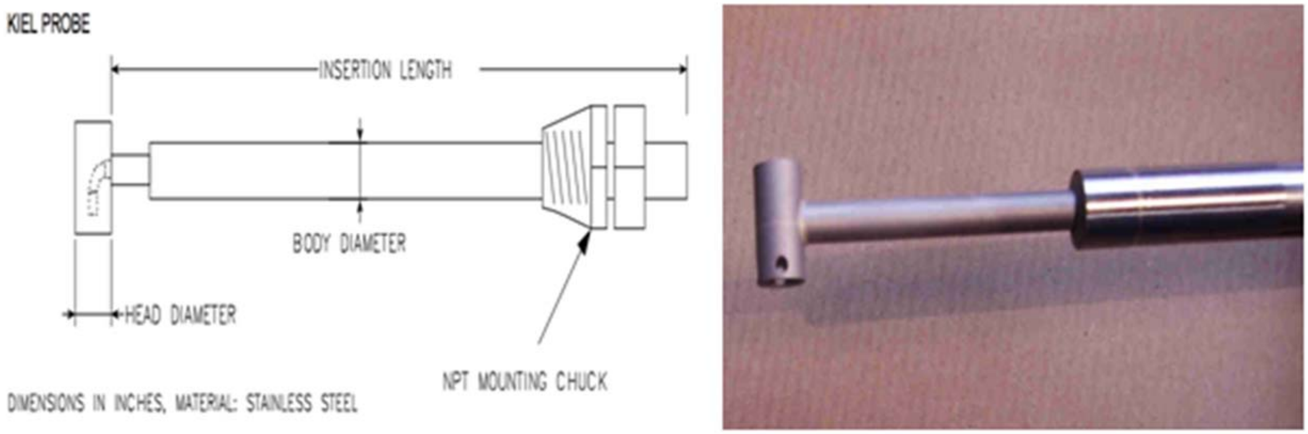


Figure 22. Kiel Probe

In our test apparatus a flow conditioner will limit the variations in flow to help ensure the Kiel probe does not reach its limitation. The Kiel probe is a variation of a pitot tube with a shrouded tip which captures fluid flow in different directions. The Kiel probe uses the stagnation point in which the fluid velocity is zero. The stagnation pressure which is also equal to static pressure at the stagnation is equal to the total pressure which can be seen from equation below.

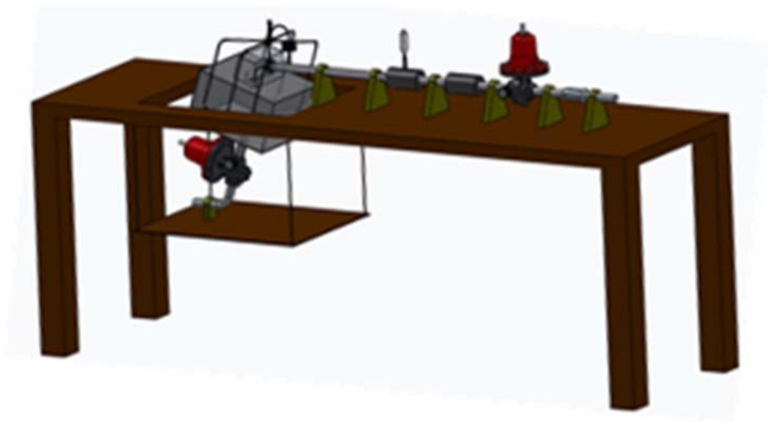
$$P_{total} = \frac{1}{2}\rho v^2 + P_{static}$$

Data Acquisition System

This test apparatus will also utilize a data acquisition system to take data from the thermocouple, flow meter, and differential pressure transducer. Testing at different boundary pressure conditions, while also varying the system flow rates to span a range of working Reynolds number will yield a great deal of data. Choosing which data acquisition system to use is very important to ensure working cohesiveness with our instrumentation. We are considering using Lab View but are looking into other potential options which are available to us at Cal Poly. Our team envisions a robust data acquisition system that can handle all our data input and make necessary calculations to plot port geometry design curves.

Concept Model

To visualize what a fully assembled test apparatus will look like we assembled a SolidWorks concept model. The test apparatus will be mounted on a table that will be mobile in case we have to move to another location for testing. The mounting table will have cutout section in order to accommodate our test blocks having multiple inlet mounting angles. The suspended part of the test section will be secured using tensioning wires. Figure 23 also shows an estimate for the total size of the test apparatus with some major dimensions. There are multiple views of the concept model with all major components labeled.



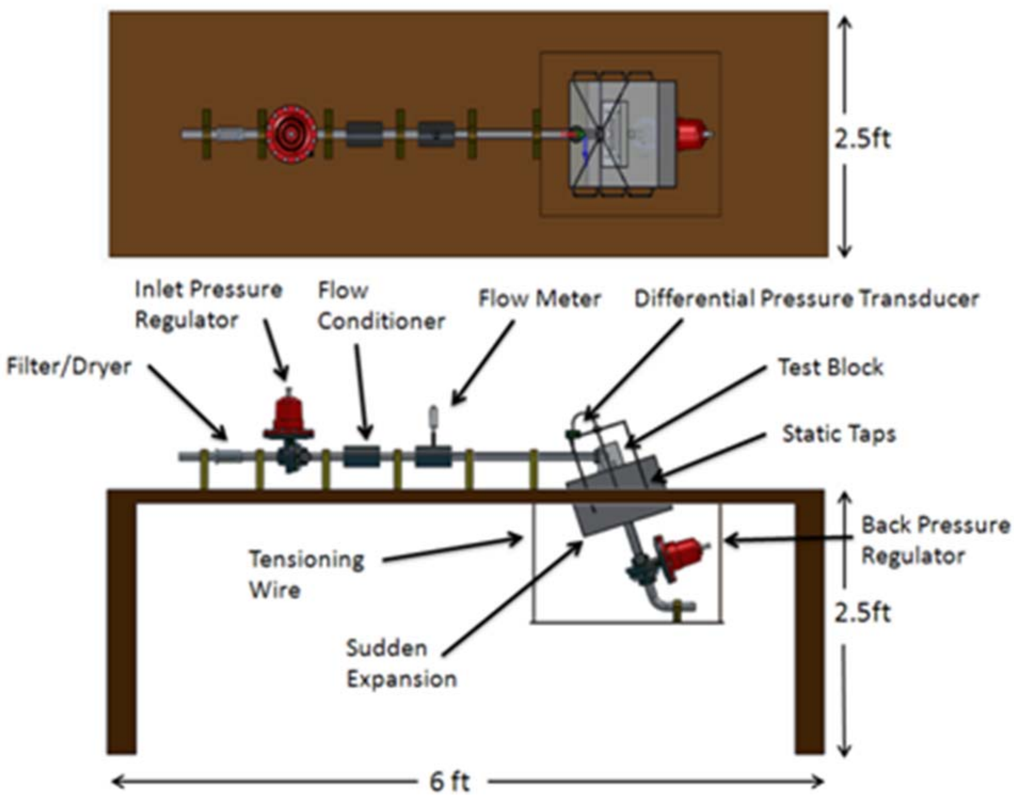


Figure 23. SolidWorks Concept Model with major components and overall dimensions

Design Concept Finalization

In order to finalize the preliminary concept design for the build phase of the project, it was required to validate the selected components with further engineering analysis. This was done by analyzing how each individual component, as well as the entire system, is expected to function. Consistent communication with the sponsor and project advisor played an important role in finalizing the design. Significant discoveries about the apparatus' predicted function resulted from PreFlow System's engineering analysis and the associated feedback from the other parties. Although the overall preliminary concept design had not changed to accommodate such findings, many important aspects were altered to yield a successful final design.

As documented in the following pages which precede chapter four, the considerations made to finalize the design include changes to the apparatus dimensions, test block exit orientation, operating conditions, and alternative component selections. The most significant change to the preliminary design was in eliminating the expansion box test section exit. This was due primarily to complications associated with the requirement to operate the apparatus at high pressures.

Pressure Vessel Problem

After reviewing the ASME Boiler and Pressure Vessel codes, it was discovered that the test section and exit vent would be considered a pressure vessel because of its cross sectional size. According to section 1.2.4.2 of the ASME Boiler and Pressure Vessel code, "The following vessels are not included in the scope of this division. […] Vessels with an inside diameter, width, height, or cross section diagonal not exceeding 150 mm (6 inches), with no limitation on length of vessel or pressure." With the expansion vent and max flycut exit over 6 inches wide, the design would have to follow all the pressure vessel standards. To avoid the difficult issues that come from designing a pressure vessel, the test section design and sizing would need to be changed.

Altered Test Section Exit

After discovering that the vent concept would be considered a pressure vessel, PreFlow Systems began reviewing suggestions from engineers at Solar Turbines. The engineers had done basic CFD on the problematic geometries selected by PreFlow Systems. The main observations from the CFD were that the total pressure largely varied along the exit of the flycut. Figure 24 shows this variation at the wall of the flycut.

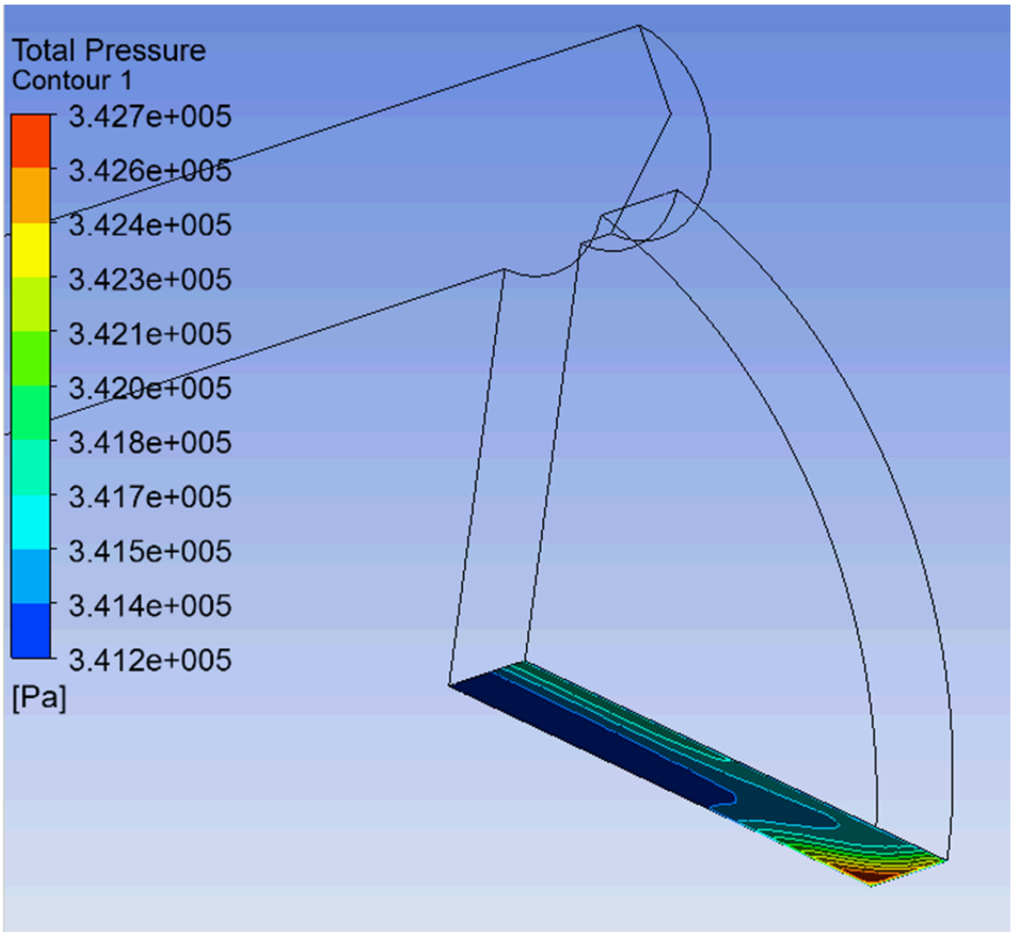


Figure 24. Pressure distribution at the end of the flycut

As a result, multiple total pressure sensing equipment like several kiel probes would be needed to find the distribution of the varying total pressure. This supports PreFlows original idea to design a vent with sensing equipment after the test section because placing only one sensor in the flycut would be inaccurate. On the other hand, the CFD results showed that the static pressure could be measured in the flycut because the static pressure varies little at the exit of the flycut. Figure 25 shows the comparison of total pressure and static pressure along the plane of the flycut exit.

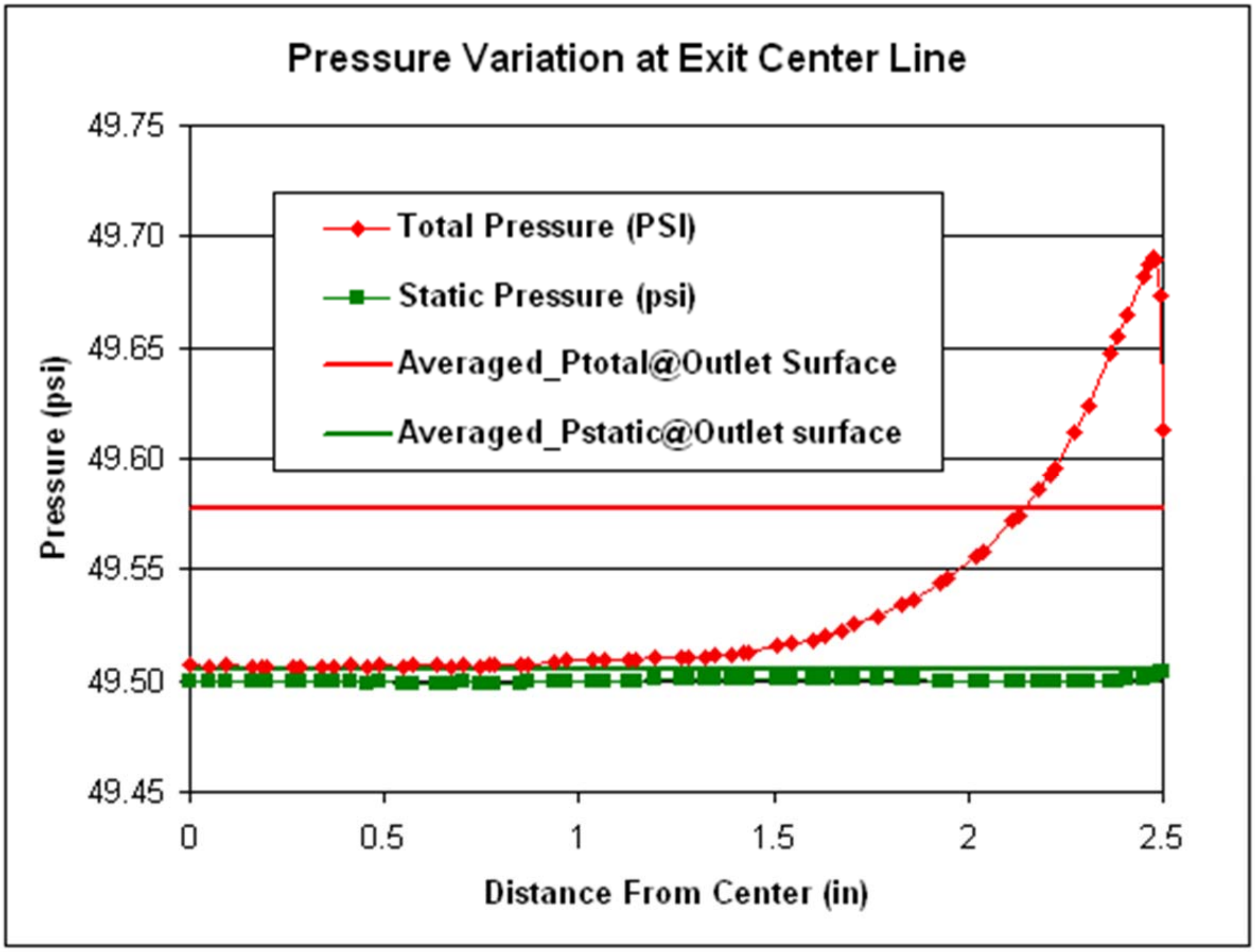
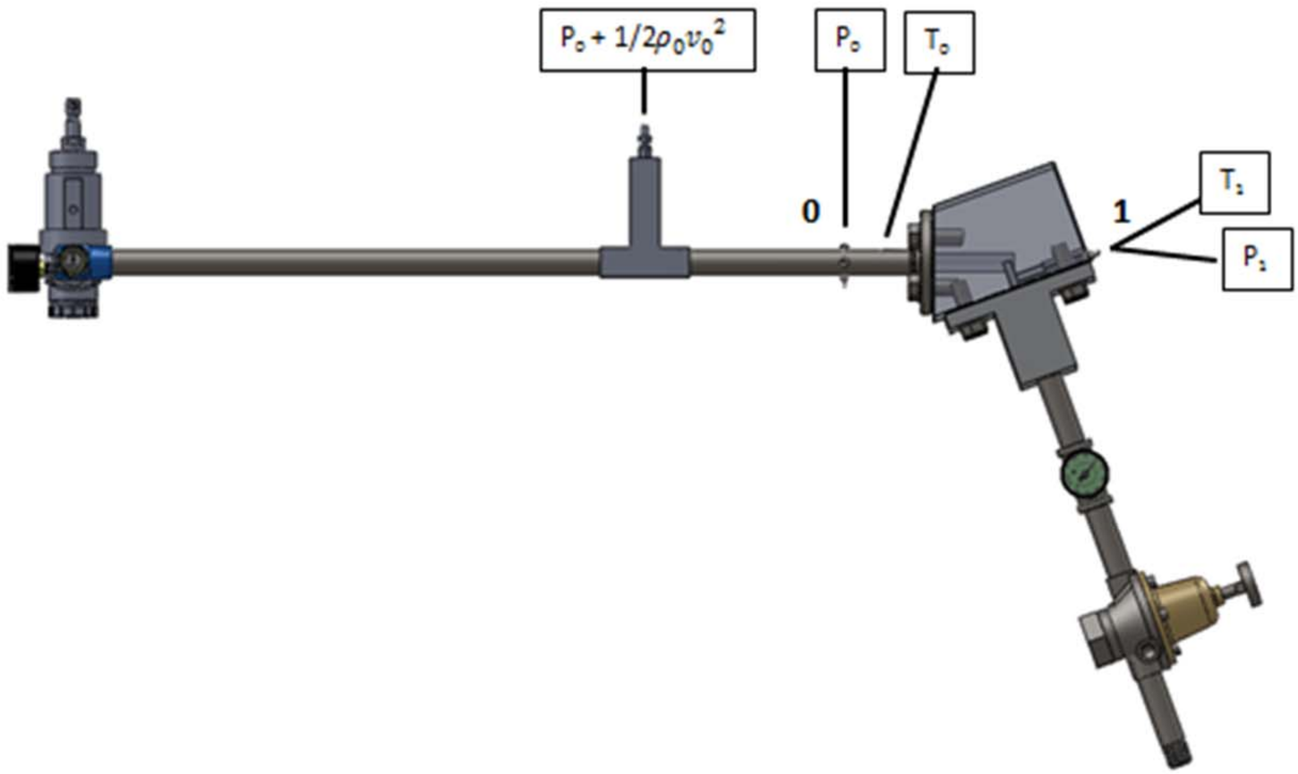


Figure 25. Static and Total Pressure alone the plane of the exiting flycut

The entire Solar Turbines CFD results can be found in Appendix F.

From this analysis, PreFlow concluded that placing static pressure taps in the flycut would produce accurate results for the pressure in the flycut. With the ability to measure inside of the flycut, PreFlow was able to derive a better approach to finding the pressure loss coefficient of the problematic geometry.

Figure 26 shows the governing equations and setup of the apparatus. The total and static pressure as well as the temperature are measured before the test section. These values can be used to find the inlet velocity. Then, at the exit of the flycut, the temperature and static pressure are measured. Using the assumption that the air is an ideal gas, the density at each point can be calculated with the static pressure and temperature. Then, the law of conservation of mass can be used with the effective cross sectional areas to determine the velocity of air in the flycut. With these know values the pressure loss coefficient can be determined.



$$LC_{01} = \frac{\left(P_0 + {}^1/_2\rho_0 v_0^2\right) - \left(P_1 + {}^1/_2\rho_1 v_1^2\right)}{{}^1/_2\rho_0 v_0^2}$$

$$\rho_0 = \frac{P_0}{RT_0} \qquad \rho_1 = \frac{P_1}{RT_1}$$

$$\rho_0 v_0 A_0 = \rho_1 v_1 A_1$$

Figure 26. New Theoretical Setup to Measure the Pressure Loss Coefficient

This approach is better than before because the sudden expansion vent is no longer needed. By having all the measuring equipment before or inside the test block, PreFlow was able to change the sudden expansion piece into a small transition piece that would be less than 6 inches wide.

Test Section Dimensional Scaling

In addition to the alteration of the test section exit, it was also required to scale the model by a factor of two. This was done to meet the requirements outlined in ASME Boiler and Pressure Vessel code that would exempt the test apparatus from its scope.

The largest dimension of the full scale test section included a fly cut diameter of nearly 12 inches and thus is the driving factor for scaling the apparatus. This is an acceptable approach to avoiding the pressure vessel code because scaling is common to fluid systems. As discussed previously in this chapter, the Reynolds number is the dimensionless parameter that is the primary outlet of comparison between the PreFlow Systems model and the actual ports of the Solar Turbines gas compressor end caps. By matching the Reynolds numbers found from the operating conditions of the actual ports to the flow occurring in the PreFlow Systems test apparatus, one may obtain a direct correlation between the test results and the actual port losses.

By cutting the flycut lengths and measuring at a uniform distance from the drilled hole, the cross sectional width for all the flycut dimensions could technically be less than 6 inches. Unfortunately, to accomplish this, the flycut length would have to be cut very short which causes issues. If the flycut is too short, then the flow might not have enough distance to develop before the static pressure measurements are made. PreFlow Systems found that with the maximum and minimum flycut radii of the original scale, the distance between the drilled hole and the line where the static pressure taps would need to be placed is only 0.89 inches. With a drilled hole diameter of 1 inch, the flow has 0.39 inches to develop and drop in pressure. This distance is extremely small and if this was setup with such geometries, the static pressure taps would most likely not measure the pressure drop accurately. Figure 27 shows this geometry.

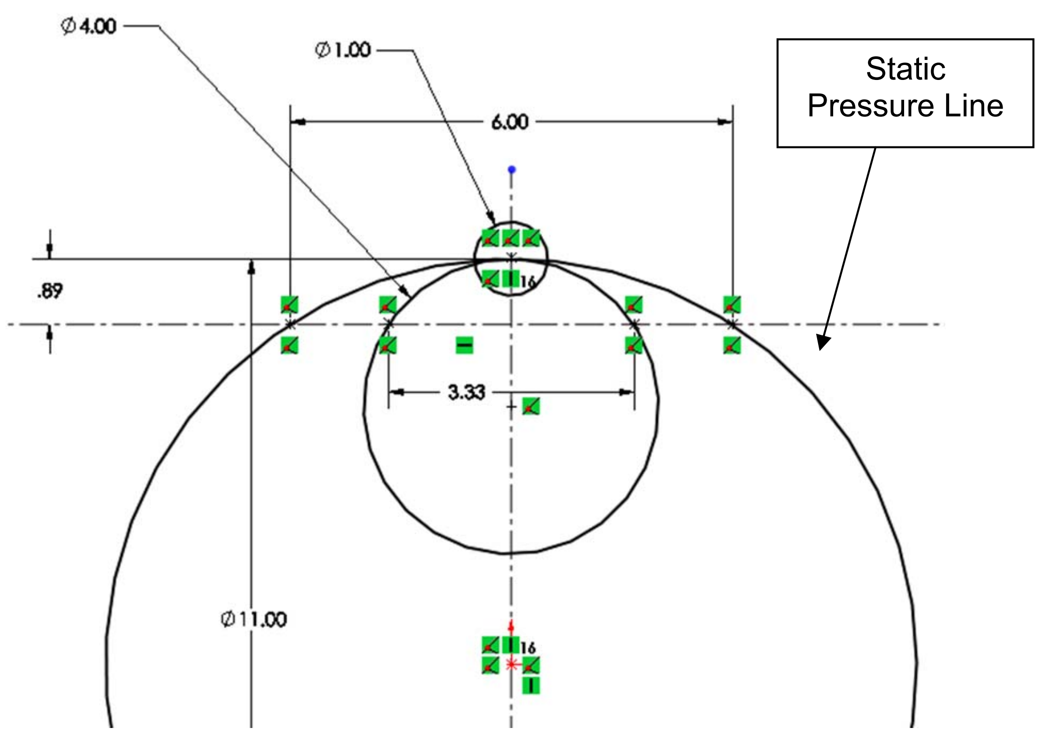


Figure 27. Original Flycut radius geometry

The same approach was setup with the half scaled dimensions and the resulting image is Figure 28. With the half scaled geometry, the distance for the flow to develop and drop pressure is 0.75 inches which is almost double the original setup distance. By half scaling the flycut radii, the accuracy of the measurements will increase.

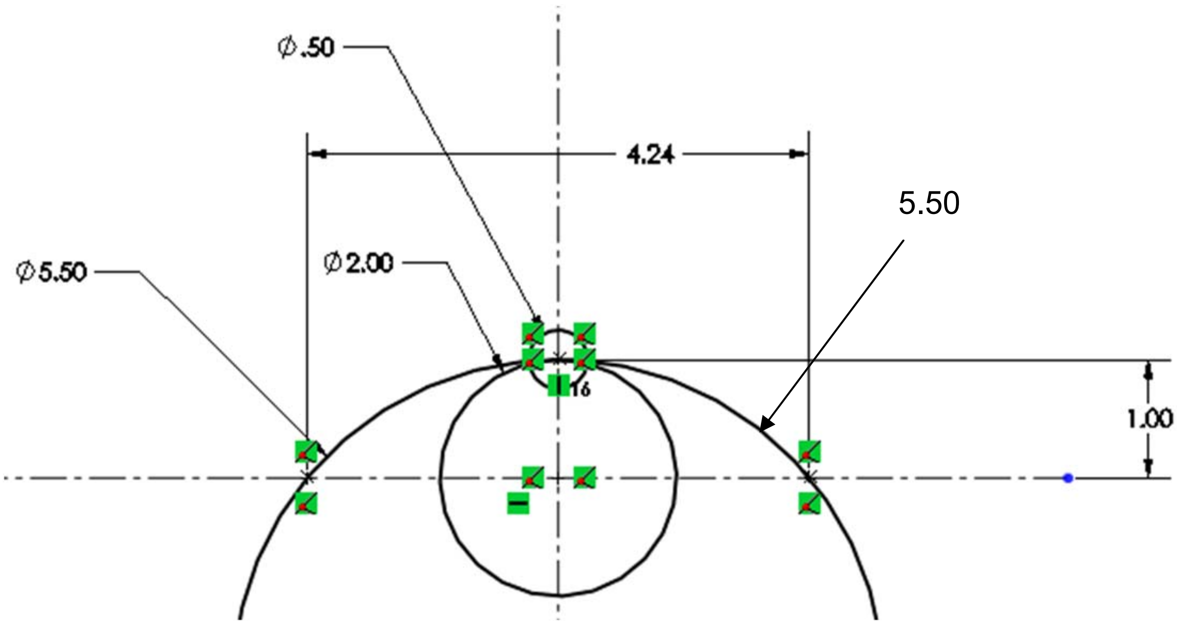


Figure 28. Half scaled Flycut radius geometry

The entire test section must be scaled by a factor of two to adequately model the full scale geometry. In addition to the scaling of the test section itself, dimensional scaling was required for the rest of the test apparatus for purposes of interchangeability. The piping upstream of the test section is now half an inch to accommodate the new scale. This then requires a slight change in the components originally selected for the test apparatus. Details of such changes are documented in the final section of this chapter.

Furthermore, in order to verify the validity of the direct correlation one would expect between scaled systems, the operating conditions of the actual compressor end caps ports must be analyzed. The methods to derive the values needed for the Reynolds number are discussed in the following section.

Port Flow Conditions

Analysis of the actual Solar Turbines gas compressor port flow conditions is crucial to fulfilling the primary project objective of flow simulation. By making simple manipulations to the port flow information provided by Solar Turbines, the operating conditions of the test apparatus may be predicted for proper simulation. Due to limited information being available to PreFlow Systems of the port flow conditions, only one type of the five major ports was included in this analysis. Appendix G includes the portion of information applicable to the Separation Seal (Buffer Air) ports that were in consideration for the analysis.

The first step in the analysis was to record the information from Appendix G in the appropriate fields of the port library. Of approximately 140 ports, only 20 corresponded to the information provided by the sponsor. Each piece of information from the boundary conditions document was important in determining the occurring within the ports. In particular, the fluid properties of temperature, pressure, and ideal gas constant were crucial in determining the gas' density and actual cubic feet per minute (ACFM) flow rate. Furthermore, the Reynolds number, the key value in correlating the test apparatus to the actual ports, requires information about the fluid properties.

$$Re = \frac{\rho V D}{\mu}$$

The velocity of the fluid can be determined from the simple relation that a volumetric flow rate (*Q*) is simply the magnitude of the flow velocity (*V*) normal to the cross-sectional area (*A*) of the flow path.

$$Q = VA$$

The simple flow rate relation becomes slightly more complicated when involved with turbo machinery because of the industry protocol to relate flow rates at different fluid conditions to a baseline operating condition. The principle behind this practice is the fact that density is highly dependent upon the fluid's temperature and pressure. In order to compare flow rates at different conditions, the convention of standard cubic feet per minute (SCFM) flow rate is used. In particular, this value is intended to easily comparing different operating conditions of a particular machine on a single performance map. When a max flow is given in SCFM it relates the working fluid to what the flow would be at standard temperature and pressure. ACFM is a volumetric flow rate at the operating conditions and is implied by the aforementioned relation for Q.

Thus, in order to estimate the fluid velocity, it is first necessary to convert the SCFM flow rates, provided by the boundary conditions document, to the ACFM. The standard conditions in this case were taken as atmospheric pressure, 14.7 psi absolute, and room temperature, 528 degrees Rankine (68 degrees Fahrenheit). For each compressor port, the actual conditions are specified individually as based upon the operating conditions.

$$SCFM = ACFM\left(\frac{P_{actual}}{P_{standard}}\right)\left(\frac{T_{standard}}{T_{actual}}\right)$$

The flow velocity can then be estimated from the ACFM (*Q*) relation by calculating the cross-sectional area of the drilled hole inlet for each port. Finally, once the dynamic viscosity (μ) and density (ρ) are determined by published values and the ideal gas law, respectively, the Reynolds number (*Re*) for each case can be determined.

These fundamental fluid property considerations are also very important when determining the operating conditions of the PreFlow Systems test apparatus for two primary reasons. In order to relate, by the Reynolds number, the working fluid of the compressors to the air in the test apparatus, their respective densities must be accounted for. Also, because the air velocity of test rig will be changed with alterations to the system's differential pressure (and to correct for ambient test temperature), it is necessary to account for the resulting density variations. Overall, density of the working fluid is key to determining values (Re, SCFM) that describe system performance, which, in terms of port flow, is the ultimate goal of this project.

Predicted Operating Conditions

In order to best fulfill the objectives of this project, PreFlow Systems would like to simulate the port flow actually occurring within the wide array of Solar Turbines' gas compressor end-caps. The key parameter which relates a fluid system model to an experimental prototype is the Reynolds number. Because the Reynolds numbers for the model were estimated with the values obtained in the sponsor boundary conditions document in Appendix G, it is now possible to predict the operating conditions of the test apparatus by equating the respective model and prototype dimensionless parameters.

With the known prototype fluid properties (density and dynamic viscosity) and the inlet geometry of the test section, the equation can be solved to yield the desired prototype operating velocity. As shown in the table of Appendix H, the ideal operating velocities of the prototype range from 7.81 to 45.52 feet per second. These values are as expected because they are approximately double that of the model flow velocities. This is due to the fact that the fluid properties do not change significantly in the half scale prototype.

The next step in determining the proper operating conditions of the test apparatus lies in feasibility studies of what is realistically achievable with the compressed air supply. Two primary methods were used to estimate the achievable flow velocities at various differential pressure settings. Although the accuracy of these predictions are uncertain, the resulting "ball park" information is still very valuable for validation of component selection and detailed test plan development.

Computational Fluid Mechanics Estimates

The first prediction method utilized the very basic computational fluid program (CFD), *FlowXPress,* in *SolidWorks 2010.* A solid model of the standard baseline geometry test section is what defined the flow path. As shown in Table 6, multiple iterations of specifying inlet and outlet pressure parameters were required to reveal the trends about the relationship between flow speed and pressure difference. The velocities recorded in Table 6 were taken at the estimated location of the fly cut static taps. The color scale on Figure 29 was the indicator of velocity magnitude. The CFD models of the other iterations can be found in the supporting analysis of Appendix I.

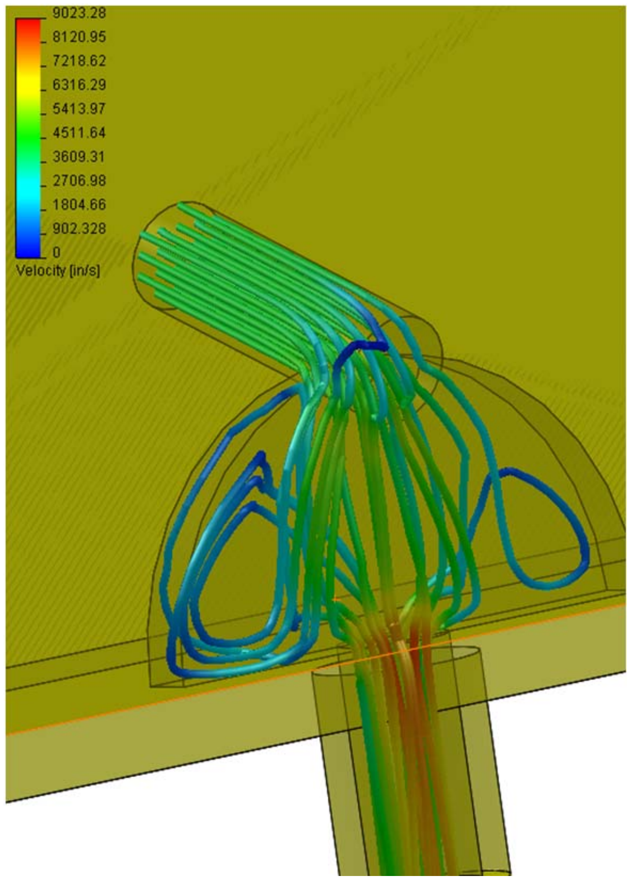


Figure 29. CFD Display of Port Analysis

The common trend discovered in this analysis was that lower flow velocities are achievable at small differences in high pressures. Although this relationship may seem counterintuitive, it follows suit with what should be expected, according to fluid mechanic fundamentals.

Table 6. Results obtained in computational modeling iterations

Set Parameters			Velocity at Static Taps		Additional Analysis			
Pin (psi)	Pout (psi)	Delta P	V (ft/s)	V (in/s)	ACFM	SCFM	Mach No.	Dynamic P (psi)
70	20	50	634.5233	7614.28	51.91182	247.1991	0.56312	3.2573
50	20	30	451.1667	5414	36.91099	125.5476	0.400396	1.6468
30	20	10	375.9167	4511	30.75461	62.76451	0.333614	1.1433
70	60	10	230.6667	2768	18.87137	89.86368	0.20471	0.4305
80	75	5	146.5	1758	11.9855	65.22723	0.130014	0.1736
90	89	1	68.66667	824	5.617779	34.39456	0.06094	0.0381

If one were to recall the energy balance required between two points on a stream line, that is, Bernoulli's equation, it would become clear that lower velocities would result from higher pressures. This is because the pressure and velocity at one particular point on the streamline are inversely proportional to account for the energy balance. Although Bernoulli's equation is not directly applicable to the port flow because of the sudden expansion, it still allows for a simple representation of the law of conservation of energy.

$$\frac{v^2}{2} + gz + \frac{P}{\rho} = constant$$

In conclusion of the first method, PreFlow Systems trusts that the CFD models provide a reasonable prediction for the operating conditions because they exhibit trends explained by fluid mechanic fundamentals. In addition to validating this trend, the computer models also provide additional information about the actual test apparatus operation. Unfortunately, the prediction reveals that the compressed air supply is not adequate enough to reach the velocities found in simulating the model and prototype Reynolds numbers.

Rough Calculation Estimate

To further validate the computational modeling results, a rough energy balance was conducted for various operating pressures. Again, by assuming that Bernoulli's equation applies to the test section flow path, one can obtain the velocity in for a specified inlet and outlet pressure. Under that advisement of Cal Poly fluid faculty expert, Dr. Russ Westphal, the loss coefficient (*K*) of the test section was estimated as 1.5. This is based upon the losses expected from a 90 degree bend and an expansion.

$$P_{in} - P_{out} = \frac{1}{2}\rho V^2 K$$

Supporting analysis and the table of pressure ranges results can be found in Appendix J. Only pressures between 40 and 80 psi were considered across a difference of only 10 psi. This is because it was desired to obtain the low range velocity values. Although the findings of this analysis method do not closely match those found in the CFD estimations, they still provide valuable insight to the expected operation of the test apparatus. Again, it is shown that the ideal operating conditions of the prototype will not be attainable.

Furthermore, the high fluid velocities highlight the importance of considering the Mach number. For purposes of density calculation and simulation, it is necessary to avoid transonic flow. That is, the ratio of fluid velocity to the speed of sound in the fluid must be below 0.7. As shown in Figure 30, the Mach number increases rapidly with greater differences between inlet and outlet pressures.

Curious to this particular method of analysis is that the Mach distribution does not change with increasing pressures. According to what would normally be expected, the higher inlet and outlet pressures would result in lower Mach numbers. The explanation for this lacking trend is merely because the rough calculation only accounts for the total pressure difference.

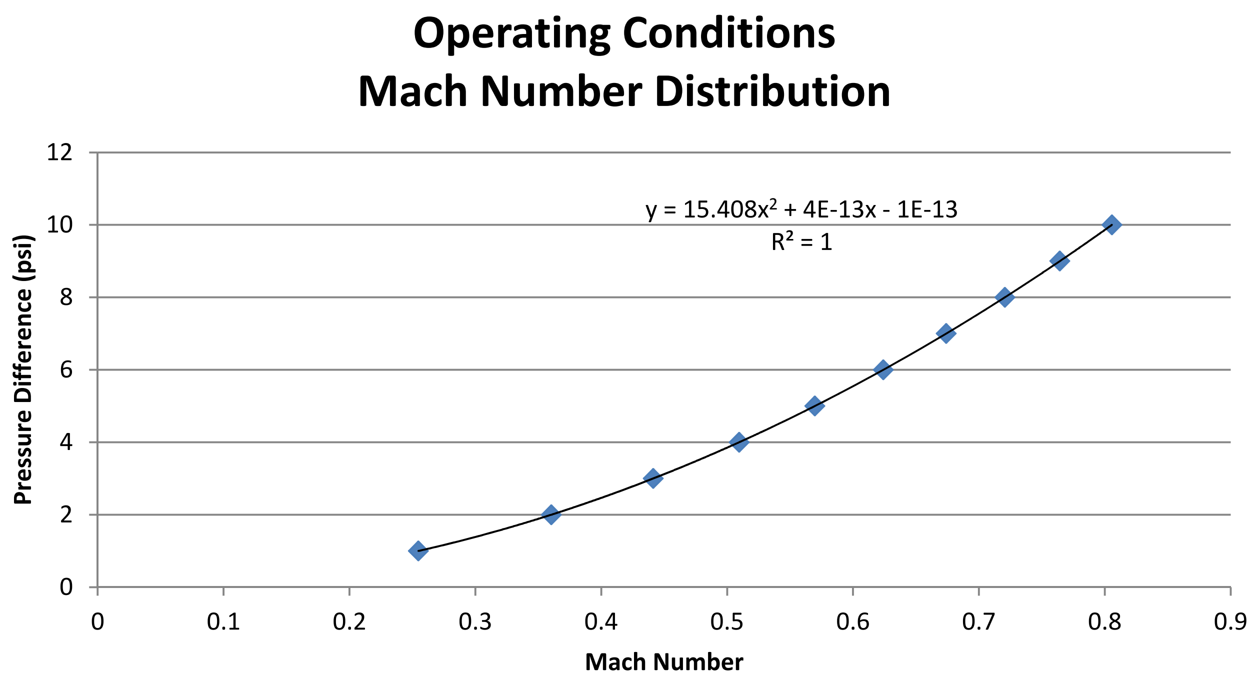


Figure 30. Mach number distribution for a 10 psi

Overall, the CFD and rough calculation predictions reveal that the test apparatus must operate at velocities higher than desired by the Reynolds number simulation. Despite this fault, due to incorrect design specification of supply pressures, the test apparatus is still expected to provide valuable information about the losses in the port flow. The ultimate advantage that the test apparatus will provide is, at minimum, a validation of Solar Turbines' more advanced CFD models.

Also, it should be noted that some positive attributes associated with operating at lower pressures include:

- Meeting the desired lower velocities range would result in operating at very high pressures
- Safety would be of even higher concern
- Budget would be exceeded due to the need for sturdier components
- Pressure loss accuracy would be sacrificed since the transducer reading are based upon dynamic pressure (lower at lower velocities)

Furthermore, this analysis, while rough, highlights the importance of monitoring the fluid's Mach number to avoid reaching transonic flow and provides a basis for ensuring correctly specified components.

Finalized Component Selection

While the fundamental test apparatus design has not changed significantly from the conceptual design, many of the components have since required alterations and/or further detail to justify its selection. Figures 31 and 32 below depict the primary changes made to the preliminary concept design. The red crosses, yellow squares, and green circles indicate which components have been eliminated, altered, or added to the design, respectively. The sections following will describe the analysis involved in determining the final major design components.

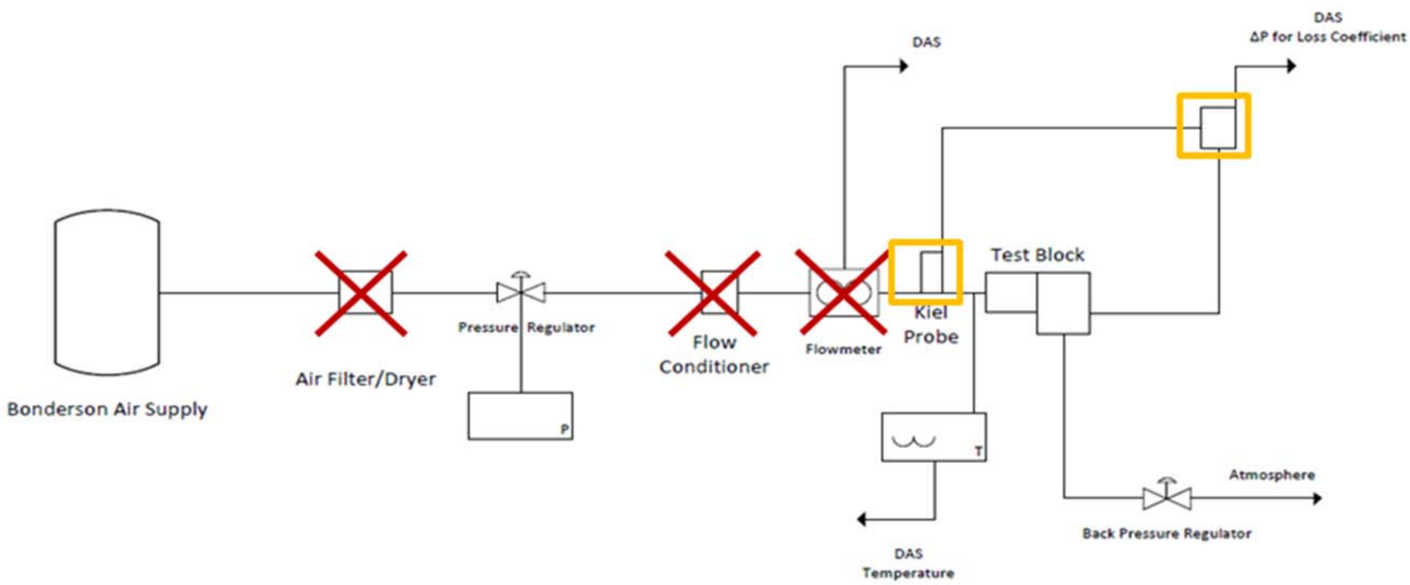


Figure 31. Preliminary Concept Design with changes indicated.

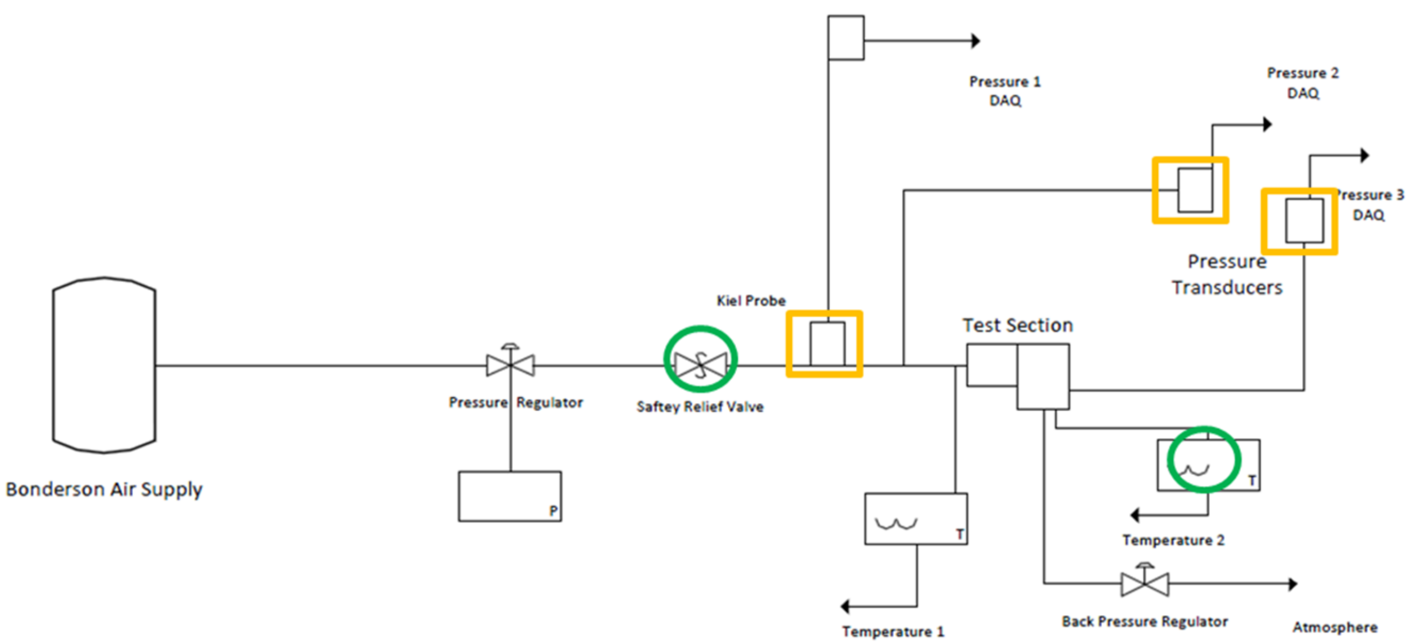


Figure 32. Final Concept Design diagram with changes indicated

Eliminated Components

Since the development of the preliminary design concept, many more discoveries were made about the operating conditions of the test apparatus. This is the primary factor concerning the elimination of the air dryer, flow conditioner, and flow meter.

Air Dryer

Upon prediction of the actual test apparatus operating conditions, it was discovered that the air dryer would not be suitable for the flow rates imposed on the system. The originally selected air dryer was only rated for 30 SCFM, whereas the predictions foresaw standard flow rates as high as 400 SCFM. Clearly, to ensure that hundreds of dollars would not be wasted on a ruined dryer, an alternative solution was absolutely necessary.

Due to the importance of controlling the fluid properties of the system in order to obtain accurate test results, other air dryers were considered. Unfortunately, this became a mute option because high flow rated air dryers are quite pricey (approximately $1000). Thus, the next alternative was merely to account for the air moisture that may exist in the compressed shop air supply. Thus, it can be then be shown that the density of humid air may be calculated as a mixture of ideal gases.

$$\rho_{humid\ air} = \frac{p_d}{R_d T} + \frac{p_v}{R_v T}$$

The terms of the density relation are as follows: partial pressure of dry air (p_d), specific gas constant for dry air (R_d), temperature (T), pressure of water vapor (p_v), and the specific gas constant for water vapor (R_v). The vapor pressure of dry air then reveals the key term of measurement required for this alternative. That is, vapor pressure is equal to the air relative humidity times the saturation vapor pressure.

$$p_v = \emptyset \cdot p_{sat}$$

It should also be noted that the partial pressure of dry air is equal to the difference between the systems' absolute pressure and the vapor pressure.

$$p_d = p - p_v$$

The alternative solution is thus to take a measurement of the system's relative humidity to account for the density of wet air. Relative humidity is measured by a hygrometer, such as the one of Figure 33.

Figure 33. Hygro-Thermometer measures relative humidity within +/- 5%

Flow Conditioner
The purpose of the flow conditioner was merely to straighten the flow for the mass flow meter. The mass flow meter vendor then indicated that a flow conditioner is not required if a minimum amount of straight length pipe is located upstream and downstream, 25 pipe diameters and 10 pipe diameters, respectively. Flexibility of the table dimensions allowed for this accommodation and thus the flow conditioner was eliminated.

Flow Meter
The primary reason behind the elimination of the mass flow meter was merely due to the scaling. The mass flow meter vendor was unable to provide a component that could be accommodated by a half inch pipe. In place of the mass flow meter is now the sponsor furnished kiel probe and static taps. The dynamic pressure can be calculated from total pressure and static pressure, measured at the kiel probe and static taps, respectively. Once the fluid density is found from known operating conditions, the fluid velocity can then be determined from the dynamic pressure relation.

The kiel probe alternative to the mass flow meter is adequate for a half-inch diameter pipe because the centerline velocity probably would not be far from the average reading obtained by a mass flow meter.

Component Additions & Alterations
Further details of the test apparatus operating conditions resulted in wiser component selections, as compared with the preliminary concept design. The new alternatives not only better suit the test apparatus in terms of structural fidelity and accuracy, but also achieve an overall more cost-effective solution.

Stainless Steel Schedule 40 Piping
One inch diameter steel pipe was first considered at the onset of the concept design. For sake of ease of assembly and cost, the sponsor then suggested using PVC piping.

Upon recognition of the ASME pressure vessel code, it was then realized that PVC is unsuitable for use in uncontained compressed gas systems. This is not only a suggestion by PVC piping manufacturers, but also specified by labor laws because of its high injury risk caused by brittle failure. For this reason as well, PreFlow systems would not be able to use rapid prototype parts because of the brittle plastic used in them. Finally, the design was then settled again upon threaded steel piping which would accommodate the new scaling at a half inch diameter.

The pre-threaded stainless steel schedule 40 piping, will be used to connect all of the major components by means of NPT threading. Ease of connectivity is accounted for with all of the major components utilizing NPT threads.

Safety Relief Valve
Also in consideration of the high operating pressures, a pressure relief valve, shown in Figure 34, was added to the system. This was for the primary purpose of protecting the expensive components that have a limited pressure rating. Because the Bonderson air supply could potentially supply up to 120 psi of compressed air but the pressure transducers can only withstand up to 100 psi, it is absolutely crucial to include the pressure relief valve. This component specifically protects the pressure sensitive components because it can be set to purge the system when it reaches a specified maximum pressure. The safety relief valve comes calibrated from the factory but can be set and calibrated to other relief pressures. PreFlow System plans to set the valve at around 80 psi.

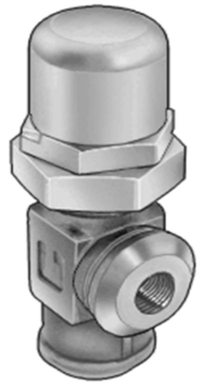


Figure 34. Pressure relief valve

Inlet and Back Pressure Regulators

The pressure regulator will be used to set the inlet pressure before entering the test block. In order to accommodate the high standard flow rates predicted for the test apparatus, a sturdier version has replaced the original regulator of the preliminary concept design.

The back pressure regulator will be used to alter the back pressure and change the pressure differential to drives the fluid velocity within our system. The backpressure regulator is adjusted with a phenolic adjustment knob. Figure 35 shows the regulators that will be used in the apparatus.

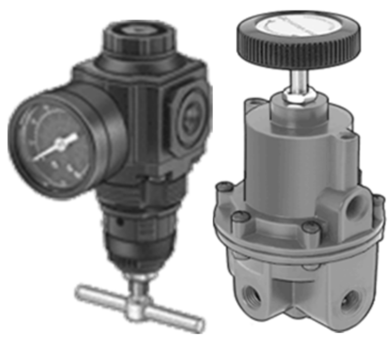


Figure 35. Pressure Regulators

Kiel Probe

As mentioned previously, the main purpose of the kiel probe is to take total pressure readings before the test section. The total pressure of the kiel probe and the static pressure of the taps will then be used to calculate the dynamic pressure before the test section. As shown in the equation below, the fluid velocity can then be calculated from the dynamic pressure term.

$$P_{total} = \frac{1}{2}\rho v^2 + P_{static}$$

Pressure Transducers

In place of the differential transducers selected for the preliminary concept design, three pressure transducers (shown in Figure 36) will be used to accommodate the kiel probe, and the two static pressure readings taken at the beginning and exit of the test section. These pressure readings are crucial measurements for determining flow velocity and pressure losses in the system.

Pressure transducers function by sensing pressure and then converting the signal into an electrical signal that can be recorded. The output signal from the pressure transducers can vary from mill volts and volts to milliamps depending on the application. The operating specifications for the PreFlow Systems pressure transducers are presented in Table 8 of this section.

Figure 36. Pressure Transducer

Data Acquisition System

The DATAQ Instruments Data Acquisition System (DAS) can receive multiple types of input signals. In order to function properly, the pressure transducers and data acquisition system must operate on the same signal type. The resolution of the DAS shown in Figure 37 is based upon the instrument with the most accurate measurement capability. In the case of the PreFlow Systems test apparatus, that instrument is the pressure transducer.

The resolution of the pressure transducer must be converted to bits so the appropriate DAS can be specified. A simple relation of the DAS parameters to the desired reading accuracy of the instrument is provided by DATAQ to determine the proper bit rating. Refer to Appendix K for this calculation.

Furthermore, upon completion of a test run, the DAS can then export the data set to Excel. This is an important capability of the DAS to allow for simple analysis of the experimental data.

Figure 37. Data Acquisition System

Power Supply

The power supply for this system, which is shown in Figure 38, must be able to power all three pressure transducers. By connecting the pressure transducers in parallel, the voltage rating of each pressure transducer is met. The sum of the individual transducer amperage ratings must be compared to the maximum output amperage of the power supply.

Figure 38. Power Supply

The wiring diagram of Figure 39 shows the pressure transducers connected in parallel with the power supply.

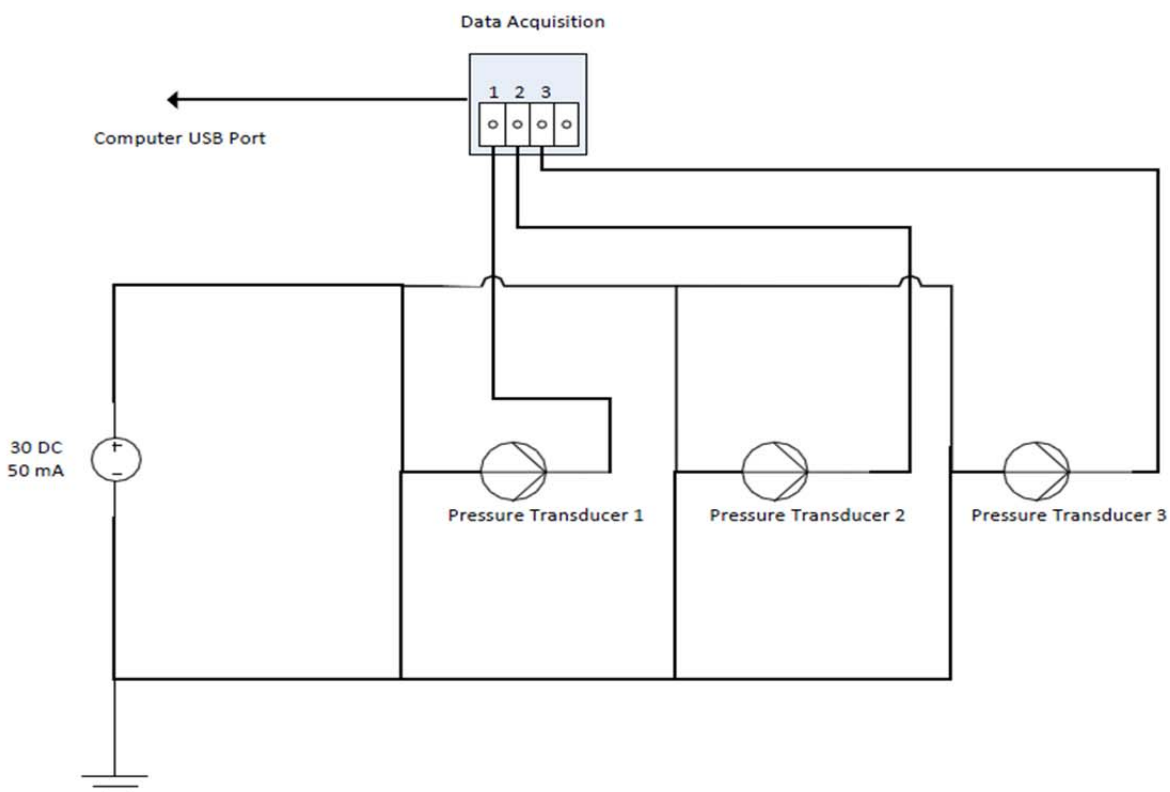


Figure 39. Pressure Transducer Schematic

Each pressure transducer requires 30 Volts DC and at least 10 mA for a total of current rating of 30 mA. This minimum requirement can be adequately provided by the power supply. Each pressure transducer will be connected to the data acquisition system in the corresponding inputs of 1, 2, and 3.

Major Component Specifications

The specifications of each major component must encompass the operating conditions of the test apparatus. Such considerations are essential to the operation and proper function of the design. As discussed previously in the *Operating Conditions* section, the actual test apparatus operates at higher flow velocities than that predicted by the Solar Turbines models in order to provide recordable pressure drops. Table 7 and 8 list the specifications of the selected major components to prove their appropriate application. The main operating conditions are a max operating pressure of 80 psi (as limited by the pressure relief valve) and approximately 400 SCFM, to which all of our components are able to withstand. The pipe connection fittings are listed to demonstrate connectivity within the major components.

Table 7. Major Components Specifications

	Max Pressure (psi)	Max SCFM	Range (psi)	Connectivity
Safety Relief Valve	125	N/A	40-125	1/2 NPT Female
Stainless Steel Schedule 40 Pipe	3467*	N/A	N/A	1/2 NPT Female
Inlet Pressure Regulator	300	N/A	40-80	1/2 NPT Female
Back Pressure Regulator	250	N/A	0-150	1/2 NPT Female

* This value was not proved by the vendor and instead was calculated by PreFlow Systems. The appropriate analysis is presented in Chapter 4.

Table 8. Specifications of Instrumentation Components

	Accuracy	Range	Resolution	Output	Input Power
Pressure Transducer	+/-0.05%psi	0-100 psi	-	0-10 Vdc	15 to 30 Vdc @ 10 mA
Data Acquisition System	13 Bit	+/-10Vdc	.03	-	USB powered
Power Supply	±0.5%Vdc	0-30Vdc	-	±15 or 30 Vdc 50 mA	115 Vac @ 60 Hz

The practical application and assembly of these major components is detailed in the following chapter, *Final Design*.

Chapter 4: Final Design

The finalized test apparatus that PreFlow Systems has designed to fulfill the needs of Solar Turbines is presented in the schematic shown in Figure 40. As noted before, changing the design to this finalized setup has simplified the design as well as decreased the overall cost.

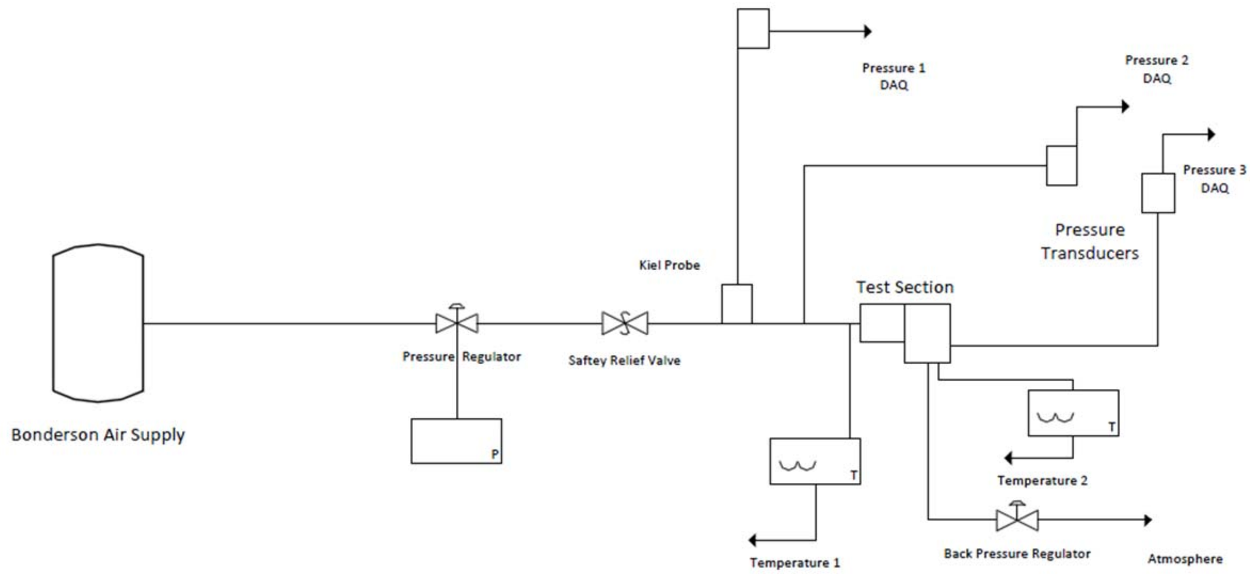


Figure 40. Finalized Diagram of Test Apparatus

The finalized test apparatus' key measurements that will be recorded are air flow rates, temperature, total pressure inlet side, static pressure inlet and static pressure outlet of the test section. These parameters will be manipulated to acquire multiple pressure loss coefficients and Reynolds numbers.

The air for the test apparatus will still be supplied by Bonderson's Engineering Projects Center's shop air located on the Cal Poly campus. To minimize losses in our system and flow changes the entire test apparatus will be connected with ½ inch NPT threaded stainless steel schedule 40 pipe with all major components accepting ½ inch NPT pipe. The connection from the incoming air supply is a standard tool ¼ inch quick disconnect coupler. This coupler will connect to the first major component the pressure regulator. This regulator will control test section inlet pressure while the back pressure regulator will control the systems flow rates. From the regulator, piping will lead to the safety relief valve. The safety relief valve protects the major system components which include pressure transducers that are easily damaged if you exceed the transducers operating pressures. After the safety relief valve, 18 inches of piping will lead to the kiel probe which will be used for determining the inlet velocity. On the next 9 inches of pipe, four static taps and a thermocouple will be placed before the test section inlet to measure pressure and temperature to determine inlet air properties. Refer to Figure 41 for a visual of the actual designed test apparatus.

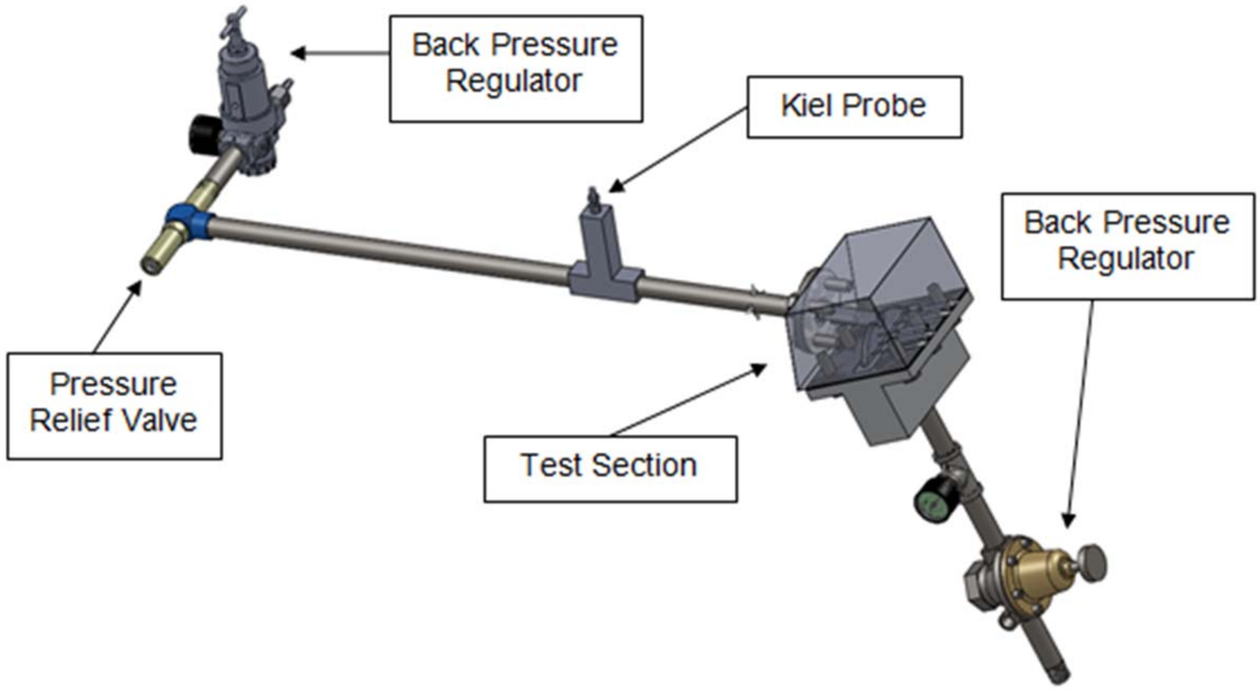


Figure 41. Final Design Model of Test Apparatus

At the exit of the test block, there will be either two or four static taps as well as a thermocouple to measure the pressure and temperature inside the flycut. The number of ports depends on the test section configuration. Figure 42 shows the components that make up the test section.

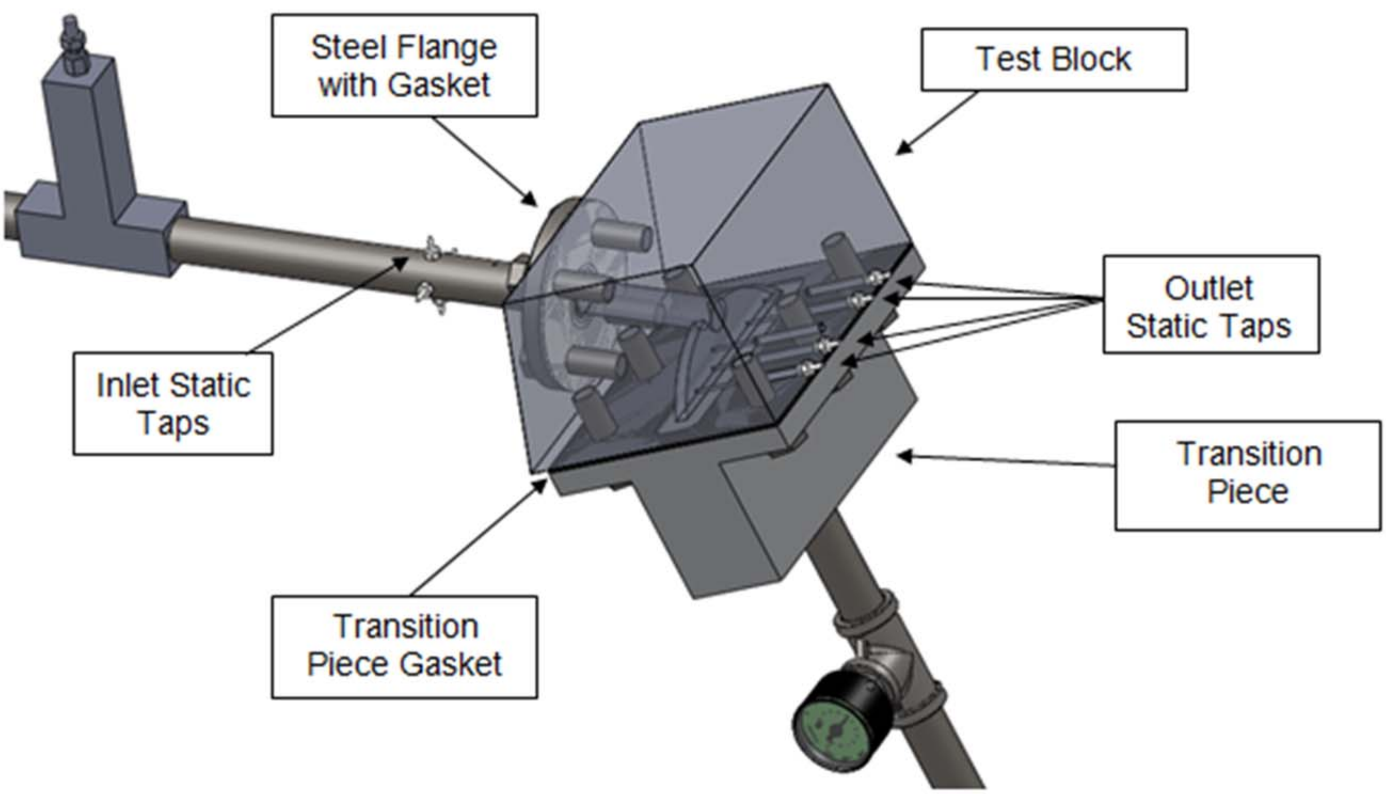


Figure 42. A Close up View of the Test Section and Other Components

After the flow exits the test block, it travels through the transition piece and into more piping. This piping leads to the back pressure regulator and gage.

To accommodate for a variety of test blocks, the test blocks were designed to connect to the rest of the apparatus with bolts. This allows the test block to be switched out or removed completely with ease. A standard inlet steel flange was selected with a gasket to connect the 9 inch stainless steel pipe to the test block. On the other end, a transition piece with rubber gasket was designed to connect the test block to the back pressure regulator.

In the test block, holes for bolts, static taps and the thermocouple port were designed for maximum clearance between each other. The bolt and static tap holes will be tapped with threads to insure good connections for the bolts and static taps. The thermocouple hole will be drilled to allow the wire to reach inside the flycut. In assembly, the thermocouple wire will be sealed within this port. Figure 43 shows the various holes in the largest flycut radius block.

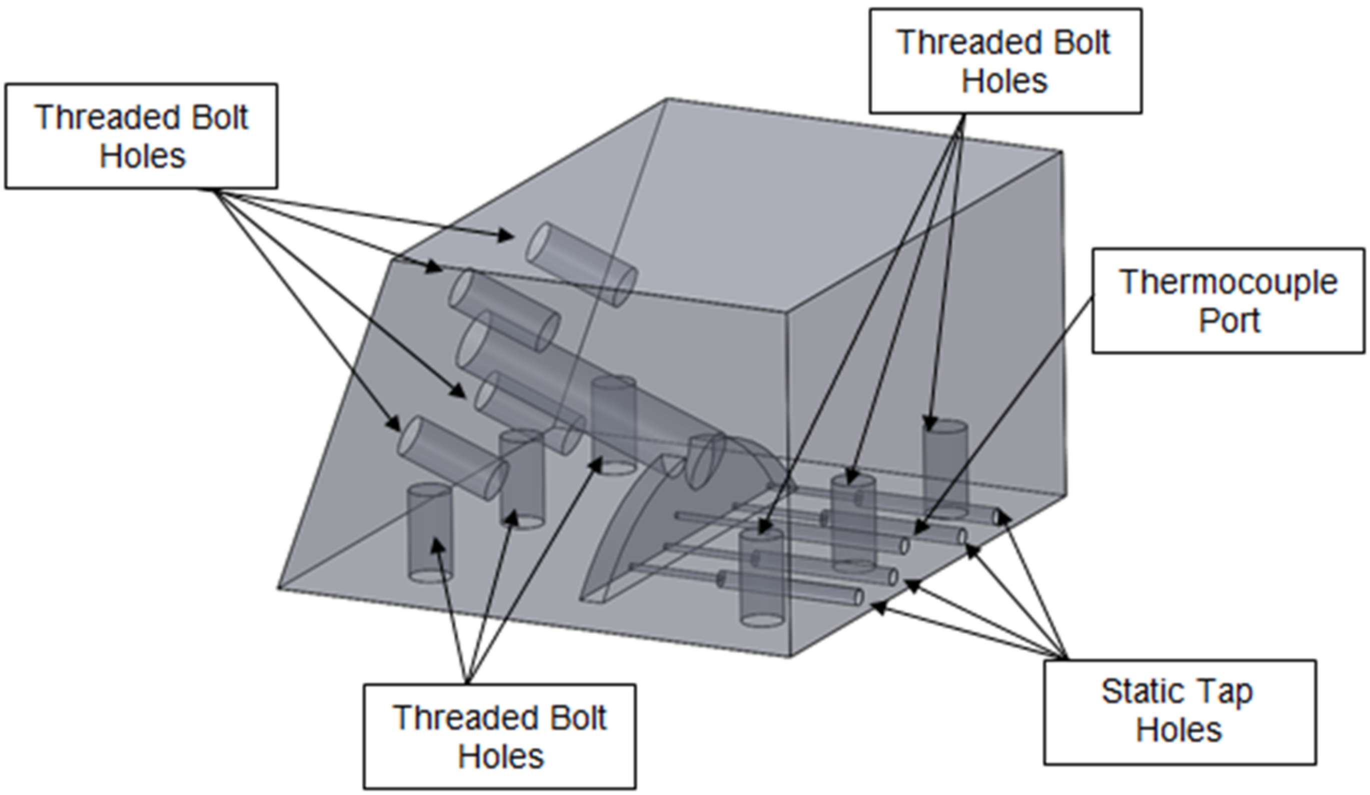


Figure 43. The Variety of Holes in the Test Block

The kiel probe and static taps will be connected with plastic tubing to 3 pressure transducers. Pipe tees will be used to average the static pressures into one pressure for the transducer to measure. A data acquisition system will be used to collect pressures. Digital thermometers with thermocouples will be used to record temperatures which will be recorded by hand. The variation of temperature will be negligible which makes using a more expensive data acquisition system to record temperatures not required. All of this equipment and the apparatus will be mounted on a rolling table. Figure 44 shows the mounting setup.

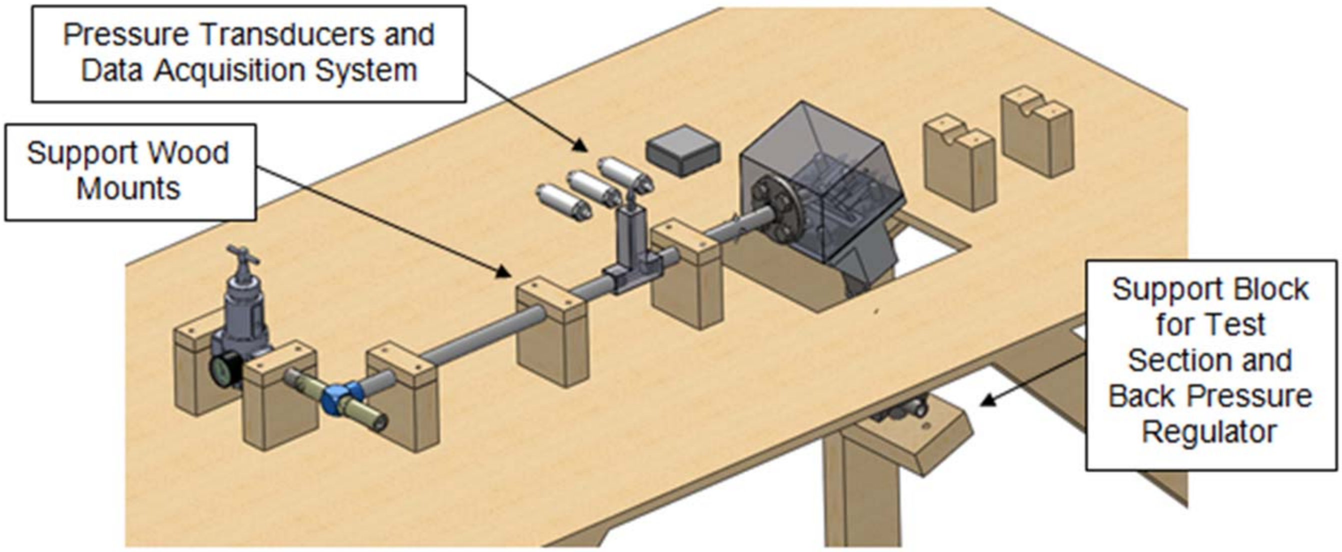


Figure 44. Test Apparatus and Equipment Mounted to the Table

Support wood mounts will keep the apparatus fixed to the table while other equipment is attached to the apparatus. A support block around the back pressure regulator supports the weight of the test section and regulator by using tensioned rope that connects itself to the supported table top. The rope is tensioned by pulling it up through the 10 inch rectangular hole and clamping it to the surface with c-clamps. This design allows for varying angles of the test block because the rope is a flexible and movable structural support.

The Bill of Materials in Appendix P shows all of the components and materials needed to build this design. To support the Bill of Materials, Appendix Q has all of the vendor specifics and information on the components and materials. In Appendix W, all of the part and assembly drawings are provided for reference. Many of the components and materials will be discussed using the part numbers in Appendix P and W to limit confusion.

Structural Analysis of Design

Being a pressurized system, structural analysis needed to be performed on the test apparatus to prove its safety. If total failure were to occur on the back pressure regulator and pressure relief valve, then the apparatus could experience a maximum pressure of 120 psi. This was used as PreFlow's design pressure for selecting piping, connectors, and designing components.

To begin the structural design, every pipe and connector was designed for the 120 psi max pressure. Table 9 shows the max pressures possess for each component. The max pressure ratings can be found for each component in the vender sheets in Appendix Q.

Table 9. Max Pressure Ratings for Piping and Connectors

Part	PART NUMBER	Max Pressure Rating
Quick Disconnect Coupler	719874	4000 psi
NPT Bushing	4464K265	150 psi
4 in pipe	4830K176	3467 psi*
18 in pipe	4457K114	3467 psi*
9 in pipe	4830K216	3467 psi*
NPT Bushing	5232T377	6400 psi
Pipe Bushing	4464K264	150 psi
Pipe Tee	4464K51	150 psi
Static Tap	5121K311	125 psi
Static Tee	2844K41	150 psi
Adapter for Transducer	5058K412	125 psi
Plastic Tubing	5006K51	120 psi
Flange	68095K226	150 psi
Gasket Material	8525T11	800 psi
Flange Gasket	9472K56	1000 psi

*These values were not proved by the vendor and instead were calculated by PreFlow Systems

The maximum pressure for the stainless steel piping was determined in the analysis in Appendix L. After analyzing the piping and connections, the test section block, the transition piece, the verification piece and the connecting bolts were designed to meet structural requirements.

In order to design the test section block and transition piece, PreFlow Systems had to start by analyzing the bolts needed with rough sizing constants. The steel flange (68095K226) was designed to fit ½ inch bolts and the vendor recommended using 1/2 by 2 inch bolts. With weight and cost differences between size bolts not being much of a concern, PreFlow decided on using the max diameter of ½ inch. With an approximate sizing, the transition piece and test block was designed for clearance between the bolts for socket wrench tightening. Bolts with a length of 2 inches seemed excessive, so the bolts and bolt pattern were analyzed in Appendix M. SAE Grade 2 bolts with proof strength of 55 ksi were used for the analysis. The length of the bolt selected was 1.5 inches. The results of this analysis are shown in Table 10.

Table 10. Bolt Analysis Summary of Inlet Flange and Outlet Transition Piece

	Inlet Steel Flange	Outlet Transition Piece
Number of bolts	4	6
Torque Required for Preload	48.78lb-ft	
Load Factor	17.92	10.52
Factor of Safety from Separation	142.32	402.99
Resulting Load on Member/Flange	5812.25lb	5838.85lb

With load factors and separation factors for both bolt patterns above one, the connections of the apparatus will be safe for a pressure of 120 psi.

For the transition piece, verification piece and test section blocks, a finite element analysis was performed to validate their safety with loading of 120 psi from internal pressure and 5,800 lbs from the resulting bolt preload. This analysis can be found in Appendix N. A summary of the analysis is provided in Table 11.

Table 11. FEA Summary of Verification piece, Test Section, and Transition Piece

	Configuration	Safety Factor
Verification Piece	1	26.55
Test Section	1	11.63
Transition Piece	1	2.27
	2	1.43
	3	13.94

With all the safety factors above a desired safety factor of 1.3, the machined components should not fail during operation. These calculations were also conservative because PreFlow Systems will most likely not apply the full preload into the bolts. This is allowable because the bolt analysis safety factors were very high and reducing the preload will still result in a safe connection with less resulting member forces into the test section and transition piece.

For the table setup, the rope (183072) used to hold up the test section block and back pressure regulator can carry up to 240 lbs. These load ratings higher than the weight of these components (22.22lb).

Manufacturing & Assembly

All custom components of the test apparatus were created using design drawings and the manufacturing process noted here within. Appendix W includes the drawings on custom manufactured parts and Appendix P includes the Bill of Materials.

Apparatus Mounting Table

The test apparatus is mounted on a table constructed from a half inch sheet of pressed wood and 2x4 posts. Following proper cutting of the sheet and posts with a table saw, wood screws were used to construct table. The posts were used as the table legs, cross supports, and apparatus mounts. Wheels (433004) were also attached to the bottom of the table legs for easy movement of the apparatus. For presentation, the table was primed and painted black.

Figure 45. Apparatus table mount painted black

Verification Piece & Transition Piece

The verification piece was machined from a one inch diameter aluminum rod (88615K441). By mounting it on a lathe, PreFlow Systems machined the inside flow path and the drilled holes for the static taps. These holes required thread tapping so as to screw the taps in. The pipe tap (VER20354) was used to create a ½ in NPT thread on either end of the verification piece. This threading was required to attach the piece to the rest of the apparatus schedule 40 piping.

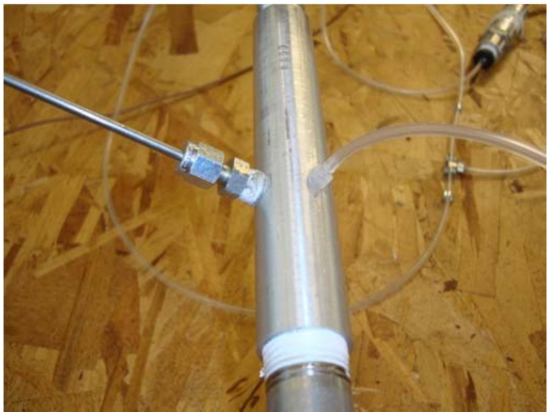


Figure 46. Verification Piece with Thermocouple and Static Tap

For the four static taps in the inlet pipe, holes were drilled into the 9 in schedule 40 pipe (4830K216) and tapped for threading the static taps. The transition piece was first cut manually from one of the ten aluminum blocks (89155K985) using a horizontal hack saw. The sides were then faced to create the proper part dimensions for CNC machining the inside pocket. After the pocket was CNC machined with the help of Cal Poly shop techs, a mill was used to pilot the through holes. The one inch through hole at the end of the pocket was then thread tapped for connection with the schedule 40 piping.

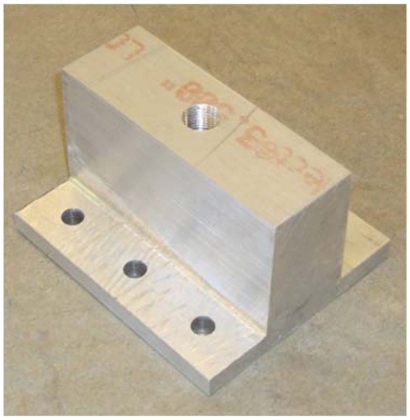


Figure 47. Transition Piece

Test Blocks Machining

In consideration of limited shop hours and the proactive schedule, only three of the original nine blocks were machined. Due to the complicated nature of the test block machining, a *FirstCut* CNC machining quote was estimated at over $800 per test block. Thus, the option of hiring outside help was not plausible due to the project budget.

For the three test sections that PreFlow Systems completed, they began as 6”x6”x3.5” aluminum blocks (89155K985). These blocks were then cut approximately in half using an automatic hacksaw at the face of the fly cut. Then, each block was CNC machined with the help of Eric Pulse, the Cal Poly Mustang ’60 machine shop. First, each block was faced on the hacksaw cut sides. Next, dowel pin holes were drilled on each block half. The minimum, baseline, and maximum fly cuts were then CNC machined on one side of their respective block.

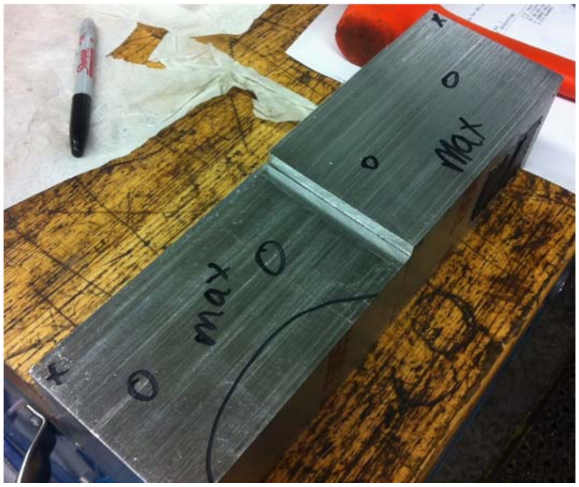


Figure 48. Test Block in two pieces before CNC machining

Figure 49. Baseline fly cut and dowel pin holes CNC machined onto one smooth side

Following the CNC machining of the test blocks, PreFlow Systems then drilled the static pressure taps and temperature taps. The taps were small holes at the fly cut face but stepped up to larger diameters at the outer face to accommodate the compression fitting and plastic tap threads. Once these holes were piloted, they then required careful thread tapping.

Following the drilled holes required to measure pressure and temperature within the fly cut, the blocks were then reassembled using JB Weld Epoxy (7605A12). To ensure a strong bond, the adhesion process required surface preparation. First, the smooth surfaces with the blind dowel pin holes were carefully sanded using a rough grit sand paper. Next, using acetone solvent, the surfaces were wiped clean. The epoxy was then mixed to create an active thick paste adhesive. This paste was then applied to the roughened surfaces with precision to ensure that the glue did not interfere with the fly cut. The dowel pins were then placed in the blind holes of the corresponding face and the two test block pieces carefully aligned. The assembled test sections were then placed under the weight of the unused aluminum blocks and left to cure overnight. The following day, a chisel was used to carefully pick out any cured adhesive that had purged from the seam into the fly cut.

The final steps required for the test block manufacturing included many additional hours of machining. Each test block was milled with consideration of precision and accuracy. The chamfered inlet side of the blocks were cut using a vertical band saw then faced with the mill. The facing of these sides as well as drilling the inlet holes and blind threaded bolt holes required use of a vice angled at twenty degrees. Six blind holes were also milled on a flat vice at the exit of the fly cut. These as well as the inlet blind holes required careful thread tapping.

Figure 50. Thread tapping was completed with care using a tap guide

Figure 51. The transition piece and three test blocks required over 200 hours of manual machine time

Data Acquisition System

Ensuring a properly functioning data acquisition system is crucial for the accurate analysis of the test block loss coefficients. Before connecting the whole system together, each connected component, which made up the data acquisition system, was tested individually. This was to ensure properly working components.

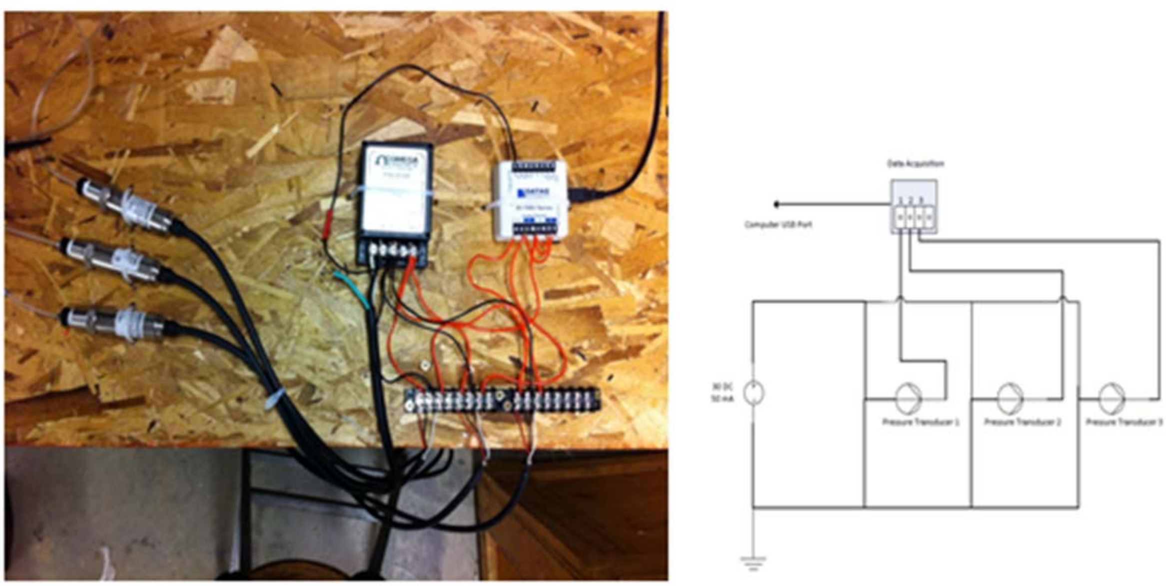


Figure 52. Data Acquisition System and Wiring Schematic

The power supply was checked with a multi-meter to measure proper voltage configuration and amperage output. The DATAQ was tested with a power supply of known output voltage to calibrate and test our data acquisition system. The pressure transducers were connected with known pressures and verified to be outputting the proper voltage and compared to the calibration specifications provided by the manufacturer.

After verifying proper component functions the data acquisition system was connected and tested to ensure the entire system was properly working. The final wiring and connections are shown in the figure below with all the main components that make up our system.

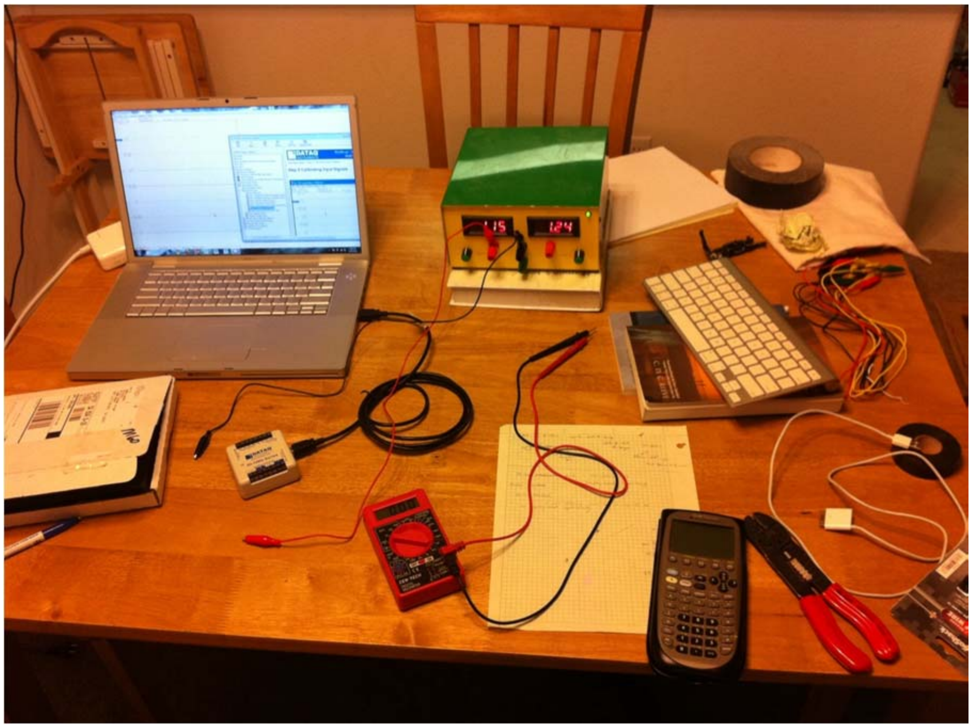


Figure 53. Data Acquisition System Testing

Apparatus Assembly

Each piping section was connected using a pipe wrench. To prevent leakage, every thread was first wrapped with Teflon tape. For the piping connections that were not to be altered, silicon seal was used to further prevent air leakage along the apparatus flow path

The test apparatus required two configurations of assembly. The first configuration for calibration of the apparatus included the verification piece connected to the piping between the thermocouple/static tap mount and the back pressure regulator. The test block apparatus set up required that the verification piece then be removed and replaced with the appropriate test block. A precut gasket at the inlet was attached between the inlet flange and the inlet of the respective test block. At the exit of the fly cut, a custom rubber gasket (8525T11) was cut to size with a razor blade and placed between the test block exit and the transition piece. Both at the inlet and exit, a number of washers were used to ensure a tight seal. The exit of the transition piece had the steel piping screwed to its end so as to connect the back pressure regulator to the flow system. For each assembly, soap was used to check for leaks before conducting any tests.

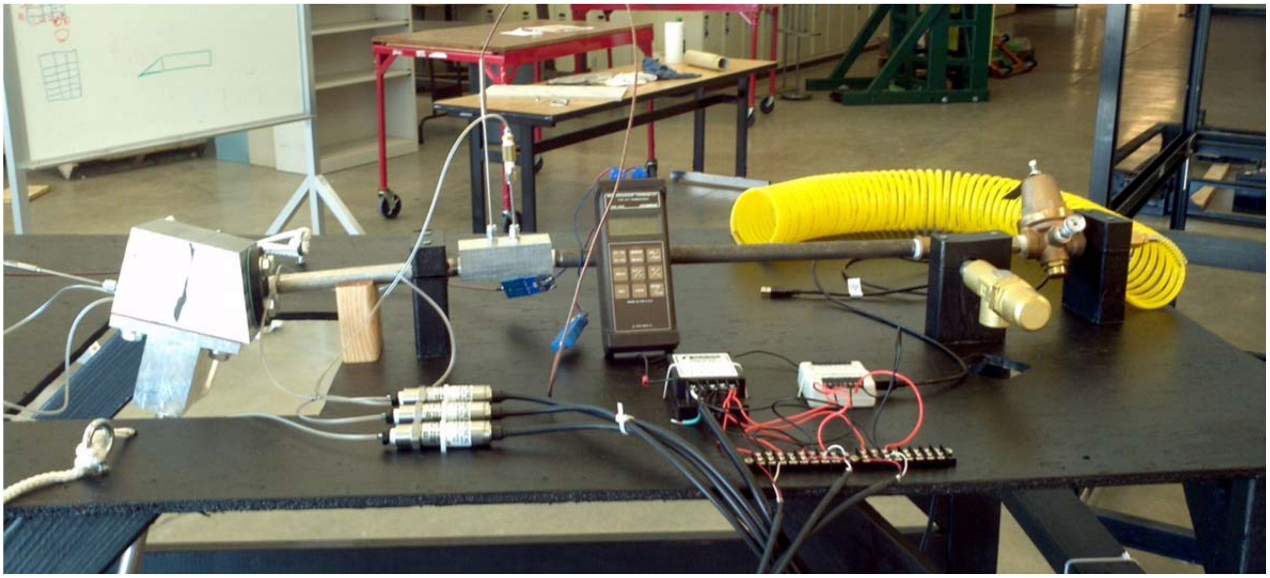


Figure 54. Completed Test Apparatus

Figure 55. Soap was used at the gasket seams and pipe connections to test for leaks

Cost Analysis

The final cost of the finalized design is located in Table 12 which is divided into three categories. A complete cost breakdown of all of the individual parts and components can be found in Appendix P. The total cost is higher than the estimated cost in the conceptual design report. Applying all the details and additional hardware have added to the overall cost. The pressure transducers are the most expensive parts in the major components which are detailed in bill of materials. Originally, a mass flow meter was to be implemented in the conceptual design. After further analysis of the conceptual design's 1 inch pipe, some of the test sections dimensions to be built would fall under the category of a pressure vessel and would require either a special welder or part certification which could have caused major delays. Switching to the ½ inch pipe caused some design problems as the flow meter could not function in a ½ inch pipe according to the vendor. A design decision was made to remove the flow meter and install a kiel probe and pressure transducer which also cut some of the cost. Charges for shipping and handling have not been applied but are estimated to be about 10% of the total cost of the bill of materials.

Table 12. Final Cost of the Test Apparatus

Major Sections	Cost
Major Components	$2961.08
Pipes and Connections	$218.35
Machined Parts	$1079.52
Total	$4258.95

Chapter 5: Design Verification Plan

Accuracy of the measurements obtained in the port flow testing is the ultimate project goal. Before PreFlow Systems is able to make this guarantee, the instrumentation must be independently validated by means of calibration. First, the pressure transducers, which are the instruments of highest accuracy concern, must be checked against a known pressure. The thermocouples and hygrometer must also be compared to a confidently known source. Finally, to verify the operation of the apparatus as a whole, a test verification piece of standard geometry will be used. The experimental results obtained from the test verification run will allow for values to be compared to theoretical results.

Instrument Calibration

Most instruments are supplied with a calibration certificate from the manufacturer. PreFlow Systems is committed to obtaining quality experimentation data and thus will check specified operation of the pressure transducers, thermocouples, and hygrometer.

Pressure Transducers

The pressure transducers will be validated against a calibration device provided by Cal Poly fluids lab. The device includes a small pump that provides known pressures to the transducer. By relating the pressure supplied to the transducer to the voltage output, the calibration constant may be determined. Ideally, the calibration constant determined by PreFlow Systems will match that specified by the vendor’s certificate. Support and lab access will be provided by California Polytechnic University (Cal Poly) faculty, Dr. Kim Shollenberger, or Dr. Russ Westphal.

Thermocouples

The thermocouples will be calibrated by means of a procedure adopted from the thermal measurements laboratory at California Polytechnic University. The baseline temperature values will be obtained with boiling and ice water. Again, the calibration constant will be determined from the relationship between output voltage and temperature input. Cal Poly faculty, Dr. Glenn Thorncroft, will provide support and lab access.

Hygrometer

Although hygrometers are also calibrated by the manufacturer, they are especially sensitive to shock and calibration of this instrument is recommended as well. In addition to its standard sensitivity, the calibration will also check how the meter reacts to high pressure and flow velocities. Upon receiving the meter, PreFlow Systems will conduct an initial calibration. Another calibration will then be conducted after subjecting the unit to high pressure “blast” from compressor hose to observe how it tolerates high air pressures and velocity. A widely accepted method of calibrating hygrometers is included in Appendix S.

Test Verification Piece

A verification test will be conducted prior to collecting pressure data about the complicated test sections. This is meant to further validate the accuracy of the pressure transducers, as well as to confirm the general proper operation of the test apparatus as a whole. The primary method behind this verification test is to match a measured pressure drop with a theoretically calculated prediction. Because trusted information about pressure losses in simple geometries is already published, PreFlow Systems is able to make a confident estimation of what should be expected from the readings obtained in the verification test.

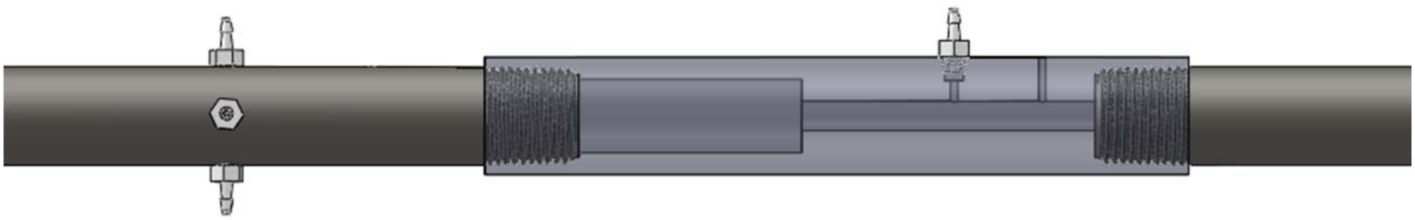


Figure 56.Test Verification Piece

As shown in Figures 45 and 46, a section of known dimensions will be fitted temporarily to the test apparatus. The pressure transducers will be attached to the static taps which are located upstream of the section and in the test section. Once the pressure regulators are set appropriately, the compressed air supply will then be actuated and the system will be checked for leaks.

Leakage detection is crucial to obtaining precise test data for any type of test run in the apparatus. This consideration will be made before each test fun by observing how soap reacts when applied to connection and fittings.

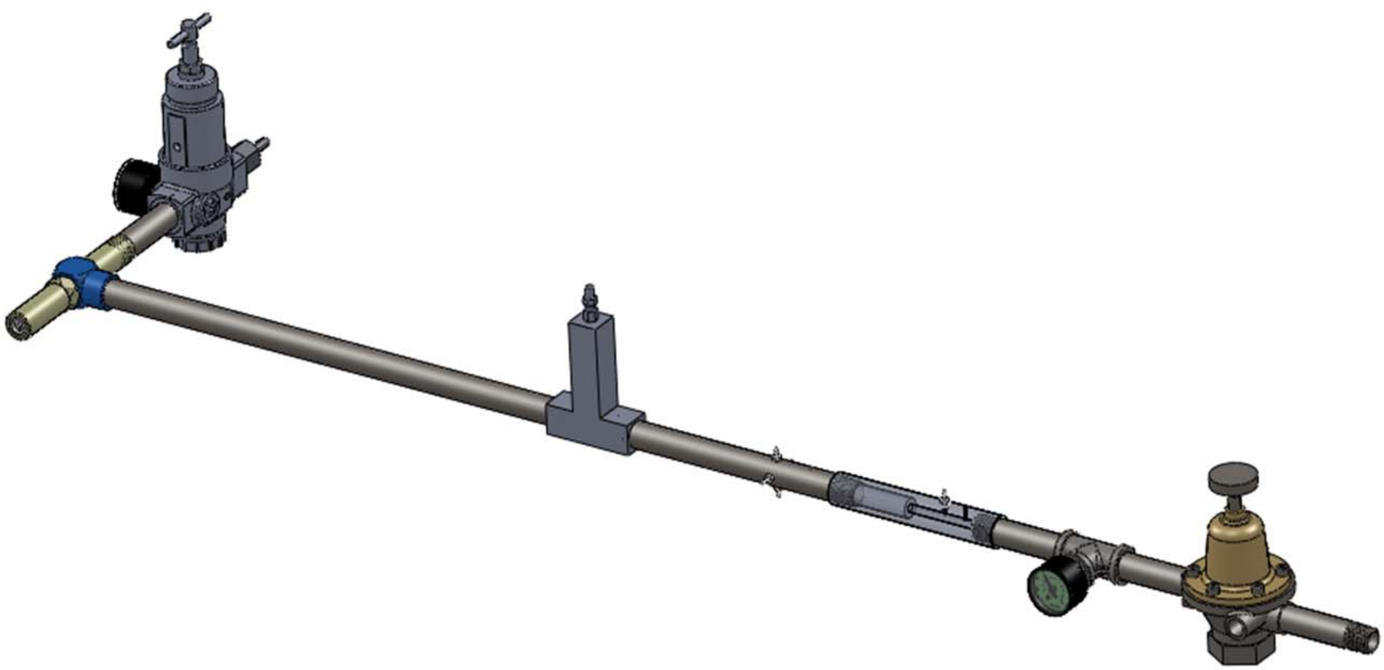


Figure 57. Setup integrated test verification piece

Following the leak tests, the data acquisition will be initiated and test data gathered for a range of pressure regulator settings. As discussed previously in the operating conditions section of this report, various inlet and back pressure settings will result in different fluid velocities. The flow velocity is required to later estimate the system losses for comparison to the theoretical values and thus will be measured by a kiel probe located downstream (not shown in the figure above) of the verification piece.

By conducting analysis on the resulting measurements of this verification test, loss coefficients across the test range will be determined. These experimentally determined loss coefficients will then be compared to the theoretical calculated values. Of course, to gain real confidence in the test apparatus design, the loss coefficients from each method should match. Further detail of how the loss coefficient is determined theoretically can be found in Appendix T.

Chapter 6: Management Plan

Roles and Responsibilities

PreFlow Systems will approach this project with individual roles as well as team responsibilities. Chelsea Crawford is in charge of contacting Solar Turbines' main contact, Bill Krehbiel, for various questions and updates on our progress. She is also responsible for planning the project and organizing the meetings. Chelsea will also be in command of testing plans, test criteria and analysis.

Daniel Chairez is in charge of the computer simulations like computation fluid dynamics (CFD) and stress analysis. He will also be accountable for purchasing and cost estimation with our budget.

Daniel Welch is in charge of producing design solid models and drawings. Daniel will also be responsible for the data acquisition system and manufacturing of the test apparatus. As a team, we will all work on hand calculations, the overall evaluation of the design, analysis of the data, and other tasks that arise.

Milestones

There are several milestones during this project that have been determined by the primary objectives as well as the framework of the mechanical engineering department course. The major milestones which essentially define the crucial deadlines are as follows:

- December 1, 2010 – Conceptual Design Review
    - Three primary design concepts
    - Focus on favorite design to specify major components
    - Test plan for selected problematic geometries test blocks
- December15, 2010 – Final Design Concept
    - Overview of engineering analysis methods
    - Precise specifications of test apparatus
    - Bill of Materials
    - Component purchasing
- January 4, 2011 - Begin Build of Test Apparatus
- May 10, 2011 – Begin Testing of Problematic Geometries
    - Upon completion of building and calibration
- May 20, 2011 – Hardware Demo
    - Include completed analysis as determined by experimentation
- Beginning June – Analysis and Project Documentation Complete
    - Presentation at Senior Design Exposition
    - Presentation to Solar Turbines

Schedule

The schedule is based upon the project milestones and the requirements of the Cal Poly Mechanical Engineering senior project course. Specific tasks were determined from the primary phases of the project:

- Research
- Apparatus Concept Generation
- Engineering Analysis
- Building
- Apparatus Testing
- Analysis of Experimental Results

As shown in the Gantt Chart of Appendix U, the tasks are detailed with assignment owner and percent complete. Also, color coding indicates the relation of a task or a milestone to its requirement basis. That is, orange indicates a strong correlation to the requirements instated by the Cal Poly course, whereas teal is directly associated with Solar Turbines. The ultimate success of the project is highly dependent upon reaching the deadlines set by the schedule, especially for the tasks that define the critical path. The dependent tasks that define the critical path are:

- Approval from Solar Turbines of a primary design concept
- Finalization of apparatus design through engineering analysis and component specifications
- Building of test apparatus
- Testing of problematic geometries
- Final documentation of project development and results

In recalling the primary project objectives, it becomes clear that the critical path has been defined appropriately and is indeed a major indication how well the project will be completed. Throughout the duration of the project, each task's percent progress will be updated. This action is an important aide to PreFlow System's communication with the sponsor, Solar Turbines.

Chapter 7: Testing & Analysis

Testing Preparation and Procedures

Preparation of the flow test apparatus begins with the installation of a new test block. Following installation of a new test block, a thorough leak check is required. Connecting the flow test apparatus to main air supply to perform a leak check is necessary to ensure that proper data is collected. The test block gasket was the most prone to leaking and use of a soapy solution could identify any problem areas visibly. Tightening of the test block bolts would correct leaking. Figure 58 below illustrates leak checking of connections.

Figure 58. Leak Checking Connections

Once the entire system is sealed and ready for testing, the main air supply is reconnected to the flow test apparatus via a male quick disconnect fitting. The DATAQ is then connected to the computer, which will handle that data acquisition and processing. The inlet pressure regulator is set to the desired pressure and then manipulation of the backpressure regulator will determine the flow velocity within the system to record at different Reynolds numbers.

The test engineer at the computer station will monitor temperatures and pressures to ensure the system is at steady state. One minute of data recording is then recorded and saved to an excel spreadsheet. Figure 59 below shows the test engineers view of the computer while testing. Flow test apparatus testing procedures and safety guidelines are available in Appendix #.

Figure 59. Testing Data Acquisition Window

Analysis of Test Data

Once all three test blocks were fully tested, the data was compiled and analyzed to determine pressure loss coefficients and Reynolds numbers. The total pressures, static pressures, temperatures, flow path dimensions, and relative humidity of the air were inputted into an Engineering Equation Solver (EES) code that performed the analysis. The EES code is in Appendix X with a sample parametric table with inputs and results.

The resulting data from the analysis was compiled into Figure 1 below. All three configurations of minimum and maximum fly cut radius with the baseline configuration as well are shown in the figure.

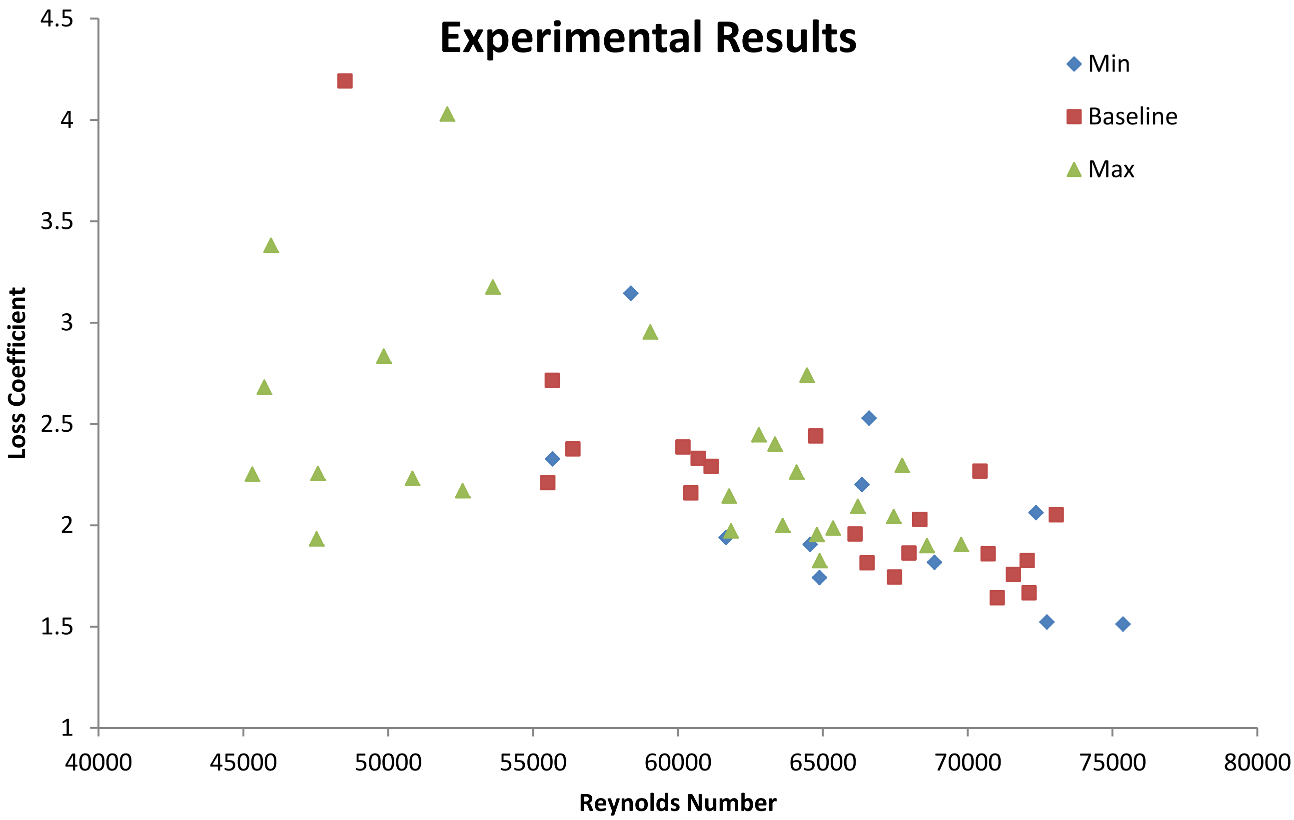


Figure 60. Experimental Data of Loss Coefficients for corresponding Reynolds Numbers

Although the data is quite scattered, it exhibits an inversely proportional trend of decreasing loss coefficients with increasing Reynolds Numbers. In addition, the maximum fly cut tends to produce more variation in loss coefficient than the baseline and minimum fly cut.

After analyzing our system, PreFlow Systems hypothesizes that the data varies a lot because of the pulsations in air pressure within the system. The apparatus has only one regulator upstream which is only able to regulate within one psi accuracy. A loss coefficient between 1.5 and 2.5 was due only to a difference in pressure of 0.02 psi. Because the regulator cannot maintain the pressure within 0.01 psi, pulsations from the compressor were still experienced within the apparatus. If the air was being supplied from an isolated supply tank, and the apparatus had multiple stages of pressure regulation to remove pulsations in the inlet pressure, then the data would most likely be more accurate. In general, this data shows that the apparatus performs as expected and that it exhibits valuable trends. Overall, the loss coefficient for our geometries range from 1.5 to 4 corresponding to Reynolds Numbers of 45,000 to 75,000.

Experimental Validation with CFD

To further verify that the experimental data seemed reasonable, we compared it to several computational fluid dynamic (CFD) simulations of the same geometries. The models were set up using SolidWorks Flow Simulator. Figure 61 below shows an example CFD flow visualization of the velocity. The green and yellow lines represent fast velocities and blue lines represent slow velocities.

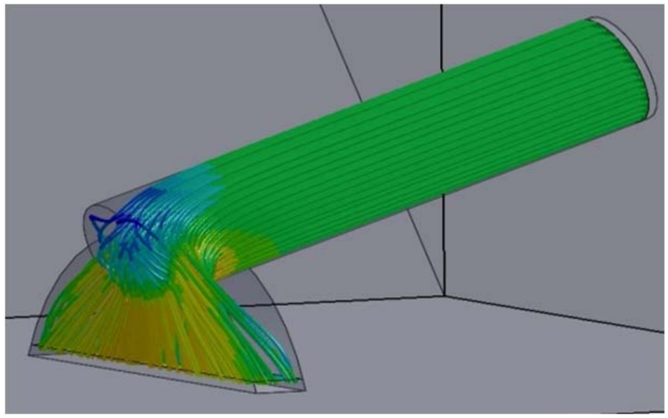


Figure 61. CFD flow visualization of the velocity

In order to better visualize the general trends for the CFD analysis, the numerical results were also processed with the EES code. This information was then input into Excel to produce the following graphs.

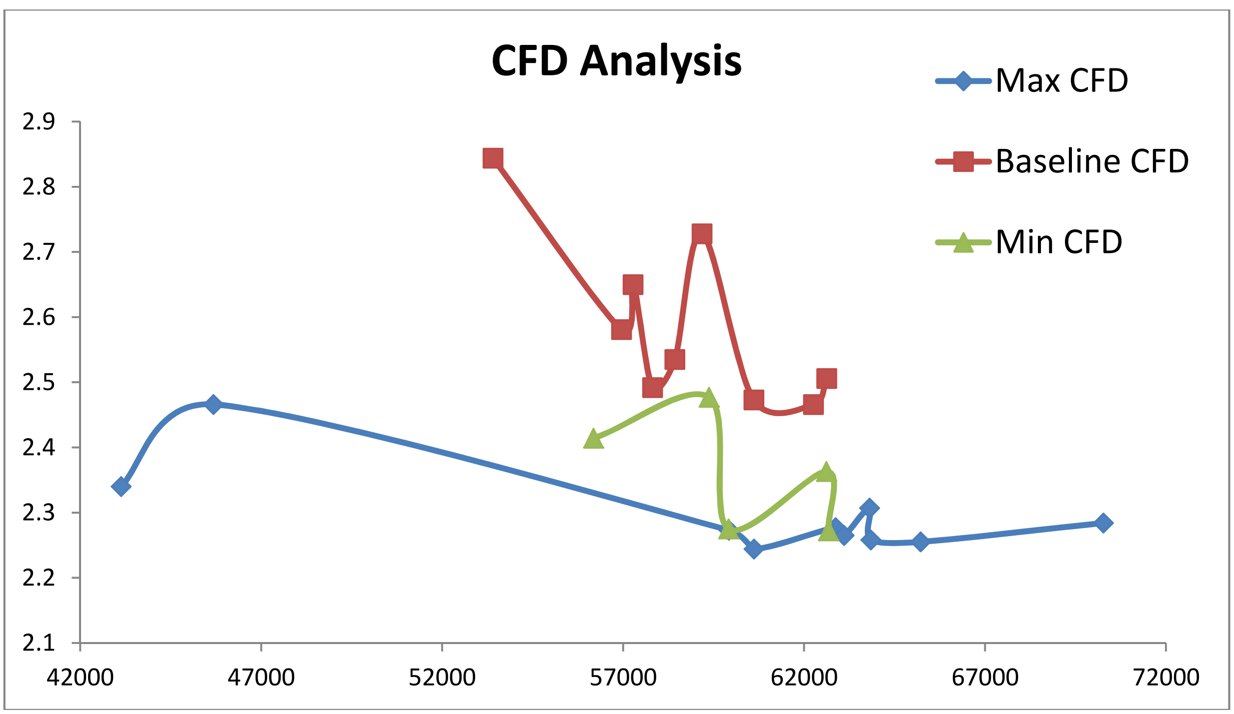


Figure 62. CFD Data of Loss Coefficients for corresponding Reynolds Numbers

The general trend of the CFD shows the maximum fly cut increases at a slower rate as Reynolds number decreases compared to the baseline and minimum fly cut radius. In addition, the baseline loss coefficients are much higher on average than the other fly cut radii.

Finally, the most valuable tool in the test data analysis was to directly compare the experimental data to the CFD results. The following pages exhibit these graphical comparisons for all three test blocks.

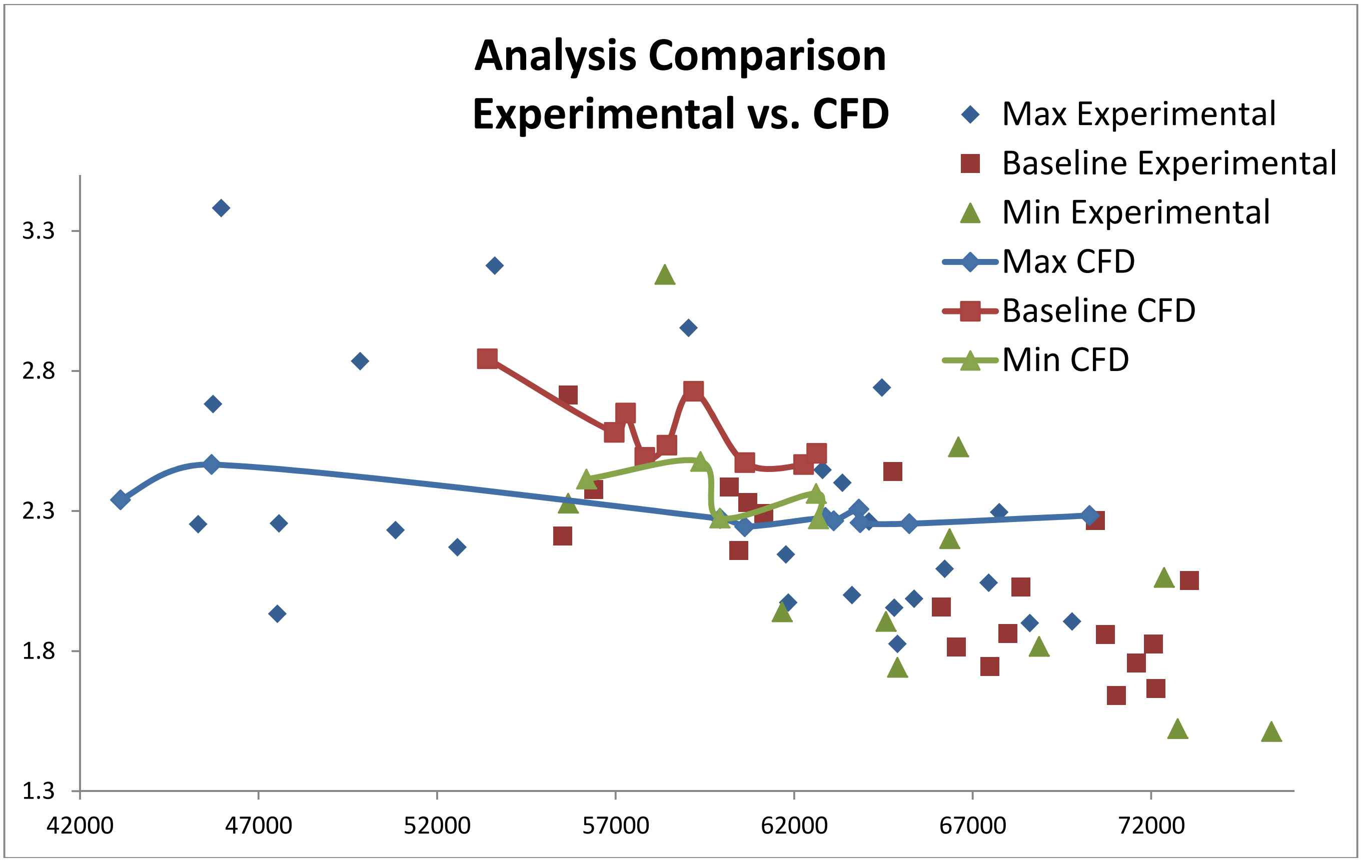


Figure 63. Experimental and CFD Analysis Comparison for all blocks

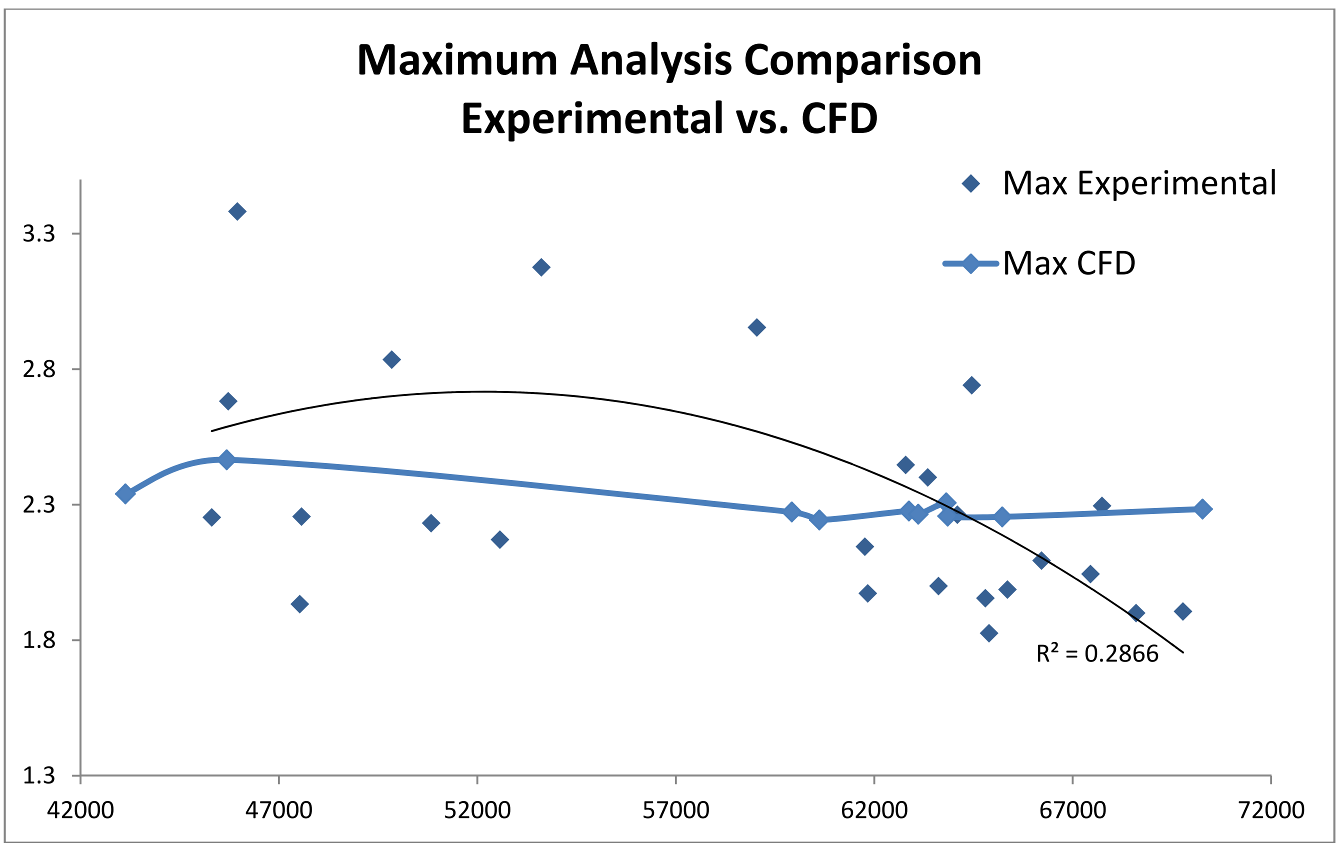


Figure 64. Maximum Fly Cut Experimental and CFD Analysis Comparison

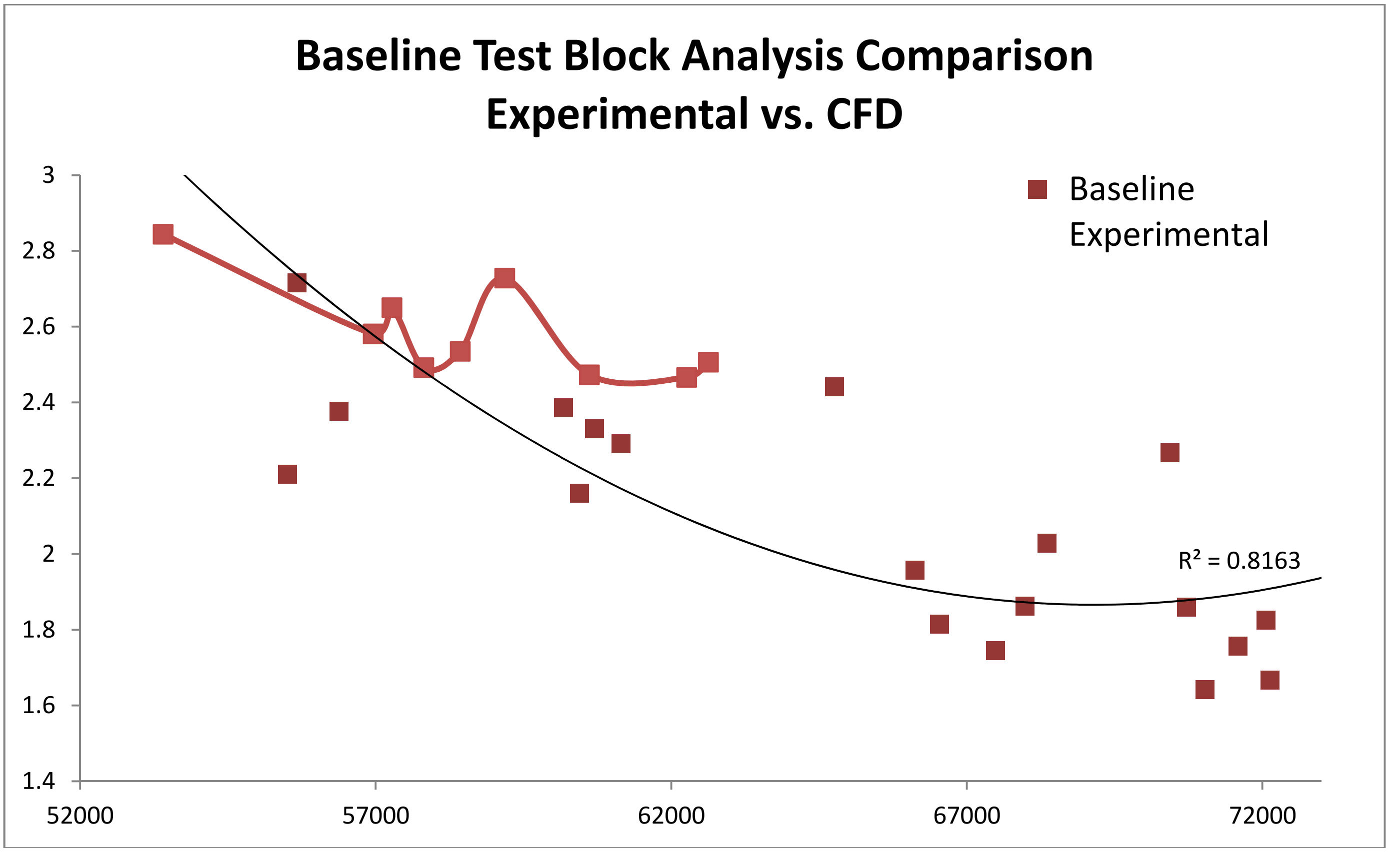


Figure 65. Baseline Fly Cut Experimental and CFD Analysis Comparison

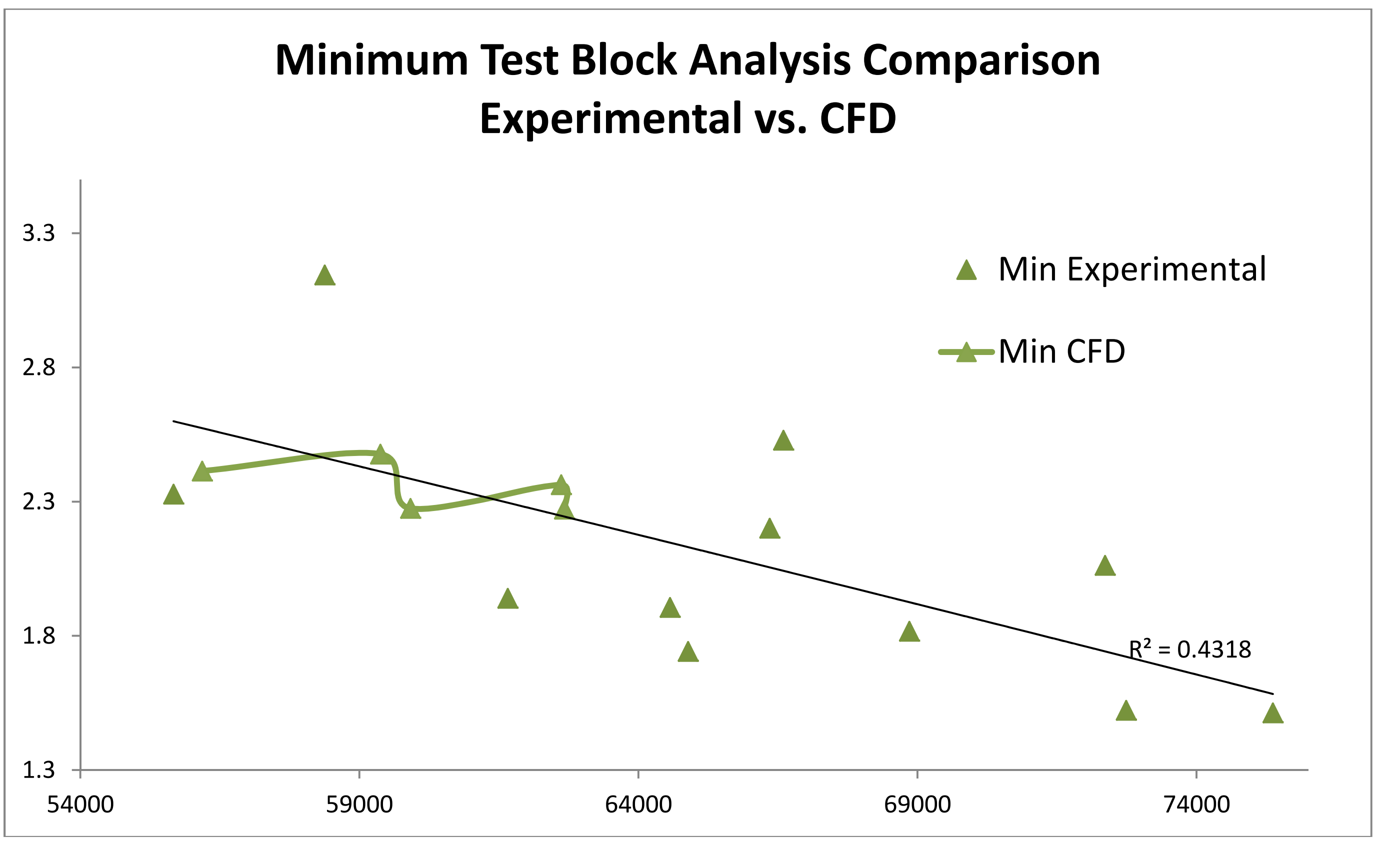


Figure 66. Minimum Fly Cut Experimental and CFD Analysis Comparison

Despite the large scatter in experimental data and the inexplicable waves for the CFD results, the general trends of the analysis comparison are valuable. These trends ultimately prove that using CFD as a tool for estimating loss coefficients for compressor port design purposes is reasonable. As mentioned previously in the report, the use of CFD was verified on a number of additional occasions including: apparatus operating conditions predictions, comparisons between Solar Turbines' CFD analysis methods, as well as for typical published loss coefficient information. The general success in all of these opportunities is what ultimately allows PreFlow Systems to suggest that CFD is a sound aide to Solar Turbines' gas compressor port design decisions. As based on this ultimate suggestion, recommendations for the continuation of this project results are included in chapter eight.

Chapter 8: Conclusion & Recommendations

To solve Solar Turbines' end-cap optimization problem, PreFlow Systems designed, built, and tested a flow test apparatus with three scaled geometric configurations. The final design was created after many weeks of collaboration with Solar Turbines. Construction and testing of the flow test apparatus was completed at Cal Poly in various locations including the Bonderson Projects Center, Mustang '60 machine shop, and the Aero Hangar machine shop. The final design and test analysis results will be presented to Solar Turbines in a final project presentation at their main facility located in San Diego, CA.

After testing of each configuration (maximum, baseline, and minimum fly cuts), a PreFlow Systems developed equation solver computed the valuable analytical results of Reynolds numbers and associated pressure loss coefficients. Computational Fluid Dynamic (CFD) iterations were generated using the same boundary conditions as the tests. The CFD results were also processed with the equation solver to produce loss coefficients and Reynolds numbers for comparison to the experimental results. The graphs of the loss coefficient and Reynolds number trends provided the most valuable tool for comparison and analysis. The PreFlow Systems results indicated a trend of higher loss coefficients at lower Reynolds. Furthermore, fly cut size had a less influence on the loss coefficient than originally predicted. The CFD data yielded more consistent and less sporadic results compared to our experimental results. The wide spread of experimental data was most likely caused by pressure pulsations within in our system. Thus, better pressure regulation and more precise equipment would yield better results. Ultimately, PreFlow Systems' primary recommendations to Solar Turbines Gas Compressor Division are the following:

- CFD is a reasonable aide in compressor end cap port design decision making
- The loss coefficients are higher at lower Reynolds numbers (low flow velocity or small diameter)
- Experiment indicates fly cut size has less influence on loss coefficient than originally predicted
- Further investment in better pressure regulation and more precise instrumentation for the test apparatus is valuable

In conclusion, the ultimate project objectives were met and there was much valuable knowledge and experience gained for all parties involved in the project. PreFlow Systems extends much appreciation to the Solar Turbines Gas Compressor Engineering Division for providing the port flow test apparatus project support and funding.

.

References

ASME International. Boiler and Pressure Vessel Code. 2007 Section VIII, Division 2. 27 Sep 2007

Baier, Edward. United States Department of Labor. “OSHA Safety Hazard Information Bulletin on the Use of Polyvinyl Chloride (PVC) Pipe in Above Ground Installations” Memorandum. 14 Feb 1989. Web. <http://www.osha.gov/dts/hib/hib_data/hib19880520.html>

Budynas R.,Shigley, J., Nisbett, J. K. Shigley’s Mechanial Engineering Design. Eighth Ed. McGraw-Hill: New York. 2008. Print.

Coffield, R. D., P. S. Brooks, and R. B. Hammond. *PIPING ELBOW IRRECOVERABLE PRESSURE LOSS COEFFICIENTS FOR MODERATELY HIGH REYNOLDS NUMBERS*. Tech. Print.Bettis Atomic Power Labratory DE-AC11-93PN38195

"CENTRIFUGAL COMPRESSOR TRAINING NOTES." ROLLS-ROYCE ENERGY SYSTEMS, INC. Ohio, Mount Vernon. 17 Oct. 2010.

Minor Loss in Pipe or Duct Components. The Engineering ToolBox. Web. 7 Feb 2011. <http://www.engineeringtoolbox.com/minor-pressure-loss-ducts-pipes-d_624.html>

Fox, Robert W., Philip J. Pritchard, and Alan T. McDonald. Introduction to Fluid Mechanics. Hoboken, NJ: John Wiley & Sons, 2010. Print

Glass, Ben. "MIT GTL Current Research." *MIT*. Web. 19 Oct. 2010. <http://web.mit.edu/aeroastro/labs/gtl/MIT_GTL_curr_research.html>.

Incropera, DeWitt, Berman, and Lavine. Fundamentals of Heat and Mass Transfer*.* Sixth Ed. Hoboken, NJ: John Wiley & Sons, 2007. Print

McLeod, Lianne. About.com. *How to Calibrate a Hygrometer*. Web. 5 Feb 2011. <http://exoticpets.about.com/od/herpresources/ss/hygrometer.html>

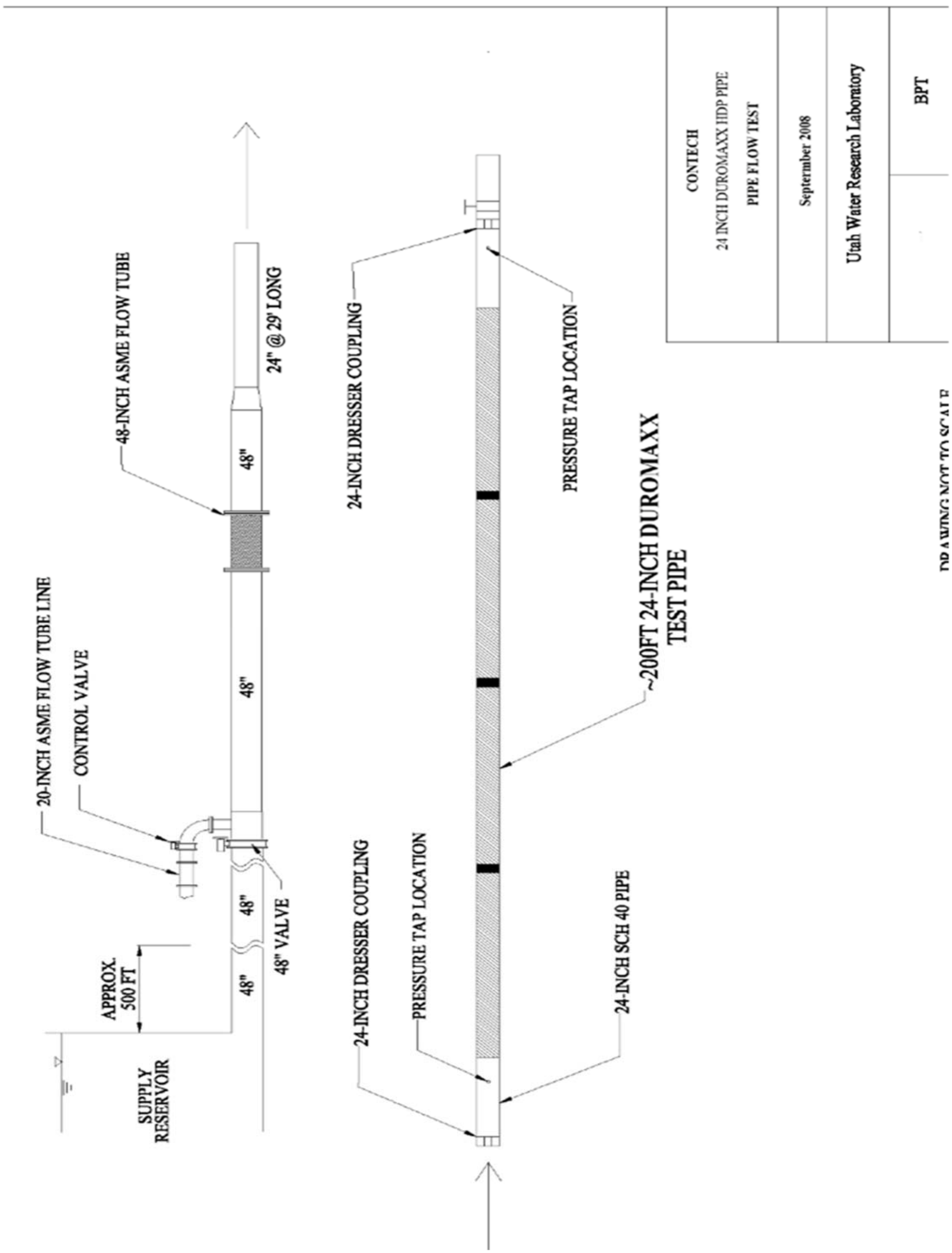
"Solar Turbines: About Solar." *Solar Turbines: Home*. 2006. Web. 19 Oct. 2010. <http://mysolar.cat.com/cda/layout?m=10683&x=7>.

Tullis, Blake P. *FLOW TESTING 24-INCH DUROMAXX HDPE PIPE*. Tech. Print.Hydraulics Report No. 1905

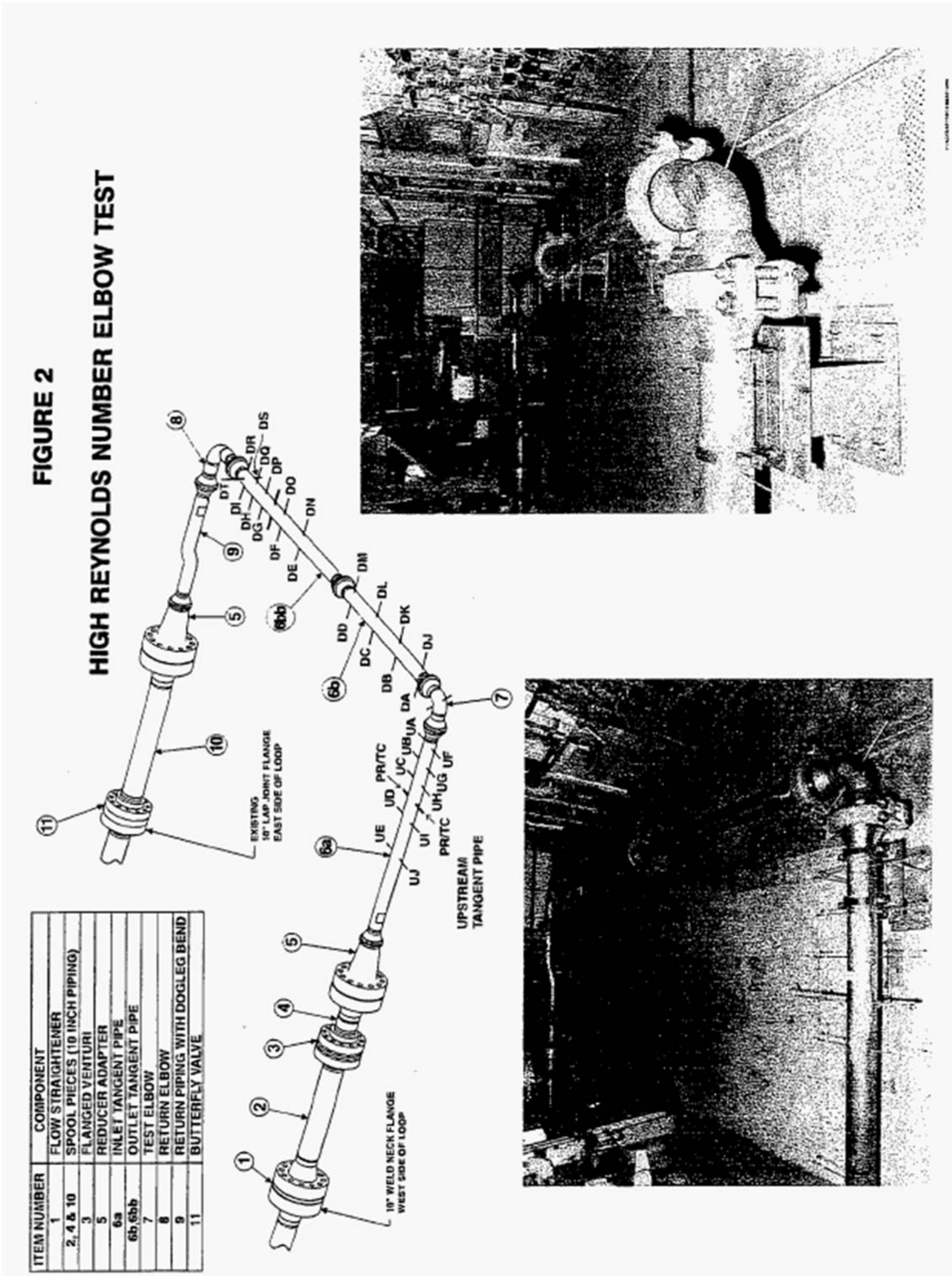
“Slitting Saw” Ebay. 1 Dec 2010. <http://cgi.ebay.com/SLITTING-SAW-5-X-3-16-X-1-HSS-FRESH-REGROUND-/160417411477?pt=LH_DefaultDomain_0&hash=item25599f7195>

“Saw Arbor” Ebay. 1 Dec 2010. <http://cgi.ebay.com/SLITTING-SAW-ARBOR-/350418236271?pt=BI_Tool_Work_Holding&hash=item51968df36f>

Appendix A: Example Flow Test System Diagram



Appendix B: Example Flow Test System



ITEM NUMBER	COMPONENT
1	FLOW STRAIGHTENER
2,4 & 10	SPOOL PIECES (10 INCH PIPING)
3	FLANGED VENTURI
5	REDUCER ADAPTER
6a	INLET TANGENT PIPE
6b,6bb	OUTLET TANGENT PIPE
7	TEST ELBOW
8	RETURN ELBOW
9	RETURN PIPING WITH DOGLEG BEND
11	BUTTERFLY VALVE

Appendix C: Quality Function Deployment

Solar Turbines — A Caterpillar Company — PREFLOW SYSTEMS

Engineering Requirements (HOWS)

Customer Requirements	Weight	No longer than 7ft	No wider than 4ft	Shorter than 3ft	Under 100 lbs	Withstand normal operation for multiple runs	Fully contained system includes all necessary operational components	Off the shelf parts	Cheap, easy to obtain and non-hazardous materials	Test sections easily machined in standard CNC Mill	On Wheels	Under $3000 entire system	Obtain test measurements within +/- 10% of predicted values	Test results reproduceable within +/- 10%	Minimum 10 data points per test section geometric configuartion	Interchangeable test sections in rig	Pressure and Temperature Sensors with Data acquisition system	Runs off standard 120V, 60Hz outlet
Reasonable Size	6	9	9	9	3		3			3	3	3				3	3	
Appropriate Weight	5	3	3	3	9	1	3		1		3	3				3	3	
Reliable function	6					9	3		1	3	1	3	3	3		3	9	3
Sturdy	5	3	3	3	3	9	3	3	9	3	1	3	1	1	1	3		1
Reasonable test duration	5					1	3					1	3	3	9	3	3	
Easy assembly/disassembly	5	1	1	1	1	3	9	9	3	3	3	3				9	3	9
Easy operation	3						3				1	3	3	3	3	9	9	9
Easy to manufacture	4	1	1	1	1	3	3	9	9	9	3	3	3	3		9	3	3
Mobile	6	9	9	9	3	1	9		1	1	9	1				9	9	9
Reasonably priced	9	1	1	1	1	1	3	9	9	9	1	9	3	3	1	3	9	3
Safe	9							1	9		1	1						3
Manufacturing Standards	6	1	1	1	1	1	1	3	3	9		1						
Accurate	9					3		1		3		3	9	3	9	3	9	
Precise	9					3		1		3		3	3	9	9	3	9	
Obtain sufficient data	9					3	3	1				3	9	9	9	9	9	
Flow visualization	2						1			9		3				1		
Understadable operation	2					1	3	3				1	3	3		3	3	
Weighted Total	100																	

Appendix D: Port Library Findings

Upon completion of the port library, the findings were graphed to discover the most important values and ranges for each dimension. For every graph discussed below, the green boxes indicate the values considered and the red boxes indicate the values selected for the first set of test section blocks.

Figure D1 is a graph of the number of gas ports with each diameter. With 117 out of the 140 ports (84%), the one inch diameter drilled hole is the most common. For the first round of tests, this common dimension will be used for every test section block designed. There are two reasons for not changing the drilled hole diameter:

1. Testing requires varying the velocity of the flow to perform the majority of the analysis which compares Reynolds numbers
2. A stepped geometry would then be required for the test section so that the upstream connection would remain compatible

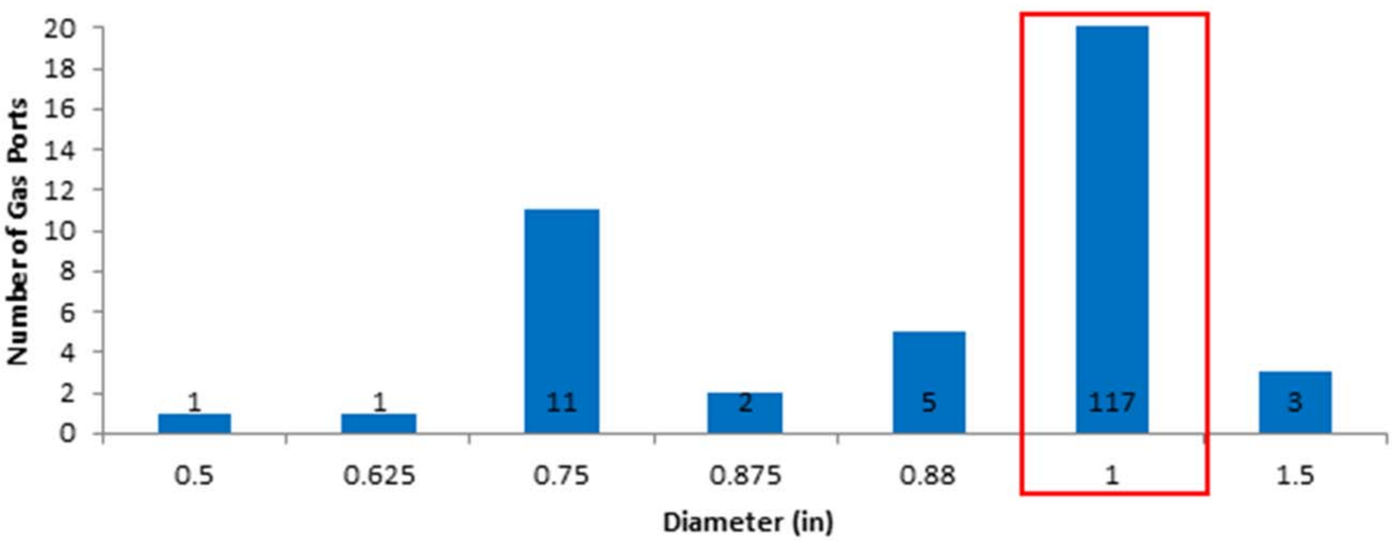


Figure D1. Number of gas ports with specific hole diameter sizes

Figure D2 shows the number of gas ports with a specific angle between the centerline of the drilled hole and the flycut. The three most common angles are 110, 115, and 120 degrees and range from 90 to 140 degrees.

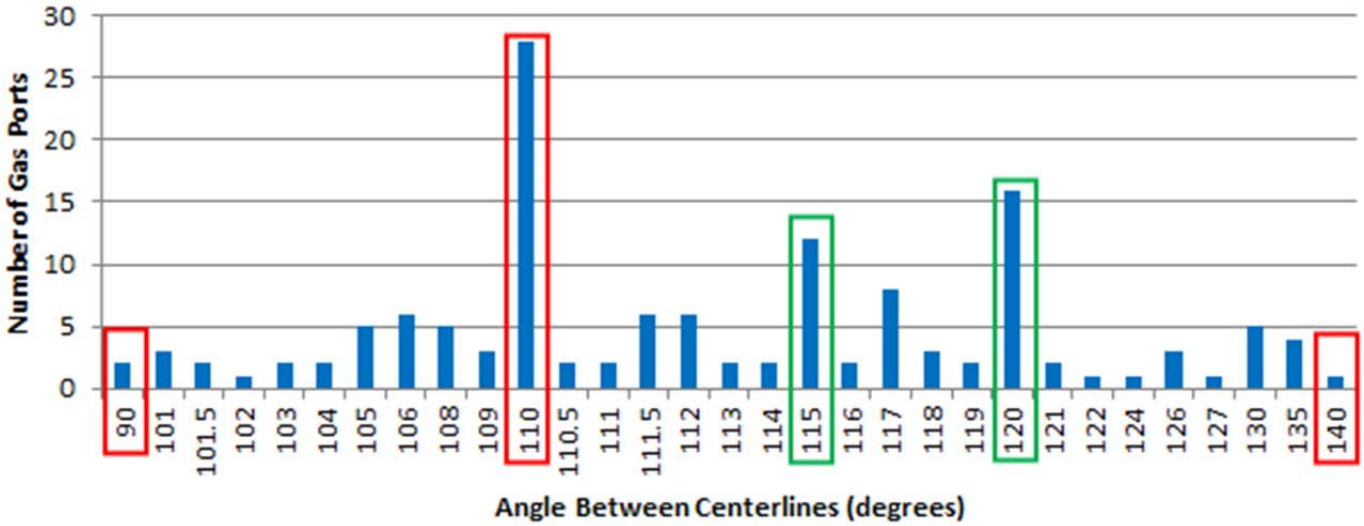


Figure D2. Number of gas ports with specific angles between centerlines of the hole diameter and flycut

The number of gas ports with a specific flycut width is shown in Figure D3. The most common flycut width is a half inch, which occurs in 77 out 140 ports (55% of all gas ports). This dimension ranges from a quarter of an inch to one inch.

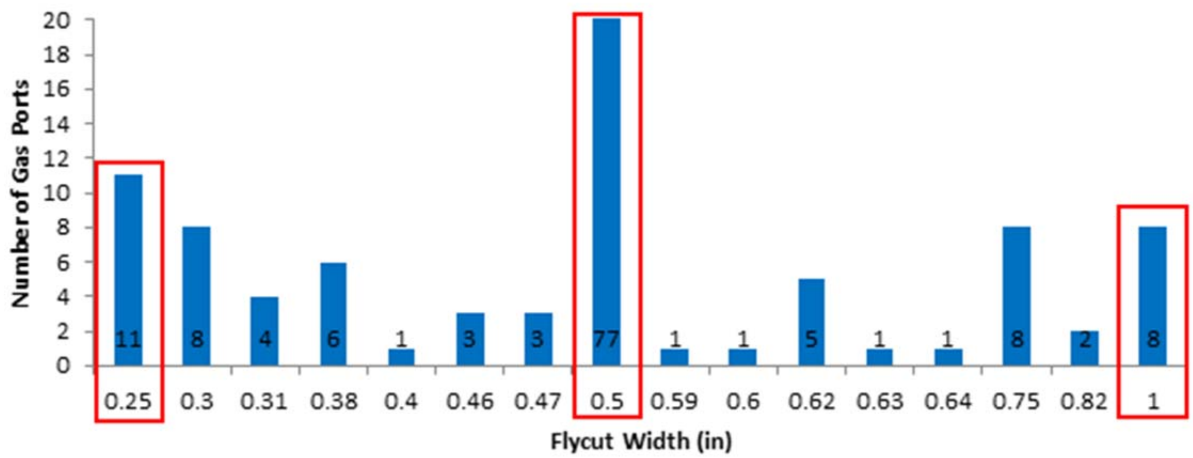


Figure D3. Number of gas ports with specific flycut widths

In order to view the relationship between each port's diameter and flycut width, analysis was conducted on this ratio. The distribution of gas ports and their ratio is shown in Figure D4. The most common ratio is two, which occurs in 70 out 140 ports (50% of all gas ports), and ranges from one to four. These ratios appear to be logical when comparing them to the trends found in the other graphs. That is, the most common dimensions of drilled hole diameter and flycut width are one inch and ½ inch, respectively. The ratio of these dimensions is also two. The same consideration applies for ratios of four and one when comparing 0.25 inch and 1 inch flycut widths with a 1 inch diameter.

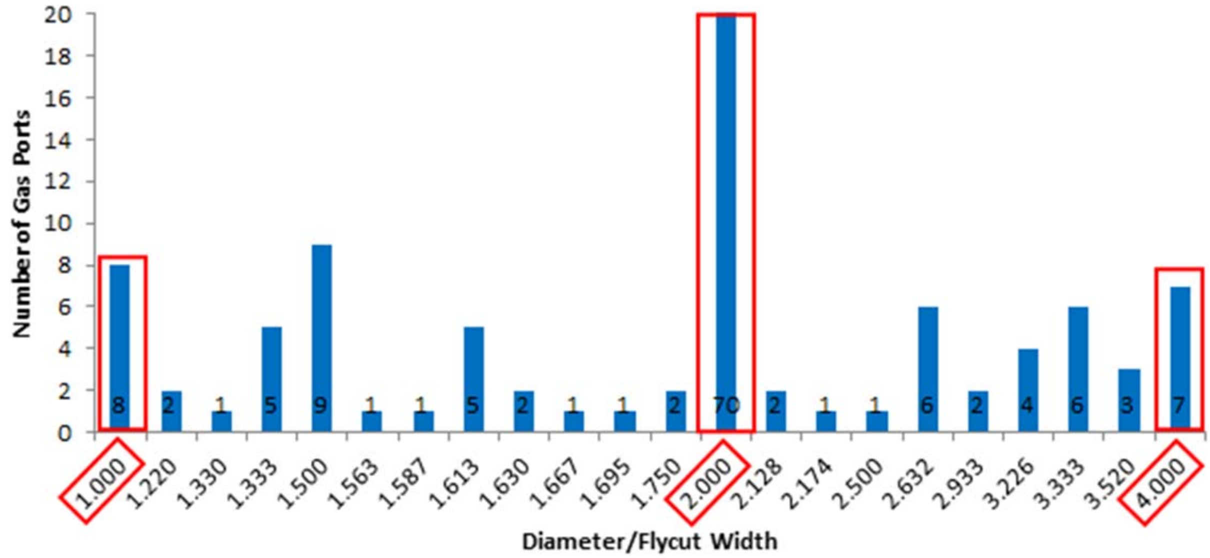


Figure D4. Number of gas ports with specific diameter to flycut width ratios

A large variation in horizontal offset values was found. Therefore, all 140 ports are sorted by their horizontal offset and then assigned a port number in order to produce a graphical representation of the commonly occurring values, as shown in Figure D5. Listed in order of their frequency, the top three most commonly occurring horizontal offset dimensions are approximately, 0.45 inches, 0.25 inches, 0.4 inches. The horizontal offset ranges from -0.06 to 0.93 inches.

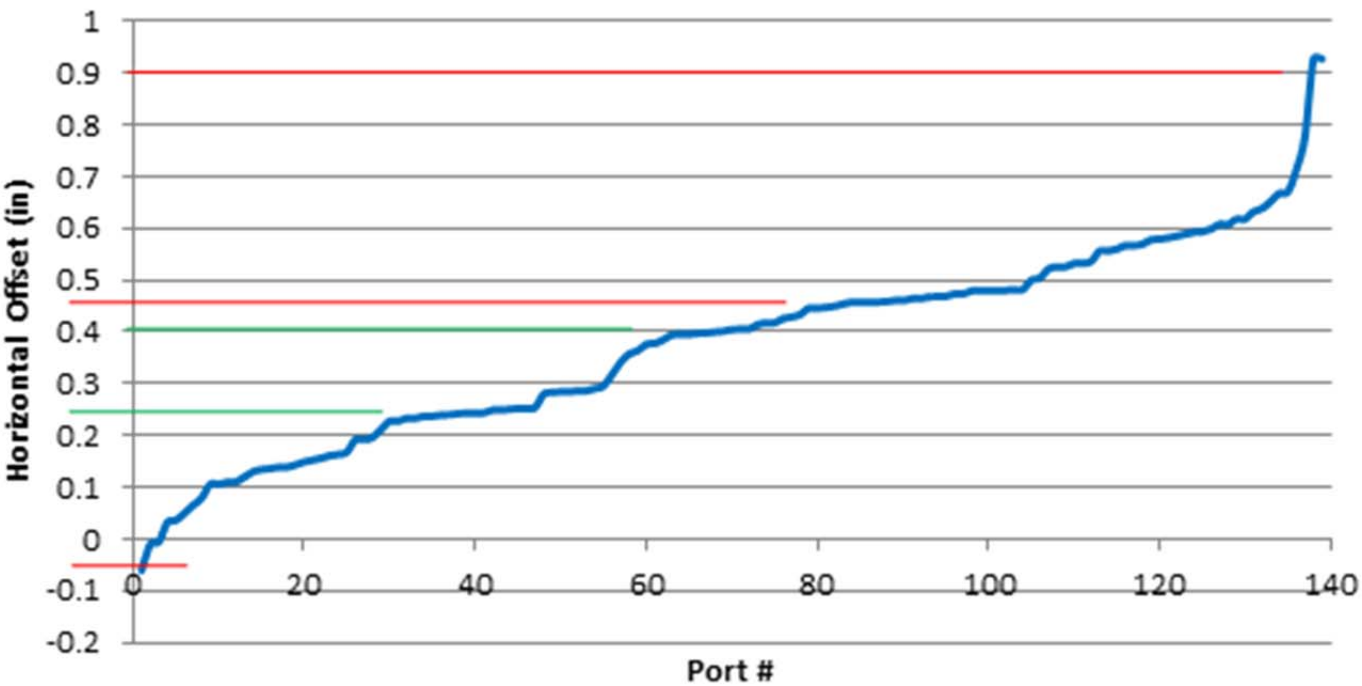


Figure D5. The horizontal offset for each gas port

Analysis of the ratio of horizontal offset to flycut width indicates how the dimensions are related. The ratios were sorted and the values were assigned a port number. These port numbers correspond only with Figure D7 and should not be mistaken to be the same as in Figure D5. The primary ratio values are between -0.16 to 1.23, with a few values falling outside of this range. The ports with ratios of three are the C401 suction end cap buffer seal air in and drain. Figure D6 shows this ratio in particular.

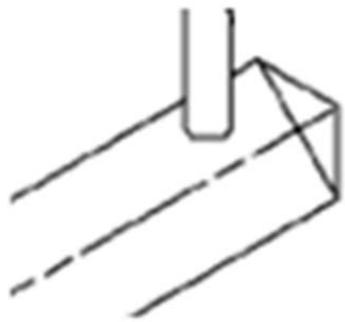


Figure D6. A visual of a horizontal offset to flycut width ratio of 3

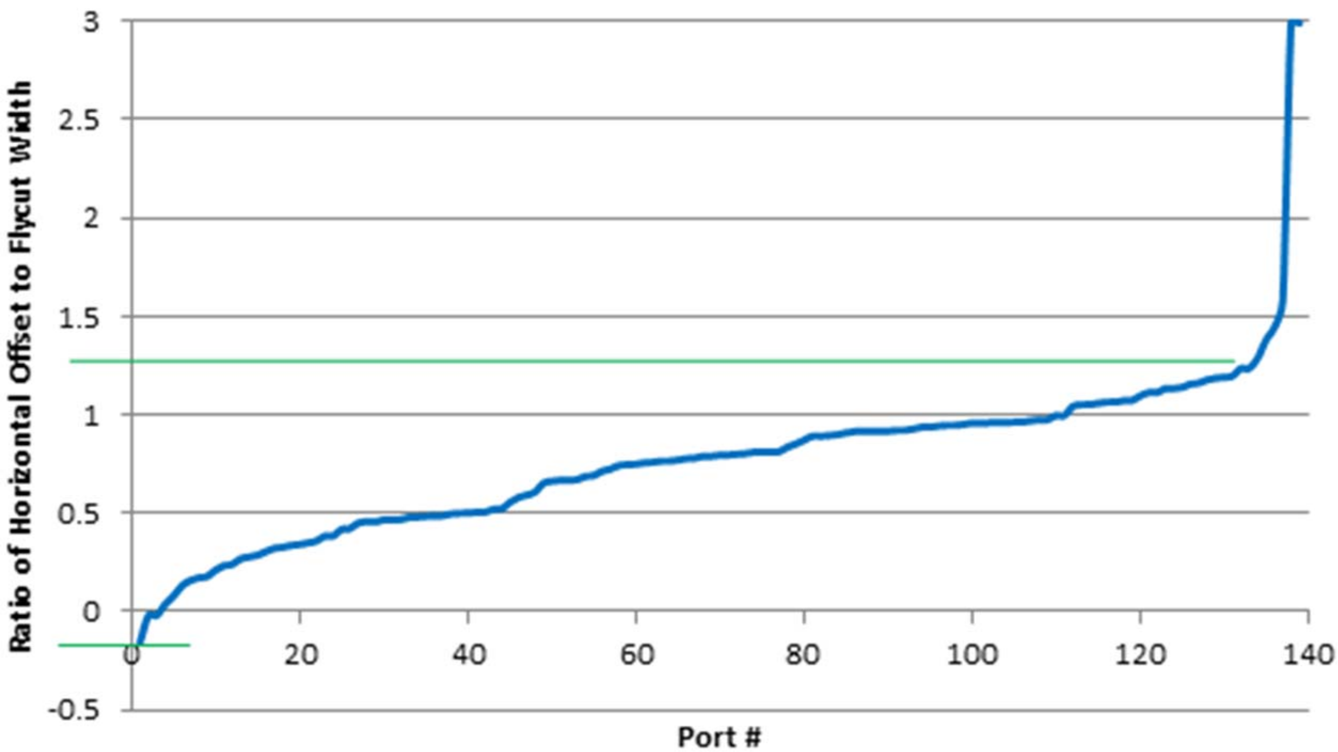


Figure D7. The horizontal offset to flycut width ratio for each gas port

The number of gas ports with a specific flycut radius is shown in Figure D8. The most common flycut radius is 2.5 inches, which occurs in 87 out 140 ports (62% of all gas ports). The second and third common values are two and three inches. The flycut radius ranges from a 1.9 to 5.65 inches.

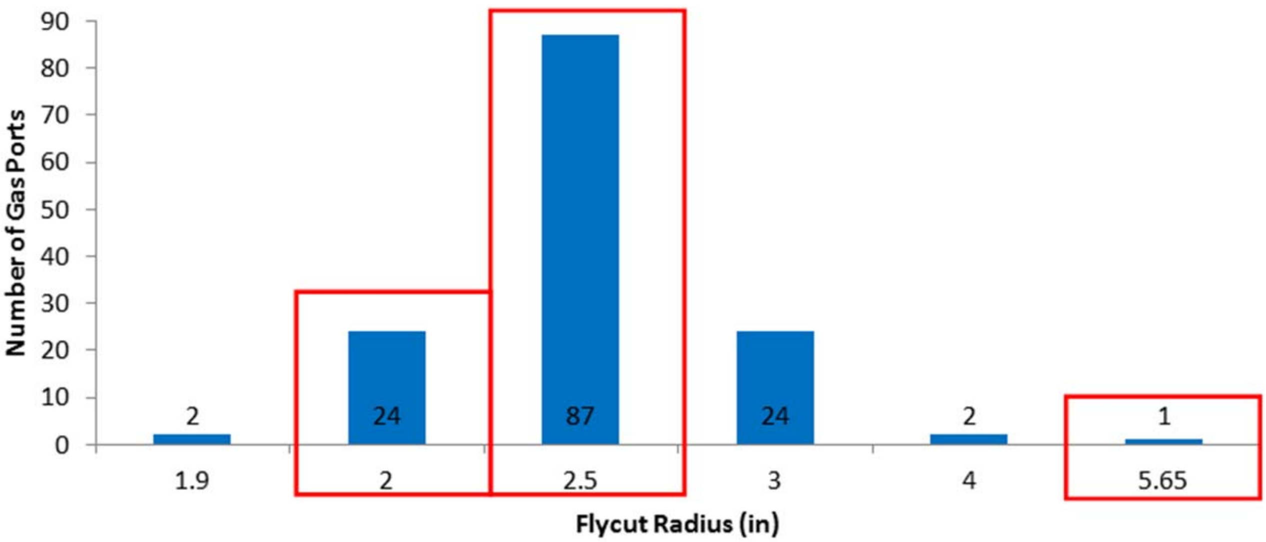
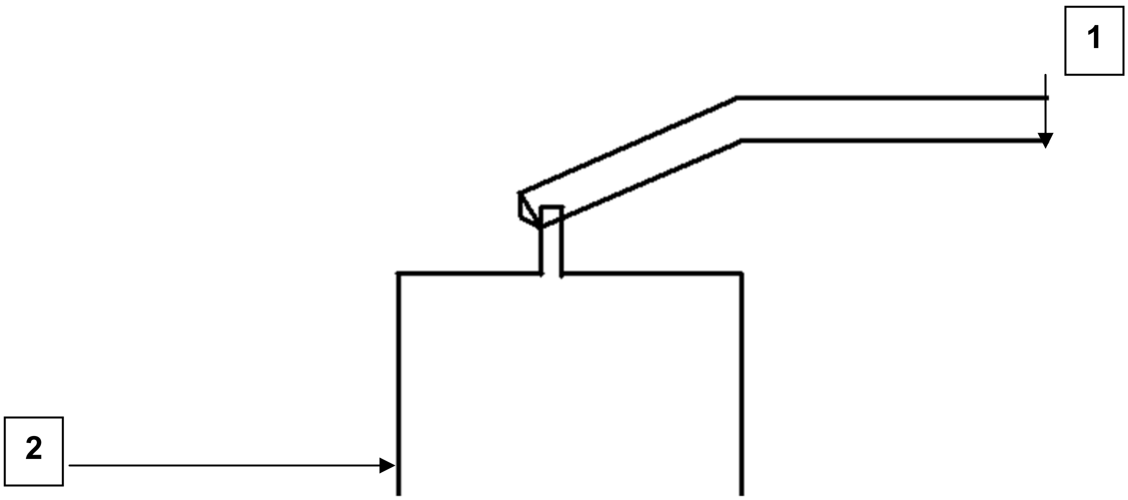


Figure D8. Number of gas ports with specific flycut radius sizes

Appendix E: Pressure Loss Coefficient



$$Static\ Pressure\ at\ point\ 1 = P_1 \qquad Static\ Pressure\ at\ point\ 2 = P_2$$

$$Dynamic\ Pressure\ at\ point\ 1 = \frac{1}{2}\rho {V_1}^2 \qquad Dynamic\ Pressure\ at\ point\ 2 = \frac{1}{2}\rho {V_1}^2$$

$$Total\ Pressure\ at\ 1 = P_1 + \frac{1}{2}\rho {V_1}^2 \qquad Total\ Pressure\ at\ 2 = P_2 + \frac{1}{2}\rho {V_2}^2$$

$$Loss\ Coefficient = \frac{Total\ Pressure\ Loss}{Dynamic\ Pressure\ at\ point\ 1}$$

$$Loss\ Coefficient = \frac{\left(P_1 + \frac{1}{2}\rho {V_1}^2\right) - \left(P_2 + \frac{1}{2}\rho {V_2}^2\right)}{\frac{1}{2}\rho {V_1}^2}$$

$$V_2 \approx 0\ , therefore{:}\ \frac{1}{2}\rho {V_2}^2 = 0$$

$$Loss\ Coefficient = \frac{\left(P_1 + \frac{1}{2}\rho {V_1}^2\right) - (P_2)}{\frac{1}{2}\rho {V_1}^2}$$

$$If\ V_2 \approx 0, then\ P_2 > P_1, but\ \|P_1 - P_2\| < \frac{1}{2}\rho {V_1}^2\ because\ Loss\ Coefficient > 0$$

$$Largest\ \|P_1 - P_2\| = \frac{1}{2}\rho {V_1}^2\ \rightarrow Differential\ Pressure\ Transducer\ Range\ 0\ to\ \frac{1}{2}\rho {V_1}^2$$

Appendix F: Solar Turbines' CFD Results

Solar Turbines provided this CFD results to help PreFlow Systems with their design. The baseline common geometry was used for most of the dimensions except the angle which was altered to 90 degrees instead of 110 degrees. To start, Figure F1 shows the velocity distribution through the flycut. The velocity is high at the farthest wall of the flycut and at the side walls.

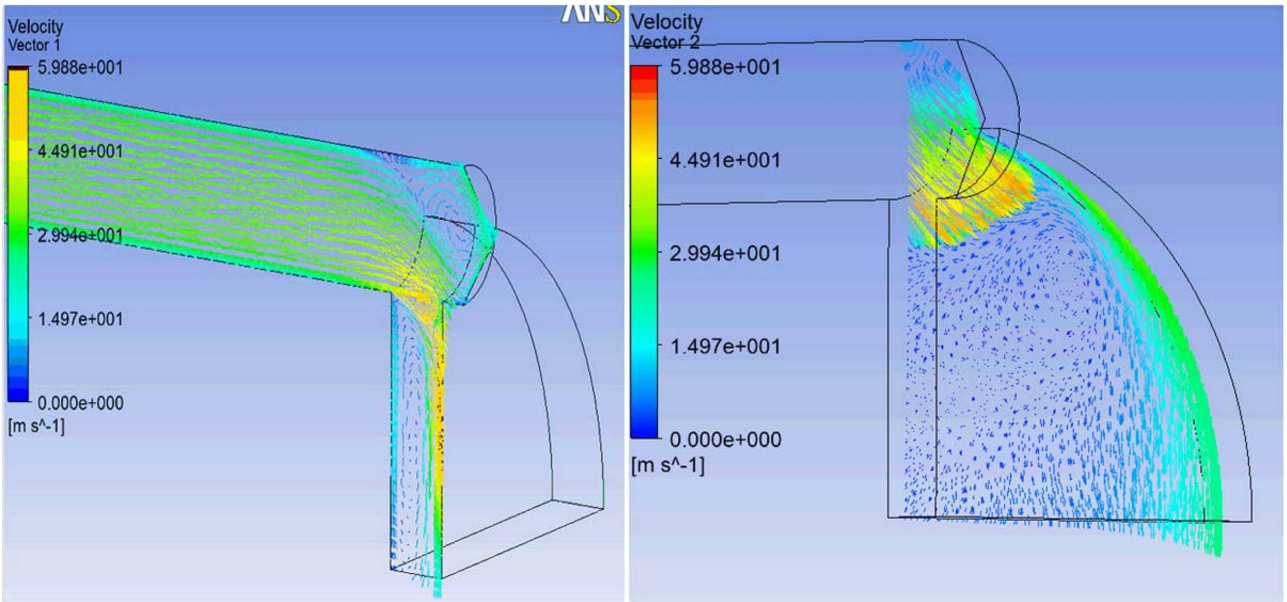


Figure F1. Velocity distribution in the flycut

Figure F2 shows that the side wall of the flycut has the smallest static pressure and highest total pressure.

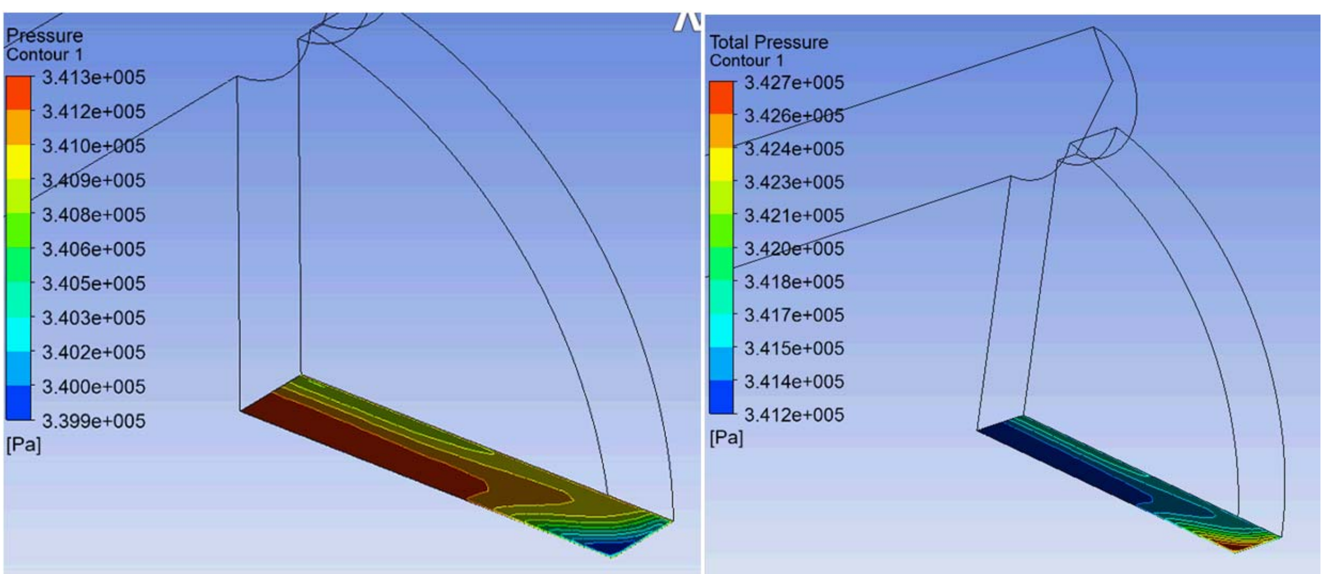


Figure F2. Static and total Pressure distribution at the end of the flycut

From Figure F3, it can be seen that the static pressure varies little at the exit of the flycut compared to the total pressure. Figure F4 shows that the total pressure increases by only 0.1 psi from Reynolds number of 1000 to 8500.

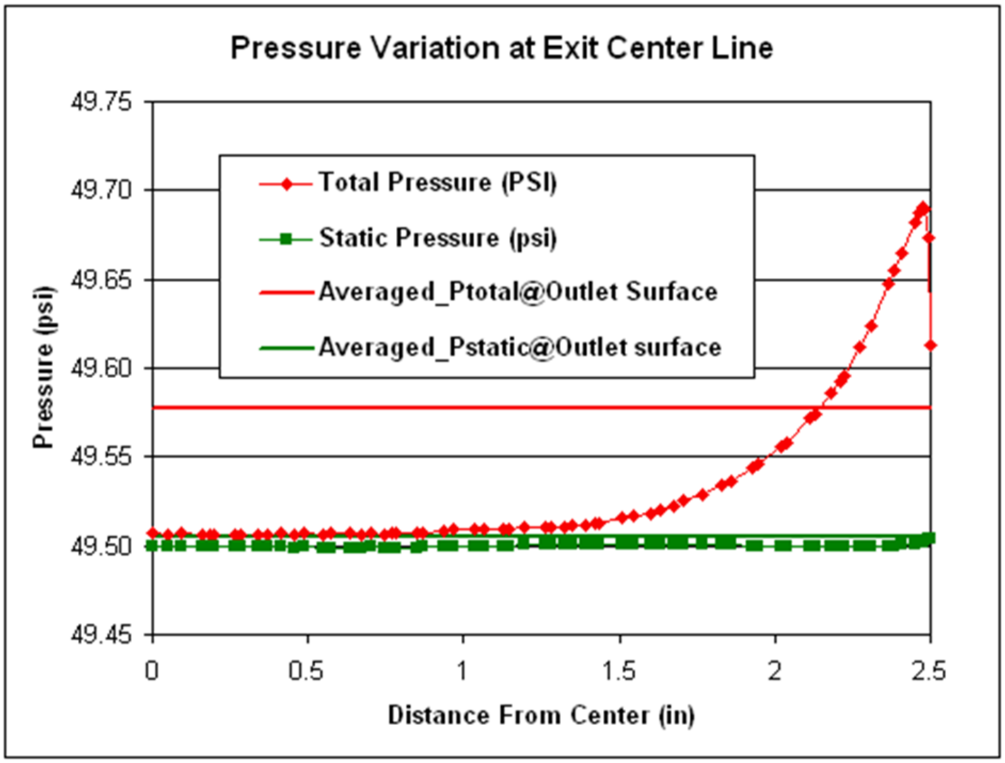


Figure F3. Static and Total Pressure alone the plane of the exiting flycut

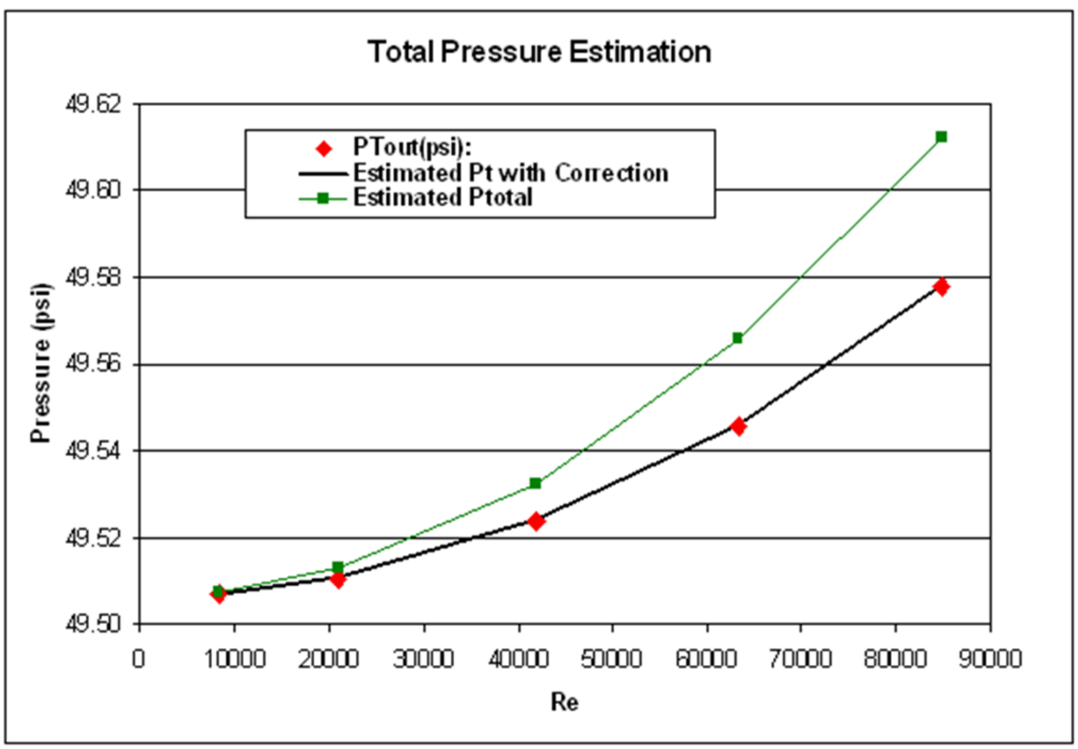


Figure F4. Total Pressure Estimate

Appendix G: Compressor Port Boundary Conditions

Solar Turbines
A Caterpillar Company

Engineering Memo – Oil & Gas Engineering Operations

3 Separation Seal Flow and Pressure Data

Separation Seal (Buffer Air)

Air or Nitrogen 32 to 150 deg F.

Model	Supply Pressure [psig]	Max Flow Per Seal [scfm] PIL1 40
C160k, C166k	25 – 30	2.3
C160r, C160, C166s, C166v, C168v', C169v	25 – 30	2.8
C304, C306	22 – 27	4.4
C33, C33i, C33e, C33el, C337i	22 – 27	4.4
C33eh	22 – 27	4.4
C401, C402	18 – 23	5.6
C404a, C406a	18 – 23	5.6
C404b, C406b	18 – 23	5.6
C41	18 – 23	5.6
C45	18 – 23	5.6
C505J	22 – 27	5.6
C505U	22 – 27	5.6
C51	18 – 23	6.4
C61	18 – 23	10.0
C65	18 – 23	6.4
C85	18 – 23	13.4

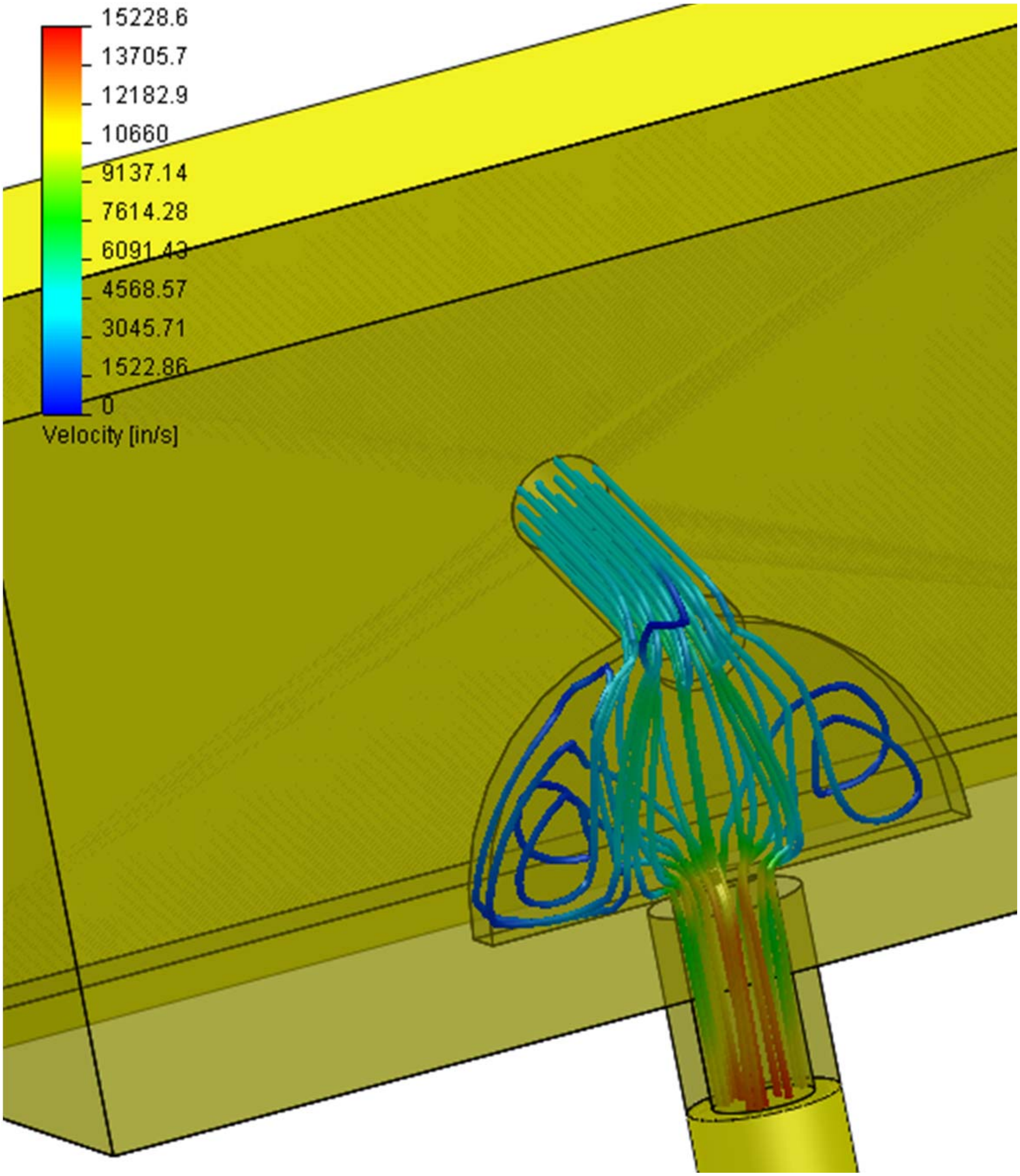
Appendix H: Ideal Operating Conditions

					R (ftlbf/lb	89.372	rho air (slug/ft	2.33E-03	viscosity air	3.81E-07	c air (ft/s)	1126.8
Compressor Endcap	Boundary Conditions Memo Designation	Drilled Hole Diameter (in)	Model Temp (deg F)	Pressure (psig)	SCFM (ft3/min)	ACFM (ft3/min)	Model Velocity (ft/s)	Density (slug/ft3)	Reynolds Number	Prototype Velocity (ft/s)	Dynamic Pressure (psia)	Mach Number
C41 Suction	Seperation Seal (Buffer Air)	1	150	18	5.6	2.91	8.89	0.00268	4847	19.03	0.002928	0.0169
C61 Suction	Seperation Seal (Buffer Air)	0.75	150	18	10	5.19	28.21	0.00268	11540	60.40	0.029513	0.0536
C28 Discharge	Seperation Seal (Buffer Air)	1	150									
C41 Discharge	Seperation Seal (Buffer Air)	0.75	150	18	5.6	2.91	15.80	0.00268	6462	33.82	0.009255	0.0300
C85 Discharge	Seperation Seal (Buffer Air)	1	150	18	13.4	6.96	21.27	0.00268	11597	45.52	0.016767	0.0404
C401 Discharge	Seperation Seal (Buffer Air)	1	150	18	5.6	2.91	8.89	0.00268	4847	19.03	0.002928	0.0169
C45 Suction	Seperation Seal (Buffer Air)	1	150	18	5.6	2.91	8.89	0.00268	4847	19.03	0.002928	0.0169
C51 Suction	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C51_2 Suction	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C51_2 Discharge	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C51 Discharge	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C61 Discharge	Seperation Seal (Buffer Air)	1	150	18	10	5.19	15.87	0.00268	8655	33.97	0.009338	0.0302
C28 Suction	Seperation Seal (Buffer Air)	1	150									
C160 Suction	Seperation Seal (Buffer Air)	0.88	150	25	2.3	0.98	3.88	0.00326	2262	10.09	0.000824	0.0090
C85 Discharge	Seperation Seal (Buffer Air)	1	150	18	13.4	6.96	21.27	0.00268	11597	45.52	0.016767	0.0404
C45 Discharge	Seperation Seal (Buffer Air)	1	150	18	5.6	2.91	8.89	0.00268	4847	19.03	0.002928	0.0169
C65 Suction	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C65 Discharge	Seperation Seal (Buffer Air)	1	150	18	6.4	3.32	10.16	0.00268	5539	21.74	0.003825	0.0193
C160 Discharge	Seperation Seal (Buffer Air)	1	150	25	2.3	0.98	3.01	0.00326	1991	7.81	0.000494	0.0069
C85 Suction	Seperation Seal (Buffer Air)	1	150	18	13.4	6.96	21.27	0.00268	11597	45.52	0.016767	0.0404
C401 Suction	Seperation Seal (Buffer Air)	1	150	18	5.6	2.91	8.89	0.00268	4847	19.03	0.002928	0.0169

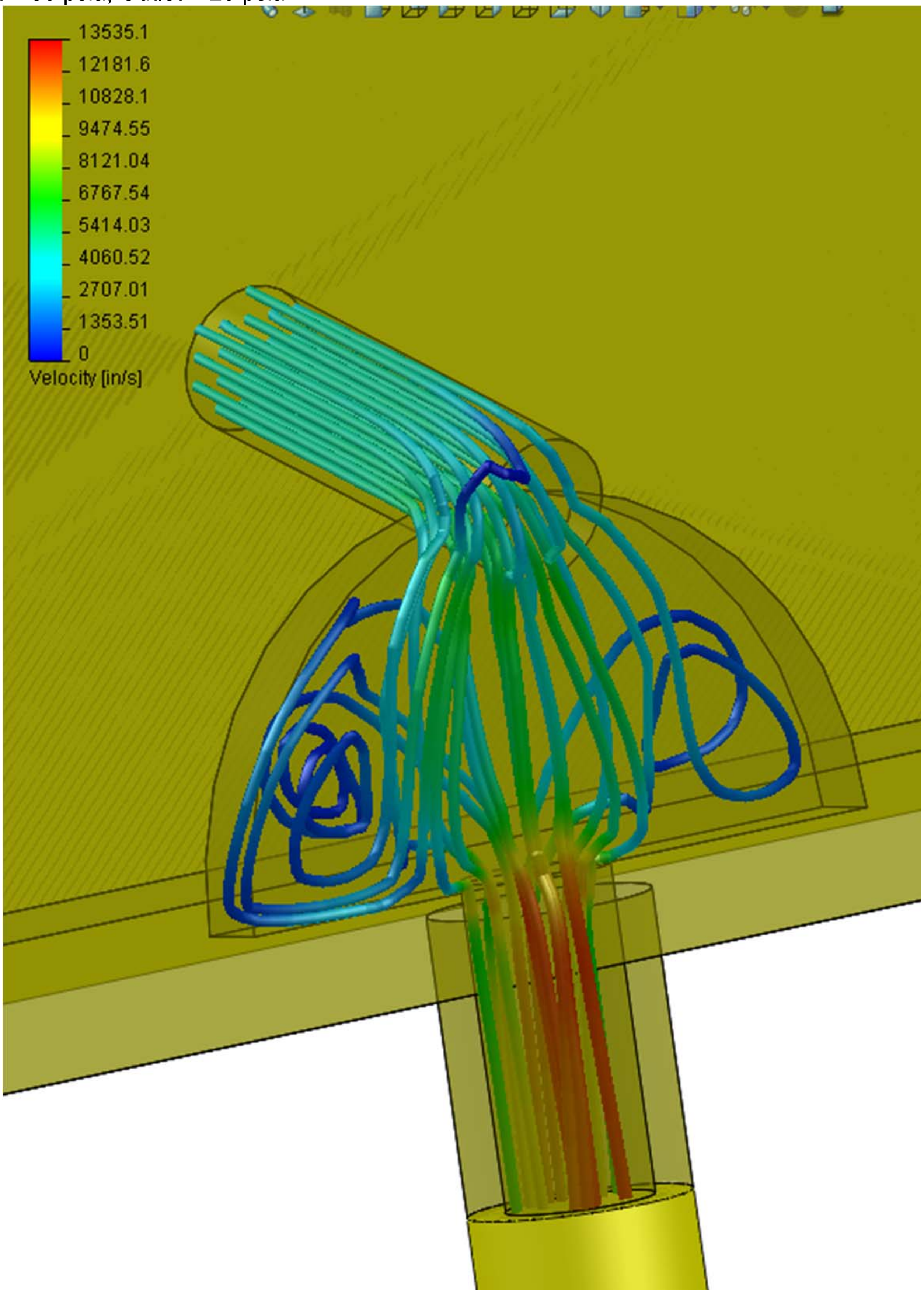
Appendix I: CFD Operating Predictions

The following images are the screenshots obtained in the iterations conducted within the SolidWorks2010 FlowXPress modeling add-in. In each image below, the working fluid was specified as air at 68 degrees Fahrenheit through the scaled standard test section geometry. The inlet and outlet pressures were the only parameters changed between iterations.

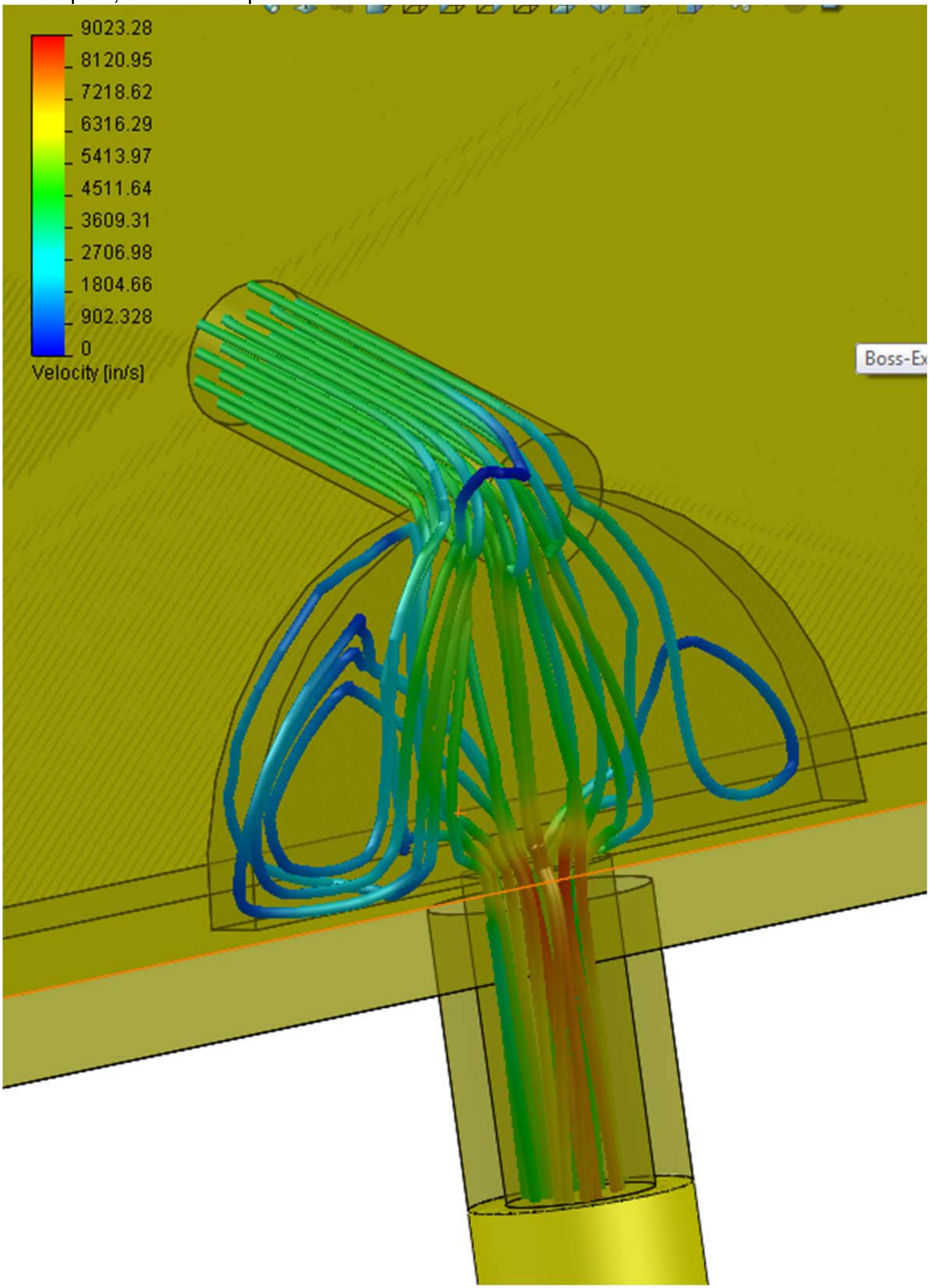
1. Inlet = 70 psia, Outlet = 20 psia



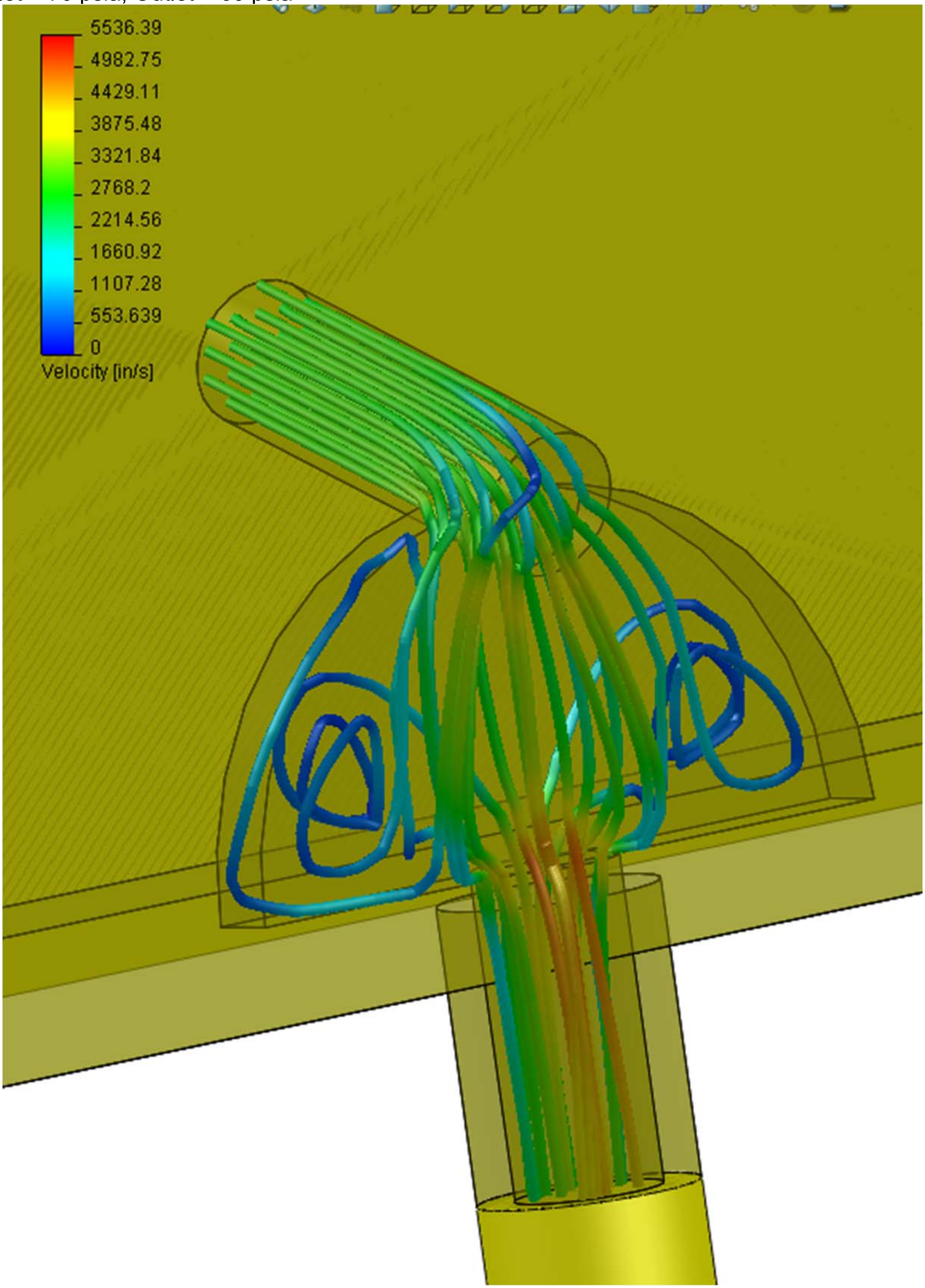
2) Inlet = 50 psia, Outlet = 20 psia



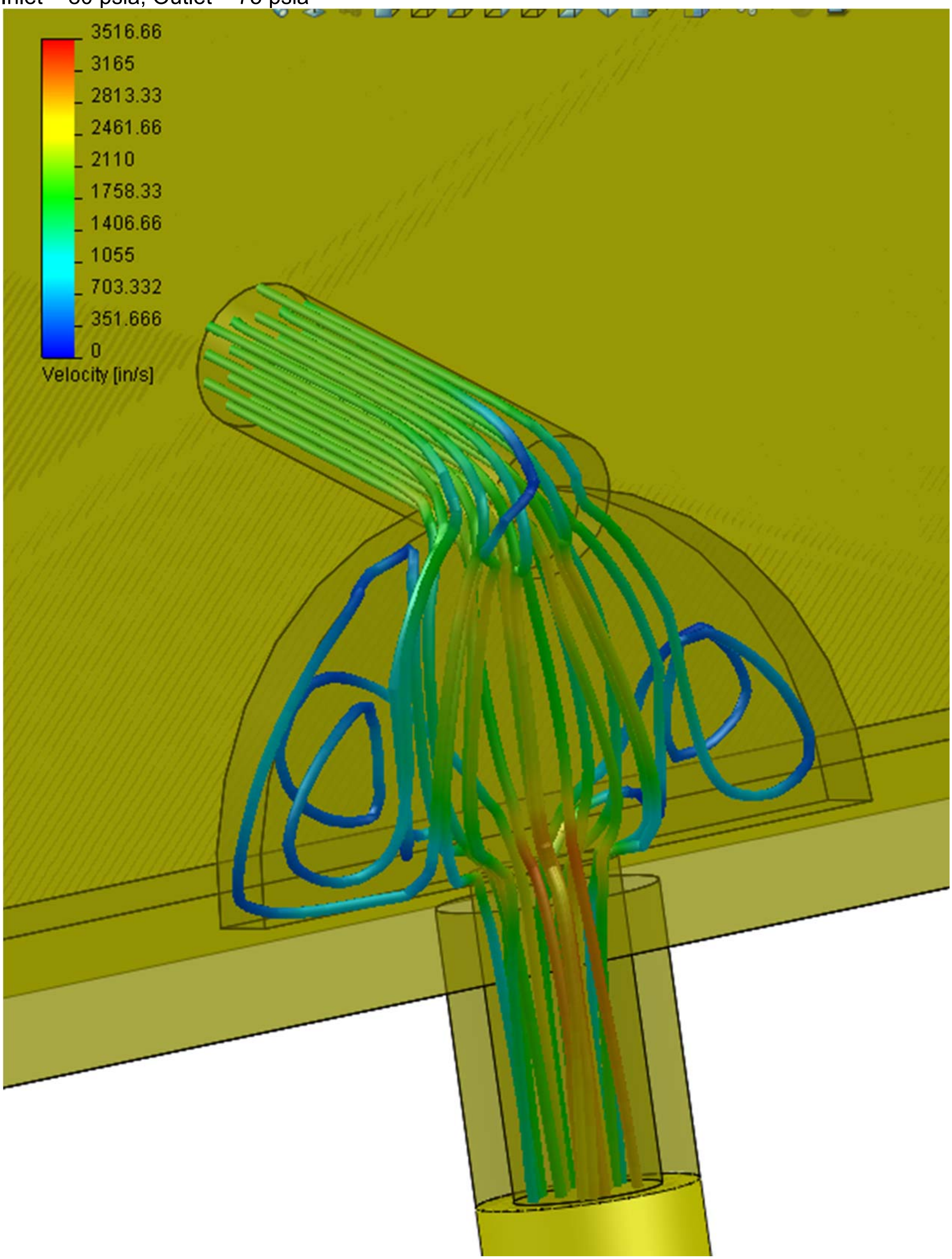
3) Inlet = 30 psia, Outlet = 20 psia



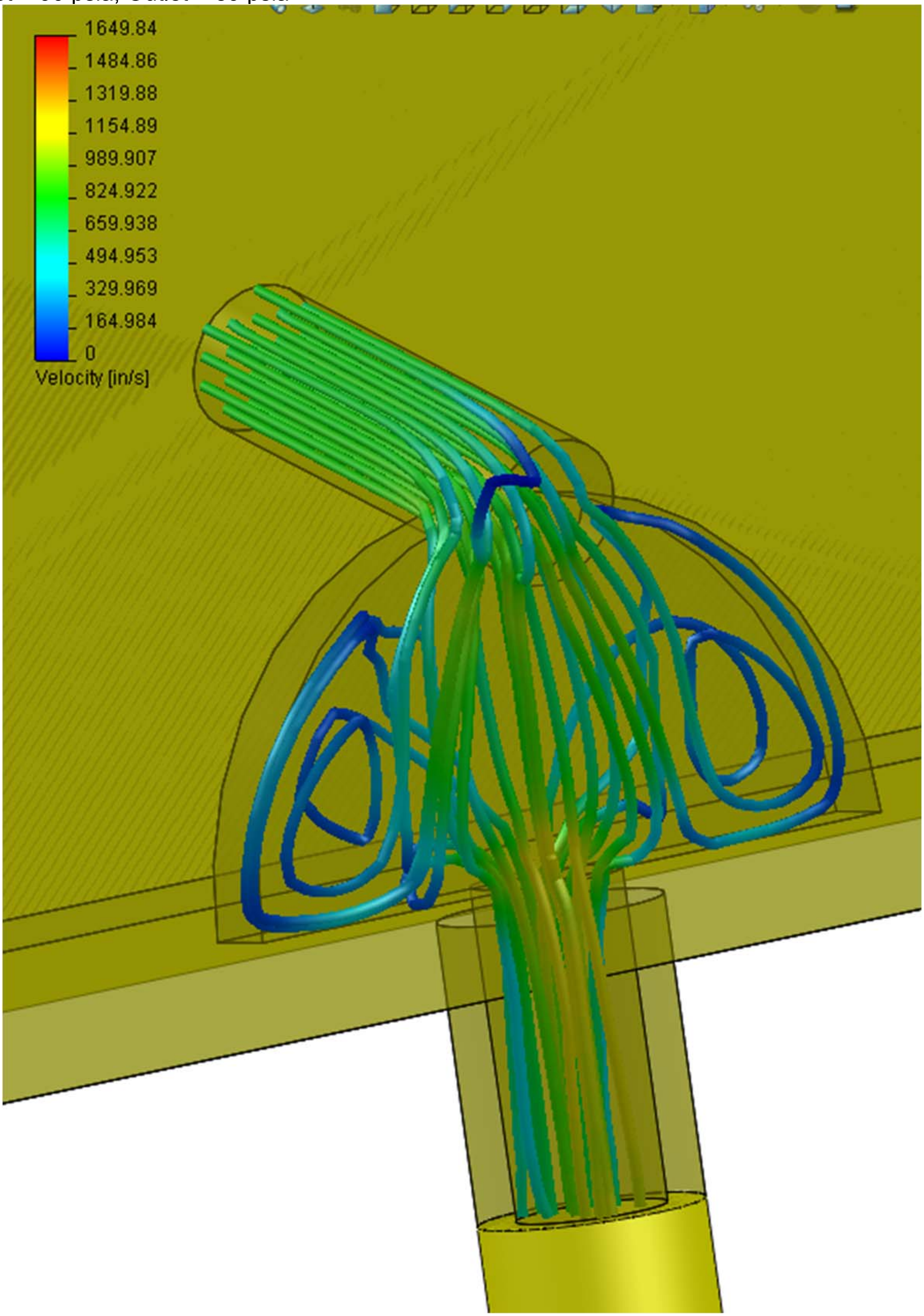
4) Inlet = 70 psia, Outlet = 60 psia



5) Inlet = 80 psia, Outlet = 75 psia



6) Inlet = 90 psia, Outlet = 89 psia



Appendix J: Estimated Operating Conditions

K		*1.5*	A (in2)		0.001364		
rho air (slug/ft3)		*2.33E-03*	*c air (ft/s)*		*1126.8*		
Pin (psi)	**Pout (psi)**	**V (ft/s)**	**V (in/s)**	**ACFM**	**SCFM**	**Mach No.**	**Delta P**
50-40							
50	49	287.06	3444.72	23.48504	79.88109	0.254757	1
50	48	405.9641	4871.569	33.21286	112.9689	0.360281	2
50	47	497.2025	5966.43	40.67728	138.3581	0.441252	3
50	46	574.12	6889.44	46.97008	159.7622	0.509514	4
50	45	641.8856	7702.628	52.51415	178.6195	0.569654	5
50	44	703.1505	8437.806	57.52636	195.6679	0.624024	6
50	43	759.4893	9113.872	62.13558	211.3455	0.674023	7
50	42	811.9282	9743.139	66.42572	225.9378	0.720561	8
50	41	861.1799	10334.16	70.45512	239.6433	0.76427	9
50	40	907.7634	10893.16	74.26622	252.6062	0.805612	10
60-50							
60	59	287.06	3444.72	23.48504	95.85731	0.254757	1
60	58	405.9641	4871.569	33.21286	135.5627	0.360281	2
60	57	497.2025	5966.43	40.67728	166.0297	0.441252	3
60	56	574.12	6889.44	46.97008	191.7146	0.509514	4
60	55	641.8856	7702.628	52.51415	214.3435	0.569654	5
60	54	703.1505	8437.806	57.52636	234.8015	0.624024	6
60	53	759.4893	9113.872	62.13558	253.6146	0.674023	7
60	52	811.9282	9743.139	66.42572	271.1254	0.720561	8
60	51	861.1799	10334.16	70.45512	287.5719	0.76427	9
60	50	907.7634	10893.16	74.26622	303.1274	0.805612	10
70-60							
70	69	287.06	3444.72	23.48504	111.8335	0.254757	1
70	68	405.9641	4871.569	33.21286	158.1565	0.360281	2
70	67	497.2025	5966.43	40.67728	193.7013	0.441252	3
70	66	574.12	6889.44	46.97008	223.667	0.509514	4
70	65	641.8856	7702.628	52.51415	250.0674	0.569654	5
70	64	703.1505	8437.806	57.52636	273.9351	0.624024	6
70	63	759.4893	9113.872	62.13558	295.8837	0.674023	7
70	62	811.9282	9743.139	66.42572	316.313	0.720561	8
70	61	861.1799	10334.16	70.45512	335.5006	0.76427	9
70	60	907.7634	10893.16	74.26622	353.6487	0.805612	10
80-70							
80	79	287.06	3444.72	23.48504	127.8097	0.254757	1
80	78	405.9641	4871.569	33.21286	180.7503	0.360281	2
80	77	497.2025	5966.43	40.67728	221.373	0.441252	3
80	76	574.12	6889.44	46.97008	255.6195	0.509514	4
80	75	641.8856	7702.628	52.51415	285.7913	0.569654	5
80	74	703.1505	8437.806	57.52636	313.0686	0.624024	6
80	73	759.4893	9113.872	62.13558	338.1528	0.674023	7
80	72	811.9282	9743.139	66.42572	361.5005	0.720561	8
80	71	861.1799	10334.16	70.45512	383.4292	0.76427	9
80	70	907.7634	10893.16	74.26622	404.1699	0.805612	10

Appendix K: Data Acquisition Resolution

The bit resolution of the DATAQ Data Acquisition System (DAS) is based upon the measurement accuracy of the pressure transducer. The following equation is provided by the DAS vendor to determine the appropriate bit resolution.

$$ADC\ bit\ resolution = \frac{log\left(\frac{V_D \times E}{R \times V_S}\right)}{\log(2)} + B$$

V_D– full-scale input voltage range of the data logger
V_S – full-scale output voltage range of the instrument
R – resolution of instrument measurement
E – max range of the instrument in the units of physical measure
B – unipolar equal to zero

In the case of the pressure transducers selected by PreFlow Systems for use in the Flow Test System, the variables are as follows. Also, the resolution, *R*, was determined by the dynamic pressure calculated from the operating range predictions.

V_D–10 V
V_S – 10 V
R – 0.03 psi
E – 100 psi
B – 0

$$ADC\ bit\ resolution = \frac{log\left(\frac{10\ V \times 100\ psi}{0.03\ psi \times 10\ V}\right)}{\log(2)} + 0$$

$$ADC\ bit\ resolution = \ 11.7\ bits$$

This requires a DAS with a rating of at least 12 bits. For the particular module selected in this project, a 13 bit rated DAS provides 12 bits for single ended use. Because the transducers are reading an absolute pressure, single ended use is required.

Appendix L: Stainless Steel Pipe Design

To determine if the stainless steel piping used in the apparatus could handle the internal pressure of 120 psi, calculations from the Process Piping Specification ASME B31.3a-1996, ASME Code for Pressure Piping. This summarized code is found in Aalco's stainless steel pressure rating article in Appendix V. The following equation is used to determine the max internal pressure for our schedule 40 piping.

$$P = \frac{2tSE}{D}$$

$$P = Internal\ Pressure \quad t = pipe\ thickness$$

$$S = Allowable\ Stress \quad D = Outside\ Diameter \quad E = Quality\ Factor$$

The piping used is ASTM A312 TP304L Stainless Steel with a thickness of 0.109 in and outside diameter of 0.84 in. From Aalco's data tables, the allowable stress was found to be 16.7 ksi and the quality factor was assumed to be 0.80 from the electric fusion welded pipe with single butt seam.

$$P = \frac{2tSE}{D} = \frac{2(0.109\ in)(16.7\ ksi)(0.80)}{0.84\ in} = 3.467\ ksi = 3{,}467\ psi > 120\ psi$$

In conclusion, the stainless steel piping chosen is safe for our operating conditions.

Appendix M: Bolt Analysis and Design

To analyze how many bolts were needed for connections between the transition piece, the test section and the steel flange, a bolt analysis was performed using the equations below from *Shigley's Mechanical Engineering Design.* All the bolt properties and material properties came from the text book as well. The governing equations are proved below.

$$load\ factor \qquad n = \frac{S_P A_t - F_i}{CP}$$

$$Separation\ factor \qquad n_o = \frac{F_i}{P(1 - C)}$$

$$Stiffness\ Constant\ of\ the\ Joint \qquad C = \frac{k_b}{k_b + k_m}$$

$$Force\ in\ member \qquad F_m = (1 - C)P - F_i$$

$$Torque\ for\ Preload \qquad T = KF_i d$$

$$Preload \qquad F_i \approx 0.75F_P$$

$$Proof\ Load \qquad F_P = S_P A_t$$

An excel sheet for both the inlet steel flange and the outlet transition piece where created with these equations. The resulting designs involve a four bolt pattern on the inlet flange and a 6 bolt pattern on the transition piece. For the 4 bolt pattern, the load factor was 17.92. For the 6 bolt pattern, the load factor was 10.52. Therefore, these designs are quite safe.

Inlet Flange Bolt Deign

Number of bolts	N =	4

Loads from Pressure			
Approximate Area of max flycut	A =	5	in^2
Max Pressure	Pi =	120	psi
External Load	P =	600	lb
Flange Dimensions			
thickness	t =	0.4375	in
Washer Dimensions			
thickness	t =	0.0625	in
Fixed Bolt Dimensions			
Diameter	D =	0.5	in
Thread per inch	N =	13	UNC
Required Length	L_r =	1.3125	in
Length	L =	1.5	in
Tensile Stress Area	At =	0.1419	in^2
Major Diameter Area	Ad =	0.19635	in^2
Modulus of Elasticity	E =	3.00E+07	psi
h =	0.5625	in	
L' =	0.8125	in	
Thread Length LT =	1.25	in	
Ld =	0.25	in	
Lt =	0.5625	in	
Bolt Grade	Steel Bolt		
SAE grade 2			
Proof Strength	Sp =	55	kpsi
Bolt Stiffness	kb =	5.73E+06	lb/in

Gasket Material			
Assume: Compressed asbetes and gasket is soft enough for using the gasket stiffness only for calc.			
Modulus of Elasticity	E =	7.00E+04	psi
Gasket Area	A =	1.932	in^2
thickness	t =	0.0625	in
Stiffness	kg =	2.16E+06	lb/in
Resulting Analysis			
Proof Load	Fp =	7805	lb
Recommended Preload			
Preload	Fi =	5853	lb
Torque needed for preload	K =	0.2	
Torque	T =	48.78	lb-ft
External load of each bolt	P =	150	lb
Stiffness Constant of the Joint	C =	0.7258	
Load Factor	n =	17.92	> 1 --> safe
Factor of Safety From Separation	n_o =	142.32	> 1 --> safe
Resulting Load on Flange For each bolt	Fm =	-5812.25	lb

PREFLOW SYSTEMS

Outlet Transition Piece

Number of bolts N = 6

Loads from Pressure			
pocketed width	w =	5	in
pocketed height	h =	2	in
Area of pocket	A =	10	in^2
Max Pressure	Pi =	120	psi
External Load	P =	1200	lb
Flange Dimensions			
Outside width	w =	7	in
Outside height	h =	4	in
Area of flange	A =	18	in^2
thickness	t =	0.4375	in
Washer Dimensions			
thickness	t =	0.0625	in
Fixed Bolt Dimensions			
Diameter	D =	0.5	in
Thread per inch	N =	13	UNC
Required Length	L_r =	1.3125	in
Length	L =	1.5	in
Tensile Stress Area	At =	0.1419	in^2
Major Diameter Area	Ad =	0.19635	in^2
Modulus of Elasticity	E =	3.00E+07	psi
h =	0.5625	in	
L' =	0.8125	in	
Thread Length			
LT =	1.25	in	
Ld =	0.25	in	
Lt =	0.5625	in	
Bolt Grade	Steel Bolt		
SAE grade 2			
Proof Strength	Sp =	55	kpsi
Bolt Stiffness	kb =	5.73E+06	lb/in

Gasket Material			
Assume: Compressed asbetes and gasket is soft enough for using the gasket stiffness only for calc.			
Modulus of Elasticity	E =	1.00E+04	psi
Gasket Area	A =	2.804	in^2
thickness	t =	0.0625	in
Stiffness	kg =	4.49E+05	lb/in
Resulting Analysis			
Proof Load	Fp =	7805	lb
Recommended Preload			
Preload	Fi =	5853	lb
Torque needed for preload			
	K =	0.2	
Torque	T =	48.78	lb-ft
External load of each bolt			
	P =	200	lb
Stiffness Constant of the Joint			
	C =	0.9274	
Load Factor	n =	10.52	> 1 --> safe
Factor of Safety From Separation			
	n_o =	402.99	> 1 --> safe
Resulting Load on Flange	Fm =	-5838.85	lb
For each bolt			

Appendix N: FEA Analysis with Mechanica

Verification Piece

From the vendor specifications in Appendix Q, the aluminum rod (88615K441) is an aluminum 2011 alloy and the yield strength was estimated with a conservative low value of 18 ksi. The two ends of the pipe were constrained for the analysis. With 120 psi loading the inside verification piece, the resulting Von Misses stress was 677.8 psi. This resulted in a safety factor of 26.55. Figure N1 and N2 show the results.

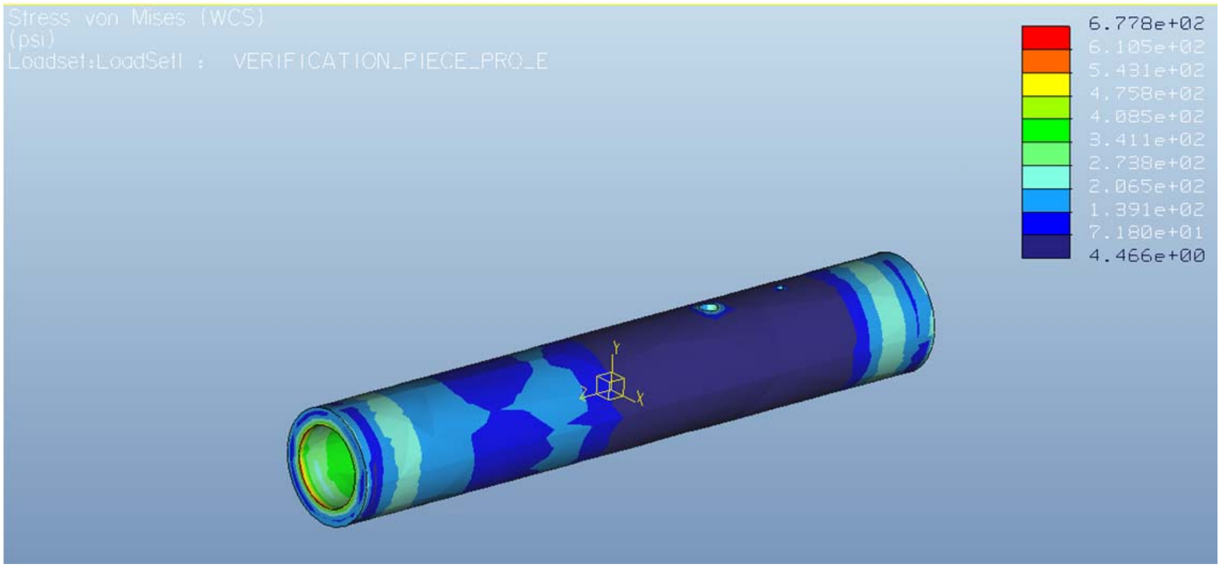


Figure N1. Resulting Von Misses stresses for the Verification Piece

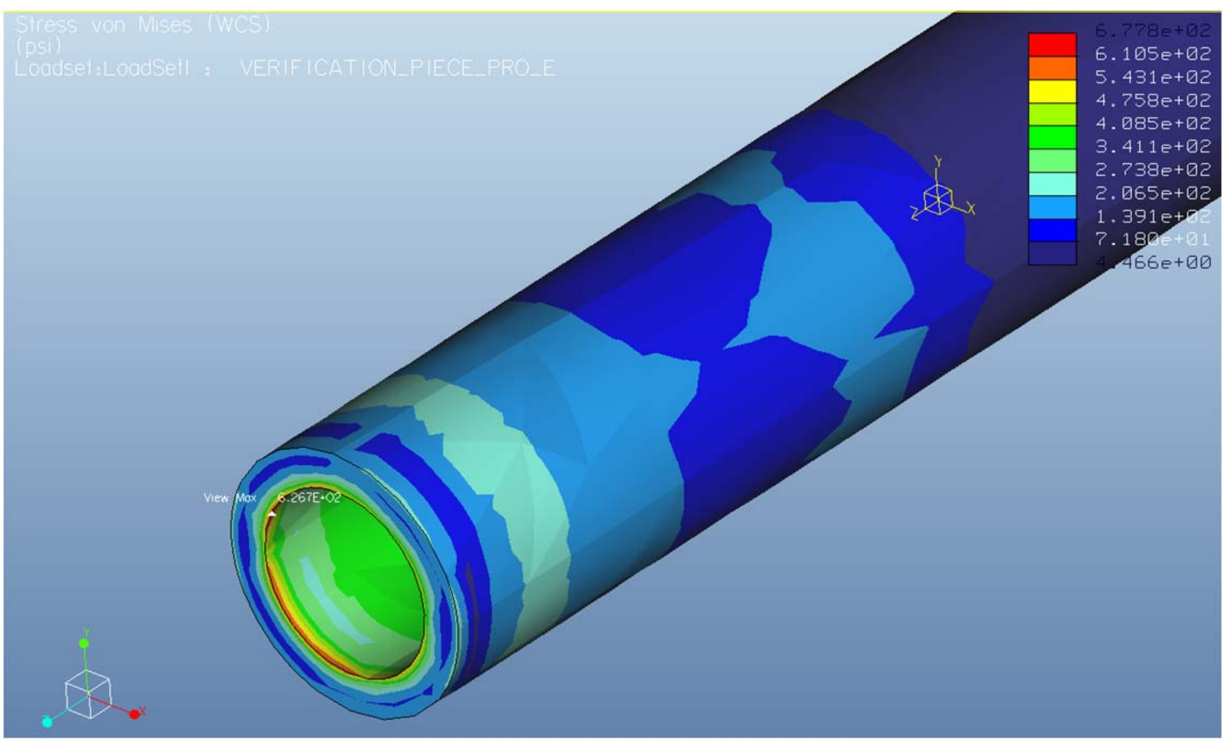


Figure N2. The highest Von Misses stresses for the Verification Piece at the far end of the piece.

Baseline Test Section

The aluminum blocks (89155K985) used for test section are an aluminum 6061 alloy with a yield strength of around 40 ksi as stated from the vendor specifications in Appendix Q. From the bolt analysis in Appendix M, the bolt force on the member was used with the pressure to model the loading of the test section. With a proof strength of 55 ksi for the bolt, a force of 5,800 lb from preload was applied at each bolt hole. In addition, a 120 psi pressure load was used inside the geometry. Both surfaces in contact with the connecting flange and transition piece were constrained. The resulting Von Misses stress was 3.44 ksi, causing a safety factor of 11.63. Figure N3 shows the results.

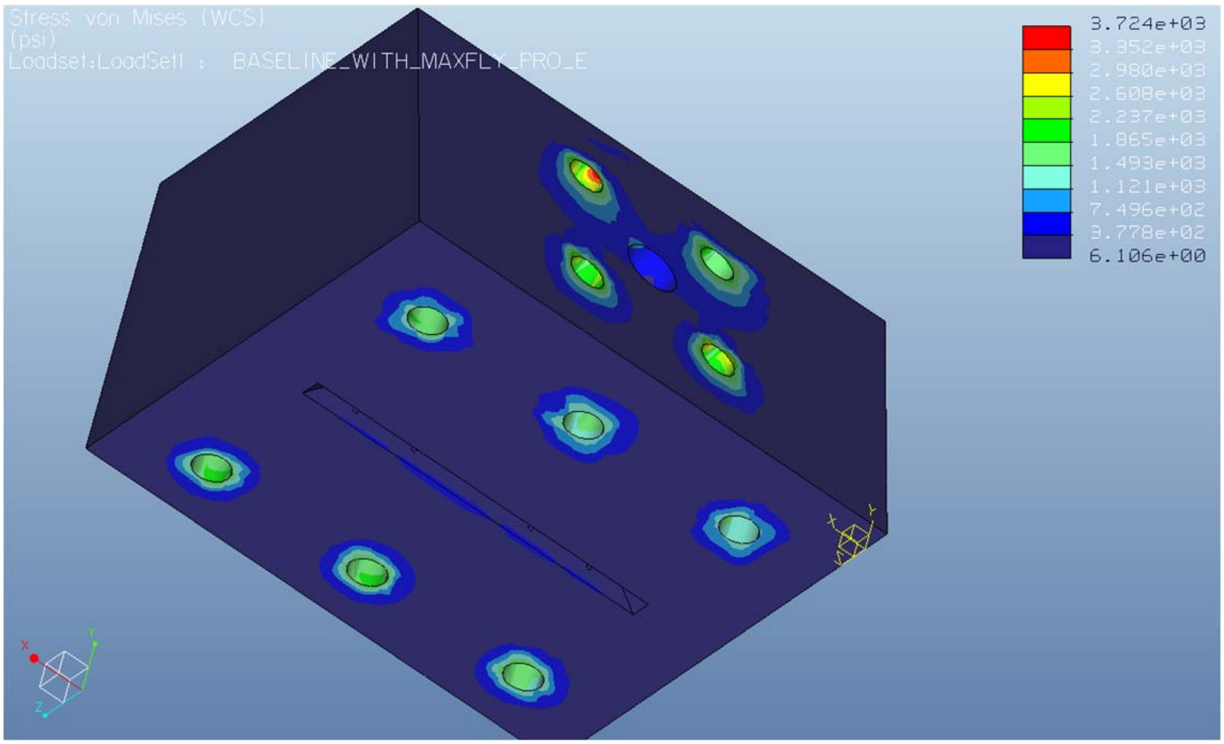


Figure N3. Test Selection Block with resulting Von Misses Stresses from loading case.

Transition piece

The transition piece is made of Aluminum 6061 Alloy as well and it was loaded with the same pressure and force conditions as the baseline test section (120 psi with 5,800 lb on each bolt hole). For the first configuration, the piece was constrained on the flat surface of the outlet one inch hole. The resulting Von Misses stress was 17.63 ksi which produces a safety factor of 2.27. Figure N4 shows the results.

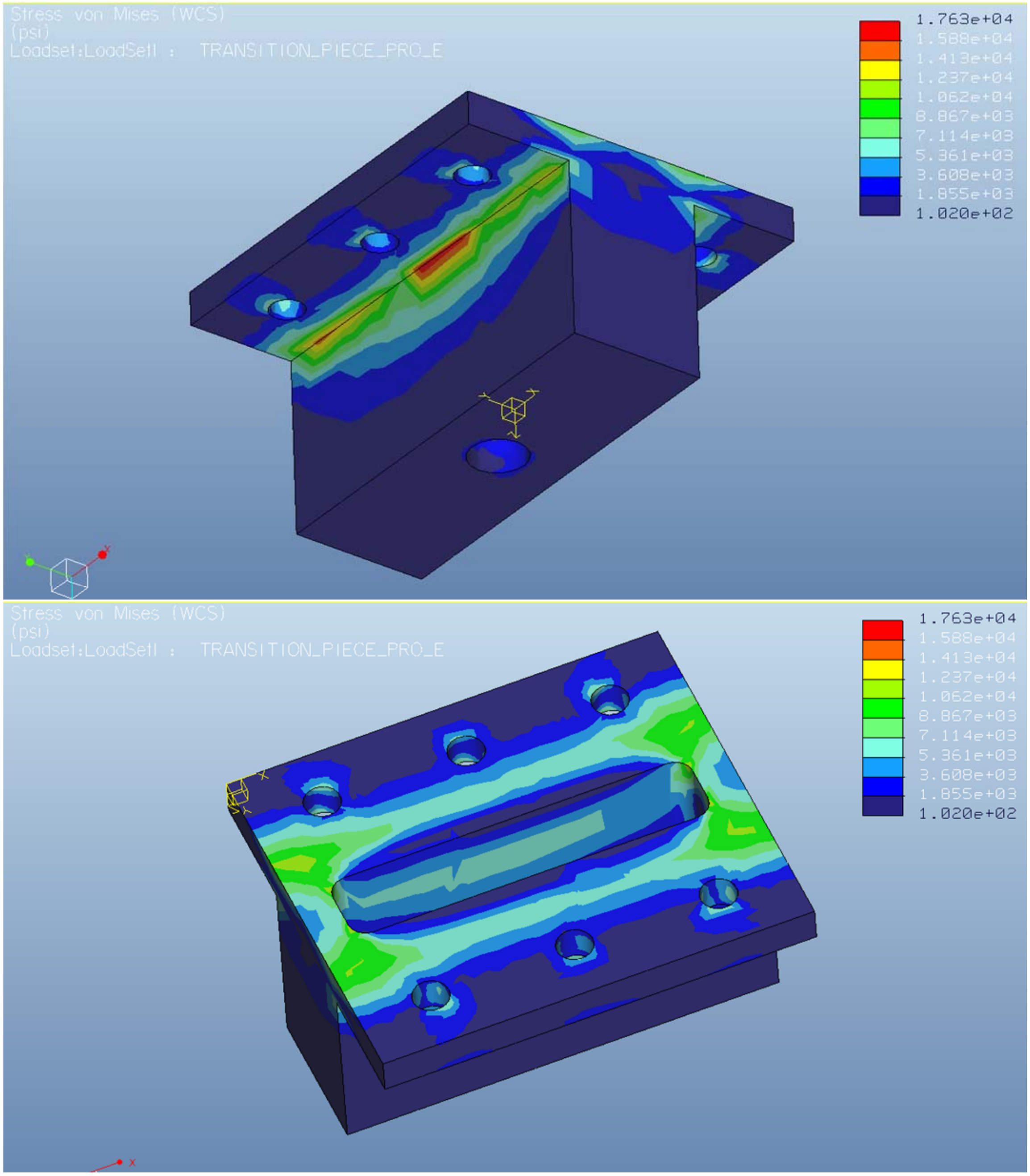


Figure N4. Transition Piece constrained only on one surface with pressure and bolt forces applied.

For the second configuration, additional constraints were added. Pin constraints were added to the bolt holes. The resulting Von Misses stress was 27.9 ksi which produces a safety factor of 1.43. The highest stresses were at the bolt holes. Figure N5 shows the results.

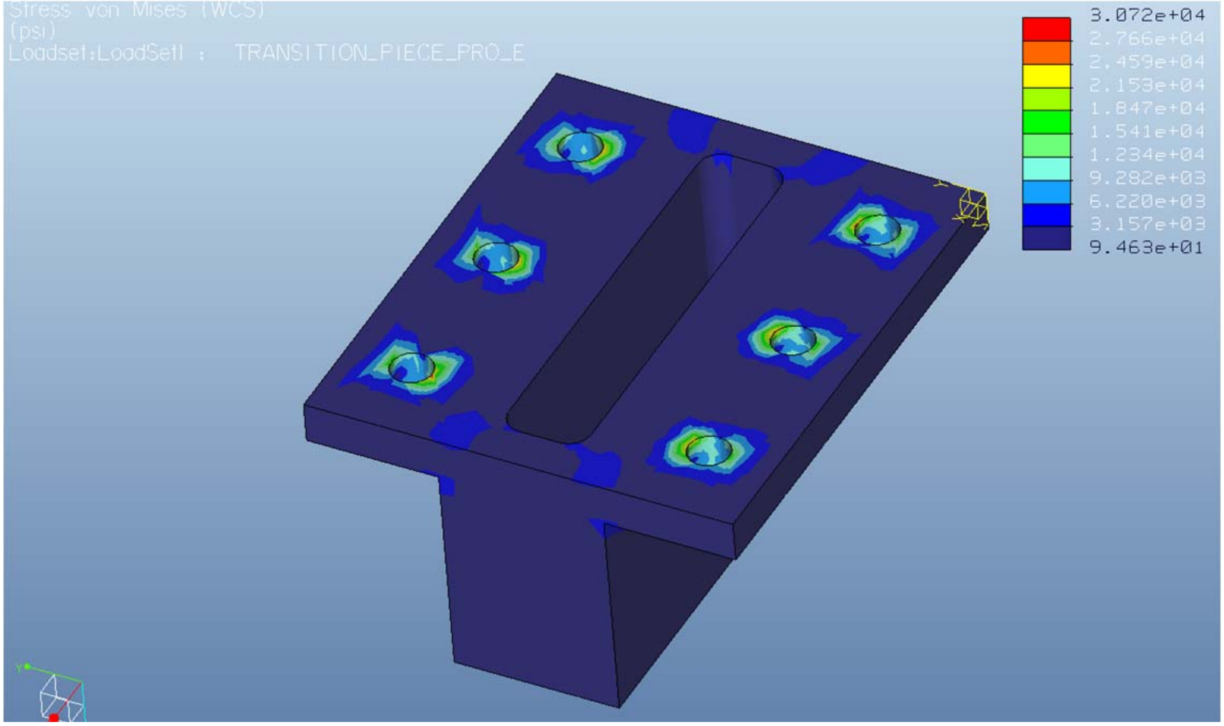


Figure N5. Transition Piece constrained with pin and surface constraints.

For the third configuration, the effect of the pressure loading was evaluated. The transition piece was loaded with only the 120 psi and constrained with the pin bolt holes and at the lower surface. The resulting Von Misses stress was 2.87 ksi which produces a safety factor of 13.94. Again, the highest stresses were at the bolt holes. Figure N6 shows the results.

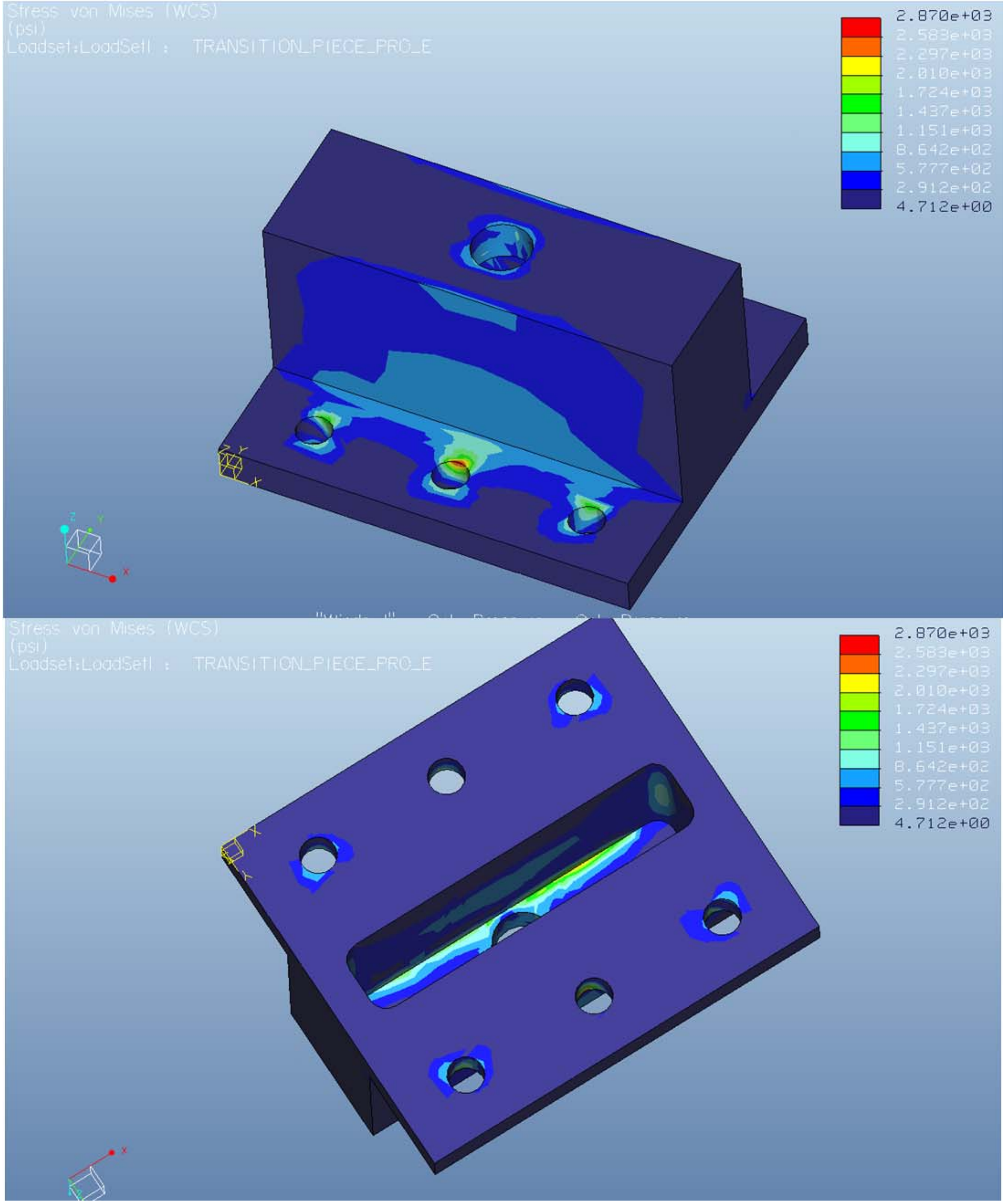


Figure N6. Transition Piece with only the pressure loading.

Appendix O: Vendor Information

Vendors	Number of Parts
McMaster-Carr	22
Omega	4
Home Depot	7
DATAQ	1
Amazon	1
Bolt Depot	1

McMaster-Carr

Contact Info:

E-Mail: la.sales@mcmaster.com
Sales and Customer Service
(562) 692-5911 (562) 463-4277
Fax (562) 695-2323
Mail
P.O. Box 54960 Los Angeles, CA 90054-0960
Street Address
9630 Norwalk Blvd. Santa Fe Springs, CA 90670-2932

Omega

Contact Info

Email: cservice@omega.com
OMEGA Engineering, INC.
One Omega Drive
P.O. Box 4047
Stamford, Connecticut 06907-0047
(800)-848-4286 or (203)-359-1660
Fax: (203)-359-7700

Home Depot

Contact Info

Email: homedepot.com
1551 Froom Ranch Rd
San Luis Obispo, CA 93405
(805)596-0857
STORE HOURS
Mon-Sat: 6:00am-10:00pm
Sun: 8:00am-8:00pm

DATAQ

Contact Info

Email:info@dataq.com
DATAQ Instruments, Inc.
241 Springside Drive
Akron, OH 44333
Tel: 330-668-1444
Fax: 330-666-5434
Hours: 8am to 5pm Eastern Time Monday through Friday

Amazon

Contact Info

Email: copyright@amazon.com
Amazon.com, Inc.
P.O. Box 81226
Seattle, WA 98108-1226
http://www.amazon.com
Phone: (206) 266-4064
Fax: (206) 266-7010

Bolt Depot

Contact Info

Email: info@boltdepot.com
286 Bridge Street (Rt. 3A)
North Weymouth, MA 02191
Phone: 1-866-337-9888 (toll free)
1-781-337-9888

Appendix P: Bill of Materials

	DESCRIPTION	MODEL	VENDOR	PART NUMBER	QTY	PRICE
MAIN COMPONENTS	Hygrometer	Extech Big Digit Hygro Thermometer	Instrumart	445703	1	$41.99
	Pressure Regulator	Brass High Capacity Pressure Regulator 1/2 NPT Female, 40 - 80 PSI with Gauge Ports	mcmaster-carr	5022K354	1	$226.05
	Back Pressure Regulator	Aluminum Adjustable Pressure-Maintaining Relief Valves	mcmaster-carr	4783K55	1	$125.80
	Power Supply	Dual output barrier strip, ±15 or 30 V output, +50 mA output, ±0.5% volt accuracy, ±0.02% line & load w/ power cord	Omega	PSS-D15A	1	$152.00
	Pressure Transducer	Absolute,Range/Units: 100 PSI,Output: 0-5 Vdc,Accuracy: +/-0.05% (PSI units only)	Omega	MMA100V10P2D0T3A5	3	$2,055.00
	Data Acquisition System	DATAQ DI-158, 12 bits, +/- 10V, 4 differential inputs	DATAQ		1	$100.00
	Air Pressure Guage	Operating Pressure Range (psi) 0 to 100 Numeral Increments (psi) 20 Graduation Marks (psi) 5	mcmaster-carr	38105K32	2	$30.00
	Kiel Probe	Supplied by Solar Turbines	FlowKinetics	-	1	$0.00
	Pressure Relief Valve	Adjustable Relief Valve Brass, 1/2 NPT Female, 40-125 PSI, Set @ 90 PSI	mcmaster-carr	4706K264	1	$230.24
CONNECTIONS	Quick Disconnect Coupler	Power Care 1/4 in. Male to 1/4 in. Female Quick-Connect NPT Coupler (Home Depot)	Home Depot	719874	1	$8.98
	NPT Bushing	Type 304 Stainless STL Threaded Pipe Fitting 1/2" Male X 1/4" Female, Hex Reducing Bushing, 150 PSI	mcmaster-carr	4464K265	1	$2.97
	4 in pipe	Std-Wall Type 304/304L SS Thrd Pipe Nipple 1/2" Pipe X 4" Length, 13/16" Thread Length (mcmaster)	mcmaster-carr	4830K176	6	$30.78
	18 in pipe	Standard Wall Black Welded Steel Pipe 1/2" Pipe X 18" L, Thrded Ends, Sch 40	mcmaster-carr	4457K114	1	$4.39
	9 in pipe	Std-Wall Type 304/304L SS Thrd Pipe Nipple 1/2" Pipe X 9" Length, 13/16" Thread Length	mcmaster-carr	4830K216	1	$9.89
	NPT Bushing	Precision Threaded Steel Pipe Fitting 1/4" Male X 1/8" Fem, Hex Reducing Bushing, 6400 PSI	mcmaster-carr	5232T377	1	$4.05
	Pipe Bushing	Type 304 Stainless STL Threaded Pipe Fitting 1/2" Male X 1/8" Female, Hex Reducing Bushing, 150 PSI	mcmaster-carr	4464K264	1	$2.97
	Pipe Tee	Type 304 Stainless STL Threaded Pipe Fitting 1/2" Pipe Size, Tee, 150 PSI	mcmaster-carr	4464K51	1	$7.18
	Static Tap	Polypropylene Barbed Tube Fitting 1/16" Tube ID X 10-32 UNF Male Thread, Max 125 psi	mcmaster-carr	5121K311	2	$5.56
	Static Tee	Nickel-Pltd Brass Barbed Vacuum Tube Fitting Tee for 1/16" Tube ID, Max Pressure 150 psi	mcmaster-carr	2844K41	4	$10.24
	Adapter for Transducer	Aluminum Single-Barbed Tube Fittings Adapter for 1/16" Tube ID X 1/4" NPT Male, Black	mcmaster-carr	5058K412	3	$11.25
	Plastic Tubing	Abrasion-Resistant Clear PVC Tubing 1/16" ID, 1/8" OD, 1/32" Wall Thickness, Max pressure 120 psi	mcmaster-carr	5006K51	1	$3.50
	Bolts	#244 - Hex bolts, Standard bolts, Steel grade 2,1/2-13 X 1-1/2 Each	Bolt Depot	244	10	$3.20
	Washers	Type B Zinc-Plated Steel Flat Washer 1/2" Screw Size, 1" Narrow OD, .05"-.12" Thk	mcmaster-carr	94744A285	2	$8.86
	Flange	Threaded Flange,NPT x NPT,Pipe Size 1/2",Maximum Pressure @ 72° F 150 psi, Steel	mcmaster-carr	68095K226	1	$12.35
	Gasket Material	1/16" Thick, 12" X 12", SBR Rubber Sheet Gasket	mcmaster-carr	8525T11	1	$2.38
	Flange Gasket	Aramid/Buna-N Flange Gasket Full Face, for 1/2" Pipe, 27/32" ID, 3-1/2" OD	mcmaster-carr	9472K56	1	$1.74
	J-B Weld Epoxies	J-B Weld Epoxy Hardens in 60 min	mcmaster-carr	7605A12	1	$16.62
	Teflon Tape	Orbit 1/2 In. x 520 In.Thread Seal Tape	Home Depot	788287	1	$1.18
	Wood Support	2 in. x 4 in. x 7-1/4 ft. Douglas Fir Stud	Home Depot	603503	5	$10.95
	Wood Screw		Home Depot		4	$4.00
	Pipe Tap	Vermont American (VER20354) TAP PIPE 1/2-14NPT	Amazon	VER20354	1	$11.16
	Plywood	19/32" X 4 ' X8 '	Home Depot	3261635	1	$31.17
	Rope	240 lb Rope	Home Depot	183072	1	$11.97
	Lock Tight	Loctite® General Anaerobic Adhesive Threadlocker 220, 0.34 Ounce, 10 ml Bottle	mcmaster-carr	1810A315	1	$11.50
MACHINED PARTS	Aluminum Blocks	Multipurpose Oversize Aluminum (Alloy 6061) 3-1/2" Thick, 6" X 6"	mcmaster-carr	89155K985	10	$1,044.40
	Aluminum Rod	Easy-to-Machine Aluminum (Alloy 2011) 1" Diameter, 1' Length	mcmaster-carr	88615K441	1	$19.28
	Rapid Prototyping	-	-	-	-	$0.00
	Machining	-	-	-	-	$0.00
	Wheels	Home depot shephard 2 in rubber wheel swivel plate 125 load rating	Home Depot	433004	4	$15.84
				SUBTOTAL		$4,269.44
				SHIPPING ESTIMATE	15%	$640.42
				TOTAL		$4,909.86

Appendix Q: Vendor Specification Sheets

Attached in order as listed on Bill of Materials

EXTECH INSTRUMENTS Product DATASHEET

Big Digit Hygro-Thermometers

Simultaneous display of Temperature and Humidity

Features:

- Attractive design for desktop or wall mounting
- Large LCD displays of Temperature and Humidity
- Max/Min memory with reset for Temperature and Humidity
- Switchable °C or °F temperature units
- Complete with built-in tilt stand, wall mounting bracket and AAA battery

445713 Additional Features

- Dual indoor/outdoor Temperature and Humidity displays
- Remote "outside" sensor on 35" (89cm) cable

445715 Additional Features

- Remote sensor on 35" (89 cm) cable
- User accessible temperature and humidity calibration adjustments
- Available with a NIST traceable certification
- Optional RH calibration bottles

445703 Big Digit Hygro-Thermometer

445713 Big Digit Indoor/Outdoor Hygro-Thermometer

445715 Big Digit Remote Probe Hygro-Thermometer

CE

Specifications:	445703	445713	445715
Humidity range	10 to 99%RH	10 to 99% RH	10 to 99% RH
Basic RH accuracy	± 5% (25 to 85%)	± 5% (25 to 85%)	± 4% (25 to 85%)
Temperature range	14 to 140°F (-10 to 60°C)	14 to 140°F (-10 to 60°C)	14 to 140°F (-10 to 60°C)
Basic Temperature Accuracy	±1.8°F/1°C (14 to 122°F)	±1.8°F/1°C (14 to 122°F)	±1.8°F/1°C (14 to 122°F)
Dimensions	4.3x3.9x0.78"(109x99x20mm)		
Weight	6 oz (169g)		

445580-C Optional calibration salt bottles for 445715

Ordering Information:

445703 ....Big Digit Hygro-Thermometer
445713 ....Big Digit Indoor/Outdoor Hygro-Thermometer
445715 ....Big Digit Remote Probe Hygro-Thermometer
445715-NIST ..Big Digit Remote Probe Hygro-Thermometer with NIST certificate
445580-C ....Optional 33% and 75% RH calibration bottles for 445715

1 WARRANTY YEAR

EXTECH INSTRUMENTS CORPORATION
285 Bear Hill Road, Waltham, MA 02451-1064, U.S.A.
Phone: 781-890-7440 • FAX 781-890-7864

ISO 9001:2000 CERTIFIED

"Make mine an Extech!™"
www.extech.com

08/01/07 - R1

For information about pipe size, see pages 2-3.

Brass Pressure Regulators

Reduce your inlet pressure down to the exact outlet pressure you need. Pressure ranges are factory set at the midpoint.

Standard have a Buna-N seal, a Buna-N diaphragm, and an internal strainer to keep out debris. Use with air, water, oil (up to 300 SSU), and gas. Ideal for humidifiers and air tools. Maximum inlet pressure is 250 psi. Temperature range is –20° to +180° F. *Valves with gauge port* have a 1/4″ NPT female side gauge port.

High capacity allow higher flow rates than standard regulators. Have a Buna-N seal and neoprene diaphragm. Use with air, water, oil (up to 300 SSU), and gas. Maximum inlet pressure is 400 psi. Temperature range is –20° to +180° F. *Valves with gauge ports* have two 1/4″ NPT female side gauge ports. They include a plug to close off one port.

Cryogenic are suitable for cryogenic fluids such as liquid oxygen, nitrogen, argon, and carbon dioxide. They are cleaned, degreased, and packaged for oxygen service and have a PTFE seal and bronze diaphragm. Maximum inlet pressure is 600 psi. Temperature range is –300° to +150° F.

Connections: NPT female.

To Order: Please specify outlet pressure range from those listed in the table.

Standard and Cryogenic

High Capacity w/Gauge Ports

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.	*Without Gauge Port(s)*	Each	*With Gauge Port(s)*	Each
Standard						
1/4″	2-30, 10-50, 25-90, 80-120, 100-180	2 1/4″	4677K51	$106.86	4677K61	$128.10
3/8″	2-30, 10-50, 25-90, 80-120, 100-180	2 1/4″	4677K55	106.86	4677K65	128.10
High Capacity						
1/4″	0-5, 2-35, 20-70, 60-125, 75-200, 100-250	2 1/2″	5022K21	184.99	5022K41	199.29
3/8″	0-5, 2-35, 20-70, 60-125, 75-200, 100-250	2 1/2″	5022K23	184.99	5022K43	199.29
1/2″	0-5, 2-25, 20-60, 40-80, 75-125, 75-200, 100-250	2 7/8″	5022K25	208.35	5022K45	226.05
Cryogenic						
1/4″	15-65, 75-175, 100-250	2 1/4″	47435K31	152.97	———	———
3/8″	15-65, 75-175, 100-250	2 1/4″	47435K32	152.97	———	———

Brass High-Purity Pressure Regulators

Suitable for specialty gases such as argon, helium, hydrogen, neon, nitrogen, nitrogen monoxide, oxygen, carbon monoxide, and xenon. Cleaned, degreased, and packaged for oxygen service per Canadian Gas Association 4.1. They have a fluoroelastomer seal, a Buna-N diaphragm with a PTFE liner, a T-handle for adjusting outlet pressure, and two 1/4″ NPT female side gauge ports. Not factory set at a specific pressure. Maximum inlet pressure is 435 psi. Temperature range is –40° to +165° F.

Connections: NPT female.

To Order: Please specify outlet pressure range from those listed in the table.

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.		Each
1/2″	5-55, 40-110, 100-200	3 5/8″	49305K21	$151.09
3/4″	5-55, 40-110, 100-200	4 11/16″	49305K22	186.67
1″	5-55, 40-110, 100-200	4 11/16″	49305K23	186.67

Nickel-Plated Brass Subminiature Pressure Regulator

Our smallest pressure regulator is nickel-plated for corrosion resistance. Use with water, oil, and gas. Seals are Buna-N. Panel mount in a 1/2″ cutout. Not factory set at a specific pressure. Maximum inlet pressure is 125 psi. Temperature range is –25° to +180° F. *Note:* Length is measured from the side of the regulator to the center of the inlet connection.

Connections: Bottom UNF straight-threaded inlet and side UNF straight-threaded outlet.

Thread Size	Outlet Pressure Range, psi	Lg.		Each
10-32	5-80	3/8″	3834T51	$25.52

Brass Precision Low-Pressure Regulators

Precision regulators compensate for even the slightest fluctuation in inlet pressure to keep your outlet pressure constant. Use in low-pressure water and No. 2 fuel oil applications. An internal strainer keeps out debris. Seal is Type 303 stainless steel. Diaphragm is Buna-N. Maximum inlet pressure is 300 psi. Temperature range is 0° to 120° F.

Connections: NPT female.

To Order: Please specify outlet pressure range from those listed in the table.

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.		Each
1/4″	0-8, 0-20, 0-50	4 1/4″	3878T41	$173.78

Brass Miniature Pressure Regulators

These small regulators fit into tight spaces to supply water to small tanks. Listed by the International Association of Plumbing and Mechanical Officials (IAPMO), unless noted. Seal and diaphragm are Buna-N. Available with and without a pressure gauge. Factory set at 40 psi, unless noted. Temperature range is 0° to 140° F.

Connections: NPT female or female garden hosexmale garden hose. **To Order:** Please specify outlet pressure range from those listed in the table.

With NPT Female Connections max. inlet pressure is 300 psi. ***With Garden Hose Connections*** max. inlet pressure is 150 psi.

With Gauge and Garden Hose Connections

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.	*Without Gauge*	Each	*With Gauge*	Each
With NPT Female Connections						
1/8″	0-25, 0-60, 0-125	1 1/2″	3823T11★	$48.34	3823T31★	$69.67
1/4″	0-25, 0-60, 0-125	1 1/2″	3823T12★	48.34	3823T32★	69.67
With Garden Hose Connections						
3/4″	10-60	3″	3823T21	45.76	3823T41	65.87

★ Not IAPMO listed. 0-25 psi factory set at 15 psi; 0-125 psi factory set at 80 psi.

Brass High-Pressure Regulators

A PTFE seal and Type 316 stainless steel diaphragm make these regulators suitable for inlet pressures up to 3500 psi. They can be used with corrosive and toxic gases, as well as air, argon, nitrogen, helium, and hydrogen. Regulators have an internal strainer to keep out particles and include gauge ports. Meets ANSI/ASME B31.3. Pressure is factory set at 0 psi. Temperature range is –15° to +165° F.

Connections: NPT female.

To Order: Please specify outlet pressure range from those listed in the table.

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.		Each
1/4″	0-25, 0-50, 0-100, 0-250, 0-500	2″	3811T11	$246.43

Brass Extreme-Pressure Regulators

The rugged design of these regulators make them capable of handling inlet pressures up to 6000 psi. Use with air, nitrogen, argon, and helium. They have a Vespel seal and an internal strainer that keeps out unwanted particles. Meets ANSI/ASME B31.3. Not factory set at a specific pressure. Temperature range is –40° to +165° F.

Connections: NPT female.

To Order: Please specify outlet pressure range from those listed in the table.

Pipe Size	Available Outlet Pressure Ranges, psi	Port-to-Port Lg.		Each
1/4″	0-500, 0-800, 10-1500, 15-2500, 25-4000, 50-6000	2 1/8″	3950T21	$669.64

Brass and Bronze Extended-Life Adjustable Relief Valves

High Accuracy

Pressure Maintaining

High Pressure

Made from a rugged bronze casting (unless noted) for long life in heavy duty applications. All are factory set at the midpoint of the pressure range.

High-accuracy valves have fine screw threads for more accurate adjustment and greater flow rates. For use with water and oil. Body is brass for ½″ and ¾″ sizes; body is bronze for 1″ and larger sizes. Seal is metal to metal and spring is Type 302 stainless steel. Temperature range is –60° to +406° F.

Connections: NPT male bottom inlet; NPT female side outlet.

To Order: Please specify pressure range: 0-14, 15-25, 26-40, 41-75, 76-110, 111-130, 131-150, 151-200, or 201-400 psi.

Pressure-maintaining valves are ideal for back-pressure relief in hydraulic systems and for hydraulic pumping units where a discharge pressure must be maintained. Use with water, liquids, and light fuel oils. They have a metal-to-metal seal and Type 302 stainless steel spring. Temperature range is –40° to +450° F.

Connections: NPT female bottom inlet and side outlet.

To Order: Please specify pressure range: 15-75, 50-150 (50-140 psi for ¼″ and ⅜″ sizes), 100-300, or 200-600.

High-pressure valves are for use with liquids only. They handle higher pressures than high-accuracy and pressure-maintaining valves. Choose a Type 316 stainless steel or fluoroelastomer soft seal. Spring is Type 316 stainless steel. Temperature range is –10° to +406° F.

Connections: NPT male bottom inlet and NPT female side outlet.

To Order: Please specify pressure range in psi: 15-75, 50-150, 100-300, 200-600, or 600-900. *Note:* 1½″ pipe size is not available in 600-900 psi pressure range.

High Accuracy

Pipe Size	Ht.		Each
½″	3¾″	4703K54	$114.44
¾″	3⅝″	4703K55	116.80
1″	4⅞″	4703K56	135.43
1¼″	5¼″	4703K57	177.69
1½″	6¼″	4703K58	213.30
2″	7⅛″	4703K59	316.26
3″	8⅜″	4703K62	773.80

Pressure Maintaining

Pipe Size	Ht.		Each
¼″	4¼″	4662K46	$162.81
⅜″	4¼″	4662K48	162.81
½″	5⅝″	4662K32	253.56
¾″	5⅝″	4662K34	253.56
1″	7⅞″	4662K36	527.66
1¼″	7⅞″	4662K38	527.66

High Pressure

Type 316 Stainless Steel Seal

Pipe Size	Ht.		Each
½″	4⅞″	4460K81	$322.87
¾″	4⅞″	4460K82	344.81
1″	4⅞″	4460K83	383.17
1¼″	5″	4460K84	427.11
1½″	5⅞″	4460K85	516.89

Fluoroelastomer Soft Seal

Pipe Size	Ht.		Each
½″	4⅞″	4460K91	$357.12
¾″	4⅞″	4460K92	392.55
1″	4⅞″	4460K93	429.30
1¼″	5″	4460K94	476.49
1½″	5⅞″	4460K95	566.29

Cast Iron Adjustable Pressure-Maintaining Relief Valves

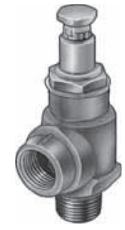
Also known as back-pressure relief valves and back-pressure regulators, these cast iron valves can be used with oil and corrosive and viscous liquids. They maintain your adjusted set pressure at the inlet regardless of the outlet pressure. If the set pressure is exceeded, the excess is vented through the bottom relief port. Use in centrifugal, reciprocating, and rotary pump bypass applications. Not for use with steam. Pressure is factory set at mid-range, but is adjustable to any pressure within the range. All have a Monel diaphragm with series 300 stainless steel seal. Temperature range is –40° to +200° F.

Connections: NPT female side inlet and outlet and vented bottom relief port.

To Order: Please specify pressure range from those listed in the table.

Pipe Size	Ht.	Available Pressure Ranges, psi		Each
½″	7″	0-25, 5-50, 30-100, 75-175, 150-400	4675K21	$576.74
¾″	8″	10-50, 20-110, 30-200, 100-250, 150-400	4675K22	656.86
1¼″	11″	20-85, 40-125, 50-230, 175-380, 300-400	4675K25	1,022.10
1½″	11″	10-55, 30-100, 40-200, 125-300, 200-400	4675K26	1,182.30
2″	11″	10-55, 30-100, 40-200, 125-300, 200-400	4675K27	1,307.44

Bronze EZ-Adjustable Relief Valves



Precision Adjustable

Change pressures without gauges or guesswork. These valves are small in size and can be used with cold water for overpressure relief, thermal expansion protection, and low-capacity pump relief. They have a bronze body, silicone rubber seal, and Type 302 stainless steel spring. **Connections:** NPT male bottom inlet and NPT female side outlet.

Adjustable valves adjust between 50 and 175 psi in 25 psi increments. Factory set at 100 psi. Temperature range is 32° to 200° F. ***Precision-adjustable valves*** adjust to any pressure between 25 and 175 psi. Valves have graduation marks every 25 psi and are factory set at 125 psi. Temperature range is 33° to 210° F.

Pipe Size, Inlet × Outlet	Height		Each
Adjustable			
½″ × ½″	2⅛″	4612K16	$22.22
¾″ × ½″	2⅛″	4612K18	24.02
Precision Adjustable			
½″ × ½″	2⅝″	8088K14	23.98
¾″ × ¾″	2⅝″	8088K16	25.86

Steel Tamper-Resistant Adjustable Relief Valves

Male × Female

Pressure setting is changed with an internal ⅜″ hex nut that can't be adjusted while the valve is installed. Come with the pressure set at mid-range. For use with oils, synthetic hydraulic fluids, and other oil-based liquids. Body is zinc-plated steel and seal is PTFE. Springs for 50-400 psi valves are stainless steel; springs for other ranges are music wire. Temp. range is –40° to +300° F. **Connections:** NPT bottom inlet (see table) and side or top outlet. Valves include a plug to cap the unused outlet. **To Order:** Please specify pressure range: 50-400, 300-1000, or 900-2000 psi.

Male Inlet × Female Outlet

Pipe Size	Ht.		Each
¼″ × ¼″	4 5/16″	5026K51	$68.18
⅜″ × ¼″	4 5/16″	5026K52	68.18
½″ × ¼″	4½″	5026K53	68.18

Female Inlet × Female Outlet

Pipe Size	Ht.		Each
¼″ × ¼″	3¾″	5026K61	$68.18
⅜″ × ¼″	3¾″	5026K73	68.18
½″ × ¼″	3⅞″	5026K72	68.18

Cast Iron High-Temperature Adjustable Relief Valves

Rugged cast iron valves are ideal for viscous liquids at high temperatures. Use with oil and liquids in hydraulic or lubrication systems. Furnished with pressure set at mid-range. Valves have a Type 416 stainless steel piston for a metal-to-metal seal. Cap seal is fluoroelastomer. Springs are stainless steel. Temp. range is –31° to +400° F.

Connections: NPT female bottom inlet and side outlet.

To Order: Please specify pressure range: 3-15, 7-35, 30-100, 60-175, 150-350, or 300-500 psi.

Pipe Size	Ht.		Each
⅜″	4″	4704K32	$101.28
½″	4½″	4704K11	106.16
¾″	5″	4704K12	126.88
1″	5 15/16″	4704K13	159.78
1¼″	7″	4704K14	$197.56
1½″	8⅜″	4704K25	256.06
2″	10″	4704K26	408.41

Aluminum Adjustable Pressure-Maintaining Relief Valves

For use with compressed air, these cast aluminum valves maintain your adjusted set pressure at the inlet regardless of the outlet pressure. If the set pressure is exceeded, the valve quickly vents the excess through the unthreaded side port. Also known as back-pressure relief valves and back-pressure regulators. Commonly used to control air pressure instruments in a system supplied by a compressor.

They have a Buna-N seal; a Buna-N-coated, polyester fabric diaphragm; a phenolic adjustment knob; and a ¼″ NPT female gauge port. They are not factory set to a specific pressure. Max. pressure is 250 psi. Temp. range is –20° to +160° F. **Connections:** NPT female side inlet and outlet and vented side relief port. **To Order:** Please specify pressure range: 0-2, 0-10, 0-30, 0-60, or 0-150 psi.

Pipe Size	Ht.		Each
¼″	5 7/16″	4783K51	$106.00
⅜″	5 7/16″	4783K53	106.00
½″	5 7/16″	4783K55	125.80

BARRIER STRIP STYLE POWER SUPPLY
PROVIDES REGULATED EXCITATION FOR STRAIN GAGES AND PRESSURE TRANSDUCERS

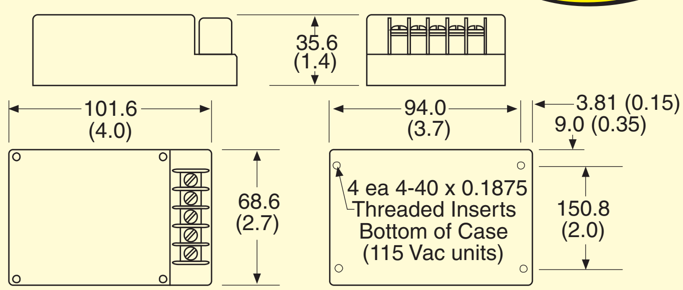
PSS Series

Starts at **$145**

PSS-10, $190, shown smaller than actual size.

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

Dimensions: mm (in)



- **Recessed Barrier Strip Secures Wire Without Twisting**
- **Compact Design Allows Mounting Where Space is Restricted**
- **Ideally Suited for Use With Strain Gages, Transducers, Microprocessor Systems, and Test Equipment**

MOST POPULAR MODELS HIGHLIGHTED!

To Order *(Specify Model Number)*

	MODEL NO.	PRICE	OUTPUT VOLTAGE	OUTPUT CURRENT	VOLTAGE ACCURACY	LINE & LOAD (NL TO FL) REGULATIONS
SINGLE OUTPUT	PSS-5A	$145	+5V	500 mA	±1%	±0.05%
	PSS-5B	190	+5V	1000 mA	±1%	±0.05%
	PSS-10	190	+10V	400 mA	±1%	±0.05%
	PSS-12	190	+12V	500 mA	±1%	±0.05%
	PSS-15	190	+15V	400 mA	±1%	±0.05%
	PSS-250	190	+250V	30 mA	±2%	±0.2%
	PSS-250-230	190	+250V	30 mA	±2%	±0.2%
DUAL OUTPUT	PSS-D12A	145	±12V or 24V	120 mA	±0.5%	±0.02%
	PSS-D12B	190	±12V or 24V	240 mA	±0.5%	±0.02%
	PSS-D15A	145	±15V or 30V	±50 mA	±0.5%	±0.02%
	PSS-D15B	145	±15V or 30V	±100 mA	±0.5%	±0.02%
	PSS-D15C	190	±15V or 30V	±200 mA	±0.5%	±0.02%
TRIPLE OUTPUT	PSS-T12	220	±12V & 5V	±12V @ 100 mA; 5V @ 600 mA	±1%	±0.05%
	PSS-T15	220	±15V & 5V	±15V @ 100 mA; 5V @500 mA	±1%	±0.05%

ACCESSORY

MODEL NO.	PRICE	DESCRIPTION
POWER CORD-SE	$7	Power cord with stripped end termination

Ordering Examples: ***PSS-10,*** *10 Vdc, 400 mA power supply,* ***$190.***
PSS-5A, *5 Vdc, 500 mA power supply,* ***$145.***

SPECIFICATIONS

Input Voltage: 115 Vac ±10V
Input Frequency Range: 50 to 60 Hz
Isolation Resistance: 50 MΩ min
Capacitance: 250 pF
Voltage: 1500 Vrms
Temperature Coefficient: ±0.01%
Noise and Ripple: 1 mVrms single and dual output; 2 mVrms triple
Output Storage Temperature: -25 to 85°C (-13 to 185°F)
Maximum Case Operating Temperature Without Derating: 50°C (122°F)
Short Circuit Protection: Foldback current limiting

MICRO-MACHINED MODULAR TECHNOLOGY PRESSURE SENSOR

NEW

Configurable—High Accuracy—High Temperature Performance For Industrial, Test and Measurement, and Aerospace Applications

MM Series Pressure Transducers

Low Pressure from 10 in-H_2O to 2.5 psi and Standard Ranges from 5 to 5000 psi

Metric Ranges: 25 mbar to 350 bar

Most Popular Models in Stock! Fast Delivery for Thousands of Configurations!

Starts at **$350**

MMG050VP5C0T3A5, $350, features 50 psi, mV output, 0.40% accuracy, cable termination.

B

MADE IN USA | NIST | CE | RoHS

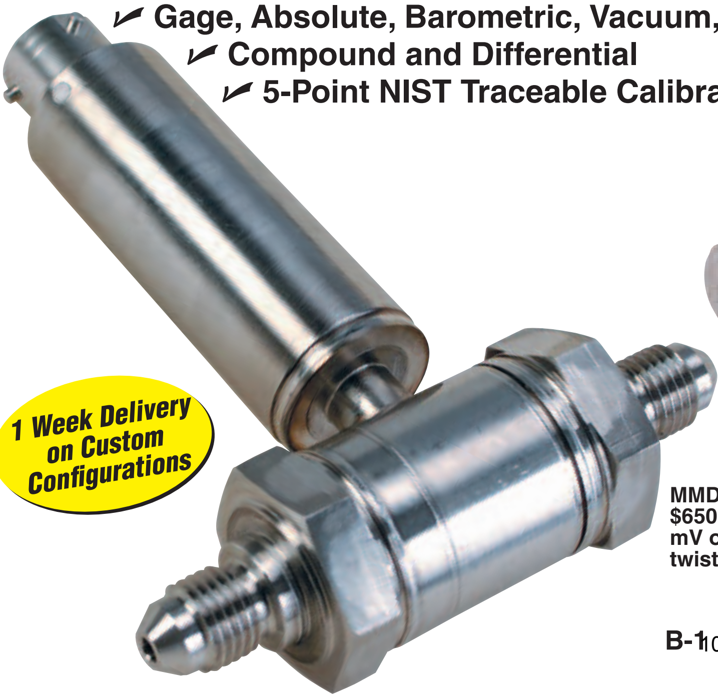
Standard Optional

- Customer Selectable Features
- Fast Delivery
- High Accuracy
- Up to ±0.03% Linearity
  - Accessories Available:
  - 0.05% FS BSL*
  - 0.08% FS BSL
  - 0.20% FS BSL
  - 0.40% FS BSL
- Premium Temperature Performance
- Broad Compensated Range
  - Gage, Absolute, Barometric, Vacuum,
  - Compound and Differential
  - 5-Point NIST Traceable Calibration

MMG100C1P5C6T3A5, $415, features 100 psi 4 to 20 mA output, 0.40% accuracy, mini DIN termination.

MMG10WVP3C1T2A2, $605, features 0 to 10 in-H_2O, mV output, 0.08% accuracy, twist-lock termination.

All models shown actual size.



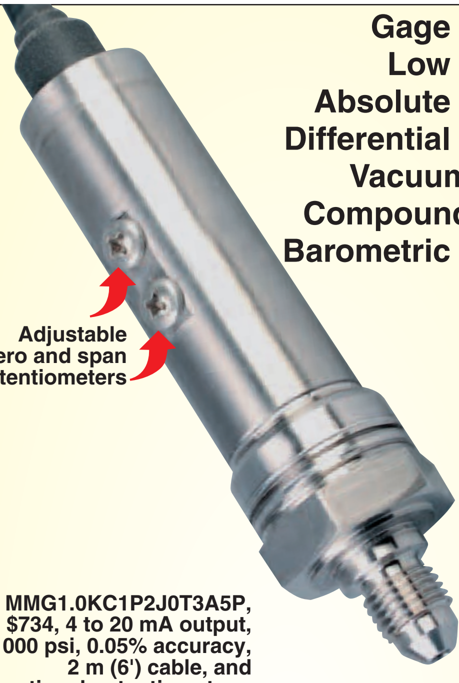
1 Week Delivery on Custom Configurations

MMDWU015VP5C1T3A5, $650, features 15 psid, mV output, 0.40% accuracy, twist-lock termination.

**Best Straight Line.*

ONE SOURCE FOR ALL YOUR PRESSURE MEASUREMENT APPLICATIONS

Gage Pressure
Low Pressure
Absolute Pressure
Differential Pressure
Vacuum Ranges
Compound Ranges
Barometric Pressure

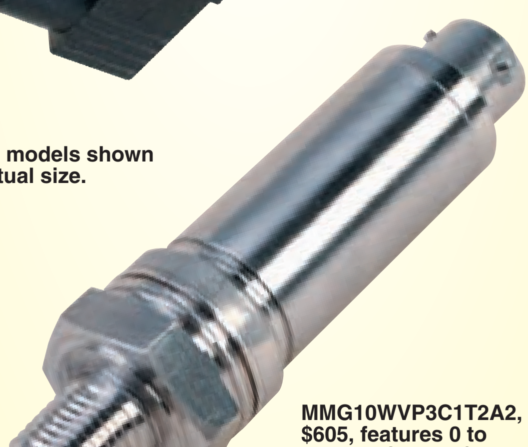


Adjustable zero and span potentiometers

MMG1.0KC1P2J0T3A5P, $734, 4 to 20 mA output, 1000 psi, 0.05% accuracy, 2 m (6') cable, and optional potentiometers.

MMG100C1P5C6T3A5, $415, features 100 psi 4 to 20 mA output, 0.40% accuracy, mini DIN termination.

All models shown actual size.



MMG10WVP3C1T2A2, $605, features 0 to 10 in-H_2O, 3 mV/V output, 0.08% accuracy, twist-lock termination.

omega.com®
OMEGA®

OMEGA has developed a rapid delivery system for its new Micro Machined Silicon product line.

You can have your pick of pressure ports, electrical connections, pressure range and units, thermal range and accuracy and accessories like trim pots. There are over 1-million possible combinations. OMEGA can deliver reasonable quantities of almost any combination within 5 working days. We have an easy-to-use configurator online at **omega.com** where you can select the transducer with the exact specifications for your project.

We also have the most popular configurations stocked for same day shipment!

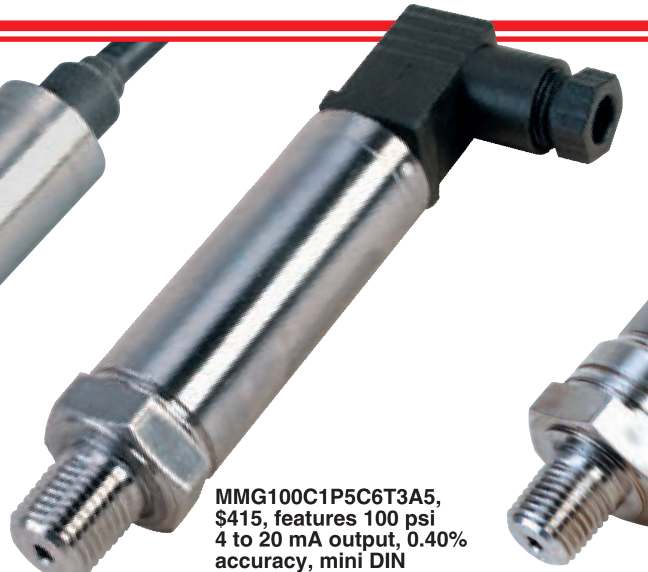
OMEGA's micro-machined piezoresistive pressure transducers have a proven record in high performance commercial, automotive, test and measurement and aerospace applications. The piezoresistive process uses strain gages molecularly embedded into a highly stable silicon wafer. The silicon wafer is diced into individual die which each contain a full strain gage bridge. The die is mounted in a sealed chamber protected from the environment by glass to metal seals and a pressure sensitive stainless steel diaphragm. A small volume of silicone oil transfers the pressure from the diaphragm to the strain bridge. The construction provides a very rugged transducer with exceptional accuracy, stability and thermal effects.

A unique design ruggedizes the transducers by providing secondary fluid containment in the event of a diaphragm rupture.

- ✓ **Five Accuracies**
- ✓ **Ninety-Two Pressure Ranges**
- ✓ **Ten Electrical Outputs**
- ✓ **Four Thermal Ranges**
- ✓ **Fourteen Pressure Ports**
- ✓ **Five Electrical Terminations**
- ✓ **Over 1,000,000 Combinations!**

MM SERIES

MMG1.0KC1P4J0T3A5P, $534, 4 to 20 mA output, 1000 psi, 0.20% accuracy with potentiometers.



MMG100C1P5C6T3A5, $415, features 100 psi 4 to 20 mA output, 0.40% accuracy, mini DIN termination.

MMG1.0KC1P2C2T3A5, $640, features 1000 psi, 4 to 20 mA output, 0.05% accuracy, cable termination with ½ NPT conduit fitting.

CABLE CONNECTION			
COLOR	mV	5/10V	mA
BLACK	– EXC	– EXC	– EXC
WHITE	+ SIG	+ Out	+ CAL
GREEN	– SIG	SHUNT	SHUNT
RED	+ EXC	+ EXC	+ EXC

M12, MINI DIN AND SOLDER PINS CONNECTION			
PIN	mV	5/10V	mA
1	+ EXC	+ EXC	+ Supply
2	– EXC	+ EXC	– Supply
3	+ OUT	+ Output	NC
4	– OUT	NC	NC

TWIST-LOCK CONNECTION			
PIN	mV	5/10V	mA
A	+ EXC	+ EXC	+ EXC
B	– EXC	– EXC	– EXC
C	+ OUT	+ OUT	+ SHUNT
D	– OUT	+ SHUNT	+ SHUNT
E	SPARE	SPARE	SPARE
F	SPARE	SPARE	SPARE

COMMON SPECIFICATIONS

Approvals: RoHS and CE
Calibration: 5-point NIST traceable
Bandwidth: DC to 1 kHz typical
Response Time: < 1 ms
Weight: 115 to 200 g (4 to 7 oz) (depending upon configuration)
CE Compliant: IEC61326
Emissions: IEC550022 Class B
Electrostatic Discharge Immunity: IEC1000-4-2
EM Field Immunity: IEC61000-4-3
EFT Immunity: IEC61000-4-4
Surge Immunity: IEC61000-4-5
Conducted RF: IEC61000-4-6
Rate Power Frequency Magnetic Field: IEC61000-4-8
Minimum Resistance Between Body and Any Wire: 100 MΩ @ 50 Vdc

Environmental

Operating Temperature: -51 to 127°C (-60 to 260°F)
Protection:
  Cable: 2 m (6') IP67
  mini DIN: IP65
  Twist-Lock: IP65
  Conduit 2 m (6') Cable with ½ NPT Conduit Fitting: IP67

Mechanical

Wetted Parts: 316L stainless steel
Media: Compatible with 316L SS
Pressure Cycles: 1 million minimum
Shock: 50 g, 11 ms half sine (under test)
Vibration: ±20 g (under test)
Overpressure Safe:
10 in-H_2O: 10 times span
1 psi: 6 times span
2.5 to 3500 psi: 4 times span
5000 psi: 3 times span
Secondary Containment Gage/Diff/Vac/Compound:
10 in-H_2O to 5 psi: To 1000 psi
15 to 150 psi: To 3000 psi
250 to 1000 psi: To 6000 psi
1500 to 5000 psi: To 15,000 psi
Secondary Containment Absolute/ Barometric:
  Barometric Ranges: To 6000 psi
  5 to 1000 psi: To 6000 psia
  1500 to 5000 psi: To 15,000 psia

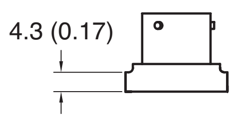
Excitation

3 mV/V: 10 Vdc (ratiometric 5 to 10 Vdc)
10 mV/V: 10 Vdc (ratiometric 5 to 10 Vdc)
0 to 5 Vdc: 10 to 30 Vdc @ 10 mA
0 to 10 Vdc: 15 to 30 Vdc @ 10 mA
4 to 20 mA: 9 to 30 Vdc (9 to 20 Vdc above 229°F)
Bipolar Amplifiers: Same as corresponding outputs from above—compound and some differential pressure models

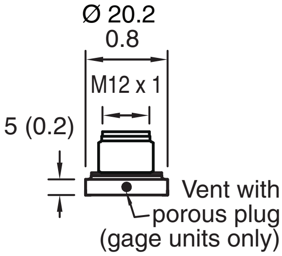
ELECTRICAL TERMINATION

6-Pin, Vented or Non-Vented Bendix

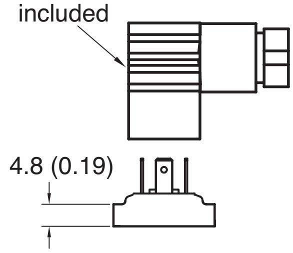
PT06F10-6S mating connector, $26.50, sold separately.



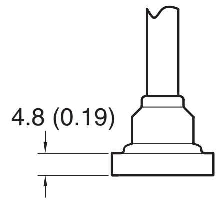
M12 Connector



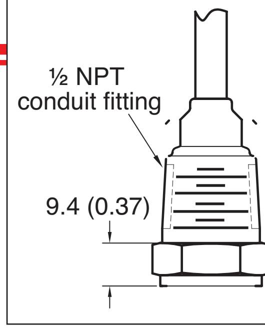
4-Pin, Vented or Non-Vented mini DIN



4-Conductor Integral Cable, 2 Meter

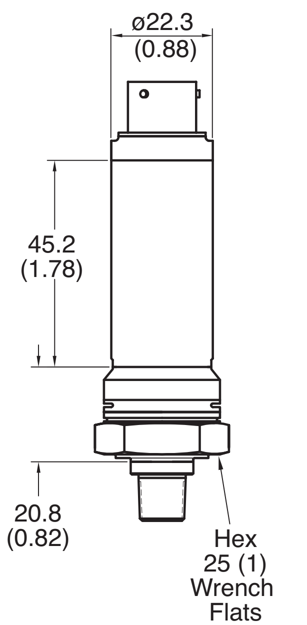


4-Pin, mini DIN

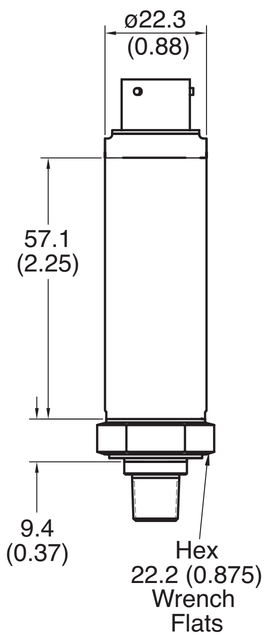


DIMENSIONS

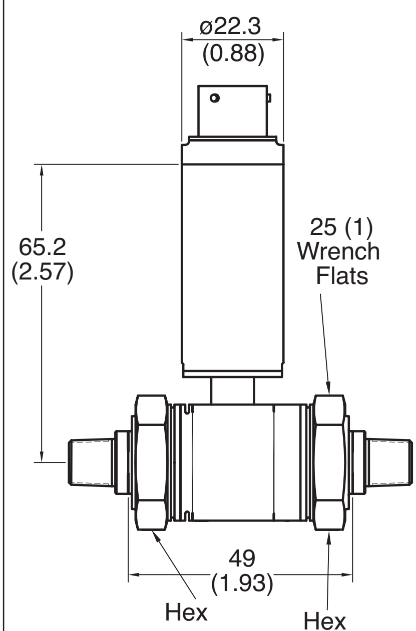
Low Range Pressure Transducer <15 psi Units



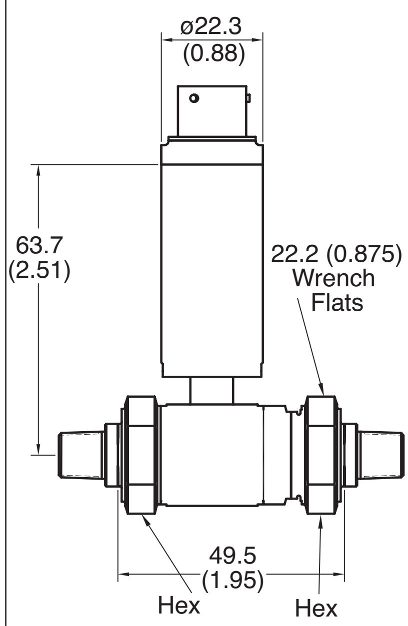
Mid Range Pressure Transducer Barometric Transducer ≥15 psi Units



Low Range Differential Pressure Transducer <15 psi Units

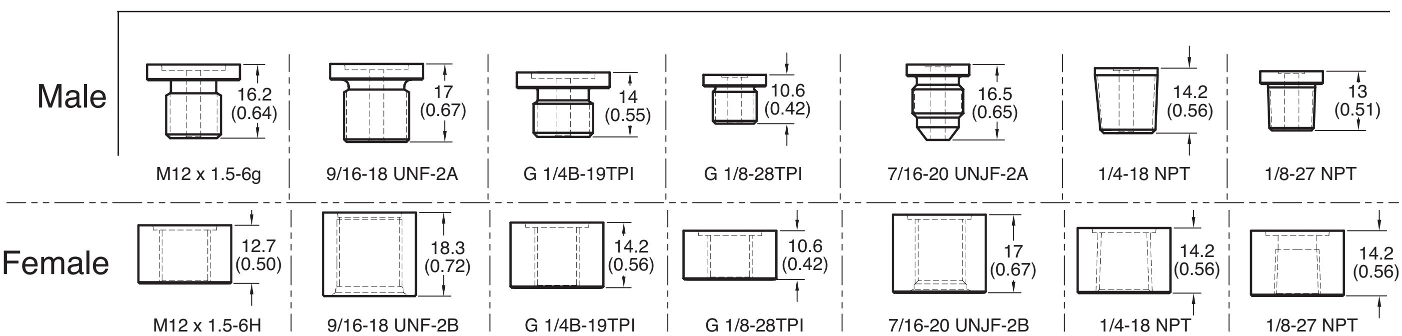


Mid Range Differential Pressure Transducer ≥15 psi Units



PRESSURE PORTS*

Ø = diameter
Dimensions: mm (in)



**** Dimensions may vary slightly for ranges >1000 psi.***

DI-158 Series of Starter Kits

DATAQ® INSTRUMENTS

Low Cost, Compact Data Acquisition Kit

Convenient USB Interface

Four ±10V or ±64V Analog Fixed Differential Inputs

Four General Purpose Digital Inputs

Supports Sample Throughput Rates up to 14,400 Hz

12-bit Resolution

DI-158 products break new ground in price and performance, offering advanced features and options usually reserved for more expensive instruments. A channel scan list, high sample throughput rates, and an advanced computer interface are just some of the features combined to produce a robust instrument that can be applied to nearly any data acquisition situation where low and high level signals need to be acquired to a PC.

The high level gain/high full scale range option provides gain ranges of 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 with a full scale range of ±64 volts. The standard model provides gain ranges per channel of 1, 2, 4, and 8 with a full scale range of ±10 volts. Units are powered through the USB interface so no external power is required.

Features

Easy to Connect and Use

The convenient USB interface allows the DI-158 to connect to any local laptop or desktop PC. Power is derived from the PC through the USB interface so no external power is required.

Two, built-in, 8 position screw terminal connectors allow easy and secure access to all DI-158 signal I/O connections without the need for extra options.

High Resolution

12-bit measurement resolution provides a responsive instrument capable of registering changes as small as one part in 2,048 ±0.05% of the full scale measurement range.

Wide Sample Throughput Range

Throughput ranges from sub-Hertz to up to 14,400 Hertz allow the DI-158 to connect to a wide range of both static and dynamic signals.

Compact

Small size—66D × 66W × 28H mm (2.6D × 2.6W × 1.1H inches)—allows the DI-158 to fit comfortably in crowded instrumentation cabinets, desktops, and other tight locations.

Built-In Channel-Gain Scan List

The Built-in channel-gain scan list eliminates unpredictable channel skews and allows channels to be selectively enabled or disabled to match your application. It also allows channel gain to be dynamically selected per channel during scanning to precisely match signal requirements on a channel by channel basis.

Built-In, Bidirectional Port

Built-in bidirectional port allows programmable discrete inputs and outputs for control.

Free Data Acquisition Software

Our WINDAQ/Lite data acquisition software offers real-time display and disk-streaming for the Windows environment. The real-time display can operate in a smooth scroll or triggered sweep mode of operation, and can be scaled into any unit of measure. Event markers with comments allow you to annotate your data acquisition session as you're recording to disk.

Raise your productivity to new heights with WINDAQ's unique multitasking feature. Record waveform data to disk in the background while running any combination of programs in the foreground — even WINDAQ Playback software to review and analyze the waveform data as it's being stored!

Specifications

Analog Inputs

Number of Channels: 4

Channel Configuration: Fixed Differential

Measurement range (Full Scale), Accuracy, and Resolution

	Gain	Range	Accuracy	Resolution
DI-158U:	1	±10V	±.25% of FSR	±4.88mV
	2	±5V	±.25% of FSR	±2.44mV
	4	±2.5V	±.25% of FSR	±1.22mV
	8	±1.25V	±.25% of FSR	±0.61mV
DI-158UP: (models with programmable high gain option)	1	±64V	±.25% of FSR	±31.3mV
	2	±32V	±.25% of FSR	±15.6mV
	4	±16V	±.25% of FSR	±7.81mV
	8	±8V	±.25% of FSR	±3.9mV
	16	±4V	±.25% of FSR	±1.95mV
	32	±2V	±.25% of FSR	±976µV
	64	±1V	±.25% of FSR	±488µV
	128	±0.5V	±.25% of FSR	±244µV
	256	±0.25V	±.25% of FSR	±122µV
	512	±0.125V	±.25% of FSR	±61µV

Input Impedance: 500KΩ either input to ground
1MΩ differential

Input bias current: 10µA for a 10V input, single channel

Normal mode voltage: 100V peak, without damage

Common mode voltage: 60V peak, without damage

Common mode rejection: 60db @ Gain=1; 1KΩ unbalance

Channel-to-channel crosstalk rejection: 100db

Gain temperature coefficient: 100ppm/°C

Offset temperature coefficient: 100µV/°C

A/D Characteristics

Type: Successive approximation

Resolution: 12-bit

Monotonicity: ±2 LSB

Conversion Time: 71.4µs

Calibration

Calibration cycle: One year

Calibration method: Digital calibration with scale and offset constant per channel and gain range.

USB Interface

Connector: USB

Max. data transfer rate: 14,400 samples per second

Analog Outputs

Number of channels: 2

Resolution: 12 bits

Integral Nonlinearity: ±2 LSB

Output Noise: 250µVrms

Output Current: ±300µA

Output short circuit current: 15mA

Voltage output slew rate: Load = 40pF: 0.44 V/µs

Output voltage swing: 0V to 1.25V

Startup time: 10µs

Digital I/O

Channels: 4 bi-directional ports

Output voltage levels: Min. "1" 3V @ 2.5mA sourcing
Max. "0" 0.4V @ 2.5mA sinking

Output current: Max. source, -2.5 mA
Max. sink, 2.5mA

Input voltage levels: Min. required "1" 2V
Max allowed "0" 0.8V

General

Input connectors: Two, 8 position terminal blocks

Operating Environment: 0°C to 70°C

Enclosure: Molded ABS plastic

Dimensions: 2.6L × 2.6W × 1.1D inches
66L × 66W × 28D mm.

Weight: 3 oz. (85 gr.)

Power Requirements

USB Models: 80mA max. @ 5 VDC. No external power required. Power derived from communications cable.

Scanning Characteristics

Max. throughput sample rate: 14,400 Hz

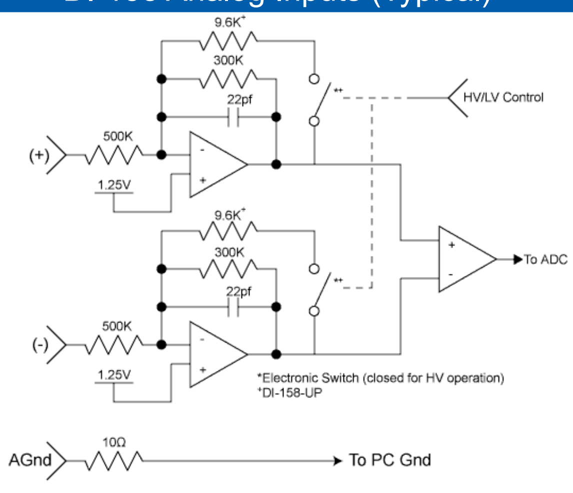
Min. throughput sample rate: 0.0137334 Hz

Timing accuracy: 100 ppm of sample rate

Max. scan list size: 6 entries

Sample buffer size: 2kb

DI-158 Analog Inputs (Typical)



Input Impedance = 500KΩ either input to 1.25V, 1MΩ Differential

Ordering Guide

Description	Order Number
DI-158U Starter Kit DI-158 with USB interface.	DI-158U
DI-158UP Starter Kit DI-158 with USB Interface and high programmable gain/voltage range.	DI-158UP
WINDAQ/HS-158 High speed WINDAQ software. Record at the speed of the instrument.	WINDAQ/HS-158

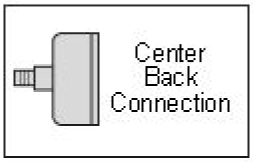
DATAQ® INSTRUMENTS
241 Springside Drive
Akron, Ohio 44333
Phone: 330-668-1444
Fax: 330-666-5434

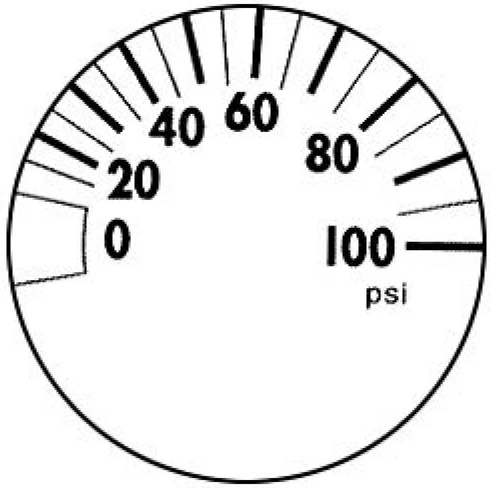
Data Acquisition Product Links

(click on text to jump to page)

Data Acquisition | Data Logger | Chart Recorder | Thermocouple | Oscilloscope

Pressure Gauges





Part Number: **38105K32** $9.92 Each

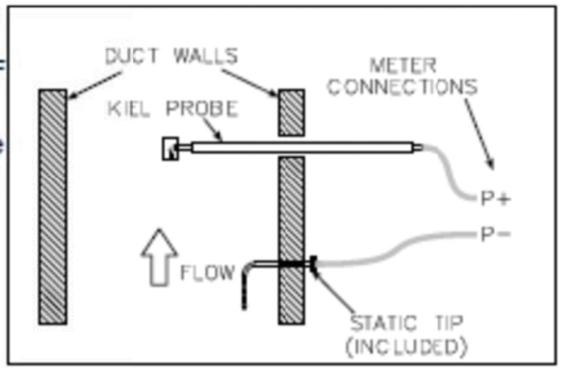
Gauge Type	Pressure
Service Type	General Service
For Use With	Compressed Air, Ethyl Alcohol, Nitrogen, Water
Accuracy	±5% Full-Scale (Grade D)
NIST Certification	Without Certificate of Calibration
Dial Type	Dry
Connection Size and Type	1/8" NPT Male
Connection Location	Center Back
Connection Material	Brass
Sensor Type	Bourdon Pressure Tube
Sensor Material (Internals)	Beryllium Copper
Case Material	ABS Thermoplastic
Lens Material	Polycarbonate
Units of Measure	psi
Operating Pressure Range (psi)	0 to 100
Numeral Increments (psi)	20
Graduation Marks (psi)	5
Round Dial Diameter	29/32"
Process Temperature Range	-40º to +150º F
Ambient Temperature Range	-40º to +150º F
Specifications Met	American Society of Mechanical Engineers (ASME)
ASME Specifications Met	B40.1
Note	Pressure tube transmits motion directly to the pointer so there are no gears or bearings to wear out.

Introduction:

Kiel probes are total pressure probes designed to measure velocity where the direction of flow changes considerably during testing. To measure the dynamic pressure a static tip (included) or a wall tap must be used with the Kiel probe. This type of probe experiences very low sensitivity to turbulence, Reynolds number and Mach number. The Kiel probe has a flow coefficient (*K*) of 1.0 and requires no calibration. Temperature rating: 900°F (482°C) if using a mounting chuck with a stainless steel ferrule; 400°F (204°C) if using a Teflon ferrule.

Measuring standard velocity

You will need a simple differential manometer. Using this method you assume that the temperature and pressure in the test area are at standard conditions where Pamb=14.696psi (101325 Pa), Temp=70°F (21.1°C) and RH=0%.



Connect the static tip / wall tap port to the low pressure port (P-) of the differential manometer. The Kiel port should be connected to the high pressure (P+) port on the differential manometer.

Standard velocity in m/sec is calculated using

$$V = K \cdot \sqrt{\frac{2 \cdot \Delta P}{density}}$$

where

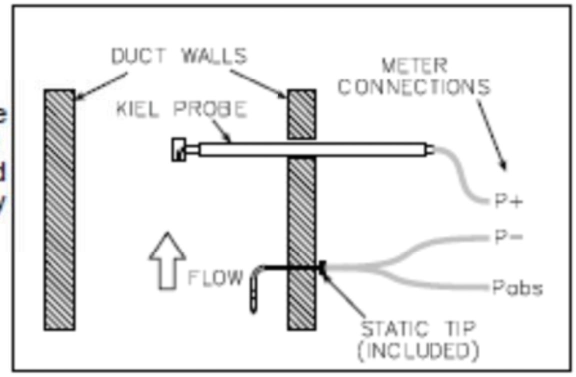
density = 1.2 kg/m^3 for standard air

ΔP is the differential pressure reading from the manometer in Pascals.

K is the Pitot flow coefficient (1.0)

If you are using a FlowKinetics manometer the velocity is calculated automatically.

Measuring actual velocity



To obtain the actual velocity you will need a differential and an absolute pressure manometer. You will also need a way to measure the temperature of the flow being tested.

Using a splitter connect the static tip / wall tap port to the low pressure port (P-) of the differential manometer and the absolute pressure port (Pabs) of the absolute manometer. The Kiel port should be connected to the high pressure (P+) port on the differential manometer. This way you can measure the differential pressure and the static pressure simultaneously. Also insert the temperature sensor into the flow.

Actual velocity in m/sec is calculated using

$$V = K \cdot \sqrt{\frac{2 \cdot \Delta P}{density}}$$

where

ΔP is the differential pressure reading from the manometer in Pascals.

$$density = \frac{Pabs + (1 - K^2) \cdot \Delta P}{R \cdot (Temp + 273.15)} \text{ in kg/m}^3$$

Temp is the temperature of the flow in Celsius.

R is the gas constant. $R = 287.026 \frac{joule}{kg \cdot Kelvin}$ for air.

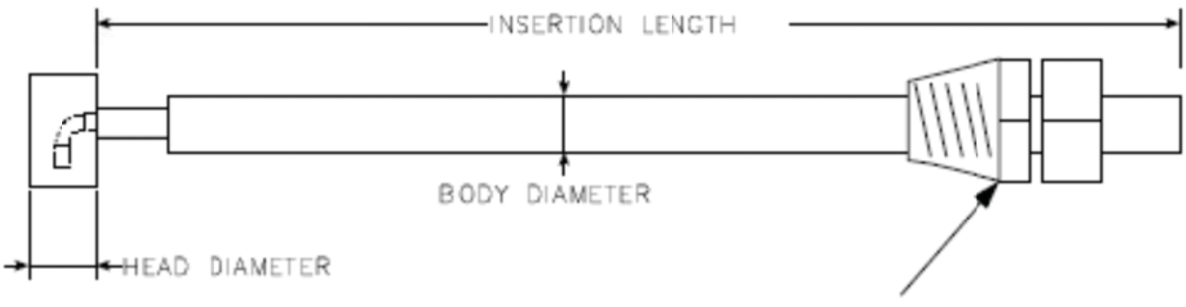
Pabs is the static pressure measured with the absolute pressure manometer in Pascals.

K is the Pitot flow coefficient (1.0)

If you are using a FlowKinetics FKT series manometer the velocity is calculated and corrected automatically for temperature, ambient pressure, humidity and gas type.

General Dimensions

KIEL PROBE



DIMENSIONS IN INCHES, MATERIAL: STAINLESS STEEL
NOT TO SCALE

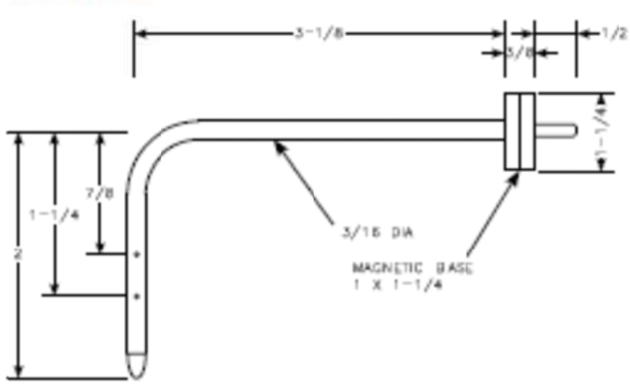
AVAILABLE SIZES:

Head diameter (inches)	Body diameter (inches)	Flow yaw/pitch range (degrees)	Head clearance hole (inches)	Mounting chuck NPT thread size (inches)
1/4	1/8, 1/4	+/- 49	1/2	1/8, 1/4
3/8	1/8, 3/16, 1/4	+/- 58	7/8	1/8, 1/4
3/4	1/4	+/- 61	1 3/4	1/4

The head clearance hole is the hole size needed for the head of the Kiel probe to pass through.

There are two types of mounting chucks: One with a stainless steel ferrule and one with a Teflon ferrule. The one with stainless steel is rated to 900°F but it can only be set once and cannot be repositioned. The Teflon ferrule allows the mounting chuck to be repositioned but it is only rated to 400°F. The chuck itself is made of stainless steel.

STATIC TIP



DIMENSIONS IN INCHES, NOT TO SCALE
MATERIAL: BRASS

For information about pop-safety and relief valves, see page 467. For pipe size information, see pages 2-3.

Pipe OD to Pipe Size Conversions

Pipe OD	3/8″	1/2″	5/8″	3/4″	1″	1 3/8″	1 5/8″	1 7/8″	2 3/8″	3 1/2″
Pipe Size	1/8″	1/4″	3/8″	1/2″	3/4″	1″	1 1/4″	1 1/2″	2″	3″

Stainless Steel Custom-Set Pop-Safety Valves

ASME w/ 3/4″ Inlet

Choose your own set pressure, temperature, and air or gas service. Valve body is Type 316 stainless steel for corrosion resistance. Seals are fluoroelastomer. Not for steam, oxygen, or carbon dioxide. In addition, ASME valves cannot be used with propane or butane.

Non-ASME valves do not have a test mechanism.

ASME-coded valves meet ASME Code Section VIII for air and gas. They have a lift lever for testing.

Connections: The 1/2″ inlet size has an NPT female bottom inlet and side outlet. The 3/4″ and 1″ inlet sizes have an NPT male bottom inlet and an NPT female side outlet.

To Order: Please specify set pressure (any pressure between 15 and 2500 psi), temperature (up to 450° F), and air or gas service.

Pipe Size, Inlet × Outlet	Ht.	*Non-ASME*	Each	*ASME Code*	Each
1/2″ × 3/4″	9″	6872K11	$388.55	6872K21	$474.43
3/4″ × 3/4″	9″	6872K12	394.44	6872K22	481.51
1″ × 1″	9″	6872K13	400.51	6872K23	488.80

Brass Relief Valves

Male × Female

Get rid of the guesswork with these nonadjustable relief valves. They're a good choice for low-pressure cold water pump applications. Body is brass, seal is rubber on brass, and spring is stainless steel. Disc is neoprene for 1/2″ through 1 1/4″ sizes; Buna-N for 1 1/2″ and 2″ sizes. Pressure is not adjustable. **Connections:** NPT bottom inlet and side outlet (see table). **To Order:** Please specify set pressure. 1/2″ to 1″ sizes are available in 30 and 75 psi. 1 1/4″ to 2″ sizes are available in 30 and 65 psi.

Pipe Size	Ht.		Each
Male Inlet × Female Outlet			
1/2″	4 1/8″	4780K11	$51.95
3/4″	4 11/16″	4780K12	55.76
1″	5 7/16″	4780K13	75.09
1 1/4″	6″	4780K14	117.36
Female Inlet × Female Outlet			
1 1/2″	6 13/16″	4780K15	226.58
2″	6 1/2″	4780K16	232.06

Brass Cryogenic Relief Valves

Pipe Adapter

Relief Valve

Ideal for extreme low-temperature, liquefied gases such as oxygen, nitrogen, and carbon dioxide. Spring is Type 302 stainless steel. Disc is fluoroelastomer for set pressures below 150 psi; PTFE for set pressures 150 psi and above. Cleaned, degreased, and packaged for oxygen service. Pressure is not adjustable. Temperature range is –320° to +165° F.

Connections: NPT male bottom inlet and 3/4″-20 UNEF female top outlet. Optional pipe adapters are available to connect to top outlet. Adapter for the 1/4″ and 3/8″ inlet size provides a 3/8″ NPT female outlet. Adapter for 1/2″ inlet size provides a 1/2″ NPT female outlet. **To Order:** Please specify set pressure: 22, 35, 50, 75, 100, 125, 150, 200, 235 (230 for 3/8″ valve), 250, 300, 350, 400, or 450 psi.

Pipe Size	Ht.	*Relief Valves*	Each	*Pipe Adapters*	Each
1/4″	2 5/8″	49315K71	$35.10	49315K94	$8.65
3/8″	2 5/8″	49315K72	37.92	49315K94	8.65
1/2″	2 13/16″	49315K73	48.44	49315K96	10.12

Brass Adjustable Vacuum/ Pressure Relief Valves

Adjust these brass valves to relieve vacuum pressure from 0 to 27″ Hg. They can also be configured to work as pressure-relief valves for low-pressure compressed air applications. Pressure adjusts from 0 to 20 psi with the knurled adjustment screw. They are not factory set to a specific pressure. Valves have a Type 302 stainless steel spring. The 1/4″ pipe size valve has a metal-to-metal seal with a Type 440C stainless steel disc; 3/8″ and 3/4″ pipe size valves have a Buna-N seal with a nylon disc. Temperature range is –15° to +250° F. **Connections:** NPT male bottom inlet and vented top outlet.

Pipe Size	Ht.		Each
1/4″	1 3/4″	48935K25	$8.32
3/8″	2 1/16″	48935K35	13.20
3/4″	2 3/4″	48935K45	31.03

Aluminum Extreme-Pressure ASME Pop-Safety Valves

- Meet ASME code section VIII for gas.

A lightweight aluminum body withstands pressures up to 5500 psi as well as environmental and internal corrosion. Valves have a Kynar seal, a Type 303 stainless steel disc, and an aluminum-coated steel spring. They discharge to atmosphere and do not have a test mechanism. Temperature range is –20° to +185° F. **Connections:** NPT male bottom inlet and vented side outlet.

To Order: Please specify set pressure: 1000, 1200, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, or 5500 psi.

ⓘ For flow capacities, go to mcmaster.com and search for **4221TAC**.

Pipe Size	Ht.		Each
1/4″	5 1/4″	4221T11	$520.16

Brass Adjustable Relief Valves

Set pressures are adjustable to any pressure within the selected range. **Connections:** NPT female bottom inlet and side outlet, unless noted.

For Use with Cold Water

Valves have a T-handle for easy pressure adjustment. Pressure setting is held by a locknut. Valves are not factory set to a specific pressure. Max. temp. is 160° F.

Standard valves have a brass seal. Ranges 0-50 and 0-300 psi have a Type 302 stainless steel spring; range 300-700 psi has a 17-7 PH stainless steel spring. **To Order:** For standard valves, please specify pressure range: 0-50, 0-300, or 300-700 psi.

High-pressure valves have a Type 416 stainless steel seal, a 17-7 PH stainless steel spring, and a pressure range of 700-1200 psi.

Connections: NPT male bottom inlet and NPT female side outlet.

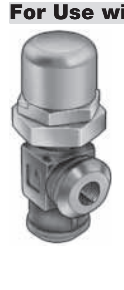
Pipe Size	Ht.	*Standard*	Each	*High Pressure*	Each
1/2″	4 1/2″	9763K11	$51.80	9763K55	$98.11
3/4″	4 1/2″	9763K12	51.80	9763K65	98.11

For Use with Highly Viscous Liquids

Suitable for high-viscosity liquids up to 500 SSU in hydraulic or lubrication systems. Valves have a Type 416 stainless steel disc. Springs are 18-8 stainless steel for all pressure ranges, except 150-350 psi and 300-500 psi, which are 17-7 PH stainless steel. Pressure is factory set at mid-range. Temperature range is –31° to +400° F. **To Order:** Please specify pressure range: 3-15, 7-35, 30-100, 60-175, 150-350, or 300-500 psi.

Pipe Size	Ht.		Each
3/8″	4″	7844K51	$119.56
1/2″	4 1/2″	7844K52	141.50
3/4″	5″	7844K53	184.16
1″	5 15/16″	7844K54	228.03
1 1/4″	7″	7844K55	296.28
1 1/2″	8 3/8″	7844K56	365.75
2″	10″	7844K57	585.12

For Use with Hydraulic Fluids or Compressed Air



Valves have a brass body, a Type 303 stainless steel disc, and a Type 302 stainless steel spring. Temperature range is –40° to +250° F. **To Order:** Please specify the pressure range from those listed in the chart:

Pressure Range, psi	Factory Setting	Pressure Range, psi	Factory Setting
Buna-N Seal		***Metal-to-Metal Seal***	
4 to 15	10 psi	630 to 1020	850 psi
10 to 50	35 psi	800 to 1500	1000 psi
40 to 125	90 psi	1400 to 2100	1750 psi
PTFE Seal		1500 to 2750	2200 psi
115 to 250	200 psi	2000 to 3100	2600 psi
235 to 450	360 psi	3000 to 3600	3200 psi
430 to 650	550 psi		
630 to 850	750 psi		

Pipe Size	Ht.		Each
1/4″	3 21/32″	4706K53	$194.60
3/8″	3 3/4″	4706K55	204.53
1/2″	5 7/8″	4706K57	$230.24
3/4″	5 29/32″	4706K59	242.57

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Quantity: 1

ADD TO CART

Add to My List

Check Store Inventory

Power Care 1/4 in. Male to 1/4 in. Female Quick-Connect NPT Coupler

Model # AP31038 Internet # 202073584 Store SKU # 719874

Be the first to Write a Review

$8.98 /EA-Each

This item does not qualify for free shipping.

Zoom View

SHOPPERS WHO VIEWED THIS ITEM ALSO VIEWED

36 In. Steel Spray Wand

$17.69/Each

18 Ft. Telescoping Extension Wand for Gas Pressure ...

$229.00/Each

5000 PSI Spray Gun for Gas Pressure Washers

$39.97/Each

Description

The Power Care 1/4 in. Male to 1/4 in. Female Quick-Connect NPT Coupler enables you to transform your pressure washer into a Quick-Connect-capable machine that accepts a wide variety of attachments.

Upgrades your wand to accept any Quick-Connect attachment
For most gas and electric pressure washers
Male-to-female design
4,000 psi maximum pressure
MFG Brand Name : Power Care
MFG Model # : AP31038
MFG Part # : AP31038

Specifications

Assembled Depth (in.) : 1 in
Assembled Height (in.) : 2 in
Assembled Width (in.) : 1 in

E-MAIL EXCLUSIVES

Sign up to receive special offers and promotions from the Home Depot

Enter Email Address

FOLLOW THE HOME DEPOT

ABOUT THE HOME DEPOT

Affiliate Program
Careers
Corporate Info
Government Customers
Investor Relations
Privacy & Security
Supplier Center
Supplier Diversity
The Home Depot Canada
The Home Depot Mexico

STRESS FREE SHOPPING

Gift Cards
Price Match Policy
Privacy Policy
Return Policy
Service Plan Registration
Site Map

PARTNER SITES

Home Improver Club
Home Decorators Collection
Garden Club
The Home Depot Racing
Eco Options

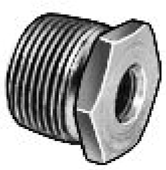
CUSTOMER SERVICE

Contact Us
Home Depot Opinion
Order Status
Product Recalls
Shipping and Delivery
Store Information

CREDIT CENTER

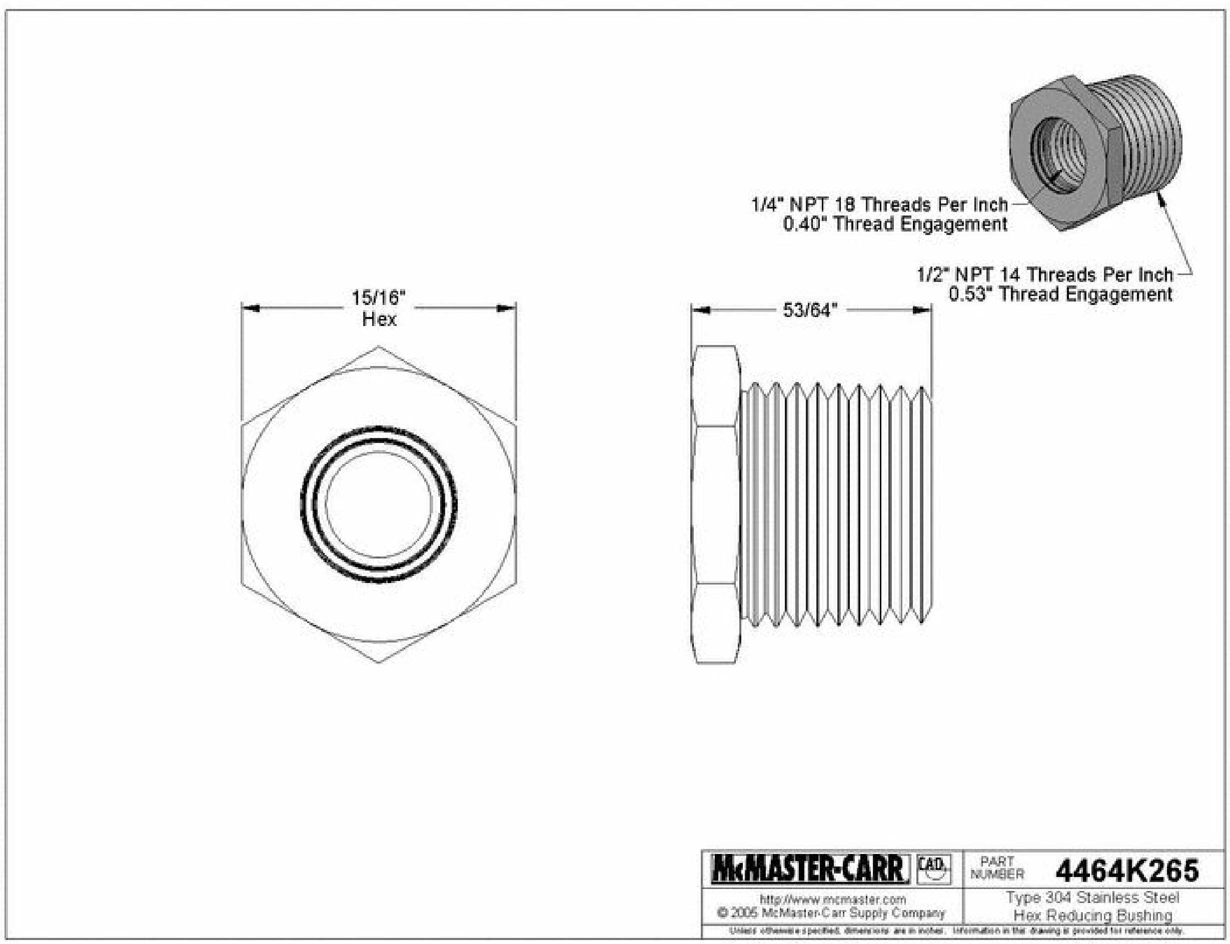
120

Stainless Steel Pipe Fittings and Pipe

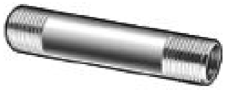


Part Number: **4464K265** $2.97 Each

Shape	Bushing (Male x Female Hex)
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2" reduced to 1/4"
Material	Type 304 Stainless Steel
Maximum Pressure @ 72° F	150 psi
Maximum Pressure Note	For steam, maximum pressure is 150 psi @ 366° F.
Flanges	Use low-pressure threaded stainless steel
Specifications Met	American Society for Testing and Materials (ASTM), Manufacturers Standardization Society (MSS)
ASTM Specification	ASTM A351
MSS Specification	MSS SP-114

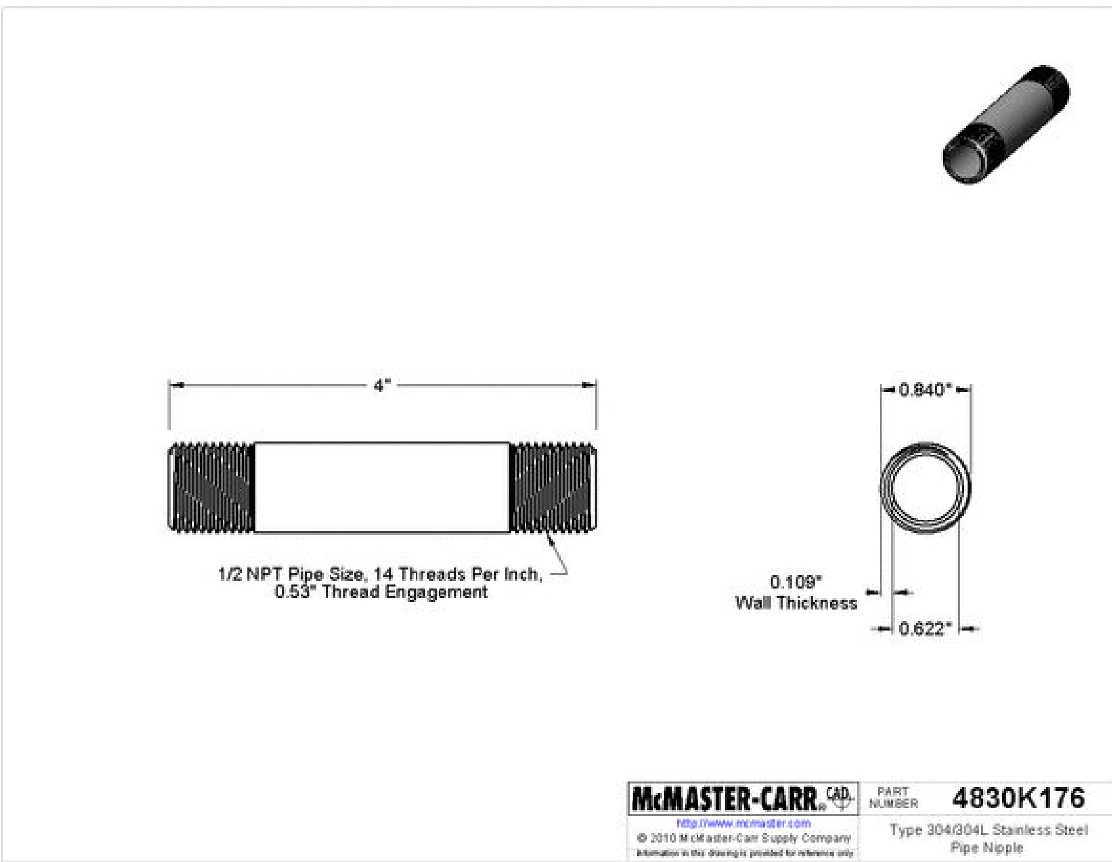


Stainless Steel Pipe Fittings and Pipe

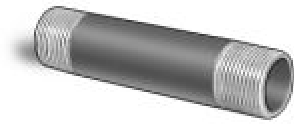


Part Number: **4830K176** $5.13 Each

Shape	Nipple
Nipple Type	Threaded Ends
Pipe Construction	Welded
Schedule	40
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2"
Length	4"
Material	Type 304/304L Stainless Steel
For Use With	Air, Natural Gas, Oil, Steam, Water
Fittings	Use low-pressure (Class 150) stainless steel threaded fittings.
Flanges	Use low-pressure stainless steel threaded flanges.
Specifications Met	American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM)
ANSI Specification	ANSI B1.20.1
ASTM Specification	ASTM A312, ASTM A733
ASME Specification	ASME B1.20.1, ASME SA312

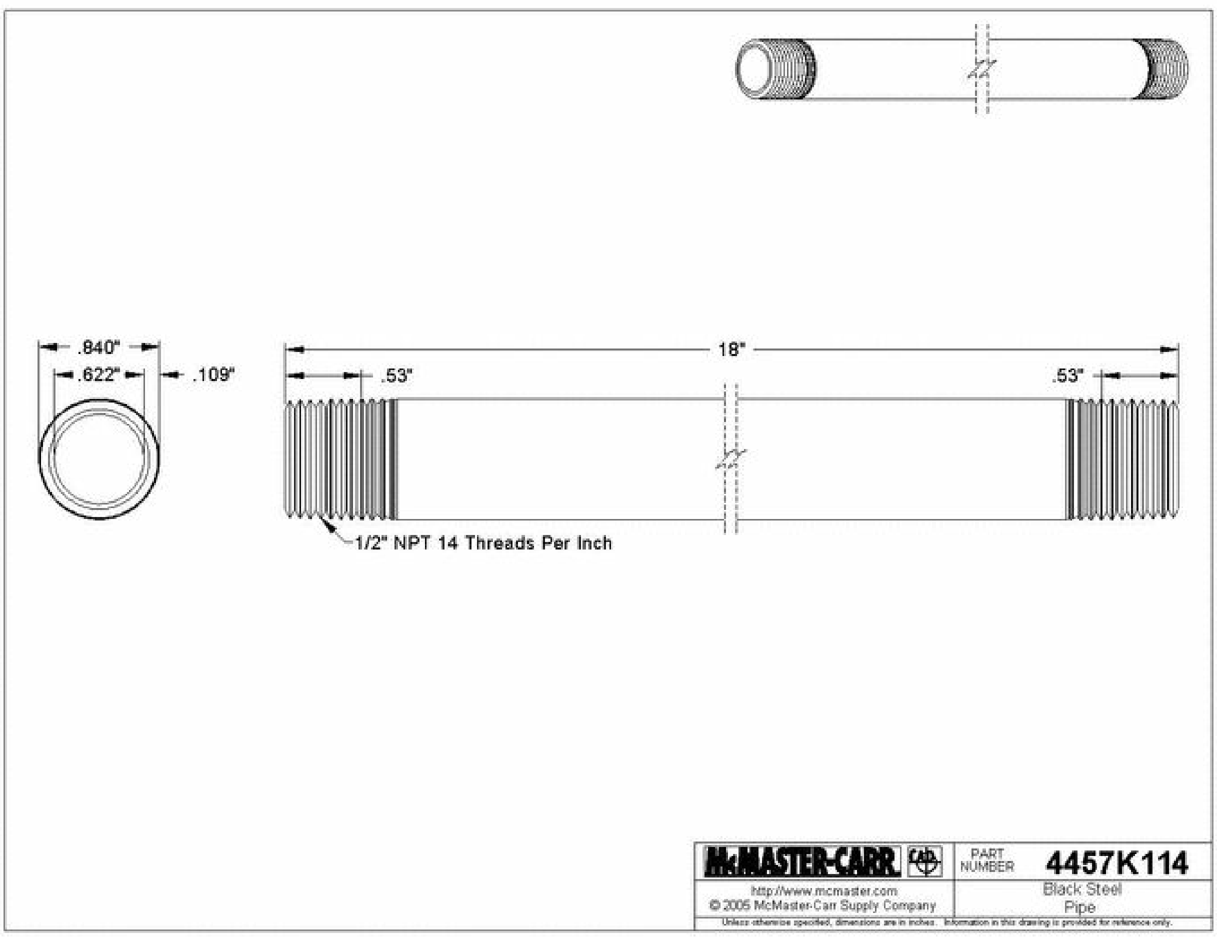


Iron and Steel Pipe Fittings and Pipe

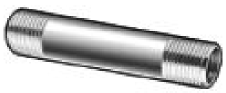


Part Number: **4457K114** $4.39 Each

Shape	Pipe
Schedule	40
Nipple End Style	Threaded Both Ends
Pipe Type	Threaded
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2"
Outside Diameter	.840"
Inside Diameter	.622"
Wall Thickness	.109"
Length	18"
Finish	Black
Steel	Welded Steel
Specifications Met	American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM)
ANSI Specification	ANSI B1.20.1
ASME Specification	ASME B1.20.1
ASTM Specification	ASTM A53, ASTM A733

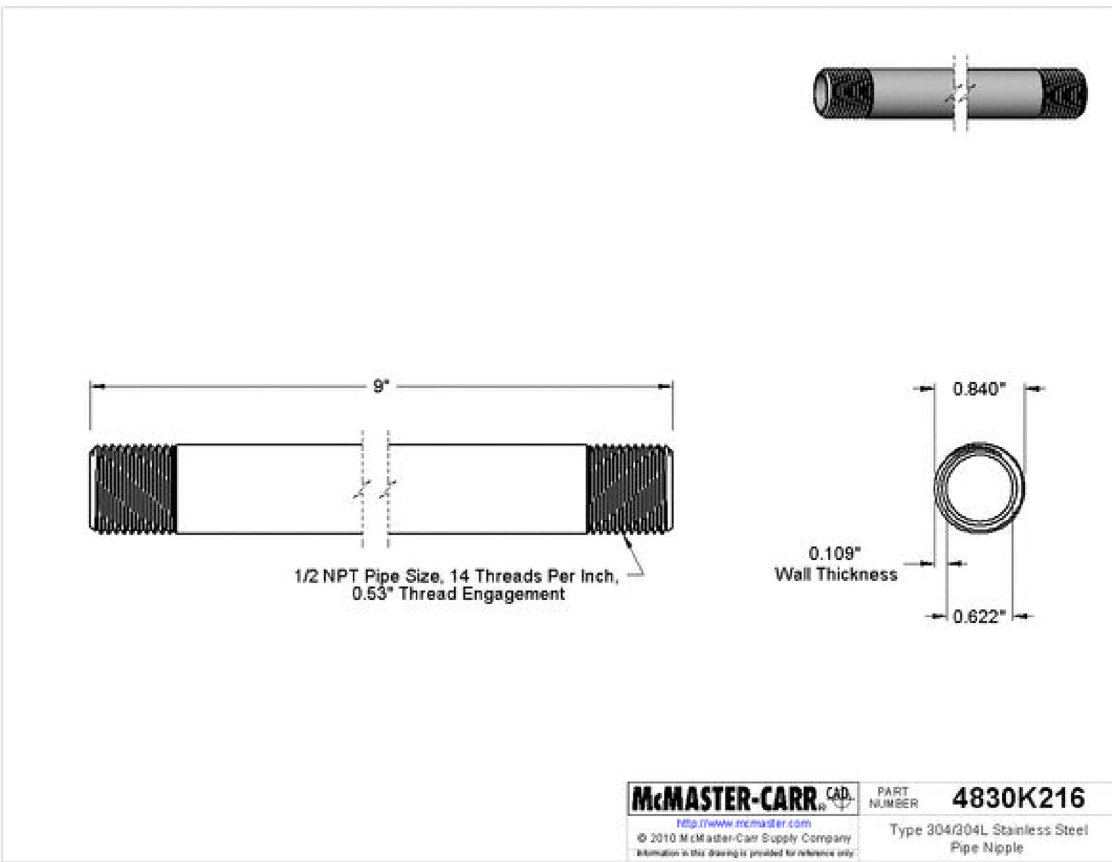


Stainless Steel Pipe Fittings and Pipe



Part Number: **4830K216** $9.89 Each

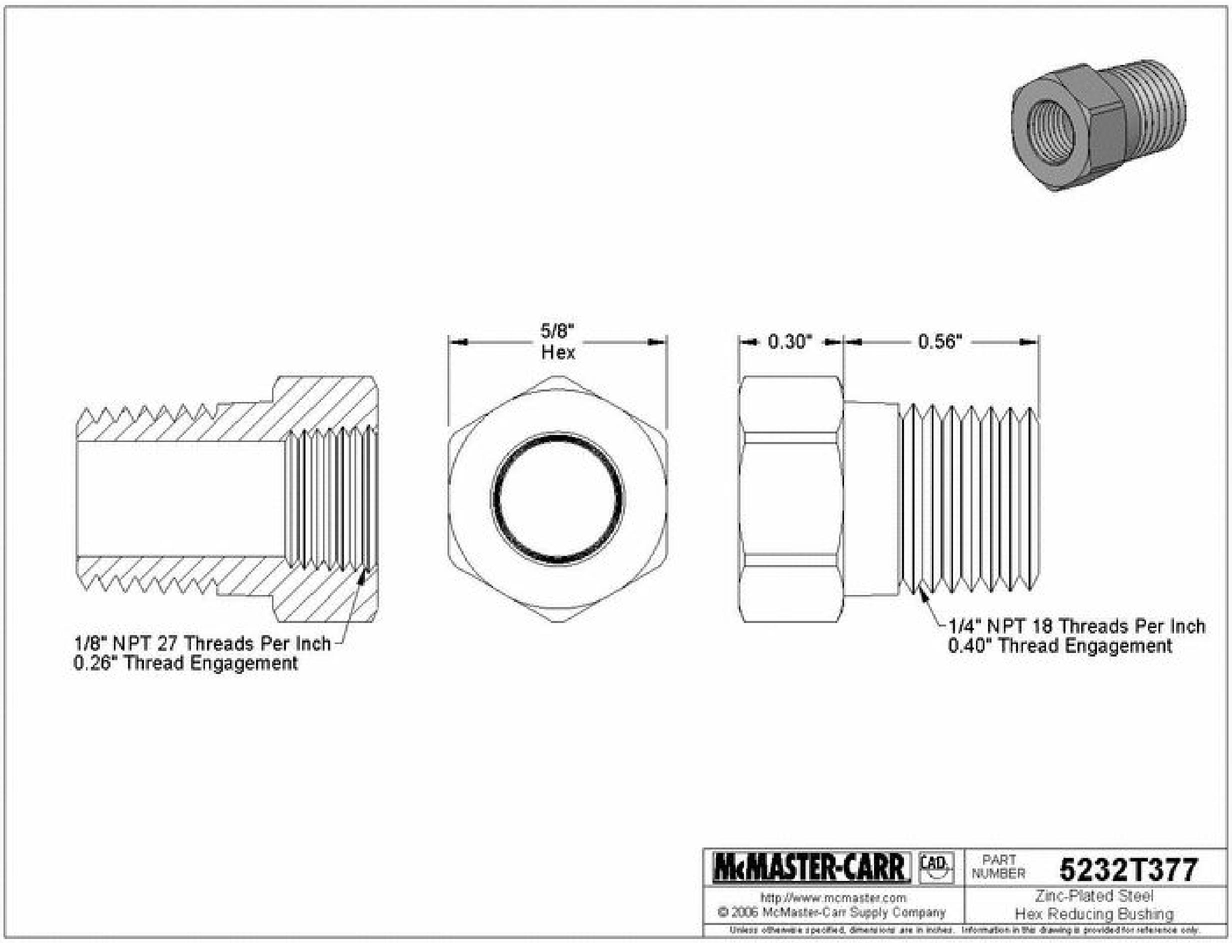
Shape	Nipple
Nipple Type	Threaded Ends
Pipe Construction	Welded
Schedule	40
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2"
Length	9"
Material	Type 304/304L Stainless Steel
For Use With	Air, Natural Gas, Oil, Steam, Water
Fittings	Use low-pressure (Class 150) stainless steel threaded fittings.
Flanges	Use low-pressure stainless steel threaded flanges.
Specifications Met	American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM)
ANSI Specification	ANSI B1.20.1
ASTM Specification	ASTM A312, ASTM A733
ASME Specification	ASME B1.20.1, ASME SA312



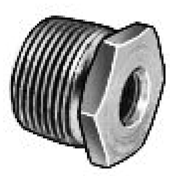
Iron and Steel Pipe Fittings and Pipe

Part Number: **5232T377** $4.05 Each

Shape	Bushing
Bushing Type	Hex Bushing (Male x Female)
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/4" reduced to 1/8"
Finish	Zinc-Plated
Steel	Machined Steel
Maximum Pressure @ 72° F	6400 psi
Specifications Met	American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM)
ANSI Specification	ANSI B1.20.1, ANSI B31.1, ANSI B31.3
ASME Specification	ASME B1.20.1
ASTM Specification	ASTM A108

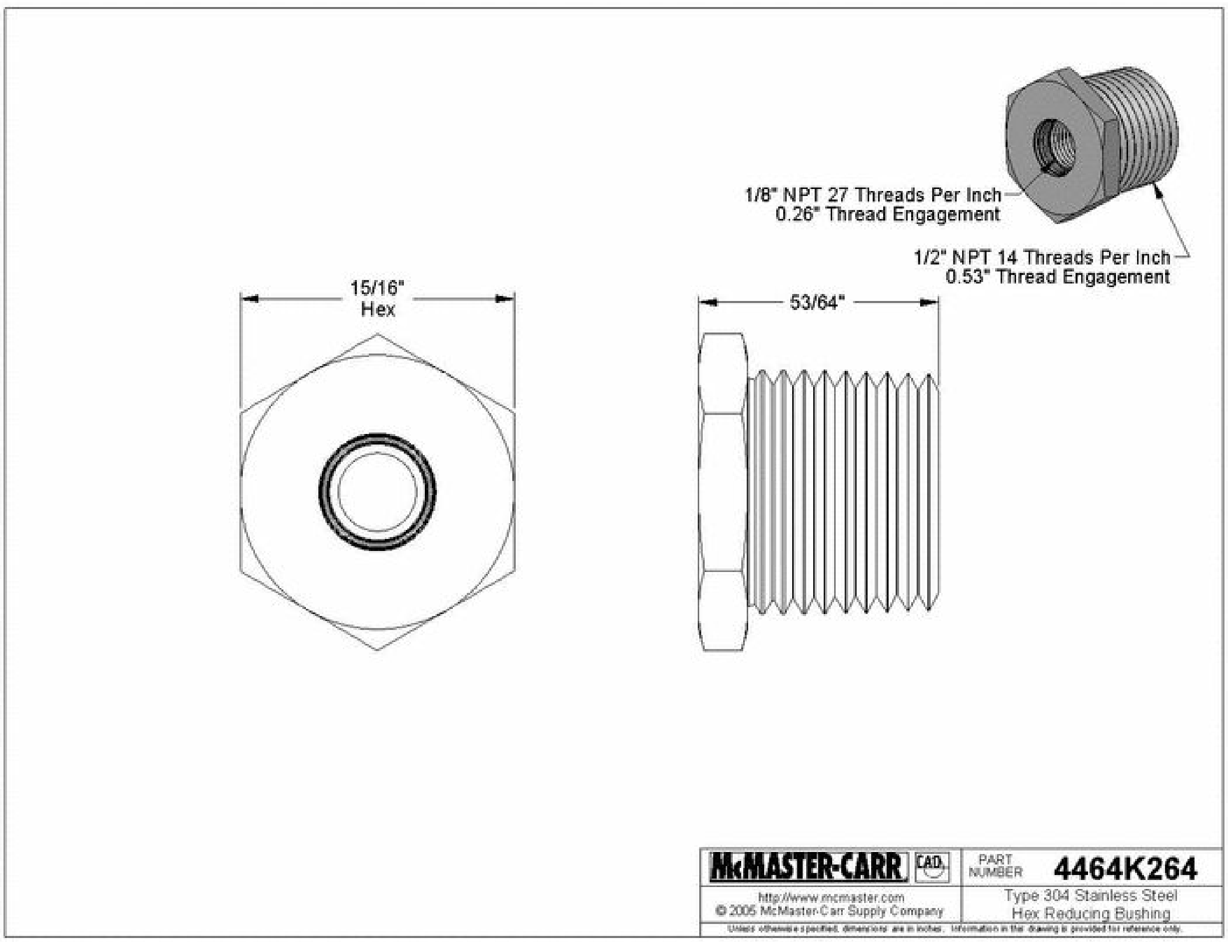


Stainless Steel Pipe Fittings and Pipe



Part Number: **4464K264** $2.97 Each

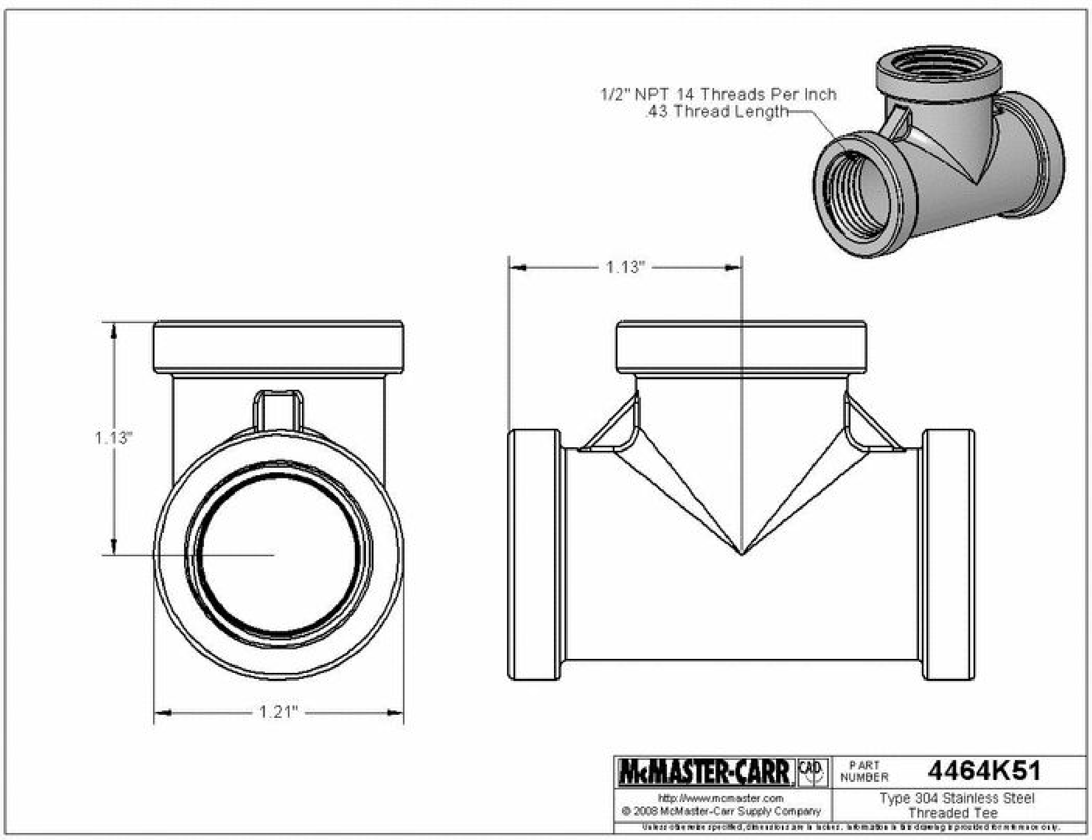
Shape	Bushing (Male x Female Hex)
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2" reduced to 1/8"
Material	Type 304 Stainless Steel
Maximum Pressure @ 72° F	150 psi
Maximum Pressure Note	For steam, maximum pressure is 150 psi @ 366° F.
Flanges	Use low-pressure threaded stainless steel
Specifications Met	American Society for Testing and Materials (ASTM), Manufacturers Standardization Society (MSS)
ASTM Specification	ASTM A351
MSS Specification	MSS SP-114



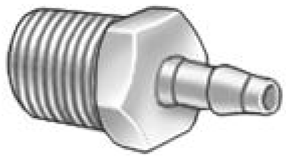
Stainless Steel Pipe Fittings and Pipe

Part Number: **4464K51** $7.18 Each

Shape	Tee
Tee Type Pipe to Pipe	Female Tee
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2"
Material	Type 304 Stainless Steel
Maximum Pressure @ 72° F	150 psi
Maximum Pressure Note	For steam, maximum pressure is 150 psi @ 366° F.
Flanges	Use low-pressure threaded stainless steel
Specifications Met	American Society for Testing and Materials (ASTM), Manufacturers Standardization Society (MSS)
ASTM Specification	ASTM A351
MSS Specification	MSS SP-114

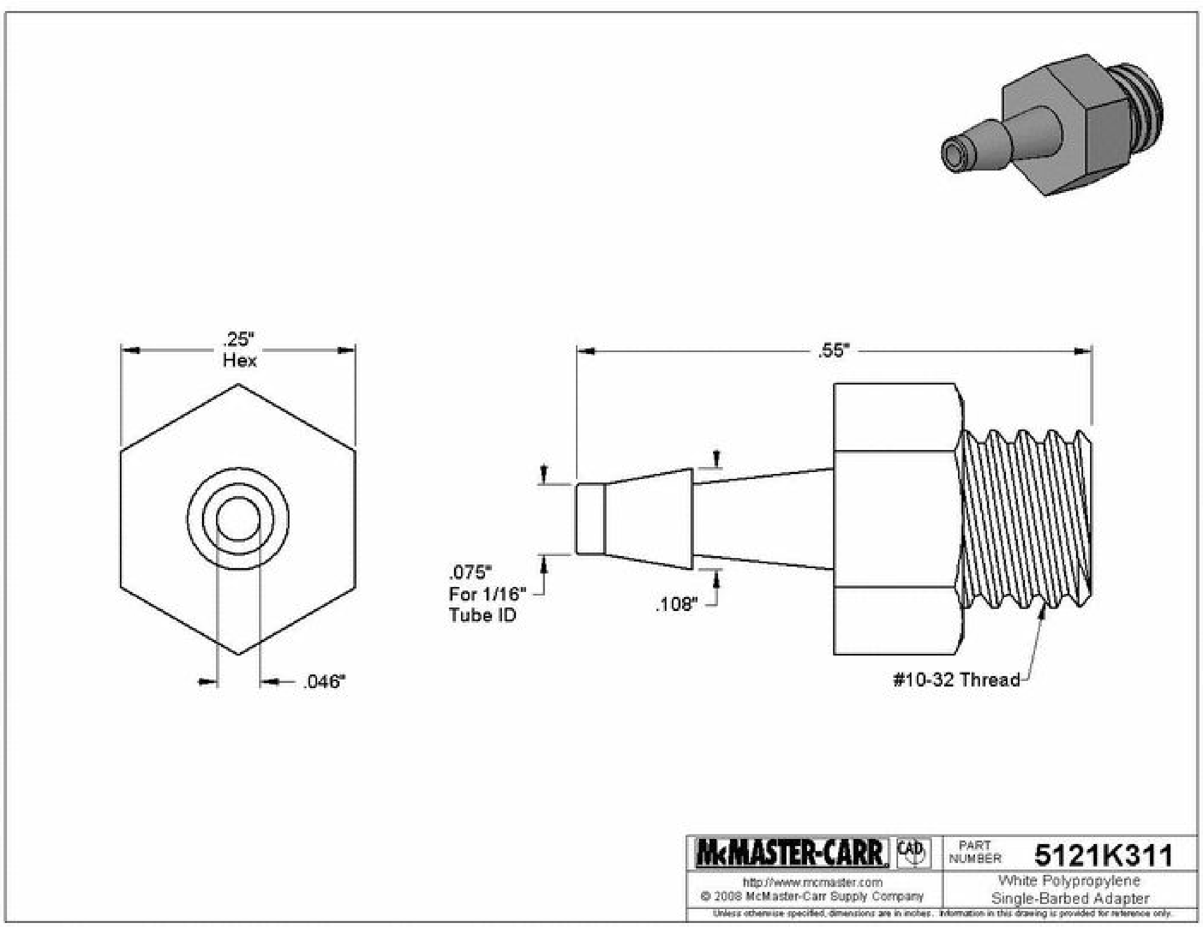


Plastic Pipe Fittings and Pipe



Part Number: **5121K311** $2.78 per Pack of 10

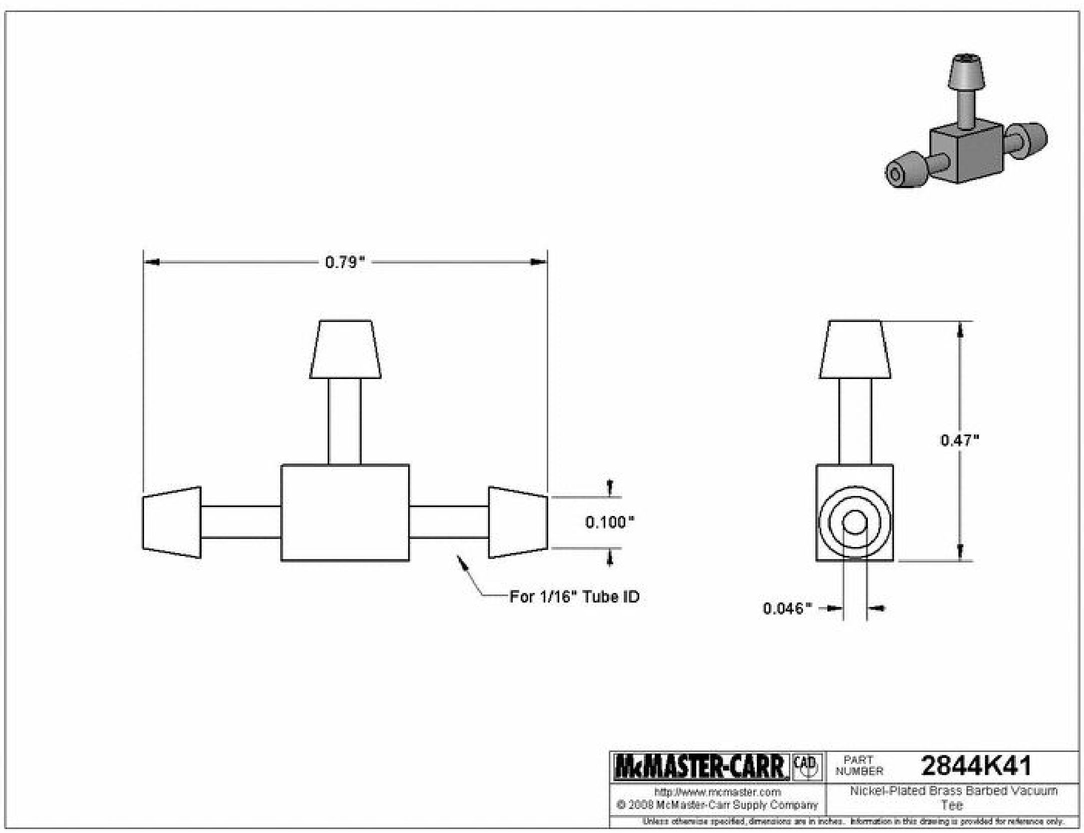
Shape	Pipe to Tube Adapter
Pipe to Tube Type	Male Pipe x Tube Adapter
Barbed Tube Fitting Type	Single-Barbed
Pipe to Tube Connection	UNF Pipe x Barbed Tube
System of Measurement	Inch
Pipe/Thread Size	10-32
For Tube ID	1/16"
Material	Polypropylene
Color	White
Maximum Pressure @ 72° F	125 psi
Temperature Range	32° to 250° F
For Use With	Air, Alcohol, Ethylene Glycol, Mild Bases, Water
Tubing Material Detail	Use with PVC and polyurethane tubing with a hardness of Shore A 75-80.
Vacuum Rating	Not Rated
Sterilize With	Not Rated
Specifications Met	Not Rated
Note	Clamps are required.



Barbed Tube Fittings

Part Number: **2844K41** $2.56 Each

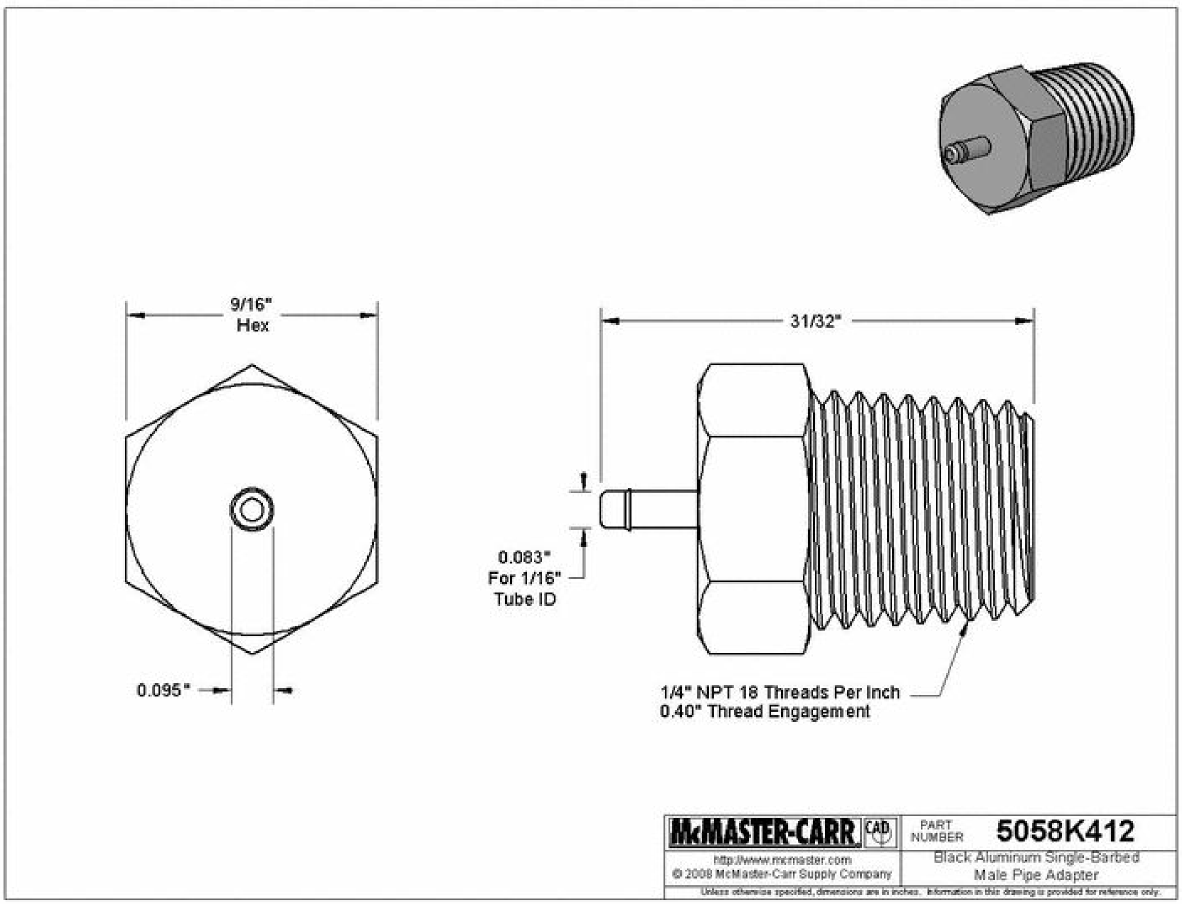
Material	Brass
Plating Material	Nickel
Tube Fitting Type	Tee
Tee Type	Tee
Inside Tube Diameter	1/16"
Number of Barbs	Single
Vacuum Rating	28.00" Hg @ 75° F
Maximum Pressure	150 psi @ 75° F
Operating Temperature Range	-30° to +160° F
For Use With	Air, Oil, Water
For Tubing Type	Polyurethane
For Tubing with Hardness	Shore A 85
Specifications Met	Not Rated
Note	To connect, simply slide the tubing over the barbed end of the fitting. A clamp is required for securing the tubing to the fitting.
Caution	McMaster-Carr does not guarantee chemical compatibility because many variables can affect the tubing and tube fittings. Ultimately, the consumer must determine chemical compatibility based on the conditions in which the product is being used.



Aluminum Pipe Fittings and Pipe

Part Number: **5058K412** $3.75 Each

Shape	Pipe to Tube Adapter
Pipe to Tube Type	Male Pipe x Tube Adapter
Pipe to Tube Connection	UNF Pipe x Barbed Tube
Pipe Size	1/4"
Tube ID	1/16"
Aluminum Type	6061-T6
Color	Black
Maximum Pressure @ 72° F	125 psi
Temperature Range	-40° to +300° F
For Use With	Air, Hydraulic Fluid, Oil, Water
Tubing Material Detail	Use with polyethylene, polypropylene, polyurethane, PTFE, and nylon tubing.
Vacuum Rating	27" Hg @ 72° F
Sterilize With	Not Rated
Specifications Met	Not Rated



Tubing

Part Number: **5006K51**

1-99 Ft. $0.14 per Ft.
100 or more $0.10 per Ft.

Type	Abrasion-Resistant Clear PVC Tubing
Material	PVC
Shape	Single Line
Outside Dia.	1/8" (.125")
Inside Dia.	1/16" (.0625")
Wall Thickness	1/32" (.0312")
Available Lengths	25, 50, and 100 feet
Reinforcement	Unreinforced
Color	Clear
Maximum Pressure	120 psi @ 73° F
Operating Temperature Range	-31° to +122° F
Bend Radius	Not Rated
Durometer	80A (Firm)
Tensile Strength	3,000 psi
For Use With	Air, Beverage, Ethylene Glycol, Food, Water
Sterilize With	Gas
Specifications Met	United States Food and Drug Administration (FDA)
FDA Specification	FDA Compliant
Compatible Fittings	Barbed
Chemical Compatibility Link	**5187KAC**
Caution	McMaster-Carr does not guarantee chemical compatibility because many variables can affect the tubing. Ultimately, the consumer must determine chemical compatibility based on the conditions in which the product is being used.

Bolt Depot.com fastener shopping made easy

Email: info@boltdepot.com
Toll Free: **1-866-337-9888**

You are here: Hex bolts » Standard bolts » Steel grade 2

Diameter: 1/2-13

Choose length and quantity.
For information on measuring bolt length see Measuring Fastener Length.

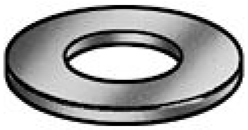
View  nuts and  washers.

<< Hide Bulk Prices | Add All Entered

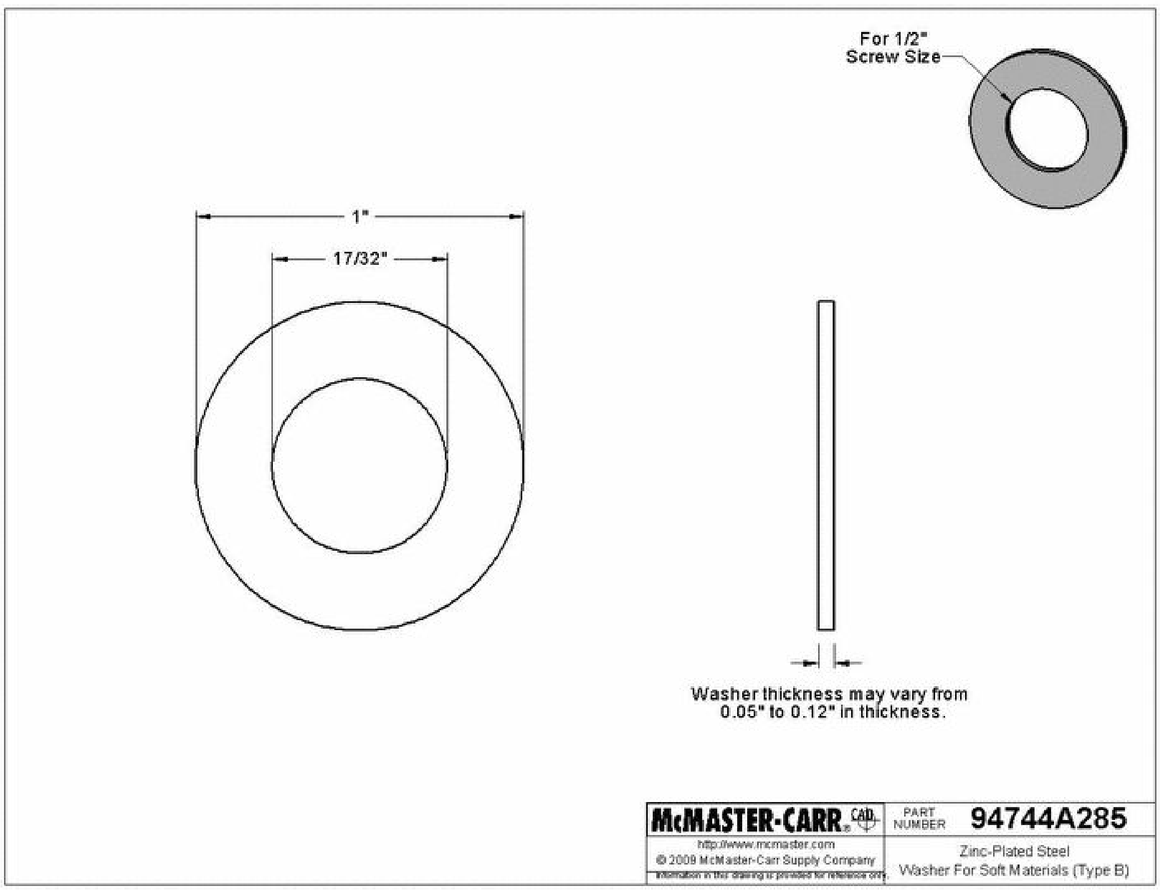
Product #	Length	Buy Each		Buy Box		Box Qty	Buy Bulk		Bulk Qty
242	3/4	$0.27	Add	$9.98	Add	50	$81.10	Add	500
243	1	$0.28	Add	$10.40	Add	50	$84.50	Add	500
7236	1-1/4	$0.29	Add	$10.84	Add	50	$88.40	Add	500
244	**1-1/2**	**$0.32**	Add	**$11.69**	Add	**50**	**$95.20**	Add	**500**
245	1-3/4	$0.37	Add	$13.28	Add	50	$108.00	Add	500
246	2	$0.40	Add	$14.69	Add	50	$120.00	Add	500
248	2-1/2	$0.47	Add	$16.69	Add	50	$136.00	Add	500
250	3	$0.54	Add	$20.97	Add	50	$170.00	Add	500
252	3-1/2	$0.61	Add	$11.90	Add	25	$96.80	Add	250
253	4	$0.69	Add	$13.73	Add	25	$111.00	Add	250
254	4-1/2	$0.79	Add	$15.36	Add	25	$125.00	Add	250
255	5	$0.89	Add	$17.08	Add	25	$139.00	Add	250
256	5-1/2	$1.02	Add	$19.51	Add	25	$159.00	Add	250
257	6	$1.10	Add	$21.20	Add	25	$172.00	Add	250
259	7	$1.53	Add	$29.70	Add	25	$242.00	Add	250
261	8	$1.73	Add	$33.73	Add	25	$274.00	Add	250
263	9	$1.89	Add	$36.16	Add	25	$294.00	Add	250
264	10	$1.95	Add	$37.63	Add	25	$306.00	Add	250
266	12	$2.34	Add	$44.59	Add	25	$363.00	Add	250

Add All Entered

Washers



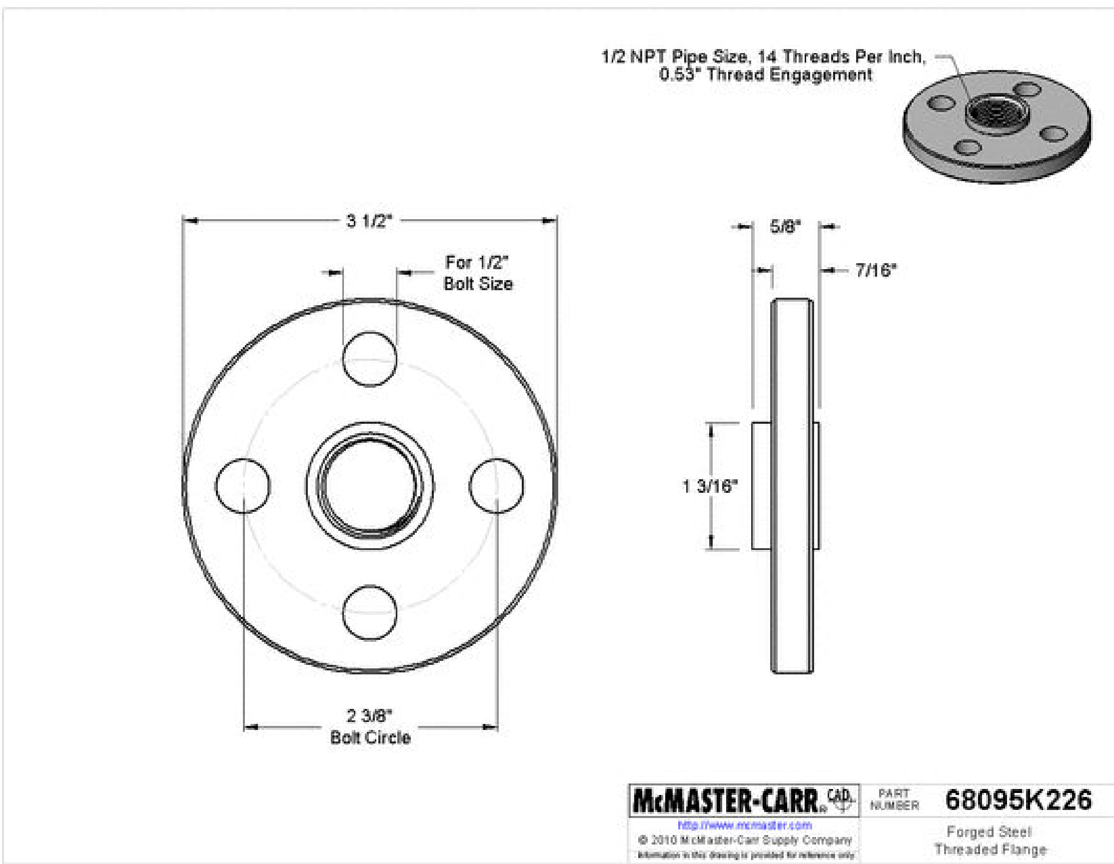
Part Number: **94744A285**	$4.43 per Pack of 5
Shape	Round Hole
For Screw Size	1/2"
Material Type	Steel
Finish	Zinc-Plated
Inside Diameter	.531" (17/32")
Outside Diameter	1"
Minimum Thickness	.05"
Maximum Thickness	.12"
Rockwell Hardness	Minimum B40
Specifications Met	American Society of Mechanical Engineers (ASME)
ASME Specification	ASME B18.22.1



Iron and Steel Pipe Fittings and Pipe

Part Number: **68095K226** $12.35 Each

Shape	Flange
Flange Type	Threaded Flange
Pipe to Pipe Connection	NPT x NPT
System of Measurement	Inch
Pipe Size	1/2"
Flange OD (A)	3-1/2"
Bolt Circle Diameter (B)	2-3/8"
Flange Thickness (C)	7/16"
Number of Bolt Holes	4
Recommended Bolt Size x Length	1/2" x 2"
Steel	Forged Steel
Maximum Pressure @ 72° F	150 psi
Maximum Pressure Note	For steam, maximum pressure is 150 psi @ 350° F.
Specifications Met	American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), Manufacturers Standardization Society (MSS)
ANSI Specification	ANSI B16.5
ASTM Specification	ASTM A105
MSS Specification	MSS SP-25
Note	A gasket is required, but not included.



Resilient Rubber Gaskets

All gaskets resist salts, water, and deformation after compression. Meet ASTM D2000. Cut *sheet gaskets* with scissors or a utility knife. *Ring flange gaskets* cover the section of flange just inside the bolt holes.

SBR— Use this rubber when dealing with low-pressure applications. Temperature range is –20° to +170° F. Maximum pressure is 800 psi. Durometer hardness is A75. Color is red.

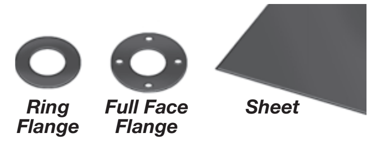
Buna-N— Ideal for oil applications. Also resists alkalies and detergents. Temperature range is –20° to +170° F. Maximum pressure is 1,000 psi. Durometer hardness is A60. Color is black, except *FDA Buna-N* is off-white.

Neoprene— Resists detergents. Temp. range is –20° to +170° F. Maximum pressure is 1,000 psi. Color is black. Durometer hardness is A70 for *neoprene* and not rated for *reinforced neoprene*. *Neoprene* meets MIL-R-3065; *reinforced neoprene* has a nylon insert.

Gum— When the pressure is on, this material can withstand up to 2,500 psi. Also resists detergents and steam. Temperature range is –20° to +160° F. Durometer hardness is A40. Color is tan.

Viton® Fluoroelastomer— Has better chemical resistance than other rubbers. Resists grease, oil, detergents, and some acids. Durometer hardness is A75. Temperature range is –20° to +400° F for *Viton®* and *FDA Viton®*, –40° to +400° F for *low-temperature Viton®*, and 0° to 400° F for *chemical-resistant Viton®* (also known as Viton® ETP). Maximum pressure is 1,000 psi for *Viton®*; not rated for all other types of Viton®. Color is black, except *FDA Viton®* is white.

Silicone— A broad temperature range of –70° to +500° F makes silicone great for use in high-temperature applications. Also resists alkalies, acids, detergents, and steam. Maximum pressure is 1,000 psi. Durometer hardness is A60. Color is red.



Sheet Gaskets

Thick.	Size	SBR Each		Buna-N Each		FDA Buna-N Each		Neoprene Each		Reinforced Neoprene Each		Gum Each	
1/16″	12″×12″	8525T11	$2.38	8525T21	$3.67	8525T61	$5.09	8525T31	$3.42	8525T55	$7.17	8525T51	$3.33
1/16″	24″×24″	8525T12	6.09	8525T22	9.06	8525T62	19.30	8525T32	8.31	8525T56	27.08	8525T52	8.74
1/8″	12″×12″	8525T13	4.59	8525T23	6.74	8525T63	9.91	8525T33	5.33	8525T57	13.92	8525T53	5.70
1/8″	24″×24″	8525T14	11.99	8525T24	17.83	8525T64	35.70	8525T34	13.17	8525T58	49.00	8525T54	13.62

Thick.	Size	Viton® Fluoroelastomer Each		FDA Viton® Fluoroelastomer Each		Low-Temperature Viton® Fluoroelastomer Each		Chemical-Resistant Viton® Fluoroelastomer Each		Silicone Each	
1/16″	12″×12″	9473K61	$31.89	9473K94	$55.76	9473K96	$98.08	9473K92	$374.65	8525T41	$15.36
1/16″	24″×24″	9473K62	115.33	—	—	—	—	—	—	8525T42	43.68
1/8″	12″×12″	9473K63	54.50	9473K95	99.59	9473K97	178.80	9473K93	688.09	8525T43	22.64
1/8″	24″×24″	9473K64	195.32	—	—	—	—	—	—	8525T44	70.50

Flange Gaskets—1/8″ Thick

RING WITHOUT HOLES

For Pipe Size	ID	OD	Pkg. Qty.	SBR Per Pkg.		Buna-N Per Pkg.		Neoprene Per Pkg.		Viton® Fluoroelastomer Each		Silicone Each	
ANSI gaskets sized to fit Class 150 flanges													
1/2″	27/32″	1 7/8″	10	9774K41	$1.38	8516T11	$6.18	97725K31	$2.76	9473K65	$3.38	8521T21	$1.32
3/4″	1 1/16″	2 1/4″	10	9774K42	1.38	8516T12	6.76	97725K32	2.76	9473K66	3.38	8521T22	1.47
1″	1 5/16″	2 5/8″	10	9774K43	2.06	8516T13	7.35	97725K33	4.50	9473K67	3.78	8521T23	1.68
1 1/4″	1 21/32″	3″	10	9774K44	2.76	8516T14	7.71	97725K34	4.76	9473K68	4.46	8521T24	2.05
1 1/2″	1 29/32″	3 3/8″	10	9774K45	2.76	8516T15	8.06	97725K35	5.26	9473K69	5.27	8521T25	2.48
2″	2 3/8″	4 1/8″	10	9774K46	4.14	8516T16	8.95	97725K36	6.50	9473K71	6.13	8521T26	3.00
2 1/2″	2 7/8″	4 7/8″	6	9774K47	2.93	8516T17	8.00	97725K37	4.43	9473K72	7.25	8521T27	3.52
3″	3 1/2″	5 3/8″	6	9774K48	2.89	8516T18	8.33	97725K38	4.86	9473K73	9.13	8521T28	4.53
4″	4 1/2″	6 7/8″	6	9774K49	4.42	8516T19	11.70	97725K39	7.29	9473K74	14.38	8521T29	7.30
5″	5 9/16″	7 3/4″	6	9774K51	5.18	8516T21	13.14	97725K41	9.72	9473K75	17.38	8521T31	8.40
6″	6 5/8″	8 3/4″	2	9774K52	2.03	8516T22	6.41	97725K42	4.53	9473K76	19.38	8521T32	10.07
8″	8 5/8″	11″	2	9774K53	2.74	8516T23	7.94	97725K43	4.74	9473K77	26.75	8521T33	13.65

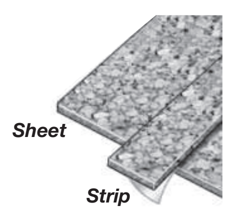
FULL FACE WITH HOLES

For Pipe Size	ID	OD	No. of Bolt Holes	Viton® Fluoroelastomer Each	
ANSI gaskets sized to fit Class 150 flanges					
1/2″	27/32″	3 1/2″	4	9473K78	$6.25
3/4″	1 1/16″	3 7/8″	4	9473K79	6.25
1″	1 5/16″	4 1/4″	4	9473K81	7.00
1 1/4″	1 21/32″	4 5/8″	4	9473K82	8.25
1 1/2″	1 29/32″	5″	4	9473K83	$9.75
2″	2 3/8″	6″	4	9473K84	12.25
2 1/2″	2 7/8″	7″	4	9473K85	14.50
3″	3 1/2″	7 1/2″	4	9473K86	18.25
4″	4 1/2″	9″	8	9473K87	$28.75
5″	5 9/16″	10″	8	9473K88	34.75
6″	6 5/8″	11″	8	9473K89	38.75
8″	8 5/8″	13 1/2″	8	9473K91	53.50

Compressible Cork Gaskets

Multipurpose cork is great for gaskets and bulletin boards. Material is highly compressible in low-pressure applications. It is also flexible, allowing it to conform to curved shapes.

All resist alkalies, acids, salts, water, grease, oil, and detergents. Temperature range is –20° to +180° F. Maximum pressure is 55 psi. Color is tan/light brown. Cut with a utility knife.



Adhesive-Backed Strips

Thick.	Size		Each
1/8″	1/2″×50 ft.	93305K61	$5.73
1/8″	1″×50 ft.	93305K63	$10.73
1/8″	2″×50 ft.	93305K64	$21.46

Sheets

Thick.	Size	Plain Back Each		Adhesive Backed Each	
1/16″	12″×36″	9487K1	$2.87	9487K51	$6.12
3/32″	12″×36″	9487K2	4.38	9487K52	7.47
1/8″	12″×36″	9487K3	4.76	9487K53	8.55
3/16″	12″×36″	9487K6	8.62	9487K62	12.51
1/4″	12″×36″	9487K4	9.40	9487K54	13.27
3/8″	12″×36″	9487K8	14.03	9487K58	16.01
1/2″	12″×36″	9487K5	20.51	9487K55	22.45

Sheeting

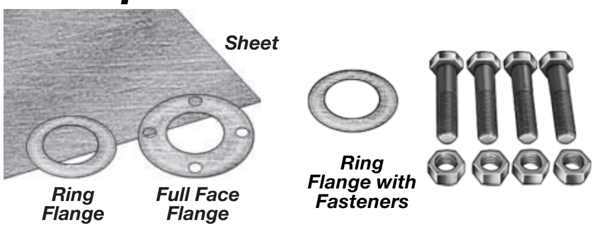
Thick.	Size	Plain Back Each		Adhesive Backed Each	
1/16″	48″×25 ft.	9487K71	$86.43	9487K81	$160.16
3/32″	48″×25 ft.	9487K72	123.50	9487K82	186.45
1/8″	48″×25 ft.	9487K73	104.83	9487K83	201.75
3/16″	48″×20 ft.	9487K74	148.13	—	—
1/4″	48″× 8 ft.	9487K36	76.40	—	—
3/8″	48″× 8 ft.	9487K37	94.86	—	—
1/2″	48″× 8 ft.	9487K38	140.28	—	—

Gaskets, Joint Sealant & Gasket Tape

For gasket cutters, see pages 2326-2327.

Looking for a different shape of gasket? Just tell us what you need and we'll get it for you.

All-Purpose Gaskets



Made of aramid fibers with a Buna-N binder, these gaskets resist water, oil, gasoline, and grease. Temperature range is –40° to +400° F. All meet ASTM F104.

Sheet Gaskets— Die cut or cut with a gasket cutter. Maximum pressure is 1,000 psi for *blue gaskets* and 1,400 psi for *green gaskets*.

Flange Gaskets— Maximum pressure is 1,000 psi. Color is blue. *Ring gaskets* cover the section of the flange just inside the bolt holes.

Ring Flange Gaskets with Fasteners— Everything you need to seal steel flanges, packed in a convenient kit. Each kit contains one green gasket, plus Grade 2 hex head bolts and nuts (ASTM A307) in the quantity listed below. Gasket is ring style without holes, so it covers the section of the flange just inside the bolt holes. Maximum pressure is 725 psi.

Sheet Gaskets

Size	1/64″ Thick	Each	1/32″ Thick	Each	1/16″ Thick	Each	3/32″ Thick	Each	1/8″ Thick	Each
Blue										
6″ × 6″	9470K25	$2.23	9470K26	$2.76	9470K27	$3.75	9470K28	$5.19	9470K35	$6.96
15″ × 15″	9470K36	10.42	9470K37	13.61	9470K38	17.73	9470K39	24.50	9470K41	32.28
30″ × 30″	9470K42	31.33	9470K43	42.24	9470K44	52.75	9470K45	72.71	9470K46	74.63
30″ × 60″	9470K47	54.48	9470K48	73.46	9470K49	91.54	9470K65	126.46	9470K66	169.75
Green										
15″ × 15″	9402K21	9.43	9402K22	12.78	9402K23	16.79	9402K24	23.48	9402K25	29.14
22 1/2″ × 30″	9402K71	21.12	9402K72	28.36	9402K73	45.00	9402K74	62.94	9402K75	85.53
30″ × 45″	9402K61	33.79	9402K62	45.38	9402K63	72.00	9402K68	99.74	9402K64	136.84
45″ × 60″	9402K81	54.07	9402K82	72.60	9402K83	115.20	9402K88	161.22	9402K84	218.95

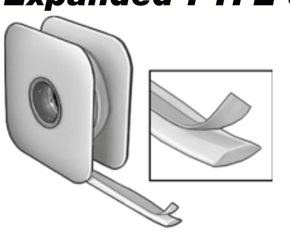
Flange Gaskets— 1/16″ Thick

For Pipe Size	Ring without Holes ID	OD		Each	Full Face with Holes No. of Bolt Holes	OD		Each
Blue— *ANSI gaskets sized to fit Class 150 flanges*								
1/2″	27/32″	1 7/8″	9472K21	$0.46	4	3 1/2″	9472K56	$1.74
3/4″	1 1/16″	2 1/4″	9472K22	0.54	4	3 7/8″	9472K41	1.85
1″	1 5/16″	2 5/8″	9472K23	0.97	4	4 1/4″	9472K42	1.95
1 1/4″	1 21/32″	3″	9472K24	1.19	4	4 5/8″	9472K43	2.46
1 1/2″	1 29/32″	3 3/8″	9472K25	1.46	4	5″	9472K44	2.82
2″	2 3/8″	4 1/8″	9472K26	1.95	4	6″	9472K45	3.82
2 1/2″	2 7/8″	4 7/8″	9472K27	2.82	4	7″	9472K46	5.17
3″	3 1/2″	5 3/8″	9472K28	3.07	4	7 1/2″	9472K47	5.58
3 1/2″	4″	6 3/8″	9472K29	4.39	8	8 1/2″	9472K48	6.75
4″	4 1/2″	6 7/8″	9472K31	4.39	8	9″	9472K49	6.75
5″	5 9/16″	7 3/4″	9472K32	6.05	8	10″	9472K51	9.97
6″	6 5/8″	8 3/4″	9472K33	6.86	8	11″	9472K52	10.54
8″	8 5/8″	11″	9472K34	9.79	8	13 1/2″	9472K53	13.37
10″	10 3/4″	13 3/8″	9472K35	12.52	12	16″	9472K54	18.27
12″	12 3/4″	16 1/8″	9472K36	20.15	12	19″	9472K55	35.12

Ring Flange Gaskets with Fasteners— 1/16″ Thick

For Pipe Size	Gasket ID	Gasket OD	Bolt/Nut Qty.	Bolt Size		Each
Green— *ANSI gaskets sized to fit Class 150 flanges*						
1/2″	27/32″	1 7/8″	4	1/2″ × 2 1/4″	9166K61	$4.34
3/4″	1 1/16″	2 1/4″	4	1/2″ × 2 1/4″	9166K62	4.37
1″	1 5/16″	2 5/8″	4	1/2″ × 2 1/4″	9166K63	4.73
1 1/4″	1 21/32″	3″	4	1/2″ × 2 1/2″	9166K64	4.80
1 1/2″	1 29/32″	3 3/8″	4	1/2″ × 2 1/2″	9166K65	5.40
2″	2 3/8″	4 1/8″	4	5/8″ × 2 1/2″	9166K66	7.46
2 1/2″	2 7/8″	4 7/8″	4	5/8″ × 2 3/4″	9166K67	8.04
3″	3 1/2″	5 3/8″	4	5/8″ × 2 3/4″	9166K68	8.31
4″	4 1/2″	6 7/8″	8	5/8″ × 3″	9166K69	14.79
6″	6 5/8″	8 3/4″	8	3/4″ × 3 1/4″	9166K71	20.37
8″	8 5/8″	11″	8	3/4″ × 3 1/2″	9166K72	21.60
10″	10 3/4″	13 3/8″	12	7/8″ × 3 3/4″	9166K73	38.88
12″	12 3/4″	16 1/8″	12	7/8″ × 4″	9166K74	42.20

Expanded-PTFE Joint Sealant



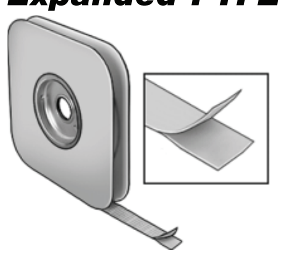
This adhesive-backed joint sealant can be used on most types of flanges, especially large, damaged, and complex ones. Chemically inert except for molten alkali metals and elemental fluorine. Color is white. Cut with a utility knife.

Gore— The original expanded-PTFE joint sealant. Temperature range is –450° to +600° F. Maximum pressure is 3,000 psi.

Value Seal— The economical choice. Temperature range is –450° to +500° F. Maximum pressure is 2,900 psi. FDA compliant.

For Pipe Size	Wd. × Thick.	Roll Lg., ft.		Each
Gore				
1/2″	1/8″ × 3/64″	25	4502K32	$47.56
3/4″ - 1 1/2″	3/16″ × 5/64″	30	4502K33	75.09
2″ - 4″	1/4″ × 3/32″	20	4502K34	74.00
5″ - 8″	3/8″ × 1/8″	12	4502K35	77.57
10″ -16″	1/2″ × 7/32″	5	4502K36	53.45
18″ -24″	5/8″ × 1/4″	7	4502K37	122.22
24″ -36″	3/4″ × 19/64″	7	4502K38	173.58
36″ -Up	1″ × 3/8″	7	4502K39	376.88
Value Seal				
1/2″	1/8″ × 1/16″	25	45925K71	19.31
3/4″ - 1 1/2″	3/16″ × 5/64″	30	45925K72	29.02
2″ - 4″	1/4″ × 5/32″	20	45925K73	25.86
5″ - 8″	3/8″ × 13/64″	12	45925K74	27.19
10″ -16″	1/2″ × 13/64″	5	45925K75	18.19
18″ -24″	5/8″ × 15/64″	7	45925K76	42.60
24″ -36″	3/4″ × 9/32″	7	45925K77	57.65
36″ -Up	1″ × 13/64″	7	45925K78	64.98

Expanded-PTFE Gasket Tape



You can shape this super-thin adhesive-backed expanded-PTFE tape for use as a flange gasket. Works well on flat and narrow surfaces. It's noncontaminating and resists alkalies (excluding molten alkali metals and elemental fluorine), acids, salts, water, steam, grease, oil, and detergents. Temperature range is –450° to +600° F. Color is white. Cut with a utility knife.

Gore— This industry favorite maintains a high level of tightness over time. It seals surface irregularities with a depth of up to 1/3 the tape's thickness. Maximum pressure is 3,000 psi.

Value Seal— An economical alternative. Max. pressure is 2,900 psi. FDA compliant.

Thick.	1/2″ Wide	Each	3/4″ Wide	Each	1″ Wide	Each
Gore						
5-ft. Rolls						
0.010″	95705K121	$34.00	95705K122	$51.63	95705K123	$61.14
0.020″	95705K131	37.86	95705K132	55.00	95705K133	65.87
0.040″	95705K141	44.55	95705K142	66.96	95705K143	79.58
0.065″	95705K151	56.96	95705K152	88.33	95705K153	110.00
50-ft. Rolls						
0.010″	95705K171	127.59	95705K175	185.00	95705K181	219.35
0.020″	95705K172	135.00	95705K176	201.61	95705K182	243.75
0.040″	95705K173	159.68	95705K177	248.44	95705K183	298.74
0.065″	95705K174	207.49	95705K178	330.30	95705K184	397.06
Value Seal						
50-ft. Rolls						
0.020″	9477K21	41.08	9477K31	58.55	9477K41	74.36
0.040″	9477K22	80.84	9477K32	111.52	9477K42	137.80
0.060″	9477K23	140.00	9477K33	201.90	9477K43	255.65
0.120″	9477K24	266.41	9477K34	382.15	9477K44	490.42

136

For information about adhesives, see page 3370.

Epoxy and Urethane Adhesives in Easy-Dispensing Syringes

Ideal for small jobs, these two-part adhesives come in a dual-cylinder syringe with built-in plunger for easy dispensing. These products are VOC compliant in all 50 states as of October 1, 2008.

Loctite® Epoxy Adhesives

Bond metal, plastic, ceramic, glass, and wood.

1 Minute—Ultra-fast hardening and resists high temperatures. Can also be used to fill and seal cracks and rebuild worn surfaces.

30 Minute—Fiberglass-reinforced for high strength and shock resistance.

Epoxy Adhesives

60-90 Second—Fast hardening. Bonds aluminum, copper, mild steel, stainless steel, ceramic, fiberglass (FRP), rigid plastic, rubber, and stone.

3-6 Minute and 4-7 Minute Gel—Rapid hardening. Bonds aluminum, brass, cast iron, copper, stainless steel, PVC, ceramic, concrete, fiberglass (FRP), glass, and wood. *4-7 minute gel* is thicker for vertical surfaces.

4 Minute—Bonds aluminum, copper, stainless steel, ABS, acrylic, polystyrene, PVC, and wood.

4-6 Minute (Acrylic)—Bonds ABS, acrylic, fiberglass (FRP), Garolite (phenolic laminates), polycarbonate, polyester, and PVC.

4-6 Minute (Epoxy)—Has high shear and peel strength. Bonds aluminum, copper, galvanized steel, mild steel, stainless steel, ceramic, rubber, and wood.

8-12 Minute—Resists water and makes extra-strong bonds on aluminum, brass, cast iron, copper, stainless steel, ceramic, concrete, fiberglass (FRP), glass, PVC, and wood.

100-120 Minute—Slower version of the 90 second adhesive.

Underwater Epoxy Adhesive

For surfaces that are dry, wet, and even under water. Bonds aluminum, brass, stainless steel, steel, ABS, acrylic, nylon, polycarbonate, PVC, ceramic, fiberglass (FRP), masonry, and wood.

Urethane Adhesives in Cartridges

Bond stainless steel, steel, ABS, acrylic, polycarbonate, polystyrene, PVC, and fiberglass (FRP). Include mixer nozzle.

90-120 Second—Also bonds etched or treated polyethylene, polypropylene, and glass.

4-6 Minute—Also bonds glass and quartz.

Begins to Harden	Loctite No.	Reaches Full Strength	Size	Temperature Range	Color	Approx. Coverage @ 0.005″ Thick.	Mix Ratio		Each
Loctite Epoxy									
1 min.	1324007	1 hr.	1 oz.	–65° to +300° F	Clear	360 sq. in.	1:1	7556A33	$6.13
30 min.	99393	24 hrs.	1 oz.	–20° to +180° F	Tan	505 sq. in.	1:1	7556A35	8.06
Epoxy									
60-90 sec.	—	3 hrs.	1.65 oz.	–40° to +250° F	Clear/Amber	345 sq. in.	1:1	7541A82	7.87
3-6 min.	—	12 hrs.	0.85 oz.	–40° to +200° F	Light Amber	305 sq. in.	1:1	7541A76	4.66
4 min.	—	24 hrs.	0.5 oz.	–40° to +200° F	Light Amber	180 sq. in.	1:1	7670A22	5.13
4-6 min.	—	24 hrs.	0.85 oz.	–67° to +250° F	Light Yellow	305 sq. in.	1:1	75395A65★	8.66
4-6 min.	—	24 hrs.	1.69 oz.	–40° to +250° F	Light Yellow	357 sq. in.	1:1	7541A84	8.18
4-7 min.	—	12 hrs.	0.85 oz.	–40° to +200° F	Off-White	305 sq. in.	1:1	7592A31	6.20
8-12 min.	—	12 hrs.	0.85 oz.	–40° to +200° F	Clear	305 sq. in.	1:1	7541A77	6.11
100-120 min.	—	24 hrs.	1.69 oz.	–40° to +250° F	Amber	329 sq. in.	1:1	7541A83	8.18
Underwater Epoxy									
60 min.	—	7 days	1 oz.	–40° to +200° F	Aqua	370 sq. in.	1:1	7456A53	6.74
Urethane									
90-120 sec.	—	24 hrs.	1.69 oz.	–40° to +250° F	Gray	496 sq. in.	1:1	7448A21	8.55
4-6 min.	—	24 hrs.	1.69 oz.	–40° to +250° F	Black	496 sq. in.	1:1	7448A22	8.55

★ Acrylic adhesive.

Epoxy in Caulk Gun Cartridge

Don't buy a new tool just to apply your epoxy. All you need is a caulk gun that holds a 10-11 oz. cartridge to dispense this two-part adhesive. Bonds aluminum, brass, copper, stainless steel, steel, ABS, acrylic, PVC, rigid plastic, ceramic, fiberglass (FRP), rubber, and wood. Includes two mixer nozzles to mix adhesive as it is dispensed. Temperature range is –40° to +200° F. Color is light amber. This product is VOC compliant in all 50 states as of October 1, 2008.

See page 3398 for caulk guns.

Size	Begins to Harden	Reaches Full Strength	Mix Ratio		Each
8½ oz.	3½ min.	24 hrs.	1:1	7646A12	$39.89

J-B Weld Epoxies

Create bonds as strong as welding or soldering. These two-part adhesives bond aluminum, brass, bronze, copper, stainless steel, steel, ABS, acrylic, polycarbonate, PVC, ceramic, concrete, fiberglass (FRP), and wood. At full strength they're waterproof, resistant to chemicals and acids, and can be drilled, tapped, sanded, and painted. Mix ratio is 1:1. Color is dark gray. Maximum temperature is 500° F for 8265-S and 8280 epoxies; 300° F for 8276 epoxy.

These products are VOC compliant in all 50 states as of October 1, 2008.

J-B Weld No.	Tube Size ♦	Begins to Harden	Reaches Full Strength	Approx. Coverage @ 0.125″ Thick.		Each
8265-S	1 oz.	60 min.	15-24 hrs.	16 sq. in.	7605A11	$5.91
8276	1 oz.	4 min.	4 hrs.	16 sq. in.	7605A13	5.91
8280	5 oz.	60 min.	15-24 hrs.	80 sq. in.	7605A12	16.62

♦ Refers to the size of each part of the adhesive.

3M Scotch-Weld Epoxy and Urethane Adhesives

Get secure bonds with these two-part adhesives. Bond aluminum, brass, copper, galvanized steel, stainless steel, steel, ABS, acrylic, nylon, polycarbonate, PVC, rigid vinyl, glass, rubber, and wood. At 0.005″ thick, 1 gal. covers approx. 320 sq. ft. Temperature range is –60° to +350° F for epoxies; –60° to +250° F for urethanes.

These products are VOC compliant in all 50 states as of October 1, 2008.

1751 Epoxy—Rigid aluminum-filled structural epoxy that has excellent adhesion and fills spaces between surfaces without losing bonding strength. Ideal for holes, dents, and cracks.

1838 and 1838L Epoxies—Rigid with high strength, these epoxies also bond reinforced plastics such as fiberglass (FRP) and PET. *1838* meets MIL-A-52194A. *1838L* is thinner so it flows quickly and easily.

2158 Epoxy—Also bonds damp concrete.

2216 Epoxy—Highly flexible and resistant to peeling. Also bonds masonry. Gray version meets DOD-A-82720.

3501 Epoxy—Hardens quickly and has good weather resistance.

3532 and 3535 Urethanes—Create tough, impact-resistant bonds. Become thicker after 30 seconds of mixing; for vertical use. *3535* hardens faster.

3M No.	Begins to Harden	Reaches Full Strength	Color	Mix Ratio	*2-oz. Tube* ♦	Each	*1-pt. Can* ♦	Each	*1-qt. Can* ♦	Each	*1-gal. Can* ♦	Each
1751 Epoxy	45 min.	7 days	Gray	3:2	75065A66	$37.03	75065A67	$133.85	75065A68	$179.18	75065A85	$543.54
1838 Epoxy	60 min.	7 days	Green	4:5	75065A69	35.89	75065A7	124.53	75065A71	144.77	75065A86	506.36
1838L Epoxy	60 min.	7 days	Translucent	1:1	75065A73	39.57	—	—	75065A74	234.86	—	—
2158 Epoxy	120 min.	7 days	Gray	1:1	—	—	75065A76	130.65	75065A77	176.70	—	—
2216 Epoxy	90 min.	7 days	Gray	2:3	75045A65	39.27	75045A66	134.50	75045A67	179.39	75045A68	546.29
2216 Epoxy	120 min.	30 days	Translucent	1:1	75045A78	35.75	75045A79	161.10	75045A8	214.76	75045A81	653.43
3501 Epoxy	6-10 min.	24 hrs.	Gray	1:1	75065A81	36.94	75065A82	162.82	—	—	75065A84	694.87
3532 Urethane	5-15 min.	24 hrs.	Brown	1:1	75025A772	27.55	—	—	75025A774	134.41	—	—
3535 Urethane	45-240 sec.	8 hrs.	Off-White	1:1	75065A92	29.61	—	—	—	—	—	—

♦ Refers to the size and container of each part of the adhesive.

137

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Zoom View

Orbit 1/2 In. x 520 In.Thread Seal Tape

Model # 31273 Internet # 202206819 Store SKU # 788287

Be the first to Write a Review

$1.18 /EA-Each

Ships FREE with $249.00 Order

This item cannot be shipped to the following state(s): AK,HI

Quantity: 1

ADD TO CART

Add to My List

Check Store Inventory

SHOPPERS WHO VIEWED THIS ITEM ALSO VIEWED

Algreen 50 Gallon 23.5 In. W x 23.5 In. D x 33 In. ...

$99.98/Each

1/10 HP Self-Priming Portable Utility Pump

$76.96/Each

Split It 9 in. Faucet Y Splitter

$10.94/Each

Description

Use Orbit's thread seal tape to effectively prevent, or eliminate, any leaks occurring in pipe fittings. Just wrap around the threading and it easily creates a water tight barrier.

Use to seal threaded joints on metal or plastic pipe fittings
Prevents leaks
Easy to use
High quality materials
MFG Brand Name : Orbit
MFG Model # : 31273
MFG Part # : 31273

Specifications

Accessory/Part Type : Tape
Assembled Depth (in.) : 2.25 in
Assembled Height (in.) : 0.75 in
Assembled Width (in.) : 2.25 in

E-MAIL EXCLUSIVES

Sign up to receive special offers and promotions from the Home Depot

Enter Email Address

FOLLOW THE HOME DEPOT

ABOUT THE HOME DEPOT

Affiliate Program
Careers
Corporate Info
Government Customers
Investor Relations
Privacy & Security
Supplier Center
Supplier Diversity
The Home Depot Canada
The Home Depot Mexico

STRESS FREE SHOPPING

Gift Cards
Price Match Policy
Privacy Policy
Return Policy
Service Plan Registration
Site Map

PARTNER SITES

Home Improver Club
Home Decorators Collection
Garden Club
The Home Depot Racing
Eco Options

CUSTOMER SERVICE

Contact Us
Home Depot Opinion
Order Status
Product Recalls
Shipping and Delivery
Store Information

CREDIT CENTER

No Interest if Paid in Full Within 6 Months*
$299 Minimum Purchase Required. Minimum Payments Required.

6 MONTHS EVERYDAY >

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Zoom View

2 in. x 4 in. x 7-1/4 ft. Douglas Fir Stud

Model # 603503 Store SKU # 603503

Be the first to Write a Review

$1.98 /EA-Each

Not Sold Online

Add to My List

Sold At Your Local Store

SHOPPERS WHO VIEWED THIS ITEM ALSO VIEWED

IDXPERT 0.318 In. x 24 Ft. Terminal Block Marker

$54.96/Each

Kensington 25 in. x 22 in. Cast Acrylic Laundry/Utility ...

$152.00/Each

9.8 oz. White KB Supreme Silicone II Caulk (12-Pack)...

$95.64/Case

Description

For your next project consider using the 2 in. x 4 in. x 7-1/4 ft. Douglas Fir Stud. This untreated lumber is ideal for framing applications in sheds, barns and houses. You can paint, prime, stain or seal it to match your home's decor.

- Made of Douglas fir
- For indoor and outdoor use
- Ideal for structural framing for houses, barns, sheds and used in other small projects and hobbies
- Untreated, dimensional lumber with a smooth texture
- Can be primed and painted or stained
- 1-1/2 in. x 3-1/2 in. x 7-1/4 ft.
- dimensional stud, douglas fir dimensional stud, stud, douglas fir stud, untreated dimensional stud, untreated stud, lumber dimensional stud
- Acquire the 2 in. x 4 in. x 7-1/4 ft. Douglas Fir Stud 603503, untreated paint, prime, stain or seal it to match your home's decor at The Home Depot
- MFG Model # : 603503
- MFG Part # : 603503

E-MAIL EXCLUSIVES

Sign up to receive special offers and promotions from the Home Depot

Enter Email Address

FOLLOW THE HOME DEPOT

ABOUT THE HOME DEPOT

Affiliate Program
Careers
Corporate Info
Government Customers
Investor Relations
Privacy & Security
Supplier Center
Supplier Diversity
The Home Depot Canada
The Home Depot Mexico

STRESS FREE SHOPPING

Gift Cards
Price Match Policy
Privacy Policy
Return Policy
Service Plan Registration
Site Map

PARTNER SITES

Home Improver Club
Home Decorators Collection
Garden Club
The Home Depot Racing
Eco Options

CUSTOMER SERVICE

Contact Us
Home Depot Opinion
Order Status
Product Recalls
Shipping and Delivery
Store Information

CREDIT CENTER

Share your own related images

Vermont American (VER20354) TAP PIPE 1/2-14NPT

by Vermont American

Be the first to review this item (0) | Share

List Price: ~~$17.78~~
Price: $11.16
You Save: $6.62 (37%)

In Stock.
Ships from and sold by **acehardwareoutlet**.

10 new from $10.43

$11.16 + $5.12 shipping
In Stock. Sold by **acehardwareoutlet**
Quantity: 1

or
Sign in to turn on 1-Click ordering.

More Buying Choices

ANTOnline
$10.43 + $6.24 shipping

Geroy's
$11.70 + $5.74 shipping

Quality Distributing LLC
$14.84 + $6.20 shipping

10 new from $10.43

Have one to sell?

Frequently Bought Together

Price For All Three: $24.36

These items are shipped from and sold by different sellers. Show details

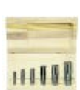
- ☑ **This item:** Vermont American (VER20354) TAP PIPE 1/2-14NPT by Vermont American $11.16
- ☑ 23/32" Quality Import High Speed Steel 1/2" Shank Drill Bit (S + D type drill) by S+D Drills $6.60
- ☑ 45/64" Quality Import High Speed Steel 1/2" Shank Drill Bit (S + D type drill) by S+D Drills $6.60

What Do Customers Ultimately Buy After Viewing This Item?

72% buy the item featured on this page:
Vermont American (VER20354) TAP PIPE 1/2-14NPT by Vermont American
$11.16

11% buy
1/2"-14 NPT National Pipe Taper High Speed Steel Pipe Tap by Taps - Pipe
$13.60

8% buy
23/32" Quality Import High Speed Steel 1/2" Shank Drill Bit (S + D type drill) by S+D Drills (4)
$6.60



6% buy
Irwin Industrial Tools 1921 Taper Pipe Tap Set, 6-Piece by Irwin (1)
$76.67

› **Explore similar items**

Product Specifications

Part Number:	20354
Item Package Quantity:	1

Item Dimensions

Weight:	3.1 Pounds

Technical Details

- 1/2"-14 National Pipe Taper Thread, Use Drill Bit Size 23/32"

- 1.375" Thread Length, 3.125" Overall Length
- Taper taps have 8 to 10 threads chamfered for easy starts in tough materials
- Four-flute design ensures fast and easy chip clearance
- Required drill size is permanently etched on the tool for quick and easy reference

Product Description

Product Description

TAP PIPE 1/2-14NPT

Product Details

Item Weight: 3.1 pounds

Shipping Weight: 4 ounces (View shipping rates and policies)

ASIN: B000O9N072

Item model number: 20354

Average Customer Review: Be the first to review this item

Amazon Bestsellers Rank: #29,602 in Home Improvement (See Top 100 in Home Improvement)
#7 in Home Improvement > Power & Hand Tools > Hand Tools > Taps & Dies > Threading Taps > **Pipe Taps**

Would you like to **update product info**, **give feedback on images**, or **tell us about a lower price**?

Buy This Product and Related Accessories

Vermont American (VER20354) TAP PIPE 1/2-14NPT

~~$17.78~~ **$11.16**

Vermont American (VER21911) TAP HANDLE #4-1/2 DP

~~$16.86~~ **$11.35**

In Stock from acehardwareoutlet.

Vermont American 20072 3/8" x 16 Machine Screw Plug Tap

~~$6.49~~ **$3.26**

In Stock from acehardwareoutlet.

Customers Who Bought This Item Also Bought

Page 1 of 3

23 / 32" Quality Import High Speed Steel 1 / 2" Sha... by S+D Drills
(4)
$6.60

45 / 64" Quality Import High Speed Steel 1 / 2" Sha... by S+D Drills
$6.60

Vermont American 20353 1 3 / 8-18 Npt Pipe Tap - by Vermont American
$5.69

Vermont American 20355 1 3 / 4-14 Npt Pipe Tap - by Vermont American
(1)
$12.06

Product Ads from External Websites (What's this?)

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Not Sold Online

Add to My List

Check Store Inventory

19/32 in. x 4 ft. x 8 ft. BC Plywood

Model # 326135 Store SKU # 326135

Be the first to Write a Review

$31.17 /PC-Piece

SHOPPERS WHO VIEWED THIS ITEM ALSO VIEWED

Clarington Designer 19 In. Round Drop in Bath Lavatory ...

$99.00/Each

31 in. W Granite Vanity Top in Beige with White Basin...

$205.00/Each

Ellipse 37 in. W Solid Surface Vanity Top in White...

$194.00/Each

Description

Every piece meets the highest grading standards for strength and appearance. Sanded and smooth BC project panels are perfect for interior and exterior applications from yard art to wainscoting, do-it-yourself projects, cabinets, shelving and furniture to porch ceilings, soffits and flooring underlayment. These panels are ready to be painted. This plywood has great strenght and stiffness. These boards are easy to handle and install. They also have excellent nail and adhesive holding ability.

Each piece of this lumber meets the highest quality grading standards for strength and appearance.
Sanded Project Panels are perfect for interior and exterior applications.
Great for yard art to wainscoting, do-it-yourself projects, cabinets, shelving and furniture to porch ceilings, soffits and flooring underlayment.
Excellent appearance when painted.
Available in 4 x 8 panels from 1/4 to 1 1/8 thickness
This lumber and plywood is of the highest quality. Every piece meets the highest grading standards for strength and appearance.
Ideal for a wide range of structural and nonstructural applications

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Quantity: 1

ADD TO CART

Add to My List

Check Store Inventory

Crown Bolt 3/8 in. x 75 ft. Camouflage Rope

Model # 17982 Internet # 202048185 Store SKU # 183072

Be the first to Write a Review

$11.97 /EA-Each

Zoom View

Ships FREE with $249.00 Order

SHOPPERS WHO VIEWED THIS ITEM ALSO VIEWED

Antique Brass rigid door stop 3

$5.19/Piece

Music Bottle

$18.96/Each

Light Bottle

$13.96/Each

Description

This Camouflage rope is ideal for camping, camping or fishing. Use around water, it floats and resists mildew. Bonus hunters spring is included which holds keys, knives or other small tools. Rope has a safe working load of 244 lbs.

Diamond-braid poly
Mildew resistant
Camouflage
Floats
MFG Brand Name : Crown Bolt
MFG Model # : 17982
MFG Part # : 17982

Specifications

Assembled Depth (in.) : 0.37 in
Assembled Height (in.) : 75 in
Assembled Width (in.) : 0.37 in

E-MAIL EXCLUSIVES

Sign up to receive special offers and promotions from the Home Depot

Enter Email Address

FOLLOW THE HOME DEPOT

ABOUT THE HOME DEPOT

Affiliate Program
Careers
Corporate Info
Government Customers
Investor Relations
Privacy & Security
Supplier Center
Supplier Diversity
The Home Depot Canada
The Home Depot Mexico

STRESS FREE SHOPPING

Gift Cards
Price Match Policy
Privacy Policy
Return Policy
Service Plan Registration
Site Map

PARTNER SITES

Home Improver Club
Home Decorators Collection
Garden Club
The Home Depot Racing
Eco Options

CUSTOMER SERVICE

Contact Us
Home Depot Opinion
Order Status
Product Recalls
Shipping and Delivery
Store Information

CREDIT CENTER

No Interest if Paid in Full Within 6 Months*
$299 Minimum Purchase Required. Minimum Payments Required.

6 MONTHS EVERYDAY

† Local store prices may vary from those displayed. Products shown as available are normally stocked but inventory levels cannot be guaranteed.

Threadlockers

For information about adhesives, see page 3370.

Loctite® Threadlockers and Retaining Compounds

Make your fasteners more secure. These adhesives prevent corrosion, seal against fluid leakage, and resist most chemicals. Reach full strength in 24 hours with the absence of air. Come in bottles (unless noted). These products are VOC compliant in all 50 states as of October 1, 2008.

Note: Primers are recommended when working with aluminum, black-oxide finishes, cadmium, stainless steel, titanium, and zinc. See Loctite® 7649™ Primer N™ on page 3383.

Also Available: Additional Loctite® threadlockers and retaining compounds. Please ask for 91458A9 and specify the Loctite® number.

Threadlockers

Prevent threaded metal fasteners from loosening due to shock and vibration and protect them from most solvents and harsh environments. *Low* and *medium strength* can be removed with a hand tool. *High strength* require heat and a hand tool.

***220™*—**For 1/4″ dia. and smaller fasteners.
***222™*—**For 1/4″ dia. and smaller fasteners.
***222MS™*—**For 1/4″ dia. and smaller fasteners. NSF-P1 certified for food-processing areas.
***242®*—**For 1/4″ to 3/4″ dia. fasteners. *8.45 oz. (250 ml)* size is NSF 61 certified for use with drinking water systems.
***243™*—**For fasteners 1/4″ to 3/4″ dia. Resists oil. *8.45 oz. (250 ml)* size is NSF 61 certified for use with drinking water systems.
***246™*—**For fasteners 1/4″ to 3/4″ dia.
***262™*—**For fasteners up to 3/4″ dia. subject to high vibration and shock. Resists oils. Great for Grade 5 and 8 fasteners.
***263™*—**For permanent locking of fasteners up to 3/4″ dia. Prevents loosening and leakage due to vibration and shock.
***266™*—**For fasteners up to 3/4″ dia. Resists oils and contaminants.
***271™*—**For up to 1″ dia. fasteners. Ideal for harsh applications and tamperproofing. UL listed.
***272™*—**For bolts up to 1 1/2″ dia.
***277™*—**For use with fasteners up to 1 1/2″ dia.
***290™*—**For locking assembled fasteners up to 1/2″ dia. *8.45 oz. (250 ml)* size is NSF 61 certified for use with drinking water systems.
***294™*—**Strong bonds even on oily fasteners.
***425™*—**Super glue (cyanoacrylate) for metal and plastic fasteners.
***2432™*—**Has low sulfur content for sensitive metals such as titanium.
***2760™*—**Strong bonds even on oily unprimed fasteners. Use for heavy duty applications, such as construction and railroad equipment.

Retaining Compounds

For nonthreaded metal cylindrical parts such as shafts, hubs, bearings, bushings, splines, pulleys, and press-fit assemblies.

***603™*—**For close-fitting parts. Fills spaces up to 0.005″.
***609™*—**Fills spaces up to 0.005″.
***620™*—**For high-temperature applications. Fills spaces up to 0.015″.
***635™*—**High strength for slip fits. Fills spaces up to 0.010″.
***638™*—**High strength for loose-fitting parts. Fills spaces up to 0.015″.
***640™*—**For high-temperature applications. Fills spaces up to 0.007″.
***641™*—**Med. strength for easy disassembly. Fills spaces up to 0.008″.
***648™*—**High strength for stainless steel and close-fitting parts. Fills spaces up to 0.006″.
***680™*—**High strength for loose-fitting parts. Fills spaces up to 0.015″. *8.45 oz. (250 ml)* size is NSF 61 certified for use with drinking water systems.

Loctite No.	Begins to Harden	Strength	Temperature Range	Color	0.02 oz. (0.5 ml)●	Each	0.34 oz. (10 ml)	Each	1.69 oz. (50 ml)	Each	8.45 oz. (250 ml)	Each
Threadlockers												
220	6 min.	Medium	–65° to +300° F	Blue			1810A315	$11.50			1810A31	$102.81
222	10 min.	Low	–65° to +300° F	Purple			1810A27	11.50	1810A28	$31.10		
222MS	10 min.	Low	–65° to +300° F	Purple	91458A130★	$1.62	91458A110★	11.80	91458A120★	31.10	91458A700★	102.81
242	10 min.	Medium	–65° to +300° F	Blue	91458A111★	1.70	91458A112★	12.39	91458A113★	32.66	91458A710★	107.94
243	5 min.	Medium	–65° to +300° F	Blue	91458A114	1.57	91458A115	11.45	91458A116	30.19	91458A460	99.82
246	20 min.	Medium	–65° to +450° F	Blue			91458A480	13.70	91458A490	34.59	91458A550	129.13
262	5 min.	High	–65° to +300° F	Red	91458A560★	1.70	91458A170★	12.39	91458A180★	32.66	91458A720★	107.94
263	20 min.	High	–65° to +300° F	Red			91458A610	11.45	91458A620	30.19	91458A630	99.82
266	10 min.	High	–65° to +450° F	Rust			91458A570	13.70	91458A580	33.93	91458A590	126.68
271	10 min.	High	–65° to +300° F	Red	91458A880★	1.70	91458A160★	12.39	91458A190★	32.66	91458A730★	107.94
272	30 min.	High	–65° to +450° F	Red					91458A650	31.10	91458A890	102.81
277	60 min.	High	–65° to +300° F	Red			91458A910★	13.00	91458A660★	29.02	91458A780★	87.94
290	6 min.	Medium	–65° to +300° F	Green	91458A117★	1.62	91458A118★	11.80	91458A119★	31.10	91458A830★	102.81
294	6 min.	High	–65° to +450° F	Green			91458A940	16.46	91458A950	44.41	91458A960	140.73
425	2 min.	Low	–65° to +180° F	Blue			91458A370♦	18.00				
2432	30 min.	Medium	–65° to +300° F	Blue					91458A760	78.64		
2760	4 min.	High	–65° to +300° F	Red			91458A300	14.04	91458A200	34.02	91458A400	119.03
Retaining Compounds												
603	10 min.		–65° to +300° F	Green			91458A340	13.11				
609	10 min.		–65° to +300° F	Green	91458A230	1.59	91458A210	11.80	91458A220	31.10	91458A740	102.81
620	30 min.		–65° to +450° F	Green	91458A850	1.62	91458A750	14.02	91458A450	36.10	91458A510	118.63
635	60 min.		–65° to +300° F	Green					91458A640	36.46	91458A670	126.68
638	5 min.		–65° to +300° F	Green			91458A430	15.00	91458A350	40.32	91458A440	131.68
640	60 min.		–65° to +400° F	Green					91458A690	33.20	91458A680	125.45
641	20 min.		–65° to +300° F	Yellow			91458A520	16.34	91458A530	38.07		
648	5 min.		–65° to +350° F	Green			91458A790	14.14	91458A770	38.07	91458A840	124.89
680	10 min.		–65° to +300° F	Green	91458A121	1.52	91458A122	13.82	91458A123	36.10	91458A330	118.63

● Come in capsules. ★ Meets MIL-S-46163A. ♦ 0.7-oz. (20 g) bottle.

Loctite® Threadlocker and Retaining Compound Sticks

These no-drip sticks prevent corrosion, seal against fluid leakage, and resist most chemicals. Reach full strength in 24 hours. These products are VOC compliant in all 50 states as of October 1, 2008.

Threadlockers prevent metal fasteners from loosening due to shock and vibration. They resist solvents and harsh environments. *248™* is for 1/4″ to 3/4″ dia. fasteners. Removes with a hand tool. *268™* is for heavy duty applications on fasteners up to 3/4″ dia. Requires heat and a hand tool for removal.

Retaining compound is for nonthreaded metal cylindrical parts such as shafts, hubs, bearings, and bushings.

Loctite No.	Temperature Range	Begins to Harden	Color	0.32 oz. (9 g)	Each	0.67 oz. (19 g)	Each
Threadlocker 248	–65° to +300° F	10 min.	Blue	1004A12	$12.90	1004A11	$27.23
Threadlocker 268	–65° to +300° F	20 min.	Red	1004A22	12.90	1004A21	27.23
Retaining Compound 668	–65° to +400° F	30 min.	Green			8075A12	32.35

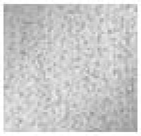
Extreme-Temperature Pipe Sealants and Threadlockers

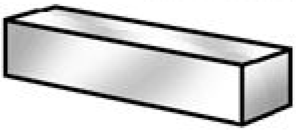
Make strong, secure bonds even in extreme temperatures. These no-drip liquid adhesives withstand temperatures from –300° to +2100° F and resist oil, fuel, acids, and alkalies. They form an electrically resistant bond on metal and ceramic threads. Seals can be broken using hand tools. Begin to harden in 24 hours; reach full strength in 2-3 days. Come in 4-oz. bottles. These products are VOC compliant in all 50 states as of October 1, 2008.

Green penetrates fine openings, such as for set, adjustment, and instrumentation screws. Fills spaces up to 0.003″.
Blue prevents loosening from vibration for medium-sized fasteners, pipe threads, and bearings. Fills spaces up to 0.005″.
Red provides high-strength bonds for studs and large fasteners, bolts, and pipe threads. Fills spaces up to 0.01″.

Green	7604A54	Each	$29.94
Blue	7604A55	Each	$29.94
Red	7604A56	Each	$29.94

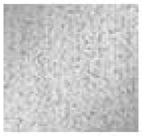
Aluminum

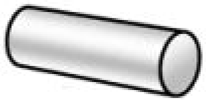




Part Number: **89155K985**	$104.44 Each
Material	Multipurpose Aluminum (Alloy 6061)
Shape	Sheets, Bars, Strips, and Cubes
Sheets, Bars, Strips, and Cubes Type	Plain
Finish/Coating	Unpolished (Mill)
Edge Type	Square
Tolerance	Oversize
Thickness	3-1/2"
Thickness Tolerance	+.115"
Length	6"
Length Tolerance	±1/16"
Width	6"
Width Tolerance	±1/16"
Test Report	Without Test Report
Temper	T651
Hardness	95 Brinell
Yield Strength	40,000 psi
Flatness Tolerance	Not Rated
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B209
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

Aluminum





Part Number: **88615K441** $19.28 Each

Material	Easy-to-Machine Aluminum (Alloy 2011)
Shape	Rods and Discs
Finish/Coating	Unpolished (Mill)
Tolerance	Standard
Diameter	1"
Diameter Tolerance	±.0025"
Length	12"
Length Tolerance	±1"
Straightness Tolerance	Not Rated
Test Report	Without Test Report
Temper	T3
Hardness	95 Brinell
Yield Strength	18,000 to 38,000 psi
Temperature Range	Maximum temperature is 212° F; minimum temperature is not rated.
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B211
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

More saving. More doing.

Welcome, (Sign In or Register) Carmichael, CA is your

Share | Email | Print

Zoom View

Shepherd 2 In. Rubber Wheel Swivel Plate Caster With Brake, Load Rating 125 Lbs.

Model # 9509 Store SKU # 433004

Be the first to Write a Review

$3.96 /EA-Each

Not Sold Online

Add to My List

Check Store Inventory

Description

2 In. general duty swivel caster. Side Brake engages wheel. Soft rubber wheels give mobility to heavy loads on smooth, hard surfaces and finished concrete floors where quiet movement and floor protection are important. Caster swivels 360 degrees. 125 lb. load rating. Caster attaches with a plate and four screws. Plate size 1-7/8 In. x 2-9/16 In.

Soft rubber wheel gives good mobility to heavy loads
For use on smooth hard surfaces such as cement
Quiet movement and protects floors.
Installed easily with pre-drilled mounting holes
MFG Brand Name : Shepherd
MFG Model # : 9509
MFG Part # : 9509

Specifications

Brakes : Yes

† Local store prices may vary from those displayed. Products shown as available are normally stocked but inventory levels cannot be guaranteed.

Appendix R: Design Verification Test Plan

REPORT DATE:		8-Feb-11	SPONSOR:	Solar Turbines		ASSEMBLY:			Flow Test System		REPORTING ENGINEER:		Crawford
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Qty	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Accuracy	Pressure Transducer Calibration	psi/volts	Chairez	PV	3	C	3/20/2011	3/30/2011				
2	Accuracy	Thermocouple Calibration	deg F/volts	Welch	PV	2	C	3/20/2011	3/30/2011				
3	Accuracy	Hygrometer Calibration	%RH	Crawford	PV	1	C	3/20/2011	3/30/2011				
4	Baseline Test	Published Geometry Design Test	Pressure Loss	Crawford	DV	1	B	3/31/2011	4/8/2011				

Appendix S: Hygrometer Calibration Procedure

Materials

- 1/2 cup table salt
- 1/4 cup water
- coffee cup
- hygrometer
- large re-sealable freezer bag

Procedure

1. Place ½ cup salt in a coffee cup.
2. Add approximately ¼ of water to the salt.
3. Stir the water-salt mixture to totally saturate the salt (the salt won't dissolve, it will be more like really wet sand).
4. Place the salt/water mix in a re-sealable plastic bag, along with the hygrometer, and seal the bag. Do not allow the mixture to come in direct contact with the hygrometer.
5. Allow the bag to sit at room temperature for at least eight hours.
6. Check the hygrometer reading after 8-12 hours while the instrument is still in the bag.
7. The relative humidity in the sealed bag with the salt/water mix should be 75 percent
8. Adjust the hygrometer reading to account for any deviation from the known environment relative humidity.
9. Record the instrument offset of the hygrometer is not adjustable.
10. Allow the hygrometer to stabilize for at least two hours before confident use.
11. Account for the offset when recording hygrometer measurements if not adjusted in step 8, above.

The above common calibration method procedure was adapted from one obtained from an About.com article. Refer to this report's *References* for source details.

Appendix T: Theoretical Loss Coefficient

The pressure loss in pipes depends on the flow velocity, pipe length, pipe diameter, and a friction factor based on the roughness of the pipe material, and whether the flow us turbulent or laminar. In particular, the loss directly associated with the pressure drop in a pipe is denoted as a minor loss and correlates directly to the dynamic pressure of the system.

The minor loss coefficient depends primarily on the geometry of the flow path. It is the ratio of pressure loss within the system to the flow's dynamic pressure. Such loss coefficients are published with confidence for common flow path geometries. In fact, the sharp edged cross-sectional area change of the test verification piece is a common geometry with known loss factors. Figure 8.15 shows the loss factors associated with various configurations of this geometry type.

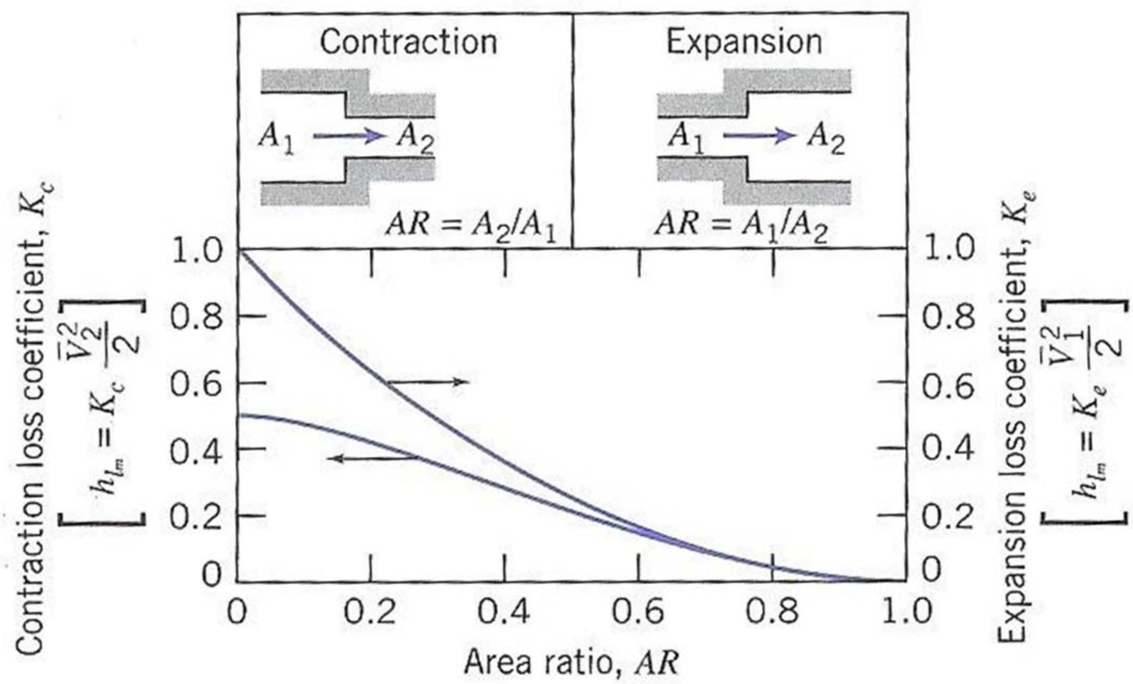


Fig. 8.15 Loss coefficients for flow through sudden area changes. (Data from [1].)

An experimental loss coefficient can be calculated using the following relation:

$$K = \frac{P_{inlet} - P_{outlet}}{\left(\frac{1}{2}\rho v^2\right)}$$

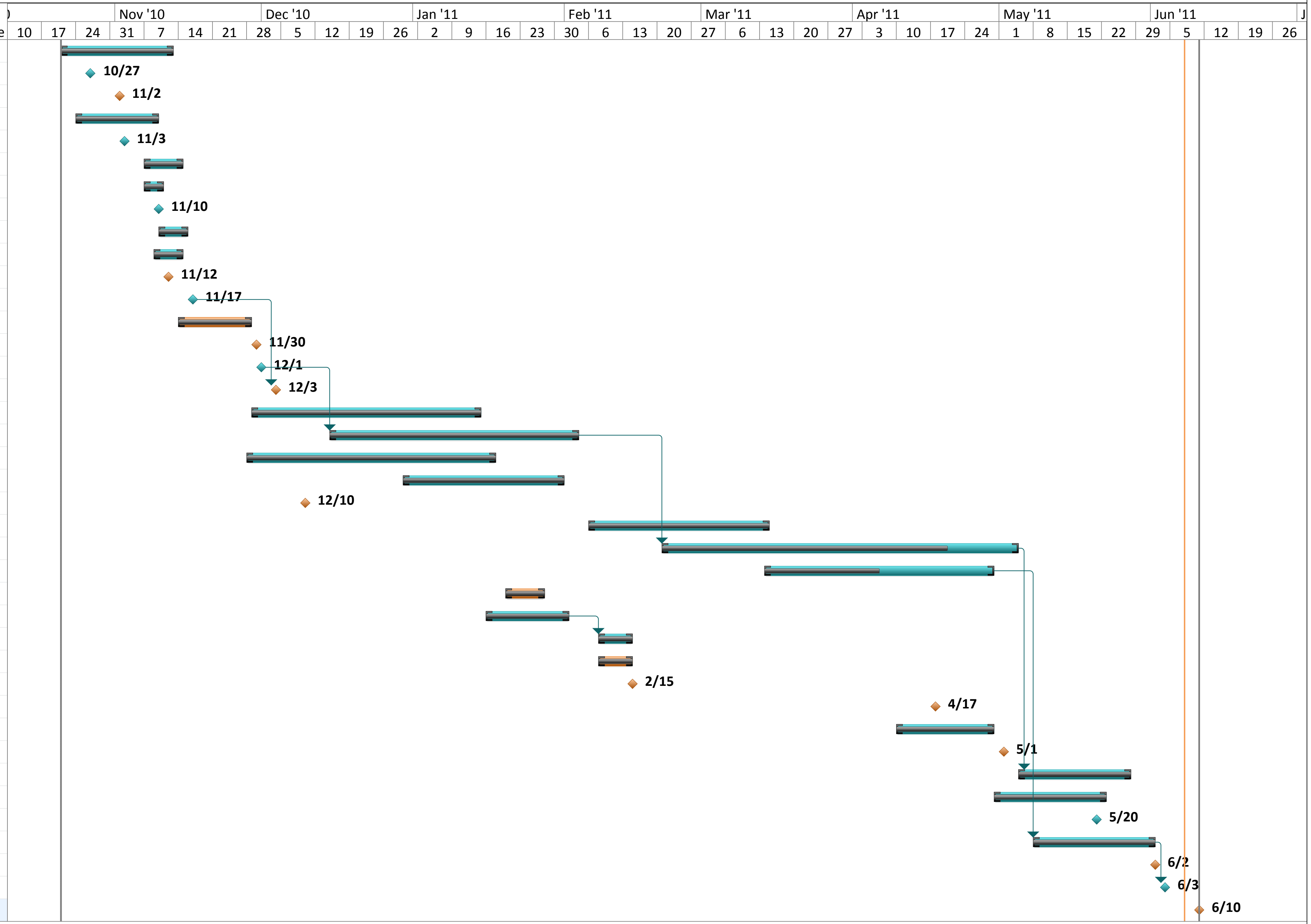
Thus, by using the experimentally determined values in the above relation, the test verification piece loss coefficient can be determined. By comparing this factor to the one obtained in the plot of Figure 8.15, the test apparatus design will ideally be validated.

Appendix U: Gantt Chart

See following page attached.

Flow Test System Project Schedule

ID	Task Name	Duration	% Complete
1	Design Conceptualization	3.4 wks	100%
2	ST First Concept Meeting	0 days	100%
3	Conceptual Model	0 days	100%
4	Port Library	13 days	100%
5	ST 2nd Concept Discussion	0 days	100%
6	Define Problem Geometries	7 days	100%
7	Research Air Supply	4 days	100%
8	ST 3rd Concept Discussion	0 days	100%
9	Define Operating Conditions	4 days	100%
10	Pugh Design Matrix	5 days	100%
11	Online Reflection 2	0 days	100%
12	ST Semi-Final Concept Design	0 days	100%
13	Create Design Presentation	12 days	100%
14	Present Concept Design	0 days	100%
15	ST Final Concept Review	0 days	0%
16	Conceptual Design Report	0 days	100%
17	Test Block Solid Modeling	35 days	100%
18	Finalize Apparatus Design	37 days	100%
19	Bill of Materials	37 days	100%
20	Apparatus Solid Modeling	23 days	100%
21	Online Reflection & Survey	0 days	100%
22	Order Parts & Materials	27 days	100%
23	Build Test Apparatus	53 days	80%
24	Computer Simulations	35 days	50%
25	Create Design Presentation	6 days	100%
26	Generate Design Report	13 days	100%
27	Design Report Due	5 days	100%
28	Engineering Ethics Study	5 days	100%
29	Ethics Presentation	0 days	100%
30	Online Reflection	0 days	100%
31	Test Apparatus Calibration	16 days	100%
32	Senior Exit Survey	0 days	100%
33	Test Problematic Geometries	17 days	100%
34	Analysis, Design Curves	17 days	100%
35	Hardware Demo	0 days	100%
36	Project Final Documentation	19 days	100%
37	Senior Design Exposition	0 days	100%
38	Project Final Report	0 days	100%
39	Online Reflection & Survey	0 days	100%



Appendix V: Aalco's Stainless Steel Pressure Rating

Pressure Ratings

Pressure Ratings for Pipes, Tubes and Fittings

Wall Thickness Calculations for Straight Pipe Under Internal Pressure

The following equations and tables are based on those provided in the Process Piping Specification, ASME B31.3a-1996, ASME Code for Pressure Piping (see Notes for references to source paragraphs and tables in this specification).

Firstly, any one of the following four equations may be used to calculate the 'pressure design wall thickness' (t) of a straight pipe subject to internal pressure.

The equations assume t<D/6 (for pipe with t ≥D/6 or P/SE >0.385 additional factors need to be considered).

The four alternative equations are:

$$t = \frac{PD}{2(SE + PY)}$$

$$t = \frac{PD}{2SE}$$

$$t = \frac{D}{2}\left(1 - \sqrt{\frac{SE - P}{SE + P}}\right)$$

$$t = \frac{P(d + 2c)}{2[SE - P(1 - Y)]}$$

where:

- t = Pressure design thickness
- d = Inside diameter of pipe. For pressure design calculation, the inside diameter of the pipe is the maximum value allowable under the purchase specification.
- P = Internal design pressure.
- D = Outside diameter pipe as listed in tables of standards or specifications or as measured.
- E = Quality factor. See the table "Basic quality factors 'E' for longitudinal weld joints in stainless steel pipes, tubes and fittings" on page 5-29.
- S = Stress value for material from the table "Basic allowable stresses 'S' in tension for stainless steels" on page 5-30.
- Y = Coefficient from table "Values of coefficient 'Y' for t<D/6" on page 5-29.

Secondly, the minimum required wall thickness t_m of straight sections of pipe is determined in accordance with the following equation.

$$t_m = t + c$$

where:

- t_m = Minimum required thickness, including mechanical, corrosion and erosion allowances.
- c = The sum of the mechanical allowances (thread or groove depth) plus corrosion and erosion allowances. For threaded components, the nominal thread depth (dimension h of ASME B1.20.1, or equivalent) shall apply. For machined surfaces or grooves where the tolerance is not specified, the tolerance shall be assumed to be 0.5 mm (0.02 in) in addition to the specified depth of the cut.

The actual minimum thickness for the pipe selected, considering manufacturer's tolerance, shall not be less than t_m

Units of Measure for Calculations

It is important to use compatible units for pressure calculations. ASTM and ASME/ANSI specifications are based upon imperial sizes.

Pipe bends

The equations above may also be used for pipe bends provided the requirement for minimum wall thickness (t_m) is met.

Further Information

Additional pressure rating information is contained in Sections 7 and 8 of this manual.

Refer to ASME B31.3a-1996 paragraph 304 for further details relating to pressure rating and wall thickness calculations applicable to elbows, branch connections, closures, flanges, reducers and other components.

Aalco Tel. 01932 250100 Fax: 01932 250101 E-mail: Marketing@amari-metals.com

Worked Example:

Taking the simplest equation: $t = \frac{PD}{2SE}$

A. If you wish to calculate what wall thickness should be used in a design for the following situation:

P = Internal Design Pressure – For this example lets say 2000 pounds per square inch = 2ksi

D = Outside Diameter – For this example lets say 4 inch nominal bore = 4.5 inches

S = Stress Value for material from table below taking into account operating temperature – For this example lets take ASTM A312 TP 316L operating at 500^{O}C for which S = 14.4 ksi

(1ksi = 1,000 psi / psi = Pounds Pressure per Square Inch)

E = Quality Factor from table below according to manufacturing specification – For this example we are using ASTM A312 TP 316L Seamless for which E = 1.0

So this gives: $t = \frac{2 \times 4.5}{2 \times 14.4 \times 1.0} = 0.313$ inches

Thus we would use 4 inch Nominal Bore Schedule 80S which has a wall thickness of 0.337 inches

If the wall thickness calculation leads to a heavier wall than is available then the pipe diameter must be increased. Depending upon the design of the system this may also reduce the pressure.

A. If you wish to calculate what design pressure could be permitted for the following situation:

D = Outside Diameter – For this example lets say 4 inch nominal bore = 4.5 inches

t = Wall Thickness – For this example lets say Schedule 40S = 0.237 inches

S = Stress Value for material from table below taking into account operating temperature – For this example lets take ASTM A312 TP 316L operating at 500^{O}C for which S = 14.4 ksi

(1ksi = 1,000 psi / psi = Pounds Pressure per Square Inch)

E = Quality Factor from table below according to manufacturing specification – For this example we are using ASTM A312 TP 316L Seamless for which E = 1.0

So this gives: $0.237 = \frac{P \times 4.5}{2 \times 14.4 \times 1.0}$

Thus P = 1.51ksi = 1,510 ponds per square inch

Values of coefficient 'Y' for t<D/6

Materials	Temperature, °F (°C)					
	≤900 (≤482)	950 (510)	1000 (538)	1050 (566)	1100 (593)	≥1150 (≥621)
	Y					
Ferritic Steels	0.4	0.5	0.7	0.7	0.7	0.7
Austenitic Steels	0.4	0.4	0.4	0.4	0.5	0.7
Cast Iron	0.0	-	-	-	-	-

Note
- The above table and the equations are based on paragraph 304.1 of ASME B31.3a-1996
- The value for Y may be interpolated for intermediate temperatures. For t > D/6:

$$Y = \frac{d + 2c}{D + d + 2c}$$

Basic quality factors 'E' for longitudinal weld joints in stainless steel pipes, tubes and fittings

Spec No.	Class (or Type)	Description	E	Notes
A 182	-	Forgings and Fittings	1.00	-
A 268	-	Seamless Tube	1.00	-
	-	Electric Fusion Welded Tube, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Tube, Single Butt Seam	0.80	-
A 269	-	Seamless Tube	1.00	-
	-	Electric Fusion Welded Tube, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Tube, Single Butt Seam	0.80	-
A 312	-	Seamless Pipe	1.00	-
	-	Electric Fusion Welded Pipe, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Pipe, Single Butt Seam	0.80	-
A 358	1, 3, 4	Electric Fusion Welded Pipe, 100% radiographed	1.00	-
	5	Electric Fusion Welded Pipe, Spot radiographed	0.90	-
	2	Electric Fusion Welded Pipe, Double Butt Seam	0.85	-
A 376	-	Seamless Pipe	1.00	-
A 403	-	Seamless Fittings	1.00	-
	-	Welded Fitting, 100% radiographed	1.00	1
	-	Welded Fitting, Double Butt Seam	0.85	-
	-	Welded Fitting, Single Butt Seam	0.80	-
A 409	-	Electric Fusion Welded Pipe, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Pipe, Single Butt Seam	0.80	-
A 430	-	Seamless Pipe	1.00	-
A 789	-	Seamless	1.00	-
	-	Electric Fusion Welded Pipe, 100% radiographed	1.00	-
	-	Electric Fusion Welded Tube, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Tube, Single Butt Seam	0.80	-
A 790	-	Seamless	1.00	-
	-	Electric Fusion Welded Pipe, 100% radiographed	1.00	-
	-	Electric Fusion Welded Pipe, Double Butt Seam	0.85	-
	-	Electric Fusion Welded Pipe, Single Butt Seam	0.80	-

Note
- This table is based on Table A-1B of ASME B31.3a-1996

1 An E factor of 1.00 may be applied only if all welds, including welds in the base material, have passed 100% radiographic examination. Substitution of ultrasonic examination for radiography is not permitted for the purpose of obtaining an E of 1.00.

Pressure Ratings

Basic allowable stresses 'S' in tension for stainless steels

ASTM Spec No.	Grade	Min Temp °F (for °C see Notes)	Metal Temperature, °F (°C)										Notes
			Min Temp to 100 (37.8)	300 (149)	500 (260)	700 (371)	850 (454)	1000 (538)	1150 (621)	1300 (704)	1400 (760)	1500 (816)	
			Basic Allowable Stress, **S** ksi										
A 312	TP321	-325	16.7	16.7	16.1	14.6	14.0	13.5	5.0	1.7	0.8	0.3	1, 2
A 376	TP321	-325	16.7	16.7	16.1	14.6	14.0	13.5	5.0	1.7	0.8	0.3	1, 2
A 269	TP304L	-425	16.7	16.7	14.8	13.5	12.8	7.8	4.0	2.1	1.1	0.9	2, 3
A 312	TP304L	-425	16.7	16.7	14.8	13.5	12.8	7.8	4.0	2.1	1.1	0.9	-
A 358	304L	-425	16.7	16.7	14.8	13.5	12.8	7.8	4.0	2.1	1.1	0.9	2
A 269	TP316L	-325	16.7	16.7	14.4	12.9	12.1	11.2	8.8	3.5	1.8	1.0	2, 3
A 312	TP316L	-325	16.7	16.7	14.4	12.9	12.1	11.2	8.8	3.5	1.8	1.0	-
A 358	316L	-325	16.7	16.7	14.4	12.9	12.1	11.2	8.8	3.5	1.8	1.0	2
A 312	TP321	-325	16.7	16.7	16.1	14.6	14.0	13.5	6.9	3.2	1.9	1.1	1, 2, 4
A 376	TP321	-325	16.7	16.7	16.1	14.6	14.0	13.5	6.9	3.2	1.9	1.1	1, 2, 4
A 312	TP321H	-325	16.7	16.7	16.1	14.6	14.0	13.5	6.9	3.2	1.9	1.1	1, 2
A 376	TP321H	-325	16.7	16.7	16.1	14.6	14.0	13.5	6.9	3.2	1.9	1.1	-
A 268	TP409	-20	20.0	-	-	-	-	-	-	-	-	-	6
A 268	TP430Ti	-20	20.0	-	-	-	-	-	-	-	-	-	6, 7
A 376	16-8-2H	-325	20.0	-	-	-	-	-	-	-	-	-	5, 6, 8
A 268	TP405	-20	20.0	17.7	17.2	16.2	10.4	4.0	-	-	-	-	6
A 268	TP410	-20	20.0	17.7	17.2	16.2	10.4	6.4	1.8	-	-	-	6
A 268	TP430	-20	20.0	19.6	19.0	17.6	10.4	6.5	2.4	-	-	-	6, 7
A 312	TP317L	-325	20.0	20.0	17.7	16.2	15.2	-	-	-	-	-	-
A 312	TP310	-325	20.0	20.0	20.0	18.3	14.6	11.0	3.6	0.8	0.4	0.2	4, 6, 10
A 358	310S	-325	20.0	20.0	20.0	18.3	14.6	11.0	3.6	0.8	0.4	0.2	2, 4, 5, 6
A 409	TP310	-325	20.0	20.0	20.0	18.3	14.6	11.0	3.6	0.8	0.4	0.2	2, 4, 5, 6, 10
A 312	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	5.0	1.7	0.8	0.3	1
A 358	321	-325	20.0	20.0	19.3	17.5	16.7	16.2	5.0	1.7	0.8	0.3	1, 2
A 376	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	5.0	1.7	0.8	0.3	1, 2
A 409	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	5.0	1.7	0.8	0.3	1, 2
A 312	TP309	-325	20.0	20.0	20.0	18.3	14.6	10.5	5.0	2.3	1.3	0.7	4, 6, 10
A 358	309S	-325	20.0	20.0	20.0	18.3	14.6	10.5	5.0	2.3	1.3	0.7	4, 5, 6, 2
A 409	TP309	-325	20.0	20.0	20.0	18.3	14.6	10.5	5.0	2.3	1.3	0.7	2, 4, 5, 6, 10
A 312	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	-
A 358	347	-425	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 376	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 409	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 312	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	-
A 358	348	-325	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 376	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 409	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	6.1	2.2	1.2	0.8	1, 2
A 312	TP310	-325	20.0	20.0	20.0	18.3	14.6	11.0	7.3	3.5	1.6	0.8	4, 6, 10, 11
A 358	310S	-325	20.0	20.0	20.0	18.3	14.6	11.0	7.3	3.5	1.6	0.8	2, 4, 5, 6, 11

Aalco Tel. 01932 250100 Fax: 01932 250101 E-mail: Marketing@amari-metals.com

Basic allowable stresses ‘S’ in tension for stainless steels (Continued)

ASTM Spec No.	Grade	Min Temp °F (for °C see Notes)	Metal Temperature, °F (°C)										Notes
			Min Temp to 100 (37.8)	300 (149)	500 (260)	700 (371)	850 (454)	1000 (538)	1150 (621)	1300 (704)	1400 (760)	1500 (816)	
			Basic Allowable Stress, **S** ksi										
A 430	FP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2
A 312	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 4
A 358	321	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2, 4
A 376	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2, 4
A 409	TP321	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2, 4
A 430	FP321H	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2
A 376	TP321H	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	1, 2
A 312	TP321H	-325	20.0	20.0	19.3	17.5	16.7	16.2	6.9	3.2	1.9	1.1	-
A 430	FP316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 5, 8,
A 430	FP316H	-325	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 5, 8,
A 269	TP316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 3, 4, 5, 8
A 312	TP316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	4, 8
A 358	316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 4, 5, 8
A 376	TP316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 4, 5, 8
A 409	TP316	-425	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 4, 5, 8
A 312	TP317	-325	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	4, 8
A 409	TP317	-325	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 4, 5, 8
A 376	TP316H	-325	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	2, 5, 8
A 312	TP316H	-325	20.0	20.0	17.9	16.3	15.7	15.3	9.8	4.1	2.3	1.3	8
A 430	FP347	-425	20.0	20.0	18.6	18.2	18.2	18.0	10.5	4.4	2.5	1.3	1, 2
A 430	FP347H	-325	20.0	20.0	18.6	18.2	18.2	18.0	10.5	4.4	2.5	1.3	1, 2
A 376	TP347H	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2
A 312	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	4
A 358	347	-425	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 376	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 409	TP347	-425	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 312	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	4
A 358	348	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 376	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 409	TP348	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	1, 2, 4
A 312	TP347H	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	-
A 312	TP348H	-325	20.0	20.0	19.9	18.6	18.2	18.0	10.5	4.4	2.5	1.3	-
A 430	FP304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 5, 8
A 430	FP304H	-325	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 5, 8
A 269	TP304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 3, 4, 5, 8
A 312	TP304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	4, 8
A 358	304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 4, 5
A 376	TP304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 4, 5, 8
A 376	TP304H	-325	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 5, 8
A 409	TP304	-425	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	2, 4, 5, 8

Pressure Ratings

Basic allowable stresses 'S' in tension for stainless steels (Continued)

ASTM Spec No.	Grade	Min Temp °F (for °C see Notes)	Metal Temperature, °F (°C)										Notes
			Min Temp to 100 (37.8)	300 (149)	500 (260)	700 (371)	850 (454)	1000 (538)	1150 (621)	1300 (704)	1400 (760)	1500 (816)	
			Basic Allowable Stress, **S** ksi										
A 312	TP304H	-325	20.0	20.0	17.5	16.0	14.9	13.8	7.7	3.7	2.3	1.4	8
A 268	TP443	-20	23.3	21.4	19.4	17.5	15.1	4.5	-	-	-	-	6
A 268	TP446	-20	23.3	21.4	19.4	17.5	15.1	4.5	-	-	-	-	6
A 789	S32304	-60	29.0	26.3	24.9	-	-	-	-	-	-	-	9
A 790	S32304	-60	29.0	26.3	24.9	-	-	-	-	-	-	-	9
A 789	S31803	-60	30.0	28.9	27.2	-	-	-	-	-	-	-	9
A 790	S31803	-60	30.0	28.9	27.2	-	-	-	-	-	-		9
A 789	S32900	-20	30.0	-	-	-	-	-	-	-	-	-	9
A 790	S32900	-20	30.0	-	-	-	-	-	-	-	-	-	9
A 789	S32750	-20	38.7	33.1	31.4	-	-	-	-	-	-	-	9
A 790	S32750	-20	38.7	33.1	31.4	-	-	-	-	-	-	-	9

Notes
- This table is based on Table A-1A of ASME B31.3a-1996.
- For specified minimum tensile and yield strengths refer to the individual ASTM specifications in Sections 2 and 3.
- Minimum temperatures in °C: -20 °F = -29 °C, -60 °F = -51 °C, -325 °F = -199 °C, -425 °F = -254 °C

1 For temperatures above 538 °C (1000 °F), these stress values may be used only if the material has been heat treated at a temperature of 1093 °C (2000°F) minimum.
2 When the material has not been solution heat treated, the minimum temperature shall be -29 °C (-20 °F) unless the material is impact tested.
3 Must be verified by tensile test.
4 For temperatures above 538 °C (1000 °F), these stress values apply only when the carbon content is 0.04% or higher.
5 For temperatures above 538 °C (1000 °F), these stress values may be used only if the material has been heat treated by heating to a minimum temperature of 1038 °C (1900 °F) and quenching in water or rapidly cooling by other means.
6 This steel is intended for use at high temperatures; it may have low ductility and/or low impact properties at room temperature after being used at higher temperatures.
7 If the chemical composition of this Grade is such as to render it hardenable, qualification under P-No. 6 is required.
8 Increasingly tends to precipitate intergranular carbides as the carbon content increases above 0.03%.
9 This steel may develop embrittlement after service at approximately 316 °C (600 °F) and higher temperature.
10 This material when used below -29 °C (-20 °F) shall be impact tested if the carbon content is above 0.10%.
11 The stress values above 538 °C (1000 °F) shall be used only when the micrograin size, is No. 6 or less (coarser grain). Otherwise, the lower stress values listed for the same material, specification, and grade shall be used.

Aalco Tel. 01932 250100 Fax: 01932 250101 E-mail: Marketing@amari-metals.com

Pipe Sizes - ANSI/ASME B36.19M-1985

Dimensions and weights per metre - stainless steel pipe

Nominal Pipe Size	OD		Schedule 5S[1]			Schedule 10S[1]			Schedule 40S			Schedule 80S		
	in	mm	in	mm	kg/m	in	mm	kg/m	in	mm	kg/m	in	mm	kg/m
1/8	0.405	10.3	-	-	-	0.049	1.24	0.28	0.068	1.73	0.37	0.095	2.41	0.47
1/4	0.540	13.7	-	-	-	0.065	1.65	0.49	0.088	2.24	0.63	0.119	3.02	0.80
3/8	0.675	17.1	-	-	-	0.065	1.65	0.63	0.091	2.31	0.84	0.126	3.20	1.10
1/2	0.840	21.3	0.065	1.65	0.80	0.083	2.11	1.00	0.109	2.77	1.27	0.147	3.73	1.62
3/4	1.050	26.7	0.065	1.65	1.03	0.083	2.11	1.28	0.113	2.87	1.69	0.154	3.91	2.20
1	1.315	33.4	0.065	1.65	1.30	0.109	2.77	2.09	0.133	3.38	2.50	0.179	4.55	3.24
1 1/4	1.660	42.2	0.065	1.65	1.65	0.109	2.77	2.70	0.140	3.56	3.39	0.191	4.85	4.47
1 1/2	1.900	48.3	0.065	1.65	1.91	0.109	2.77	3.11	0.145	3.68	4.05	0.200	5.08	5.41
2	2.375	60.3	0.065	1.65	2.40	0.109	2.77	3.93	0.154	3.91	5.44	0.218	5.54	7.48
2 1/2	2.875	73.0	0.083	2.11	3.69	0.120	3.05	5.26	0.203	5.16	8.63	0.276	7.01	11.41
3	3.500	88.9	0.083	2.11	4.51	0.120	3.05	6.45	0.216	5.49	11.29	0.300	7.62	15.27
3 1/2	4.000	101.6	0.083	2.11	5.18	0.120	3.05	7.40	0.226	5.74	13.57	0.318	8.08	18.63
4	4.500	114.3	0.083	2.11	5.84	0.120	3.05	8.36	0.237	6.02	16.07	0.337	8.56	22.32
5	5.563	141.3	0.109	2.77	9.47	0.134	3.40	11.57	0.258	6.55	21.77	0.375	9.53	30.97
6	6.625	168.3	0.109	2.77	11.32	0.134	3.40	13.84	0.280	7.11	28.26	0.432	10.97	42.56
8	8.625	219.1	0.109	2.77	14.79	0.148	3.76	19.96	0.322	8.18	42.55	0.500	12.70	64.64
10	10.750	273.1	0.134	3.40	22.63	0.165	4.19	27.78	0.365	9.27	60.31	0.500[2]	12.70[2]	96.01[2]
12	12.750	323.9	0.156	3.96	31.25	0.180	4.57	36.00	0.375[2]	9.53[2]	73.88[2]	0.500[2]	12.70[2]	132.08[2]
14	14.000	355.6	0.156	3.96	34.36	0.188[2]	4.78[2]	41.30[2]	-	-	-	-	-	-
16	16.000	406.4	0.165	4.19	41.56	0.188[2]	4.78[2]	47.29[2]	-	-	-	-	-	-
18	18.000	457	0.165	4.19	46.81	0.188[2]	4.78[2]	53.26[2]	-	-	-	-	-	-
20	20.000	508	0.188	4.78	59.25	0.218[2]	5.54[2]	68.61[2]	-	-	-	-	-	-
22	22.000	559	0.188	4.78	65.24	0.218[2]	5.54[2]	75.53[2]	-	-	-	-	-	-
24	24.000	610	0.218	5.54	82.47	0.250	6.35	94.45	-	-	-	-	-	-
30	30.000	762	0.250	6.35	118.31	0.312	7.92	147.36	-	-	-	-	-	-

Notes

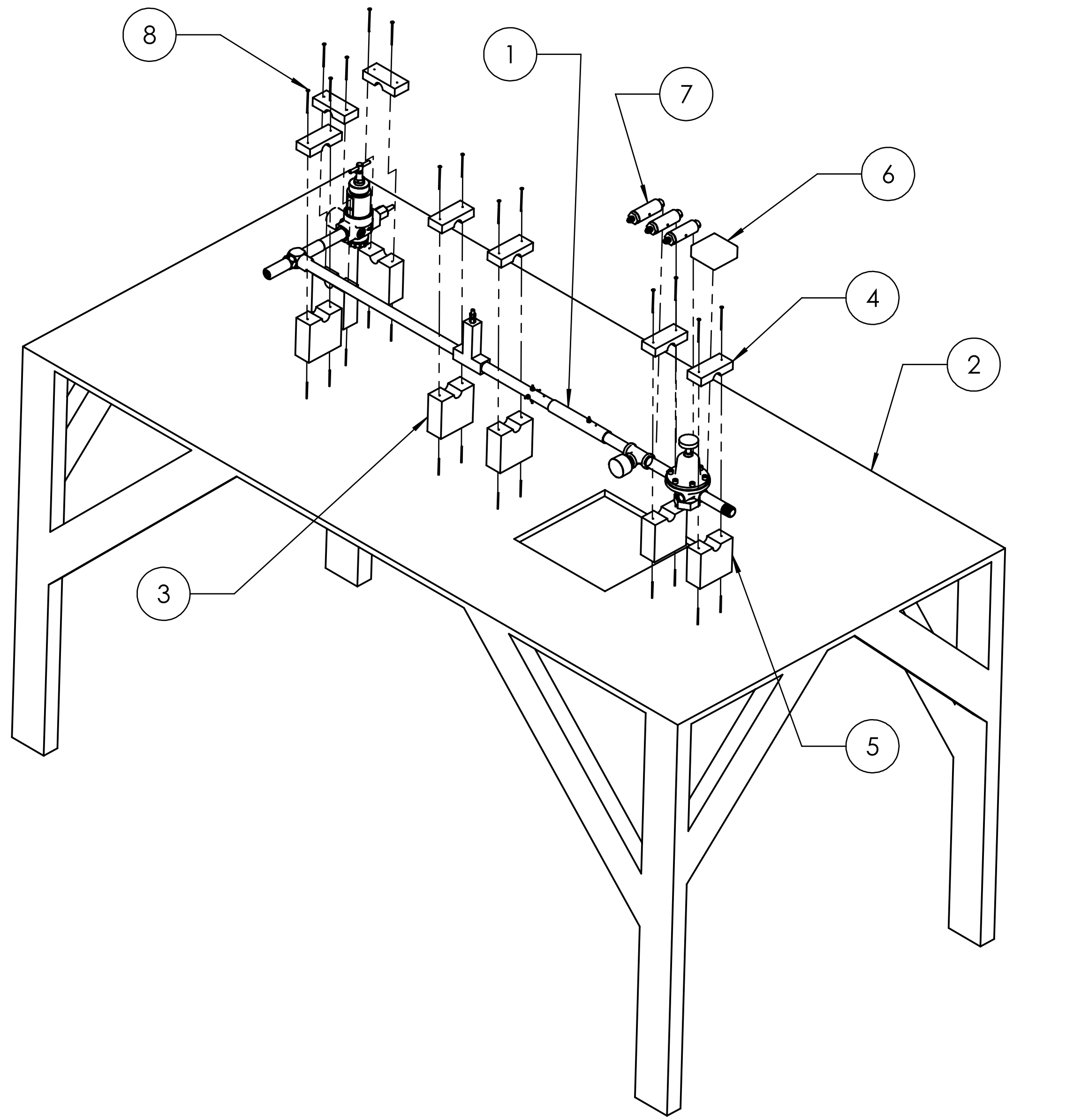
1 Schedules 5S and 10S wall thicknesses do not permit threading in accordance with ANSI/ASME B1.20.1.

2 These dimensions and weights do not conform to ANSI/ASME B36.10M.

- The suffix ‘S’ after the schedule number indicates that the pipe dimensions and weight are in compliance with this stainless steel pipe specification, ANSI/ASME B36.19M-1985, and not the more general ANSI/ASME B36.10M-1995 specification.
- Although this specification is applicable to stainless steel, quoted weights are for carbon steel pipe and should be multiplied by 1.014 for austenitic and duplex steels, or by 0.985 for ferritic and martensitic steels.

Appendix W: Drawings of Parts and Assemblies

ITEM NO.	PART NUMBER	Description	QTY.
1	6000	Verification Piece Testing Assembly	1
2	W502	Table	1
3	W501	Wood Support A	6
4	W500	Wood Support Top	7
5	W501B	Wood Support B	1
6	DI-158	Data Acquisition System	1
7	MMA100V10P2D0T3A5	Pressure Transducer	3
8	W503	Wood Screws	28

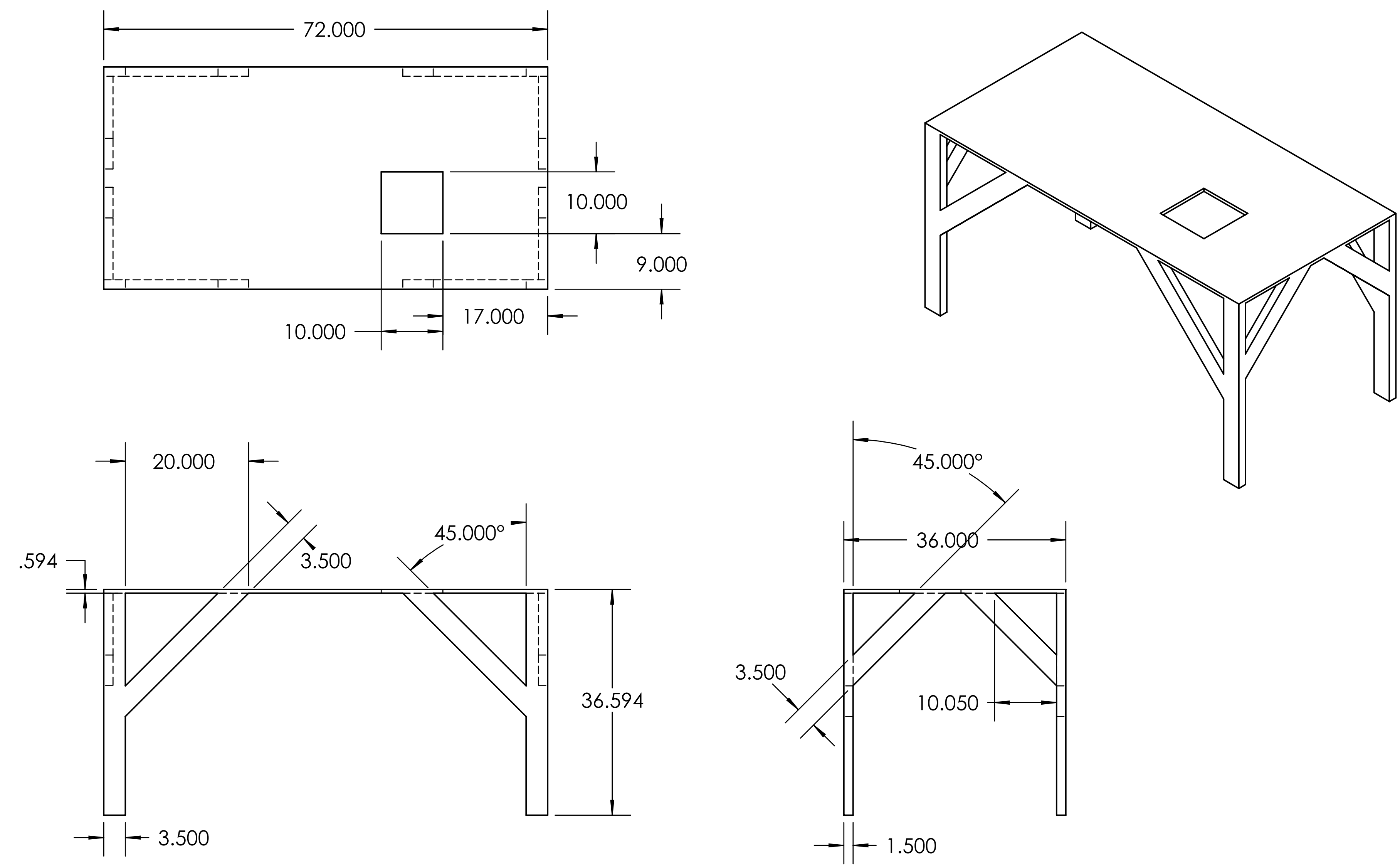


ME429 - Winter 2011

Mechanical Engineering CAL POLY

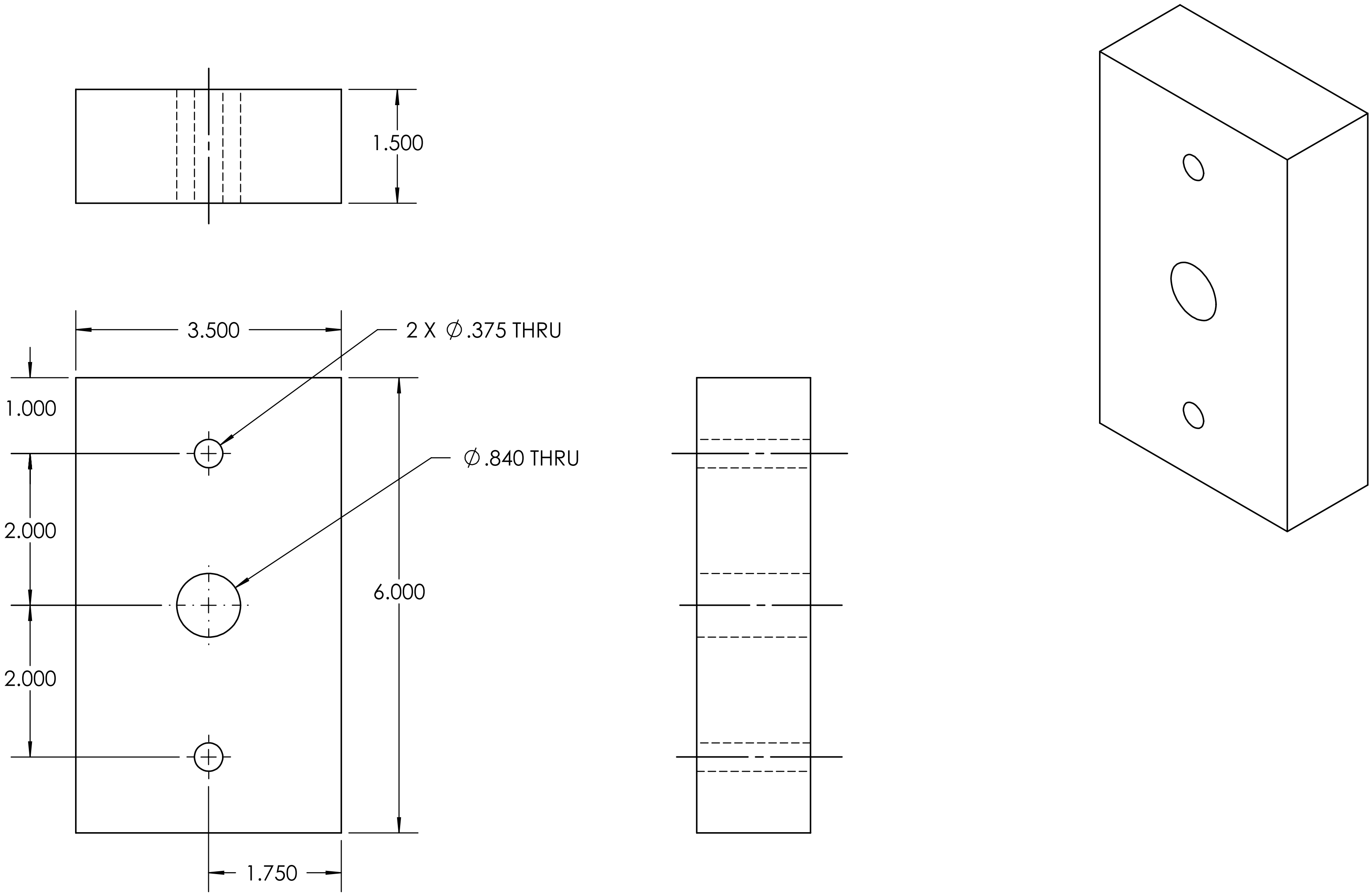
Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY:	SCALE: 1:14	TITLE: Final Verfication Piece Testing Assembly
PART #: W100	DATE: 2/4/2011	WEIGHT:

5 4 3 2 1



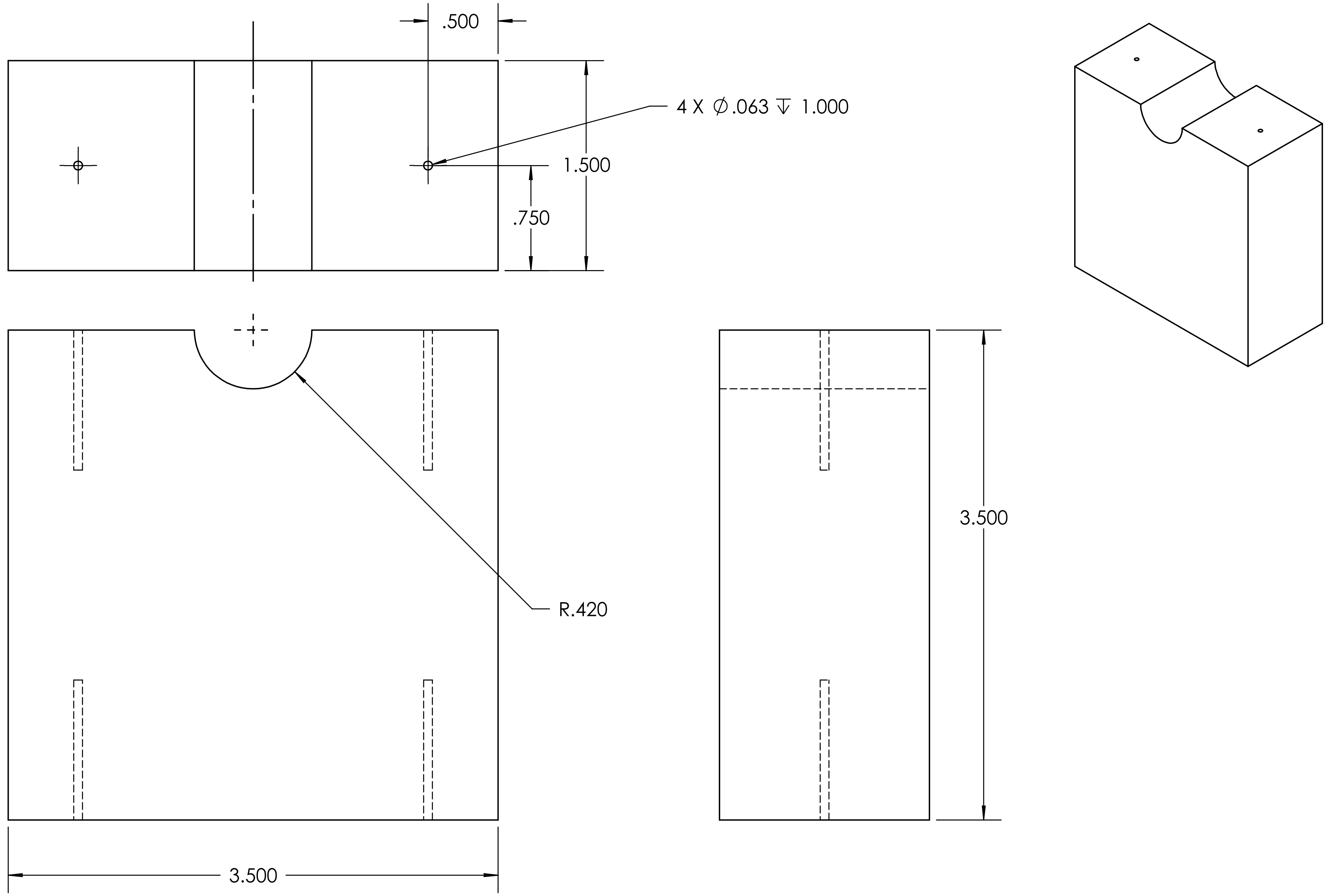
ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.1 in	UNITS: inches	MATERIAL: Ply Wood
	NEXT ASSY: W200, W100	SCALE: 1:24	TITLE: Table
	PART #: W502	DATE: 2/4/2011	WEIGHT: 38.42 lb

5 4 3 2 1



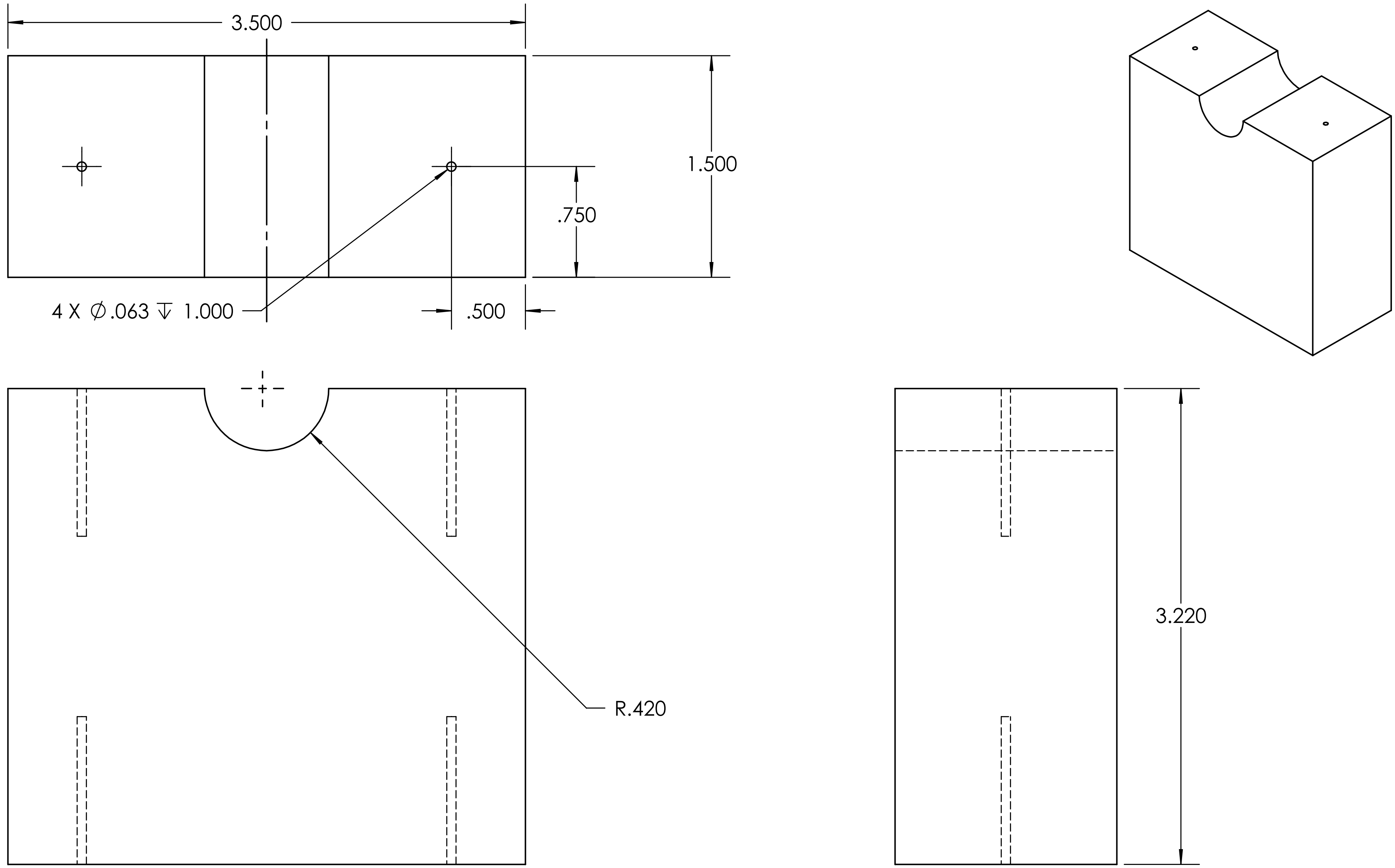
ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.1 in	UNITS: inches	MATERIAL: Ply Wood
	NEXT ASSY: W200	SCALE: 1:2	TITLE: Wood Support for Regulator
	PART #: W504	DATE: 2/4/2011	WEIGHT: 0.37 lb

5 4 3 2 1



ME429 - Winter 2011		
Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE: ±0.1 in	UNITS: inches	MATERIAL: Ply Wood
NEXT ASSY: W100, W200	SCALE: 1:1	TITLE: Wood Support A
PART #: W501	DATE: 2/4/2011	WEIGHT: 0.22 lb

Mechanical Engineering CAL POLY



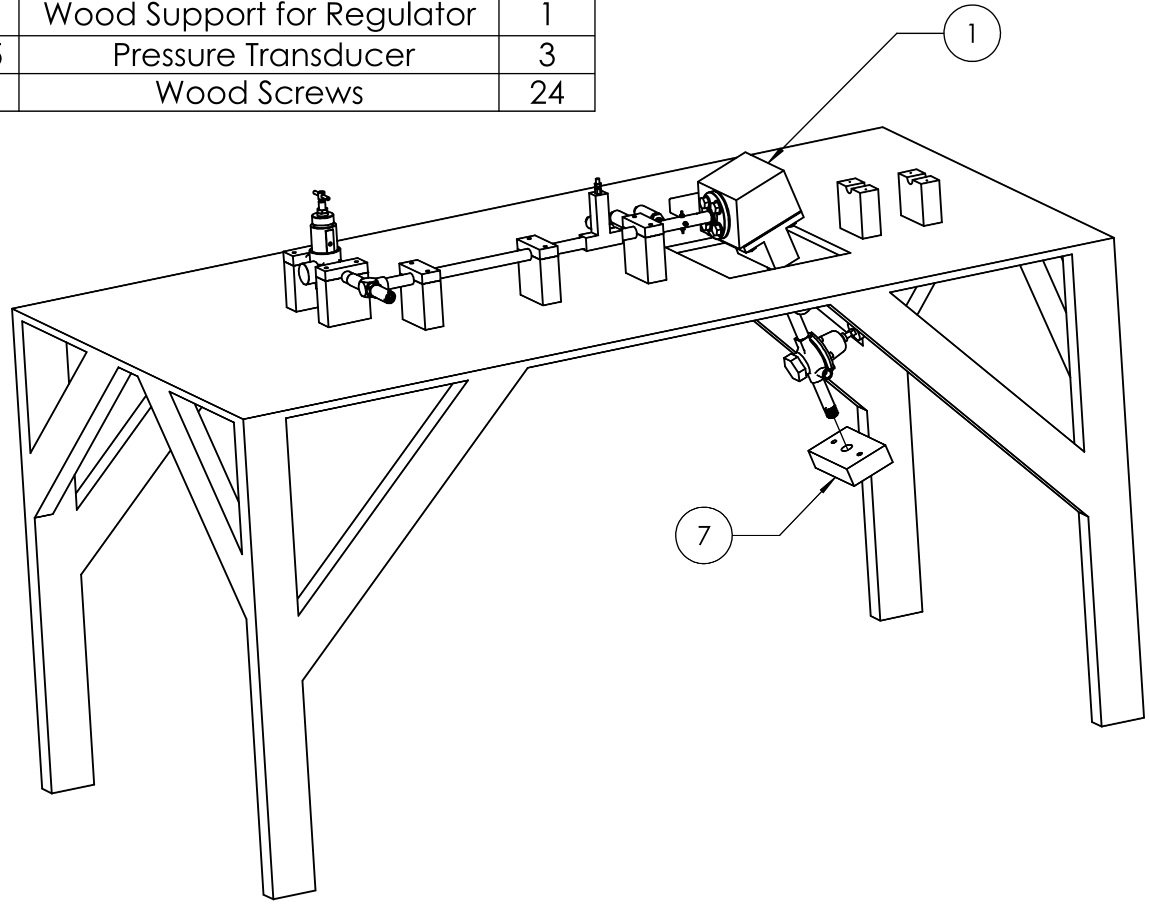
ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.1 in	UNITS: inches
	NEXT ASSY: W100, W200	SCALE: 1:1
	PART #: W501B	DATE: 2/4/2011

MATERIAL: Ply Wood	
TITLE: Wood Support B	
WEIGHT: 0.20 lb	

5 4 3 2 1

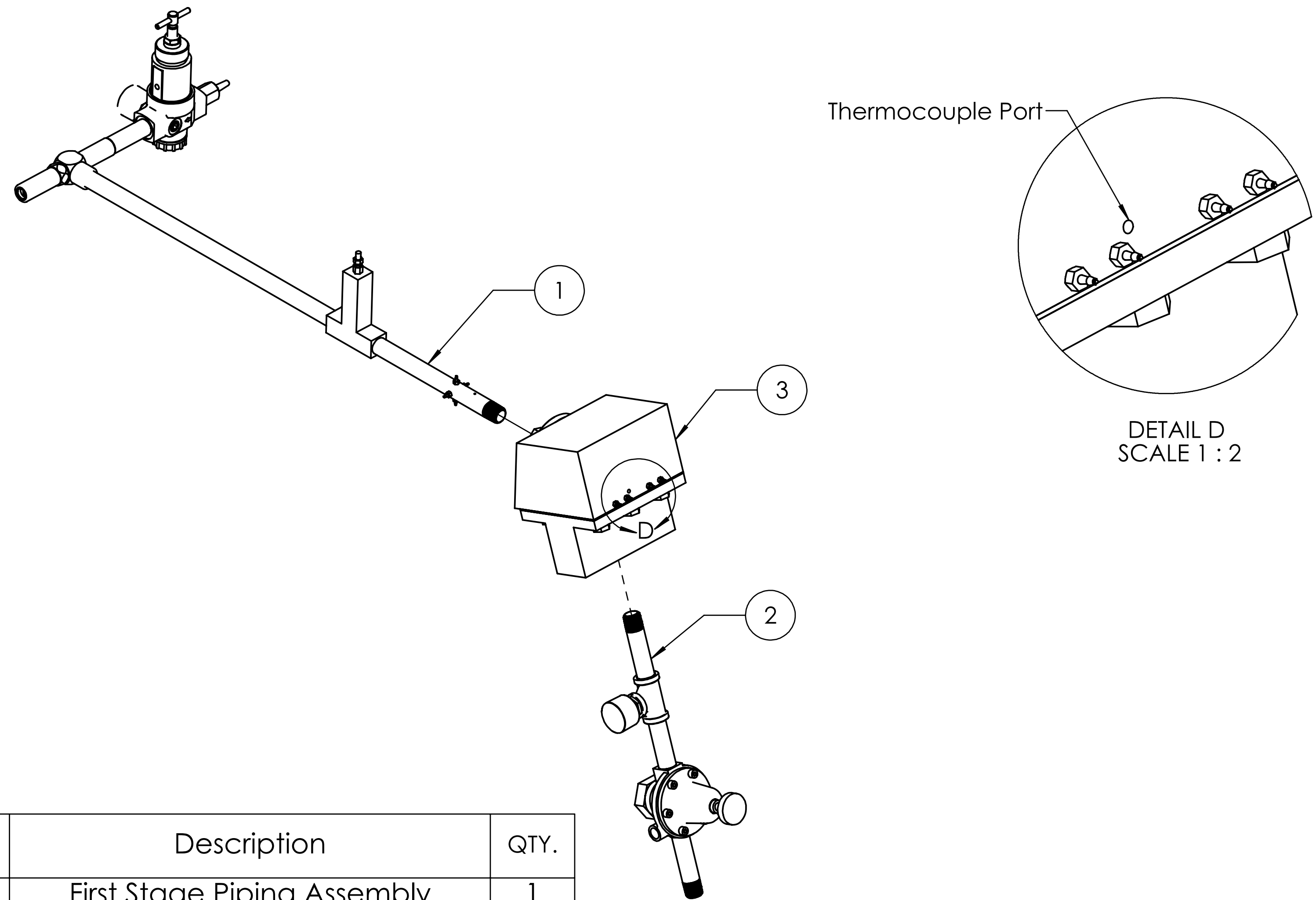
ITEM NO.	PART NUMBER	Description	QTY.
1	7000	Regular Test Setup Assembly	1
2	W502	Table	1
3	W501	Wood Support A	6
4	W500	Wood Support Top	5
5	W501B	Wood Support B	1
6	DI-158	Data Acquisition System	1
7	W504	Wood Support for Regulator	1
8	MMA100V10P2D0T3A5	Pressure Transducer	3
9	W503	Wood Screws	24

All other parts are assemblied in the same manner as W100



ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE:	UNITS: inches	MATERIAL:
	NEXT ASSY:	SCALE: 1:14	TITLE: Final Regular Test Setup Assembly
	PART #: W200	DATE: 2/4/2011	WEIGHT:

5 4 3 2 1



ITEM NO.	PART NUMBER	Description	QTY.
1	2000	First Stage Piping Assembly	1
2	4000	Back Pressure Regulator Assembly	1
3	3000	Test Section Assembly	1

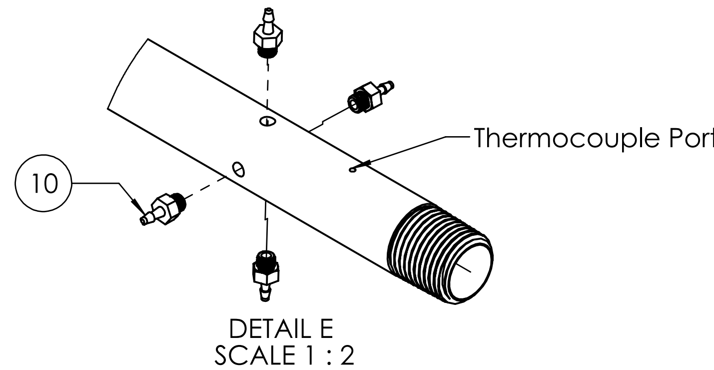
ME429 - Winter 2011

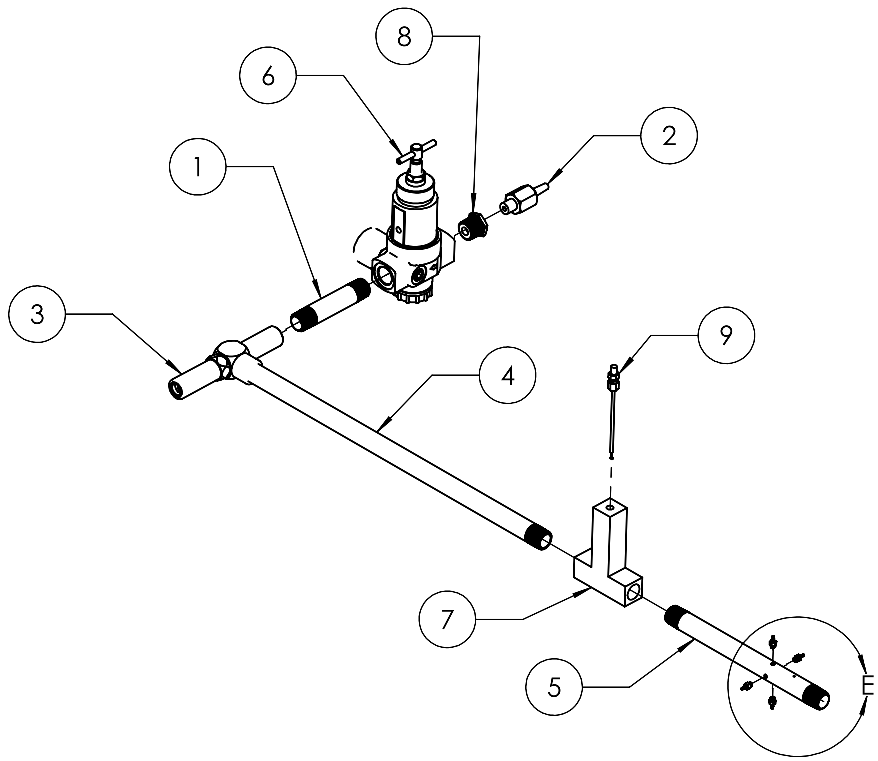
Mechanical Engineering CAL POLY

Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY: W200	SCALE: 1:8	TITLE: Regular Test Setup Assembly
PART #: 7000	DATE: 2/4/2011	WEIGHT:

5 4 3 2 1

ITEM NO.	PART NUMBER	Description	QTY.
1	4830K176	1/2 X 4 in schedule 40 pipe	1
2	719874	Quick Disconnect Coupler	1
3	4706K264	Pressure Relief Valve	1
4	4457K114	1/2 X 18 in schedule 40 pipe	1
5	9001	Static Pressure Pipe	1
6	5022K354	Inlet Pressure Regulator	1
7	1040	Kiel Probe Mounting Tee	1
8	4464K265	NPT Bushing	1
9	1050	Kiel Probe	1
10	5121K311	Static Pressure Taps	4





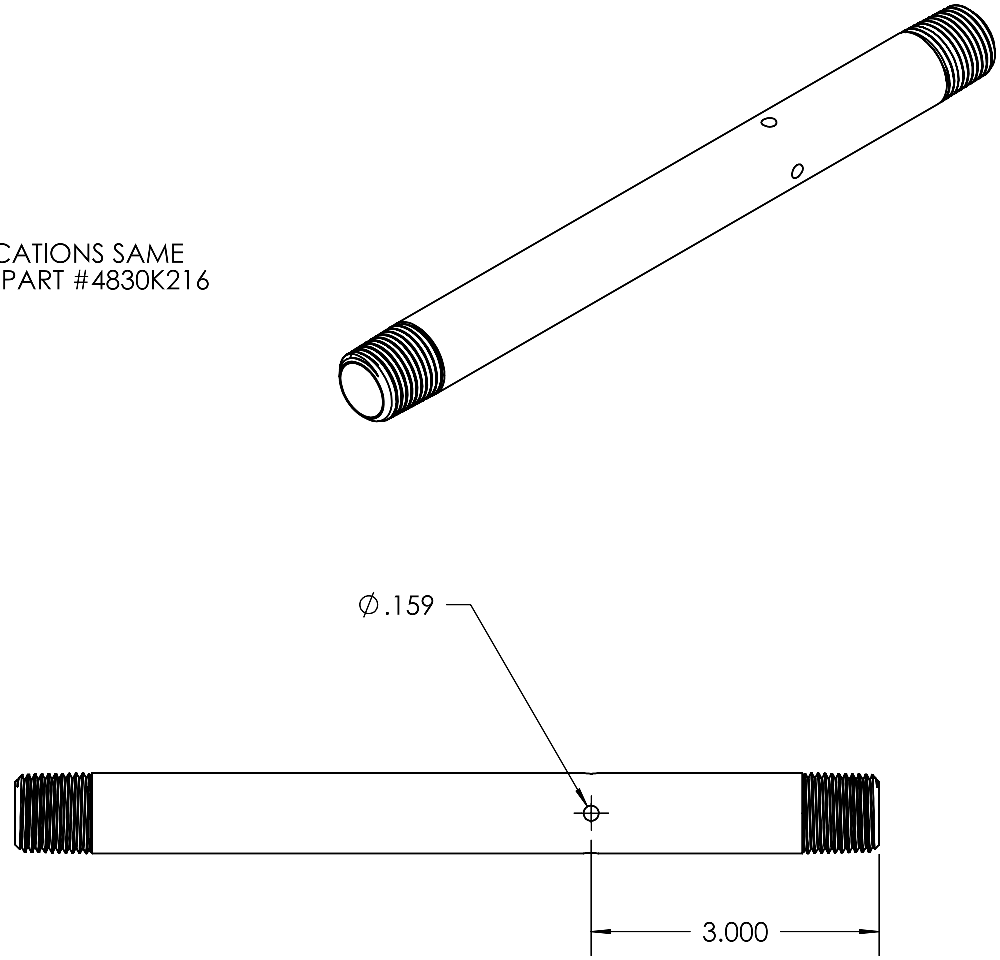
ME429 - Winter 2011

Mechanical Engineering CAL POLY

Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY: 6000, 7000	SCALE: 1:8	TITLE: First Stage Piping Assembly
PART #: 2000	DATE: 2/4/2011	WEIGHT:

5 4 3 2 1

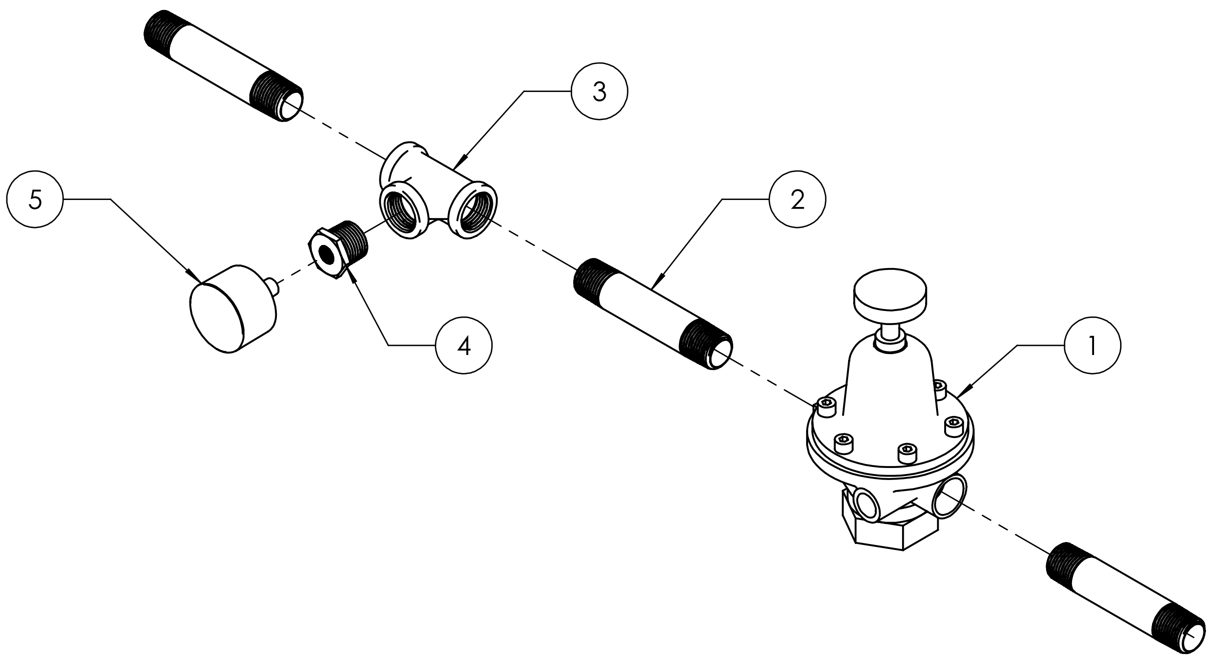
NOTE: ALL ORIGINAL DRAWING SPECIFICATIONS SAME
ADDITION OF HOLES TO EXISTING PART #4830K216



ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering	TOLERANCE: in	UNITS: inches	MATERIAL: Type 304/304L Stainless Steel
	NEXT ASSY:	SCALE: 1:2	TITLE: Static Pressure Pipe
	PART #: 9011	DATE: 2/ /2011	WEIGHT: 0.08 lb

5 4 3 2 1

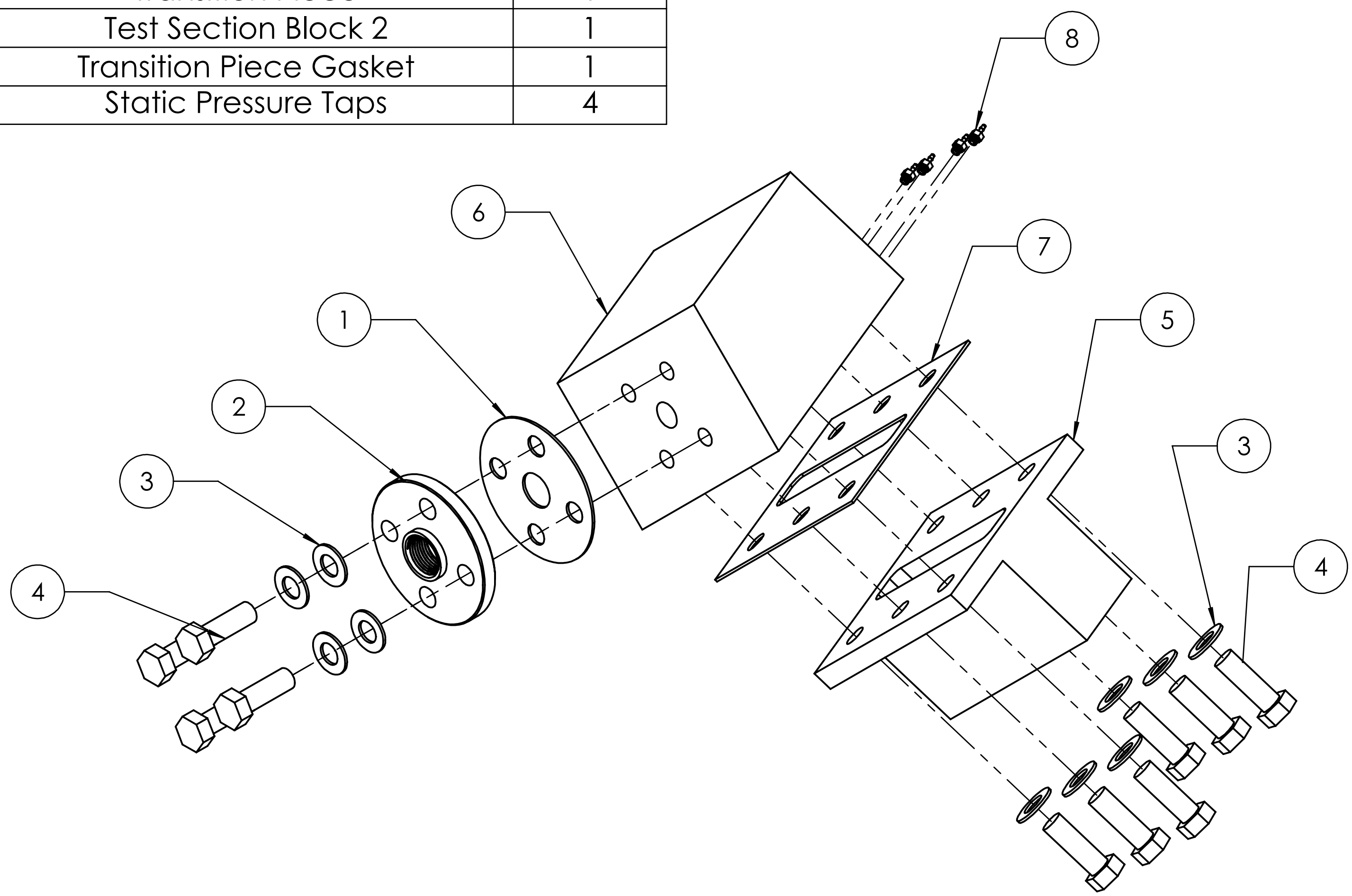
ITEM NO.	PART NUMBER	Description	QTY.
1	4783K55	Back Pressure Regulator	1
2	4830K176	1/2 X 4 in schedule 40 pipe	3
3	4464K51	Pipe Tee	1
4	4464K264	Pipe Bushing	1
5	38105K32	Pressure Gage	1



ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE:	UNITS: inches	MATERIAL:
	NEXT ASSY: 6000, 7000	SCALE: 1:4	TITLE: Back Pressure Regulator Assembly
	PART #: 4000	DATE: 2/4/2011	WEIGHT: 6.75 lb

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	9472K56	Flange Gasket	1
2	68095K226	Flange	1
3	94744A285	1/2 in Washer	10
4	244	1/2 -13 UNC Hex Bolt, SAE Grade 2	10
5	1010	Transition Piece	1
6	1002	Test Section Block 2	1
7	1011	Transition Piece Gasket	1
8	5121K311	Static Pressure Taps	4

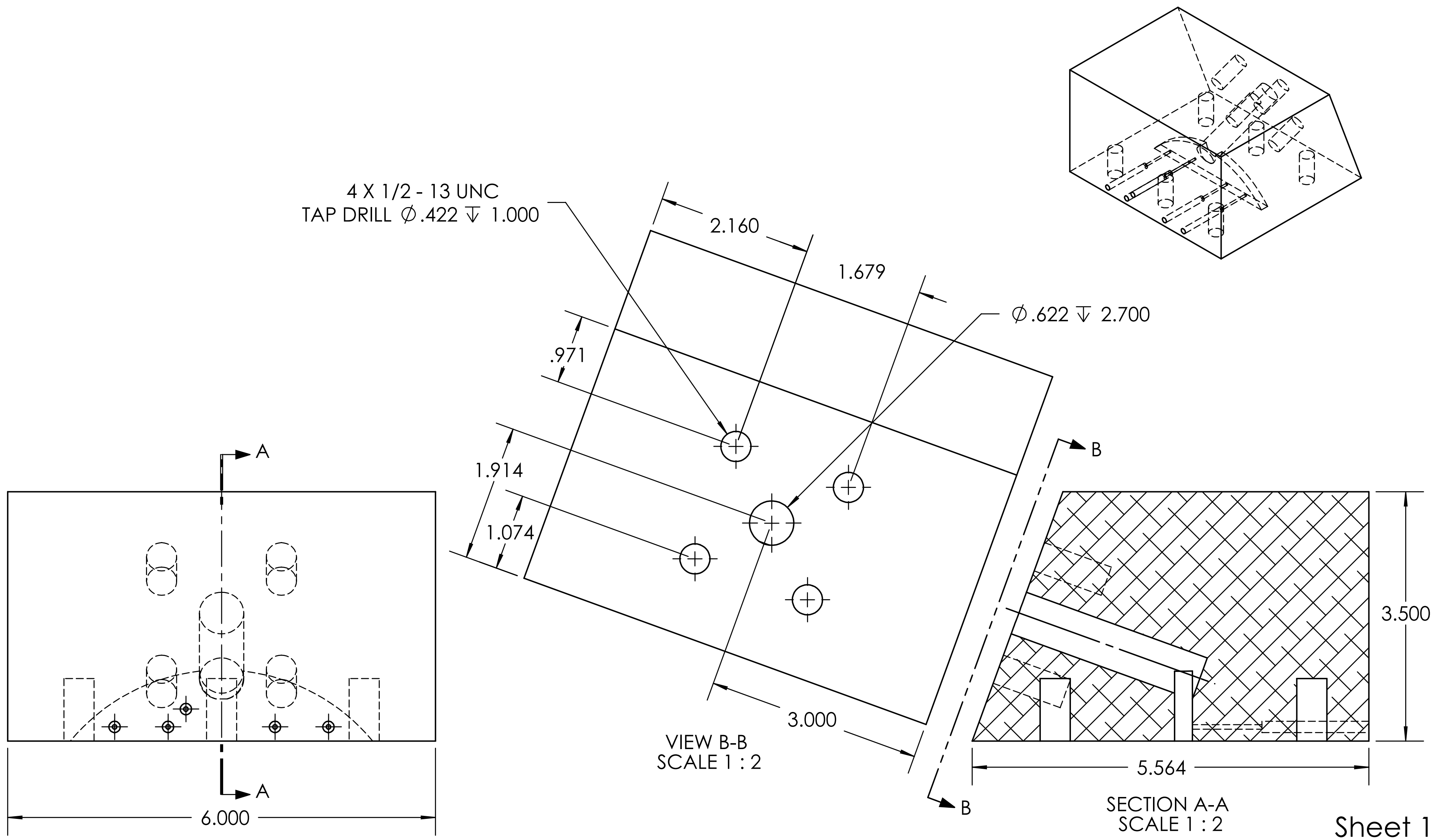


ME429 - Winter 2011

Mechanical Engineering
CAL POLY

Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY: 7000	SCALE: 1:4	TITLE: Test Section Assembly
PART #: 3000	DATE: 2/4/2011	WEIGHT: 15.47 lb

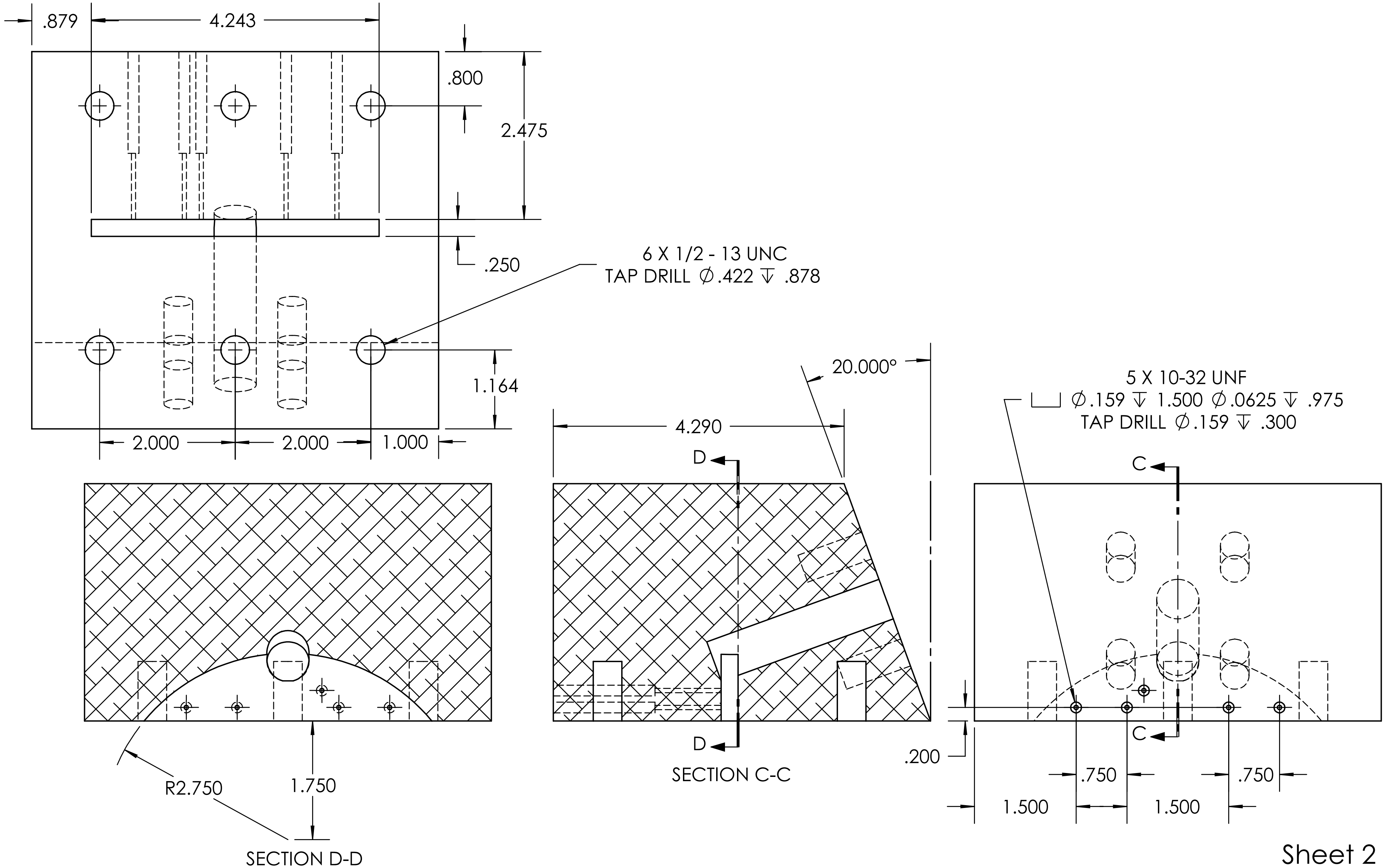
5 4 3 2 1



Sheet 1

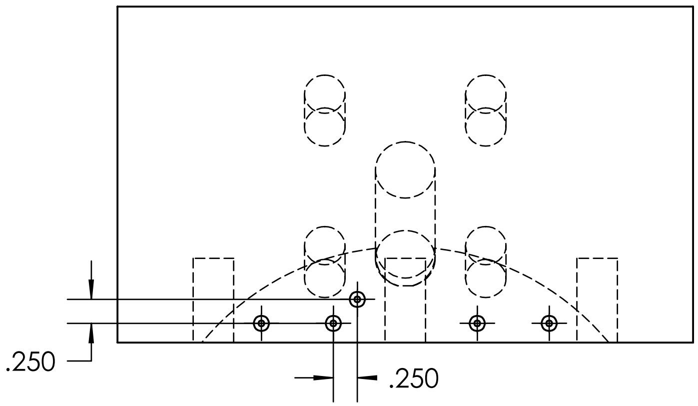
ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
TOLERANCE: ±0.005 iin	UNITS: inches	MATERIAL: Aluminum Alloy 6061
NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Block 2
PART #: 1002	DATE: 2/4/2011	WEIGHT: 9.8 lb

5 4 3 2 1



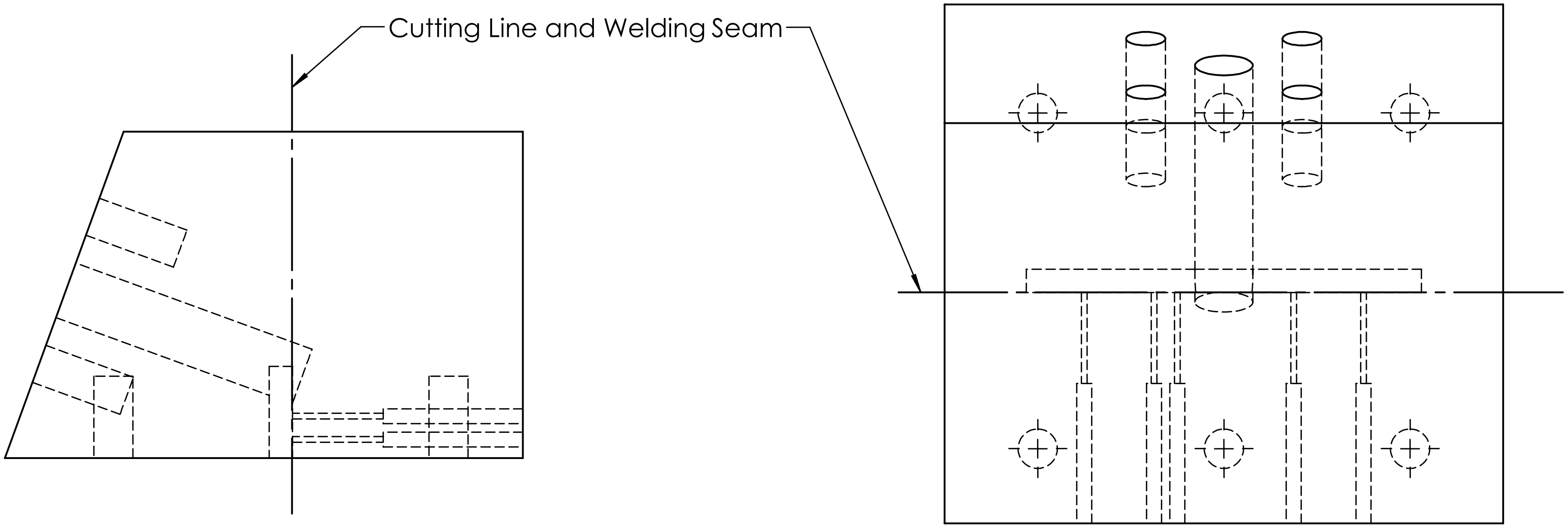
ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Block 2
	PART #: 1002	DATE: 2/4/2011	WEIGHT: 9.8 lb

5 4 3 2 1



Notes: Machining and Assembly

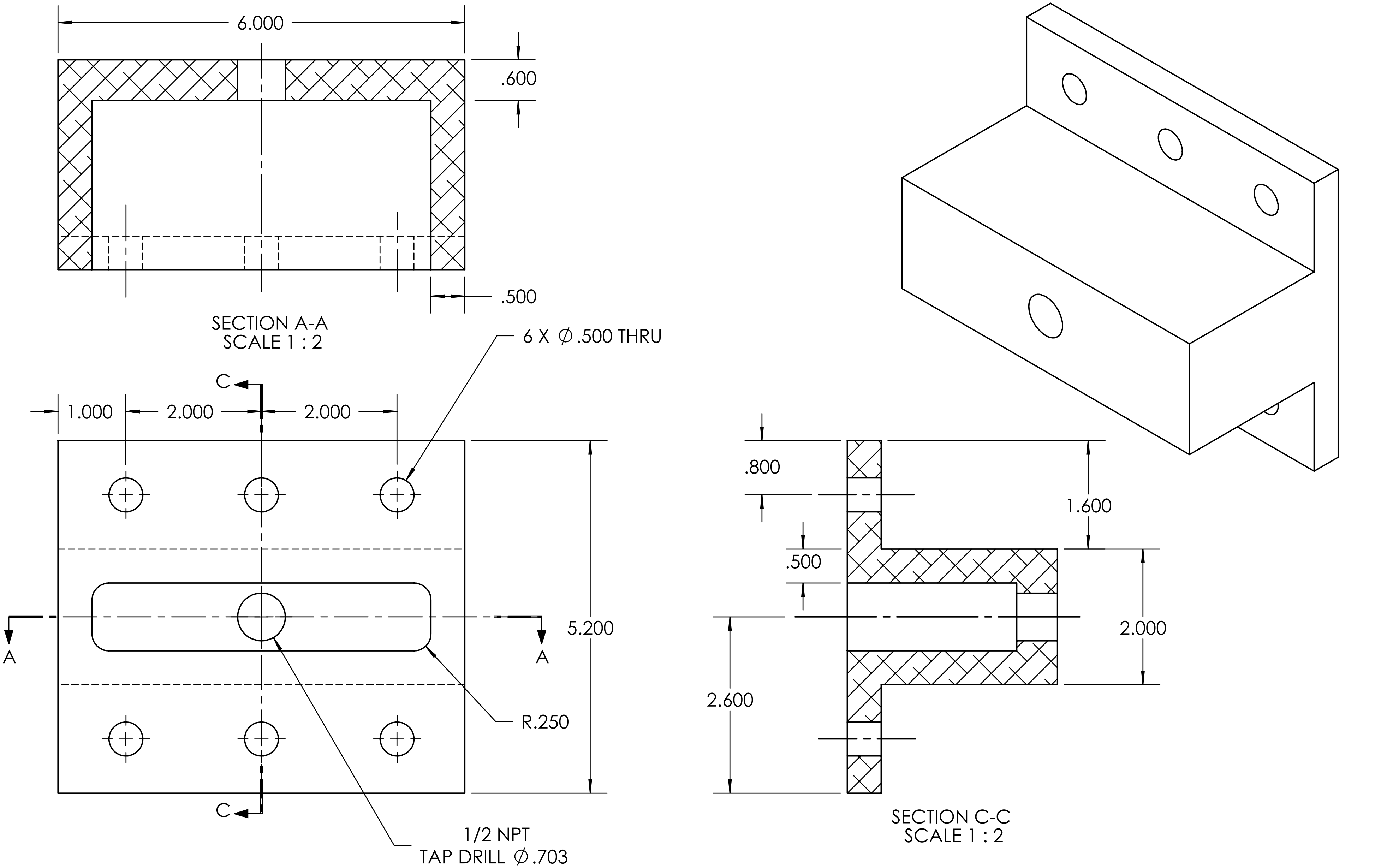
1) Cut angle slant
2) Drill 1/2 holes for bolts
3) Cut Block along noted line
4) Drill 1/16 and 10-32 UNF holes
5) Machine Semi-circle flycut
6) Epoxy blocks back together
7) Tig Weld along seams



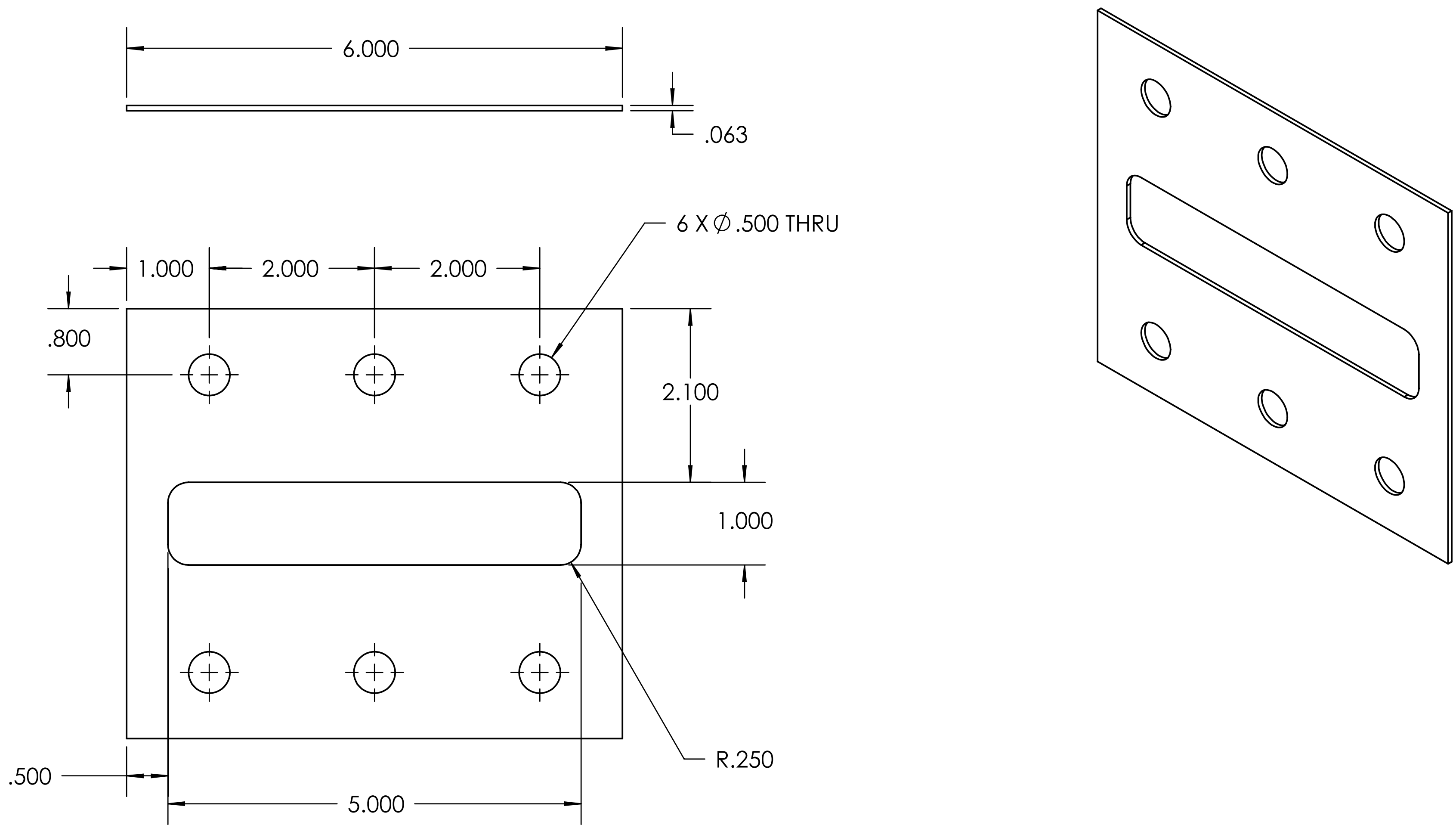
Sheet 3

ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Block 2
	PART #: 1002	DATE: 2/4/2011	WEIGHT: 9.8 lb

5 4 3 2 1

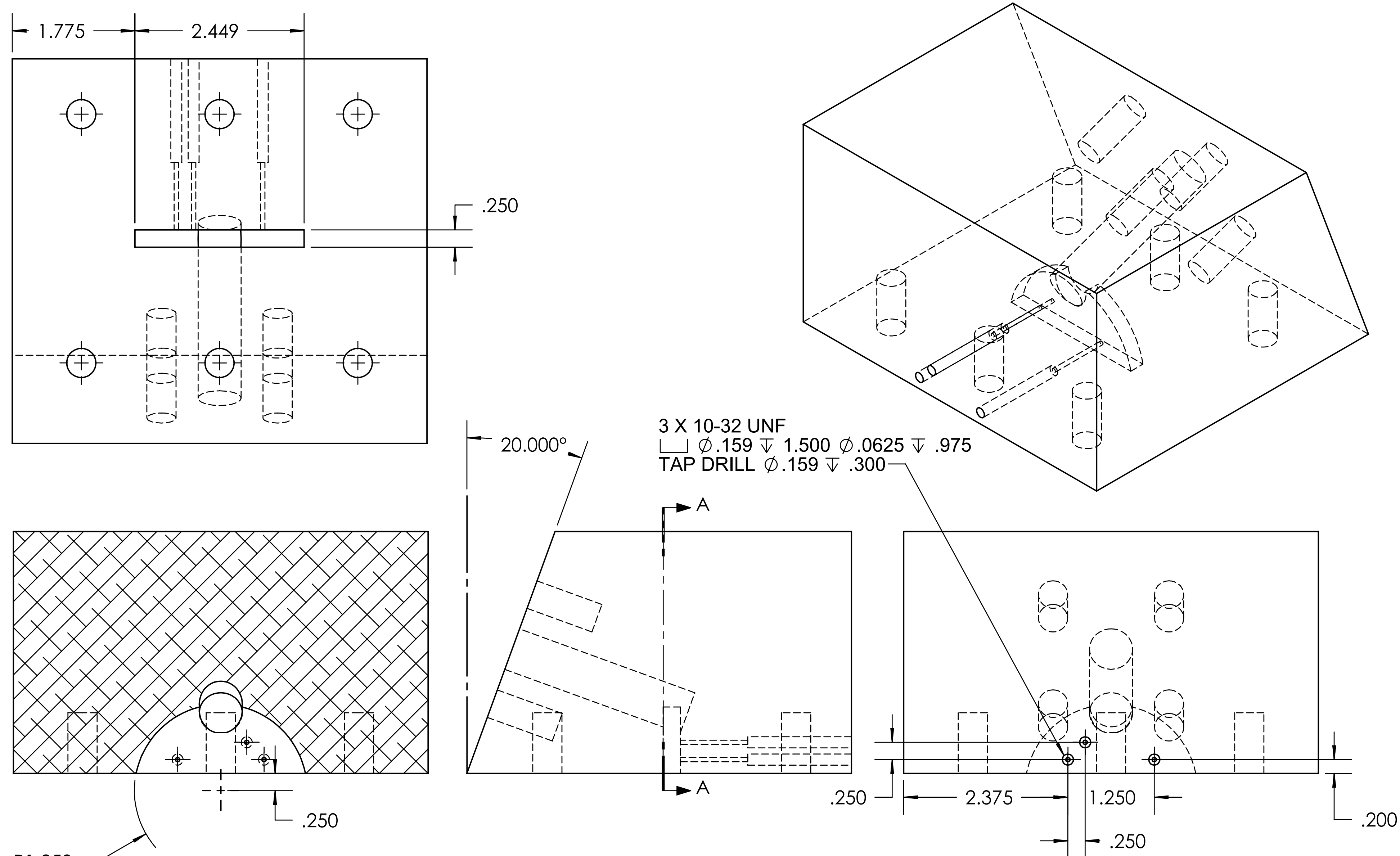


ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Transition Piece
	PART #: 1010	DATE: 2/4/2011	WEIGHT: 3.3 lb



ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.01 in	UNITS: inches	MATERIAL: Rubber (SBR)
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Transition Piece Gasket
	PART #: 1011	DATE: 2/4/2011	WEIGHT: 0.06 lb

5 4 3 2 1

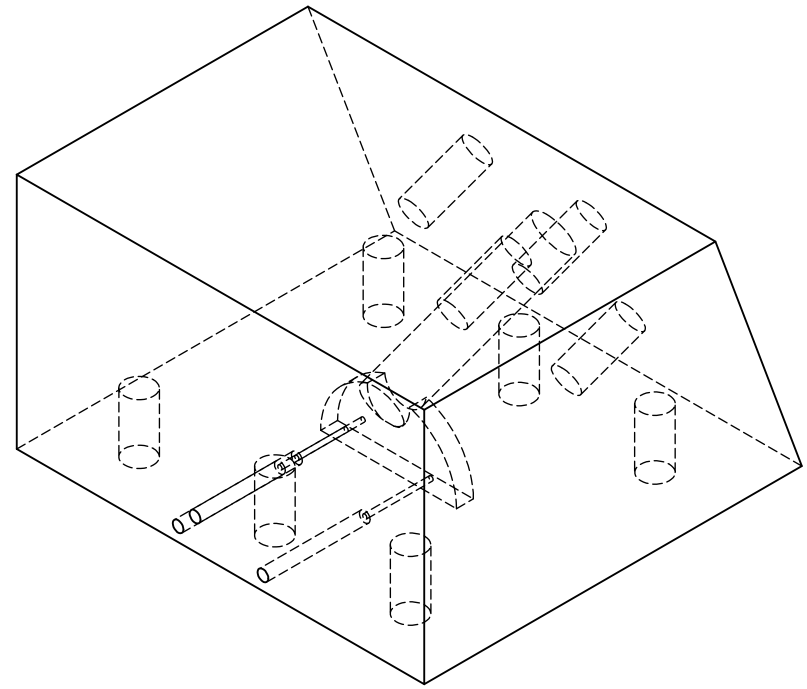


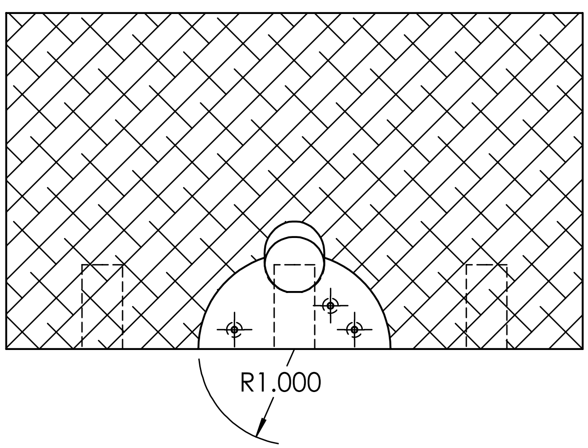
SECTION A-A

All other dimensions are the same as Part # 1002

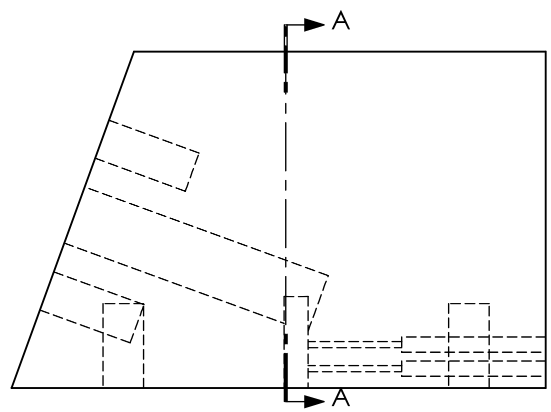
ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in · UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000 · SCALE: 1:2	TITLE: Baseline Test Section
	PART #: 1001 · DATE: 2/4/2011	WEIGHT: 9.84 lb

5 4 3 2 1





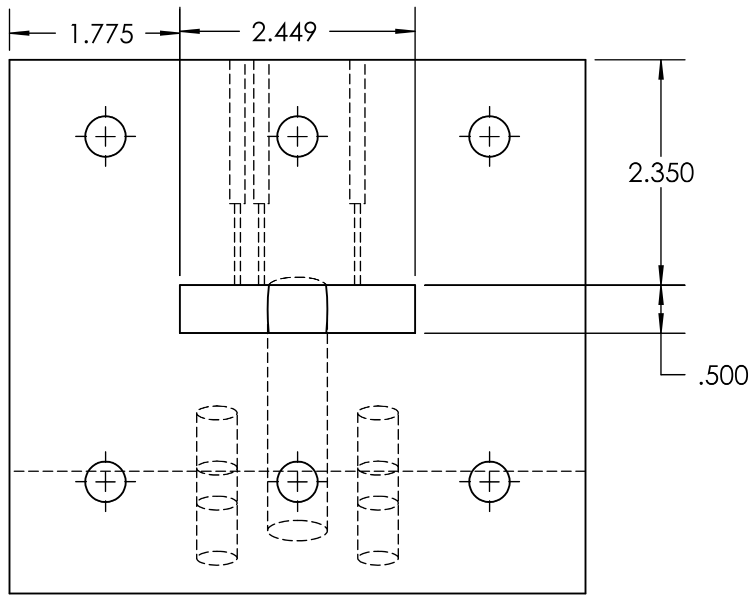
SECTION A-A

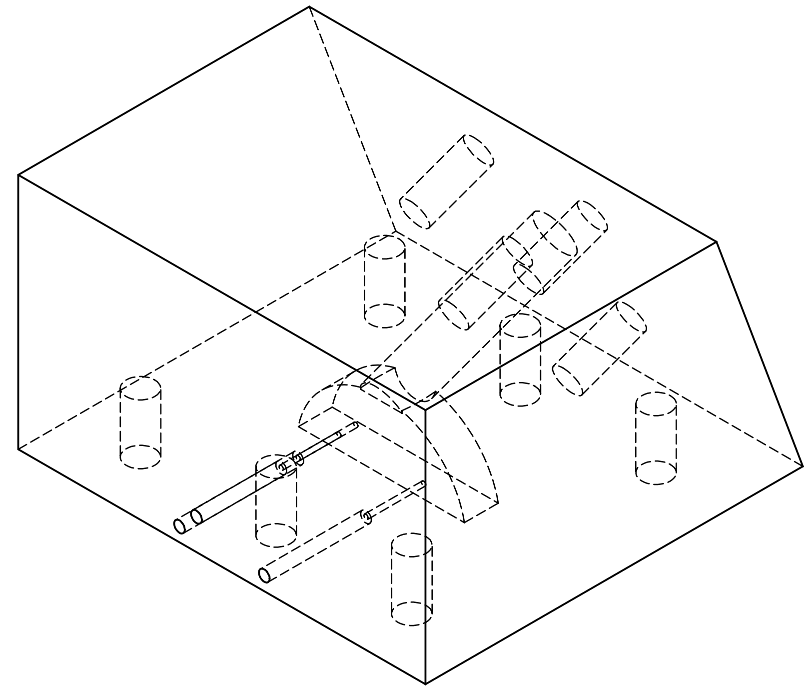


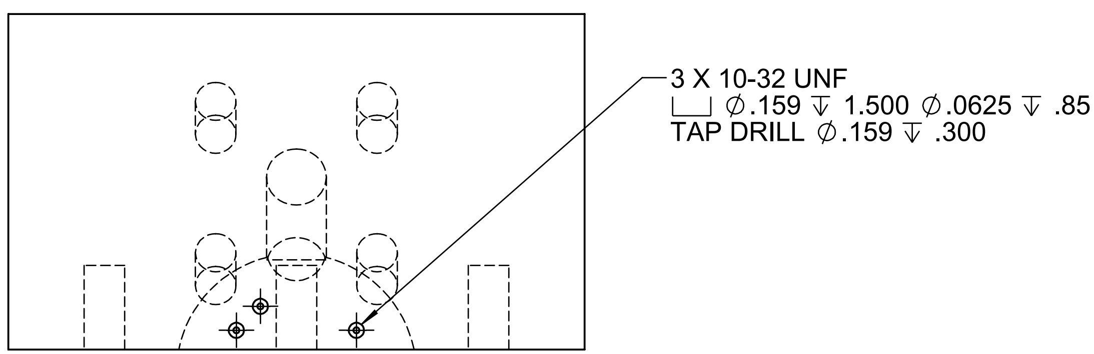
All other dimensions are the same as part # 1001

ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in / UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000 / SCALE: 1:2	TITLE: Test Section 3
	PART #: 1003 / DATE: 2/4/2011	WEIGHT: 9.84 lb

5 4 3 2 1





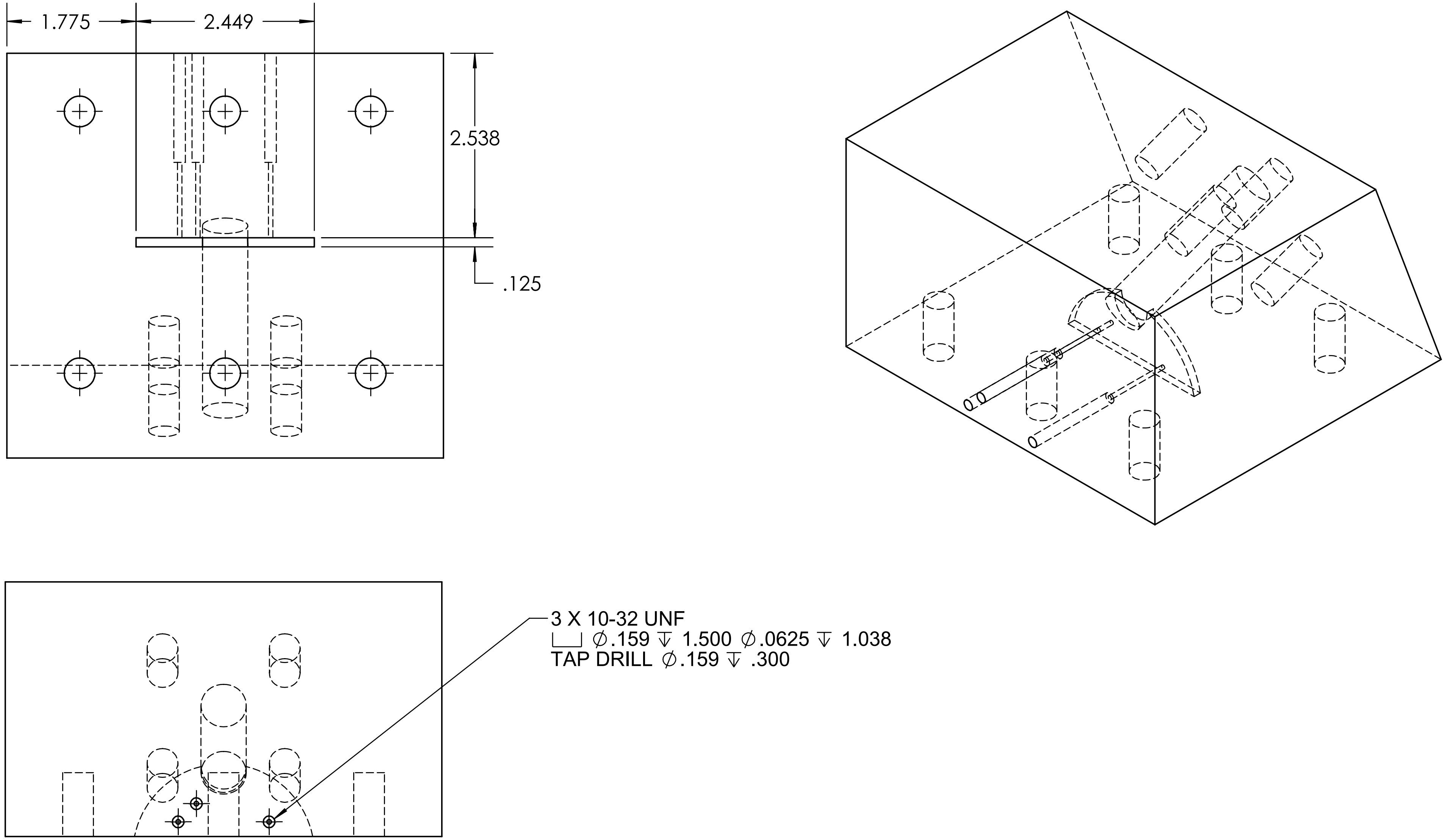


All other dimensions are the same as part # 1001

ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Section 4
	PART #: 1004	DATE: 2/4/2011	WEIGHT: 9.84 lb

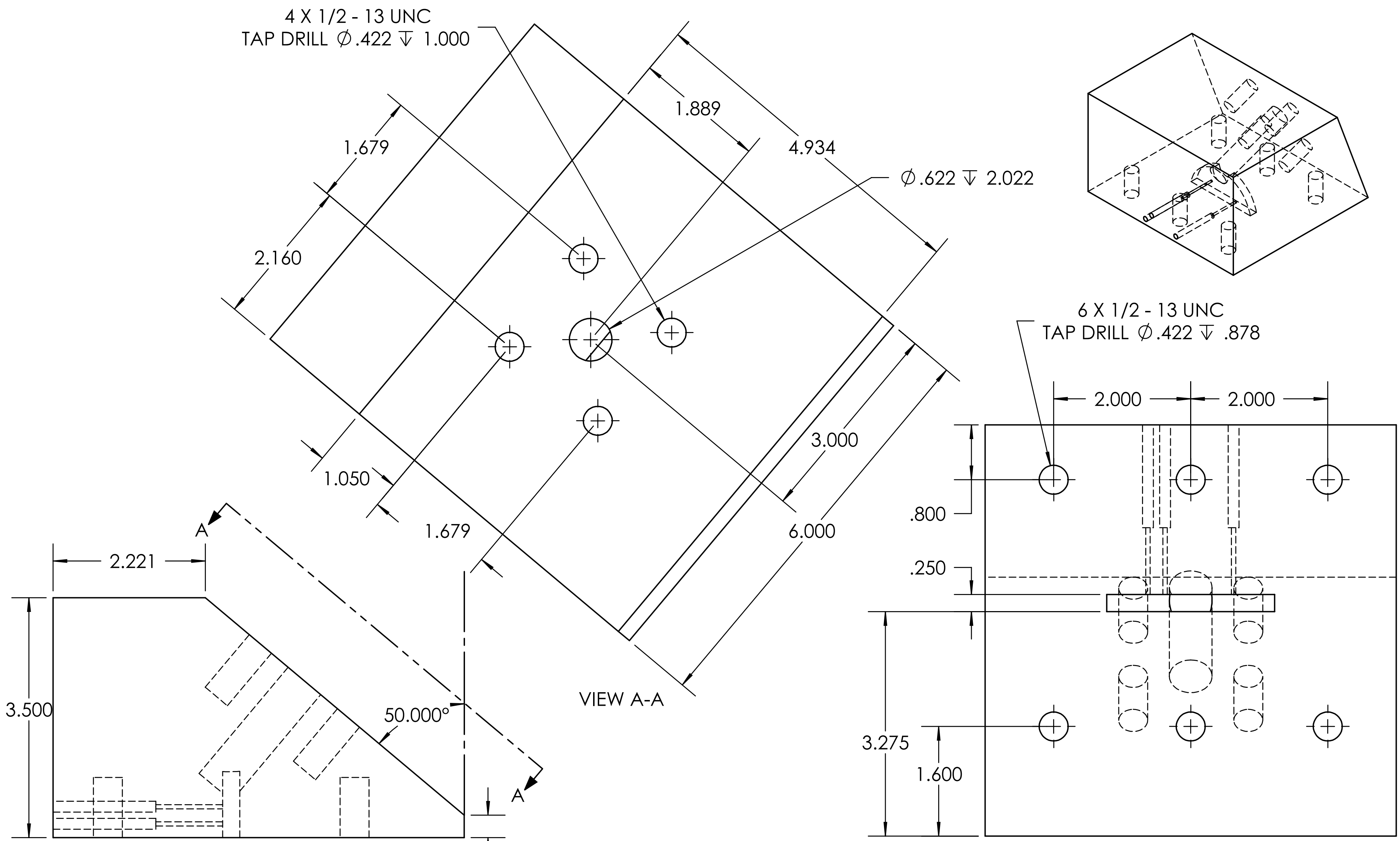
180

5 4 3 2 1



All other dimensions are the same as part # 1001

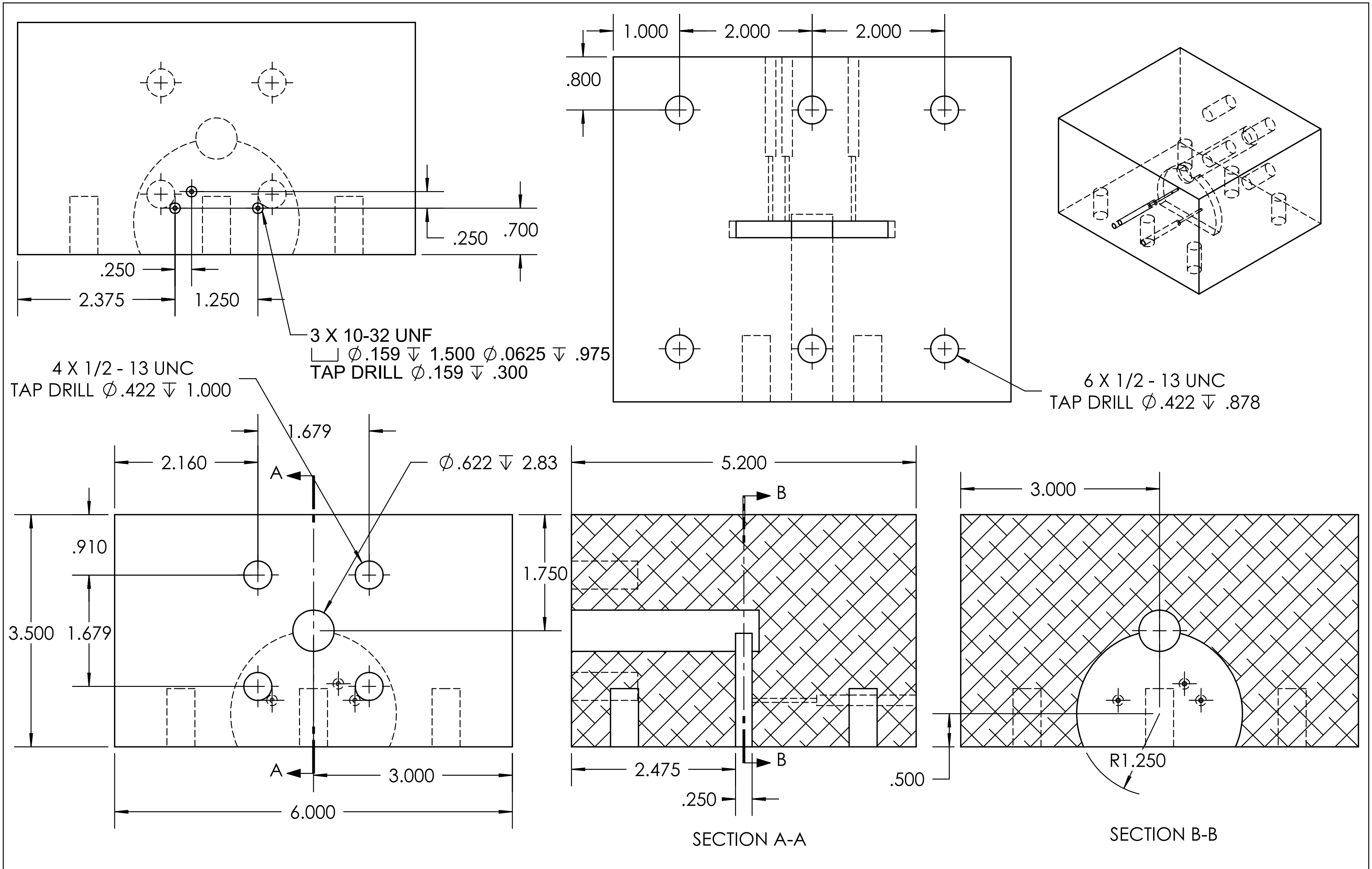
ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Section 5
	PART #: 1005	DATE: 2/4/2011	WEIGHT: 9.84 lb



All other dimensions are the same for part # 1001

ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Section 6
	PART #: 1006	DATE: 2/4/2011	WEIGHT: 9.84 lb

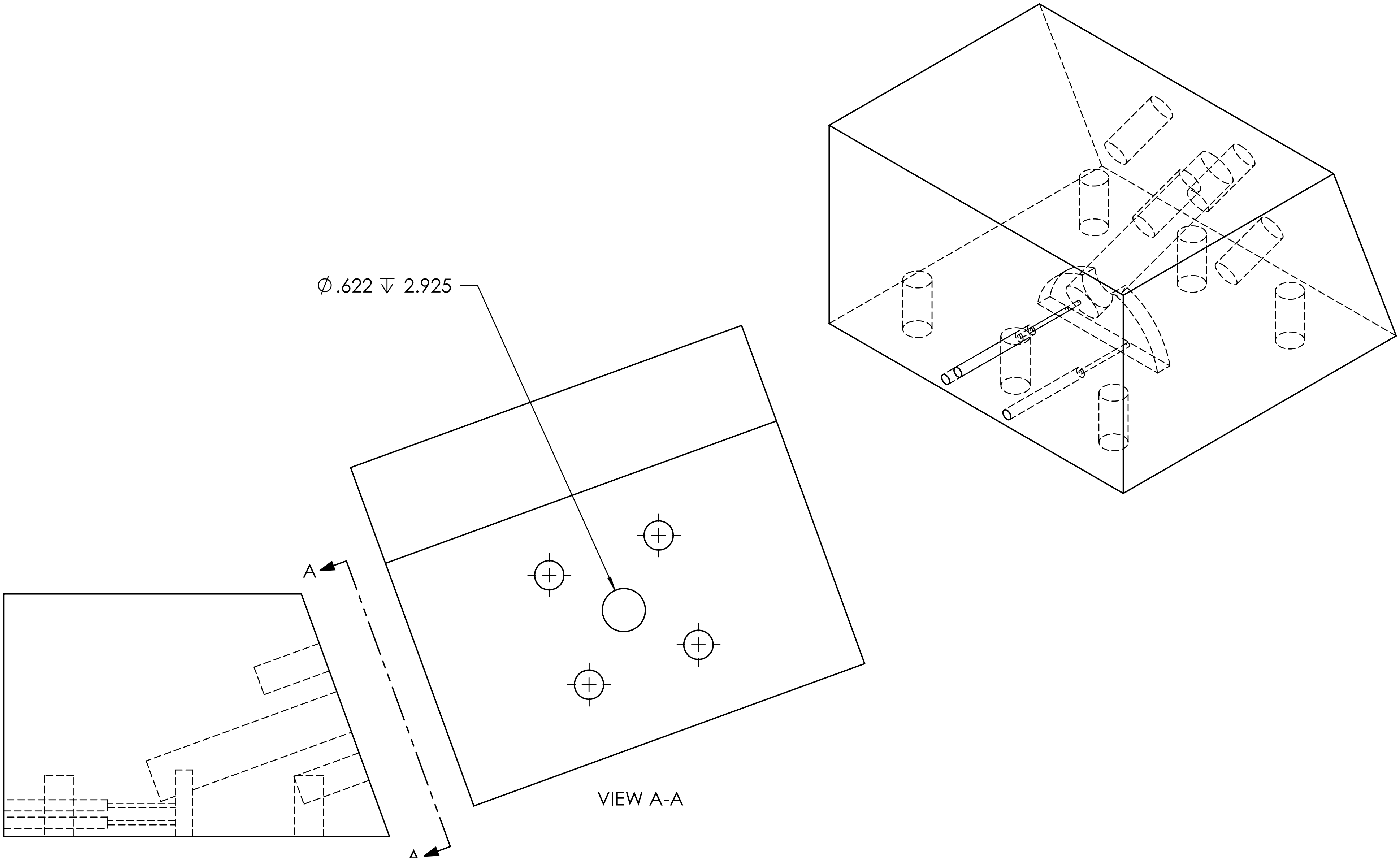
5 4 3 2 1



ME429 - Winter 2011	Sponsor: Solar Turbines		GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Section 7
	PART #: 1007	DATE: 2/4/2011	WEIGHT: 9.84 lb

183

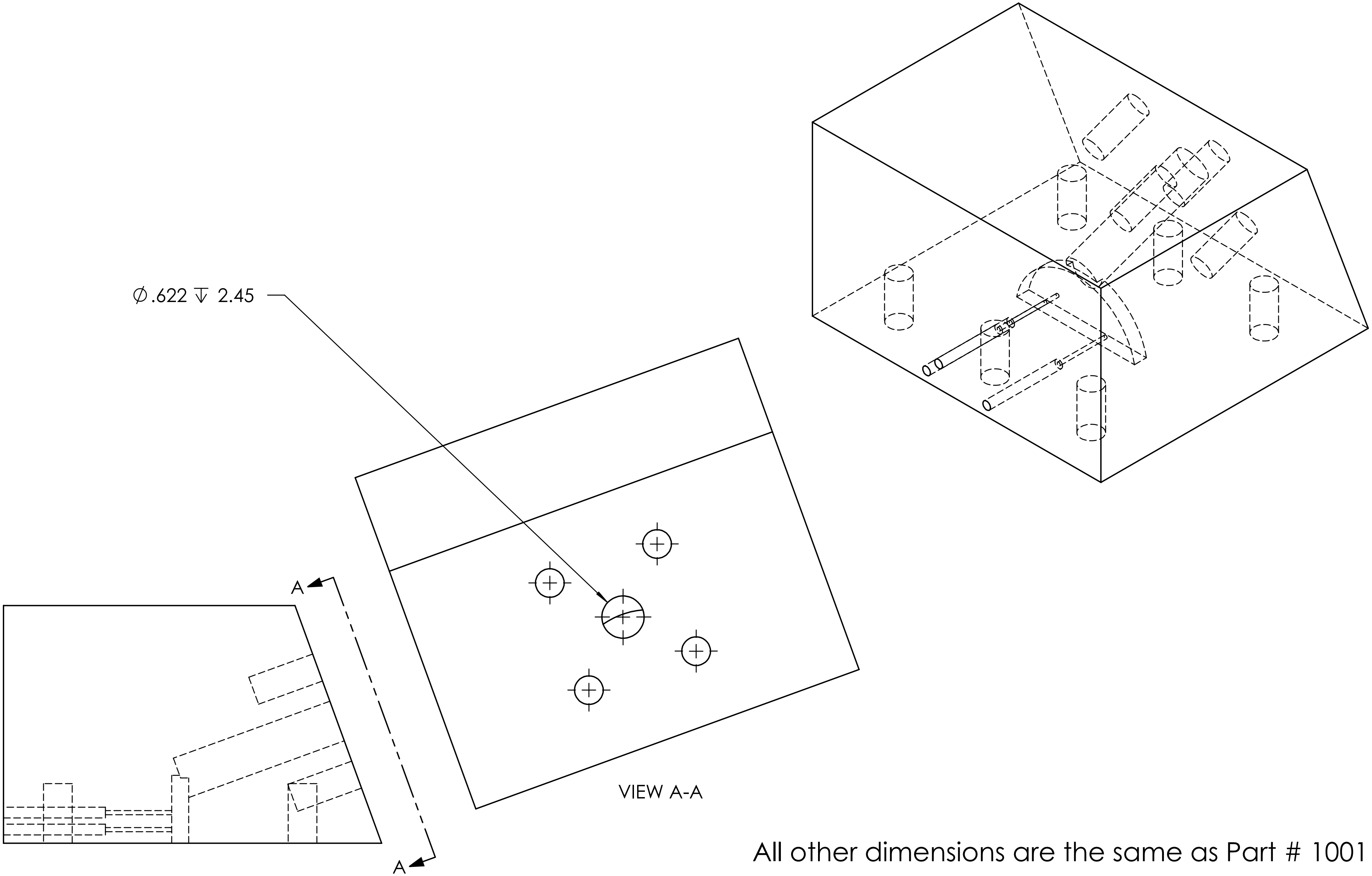
5 4 3 2 1



All other dimensions are the same as Part # 1001

ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in / UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000 / SCALE: 1:2	TITLE: Test Section 8
	PART #: 1008 / DATE: 2/4/2011	WEIGHT: 9.84 lb

5 4 3 2 1

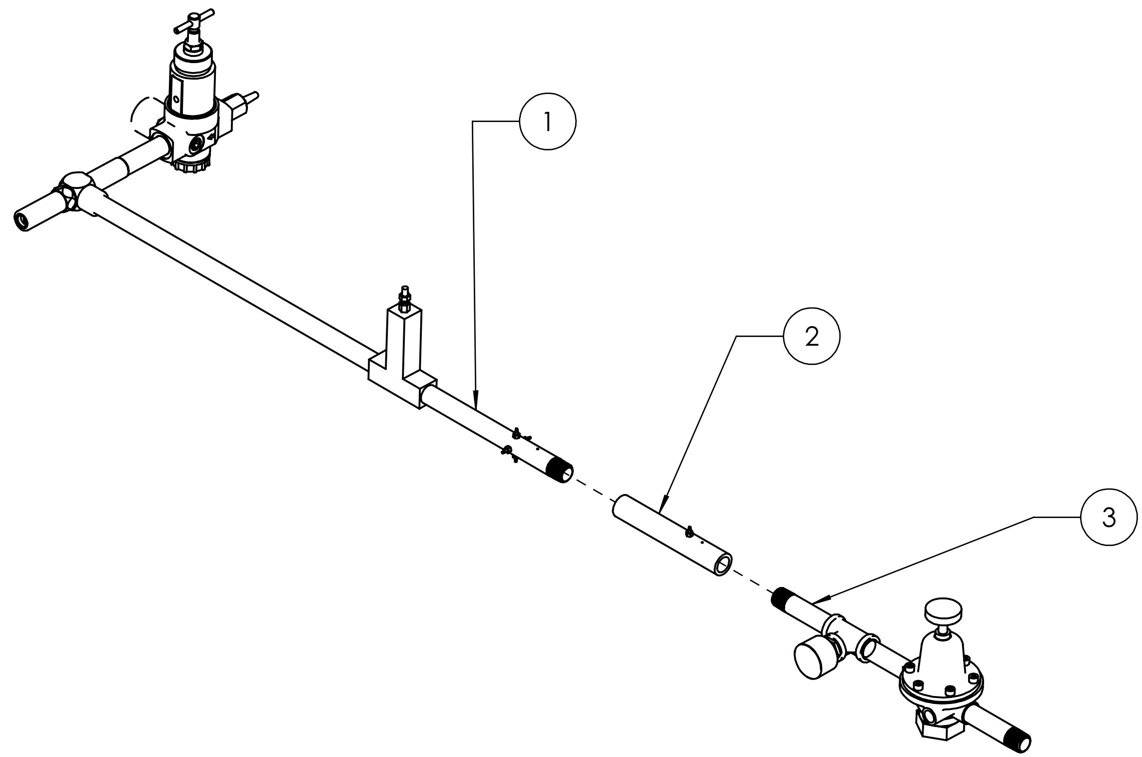


All other dimensions are the same as Part # 1001

ME429 - Winter 2011 Mechanical Engineering CAL POLY	Sponsor: Solar Turbines		GROUP: PreFlow Systems
	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 6061
	NEXT ASSY: 3000	SCALE: 1:2	TITLE: Test Section 9
	PART #: 1009	DATE: 2/4/2011	WEIGHT: 9.84 lb

5 4 3 2 1

ITEM NO.	PART NUMBER	Description	QTY.
1	2000	First Stage Piping Assembly	1
2	5000	Verification Piece Assembly	1
3	4000	Back Pressure Regulator Assembly	1



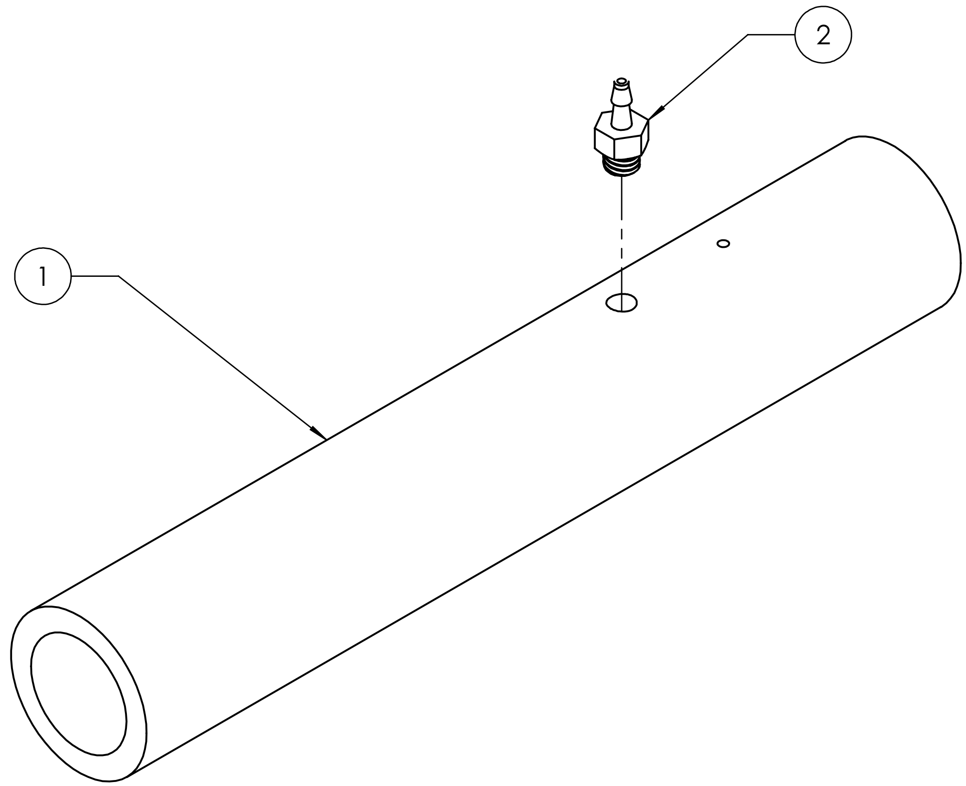
ME429 - Winter 2011

Mechanical Engineering CAL POLY

Sponsor: Solar Turbines		GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY: W100	SCALE: 1:8	TITLE: Verfication Piece Testing Assembly
PART #: 6000	DATE: 2/4/2011	WEIGHT:

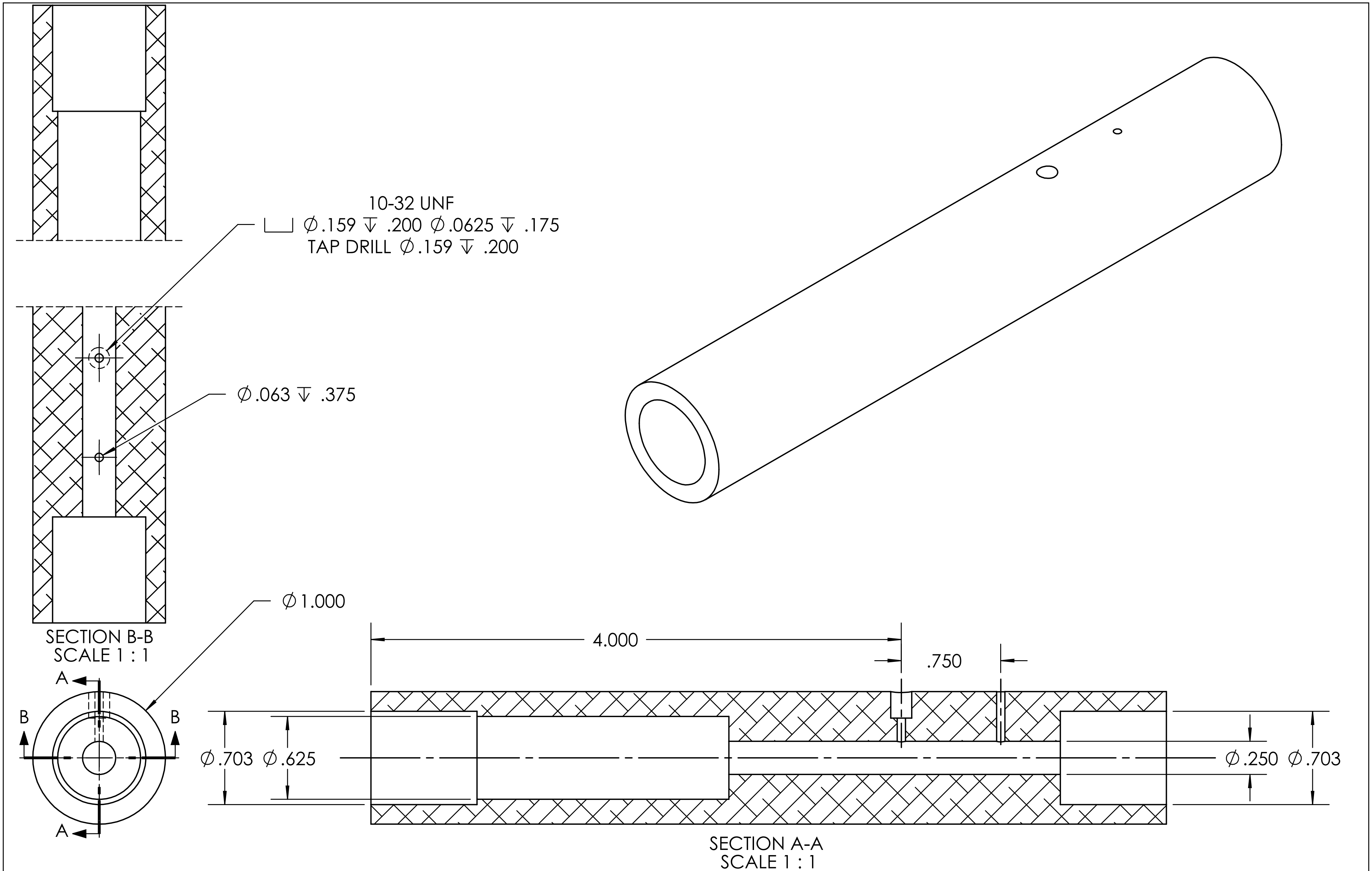
5 4 3 2 1

ITEM NO.	PART NUMBER	Description	QTY.
1	1012	Verification Piece	1
2	5121K311	Static Pressure Taps	1



ME429 - Winter 2011 Mechanical Engineering CAL POLY	Sponsor: Solar Turbines	GROUP: PreFlow Systems
TOLERANCE:	UNITS: inches	MATERIAL:
NEXT ASSY: 6000	SCALE: 1:1	TITLE: Verfication Piece Assembly
PART #: 5000	DATE: 2/4/2011	WEIGHT: 0.34 lb

5 4 3 2 1



ME429 - Winter 2011	Sponsor: Solar Turbines	GROUP: PreFlow Systems

Mechanical Engineering CAL POLY	TOLERANCE: ±0.005 in	UNITS: inches	MATERIAL: Aluminum Alloy 2011
	NEXT ASSY: 5000	SCALE: 1:1	TITLE: Verification Piece
	PART #: 1012	DATE: 2/4/2011	WEIGHT: 0.34 lb

5 4 3 2 1

Appendix X: EES Code

```
File:Senior Project Loss Coefficient 1.XPT                                    6/7/2011 3:26:43 PM  Page 1
                    EES Ver. 8.595: #552: For use by Mech. Engin. Students and Faculty at Cal Poly

"EES Code for Solving the Loss Coefficients"

"Conversion Factors"
Conv_ft =      12      [in/ft]
Conv_slug =   32.2     [lb_m/slug]
Conv_in2 =    144      [in^2/ft^2]
Conv_s =      3600     [s/hr]

"Inputs"

"Commented out becuase these inputs are put in the parametric table."
{

"Values from DATAQ"
Ptotal_psi =69.9908 [psia]          "Total Pressure at 0"
P0_psi = 69.9114 [psia]             "Static Pressure at 0"
P1_psi = 69.8085 [psia]             "Static Pressure at 1"

"Values from Thermocouple Reader"
T_0 = 67.8 [degree F]               "Temperature  at 0"
T_1 = 67.7 [degree F]               "Temperature  at 1"
R_humidity = .14                    "Relative Humidity of air"

"Known Geometry of Test Block"
L_in = 2.332   [in]                 "Length of flycut exit in inches"
W_in = .25     [in]                 "Widthof flycut exit in inches"

}

"Densities"

rho = Density (AirH2O, T = T_0, R = R_humidity, P = P0_psi)        "[lb_m/ft^3]"   "Density at 0"
rho_o = rho *(1/Conv_slug)                                          "[slug/ft^3]"   "Density at 0"
rho_1lbm= Density (AirH2O, T = T_1, R = R_humidity, P = P1_psi)    "[lb_m/ft^3]"   "Density at 1"
rho_1 = rho_1lbm *(1/Conv_slug)                                     "[slug/ft^3]"   "Density at 1"

"Pressures"

Ptotal = (Ptotal_psi)*(Conv_ft)^2     "[lbf/ft^2]"    "Total Pressure at 0"
Po = (P0_psi)*(Conv_ft)^2             "[lbf/ft^2]"    "Static Pressure at 0"
P1 = (P1_psi)*(Conv_ft)^2             "[lbf/ft^2]"    "Static Pressure at 1"

"Areas and Dimensions"

Do_in = .62             "[in]"      "Diameter of Drilled Hole in inches"
Do = (Do_in/Conv_ft)    "[ft]"      "Diameter of Drilled Hole in feet"
L = (L_in/Conv_ft)      "[ft]"      "Length of flycut exit in feet"
W = (W_in/Conv_ft)      "[ft]"      "Width of flycut exit in feet"
A1 = (L * W)            "[ft^2]"    "Area of flycut exit"
Ao = pi/4*Do^2          "[ft^2]"    "Area of Drilled Hole"

"Total Pressure Equation"
Ptotal = Po + (1/2)*rho_o*Vo^2                        "[lbf/ft^2]"

"Loss Coefficient Equation"
LC = (Ptotal - (P1 + (1/2)*rho_1*V1^2))/((1/2)*rho_o*Vo^2)    "[-]"
```

"Mass Balance"
rho_o*Vo*Ao = rho_1*V1*A1

"Reynolds Number"
mu_0 = Viscosity(AirH2O,T=T_0, R = R_humidity, P = P0_psi) "[lbm/ft-hr]" "Viscosity at 0"
mu_0_s = mu_0/Conv_s "[lbm/ft-s]" "Viscosity at 0"
Re = rho*Vo*Do/mu_0_s "[-]" "Reynolds Number at 0"

"Mach Number"
speed_of_sound_air = 1126.8 [ft/s] "Assume it is constant when it technically changes with temperature and pressure"
Ma = Vo/speed_of_sound_air "[-]" "Mach Number at 0"

EES Code for Solving the Loss Coefficients

Conversion Factors

$Conv_{ft} = 12$ [in/ft]

$Conv_{slug} = 32.2$ [lb_m/slug]

$Conv_{in2} = 144$ [in^2/ft^2]

$Conv_s = 3600$ [s/hr]

Inputs

Commented out becuase these inputs are put in the parametric table.

Densities

$\rho = \rho[\text{'AirH2O'}, T = T_0, R = R_{humidity}, P = P0_{\psi}]$ *[lb_m/ft^3] Density at 0*

$\rho_o = \rho \cdot \frac{1}{Conv_{slug}}$ *[$slug/ft^3$] Density at 0*

$\rho_{1lbm} = \rho[\text{'AirH2O'}, T = T_1, R = R_{humidity}, P = P1_{\psi}]$ *[lb_m/ft^3] Density at 1*

$\rho_1 = \rho_{1lbm} \cdot \frac{1}{Conv_{slug}}$ *[$slug/ft^3$] Density at 1*

Pressures

$Ptotal = Ptotal_{\psi} \cdot Conv_{ft}^2$ *[lbf/ft^2] Total Pressure at 0*

$Po = P0_{\psi} \cdot Conv_{ft}^2$ *[lbf/ft^2] Static Pressure at 0*

$P1 = P1_{\psi} \cdot Conv_{ft}^2$ *[lbf/ft^2] Static Pressure at 1*

Areas and Dimensions

$Do_{in} = 0.62$ *[in] Diameter of Drilled Hole in inches*

$Do = \frac{Do_{in}}{Conv_{ft}}$ *[ft] Diameter of Drilled Hole in feet*

$L = \frac{L_{in}}{Conv_{ft}}$ *[ft] Length of flycut exit in feet*

$W = \frac{W_{in}}{Conv_{ft}}$ *[ft] Width of flycut exit in feet*

$A1 = L \cdot W$ *[ft²] Area of flycut exit*

$Ao = \frac{\pi}{4} \cdot Do^2$ *[ft²] Area of Drilled Hole*

Total Pressure Equation

$Ptotal = Po + 1 / 2 \cdot \rho_o \cdot Vo^2$ *[lbf/ft²]*

Loss Coefficient Equation

$LC = \frac{Ptotal - \left[P1 + 1 / 2 \cdot \rho_1 \cdot V1^2\right]}{1 / 2 \cdot \rho_o \cdot Vo^2}$ *[-]*

Mass Balance

$\rho_o \cdot Vo \cdot Ao = \rho_1 \cdot V1 \cdot A1$

Reynolds Number

$\mu_0 = \textbf{Visc}\left['AirH2O', T = T_0, R = R_{humidity}, P = P0_\psi\right]$ *[lbm/ft-hr] Viscosity at 0*

$\mu_{0,s} = \frac{\mu_0}{Conv_s}$ *[lbm/ft-s] Viscosity at 0*

$Re = \rho \cdot Vo \cdot \frac{Do}{\mu_{0,s}}$ *[-] Reynolds Number at 0*

Mach Number

$speed_{of,sound,air} = 1126.8$ [ft/s] *Assume it is constant when it technically changes with temperature and pressure*

$Ma = \frac{Vo}{speed_{of,sound,air}}$ *[-] Mach Number at 0*

Parametric Table: Table 1

	W_{in}	L_{in}	$R_{humidity}$	$Ptotal_\psi$	$P0_\psi$	$P1_\psi$	T_0	T_1	LC	Re	Vo
Run 1	0.25	2.332	0.14	69.9908	69.9114	69.8085	67.8	67.7	2.029	68352	45.37
Run 2	0.25	2.332	0.14	69.9900	69.9242	69.8100	67.8	67.7	2.466	62259	41.32
Run 3	0.25	2.332	0.14	68.9836	68.9304	68.8248	67.2	67.1	2.715	55664	37.4
Run 4	0.25	2.332	0.14	68.9836	68.9279	68.8248	67.2	67.1	2.581	56956	38.27
Run 5	0.25	2.332	0.14	69.6909	69.6067	69.5118	65.1	65.1	1.859	70709	46.71
Run 6	0.25	2.332	0.14	64.7899	64.6959	64.5930	64.9	64.9	1.827	72048	51.18
Run 7	0.25	2.332	0.14	64.7899	64.7189	64.5930	64.9	64.9	2.506	62626	44.47
Run 8	0.25	2.332	0.14	72.5858	72.5268	72.4425	64.9	64.9	2.16	60449	38.3

Appendix Y: Testing Procedure

Safety Note: Ensure the use of safety glasses and hearing protection while operation flow test apparatus; failure to comply could result in loss of hearing. Use caution when working around a pressurized system.

1. Ensure backpressure regulator is fully closed
2. Connect inlet male quick disconnect fitting to main air supply
3. Set inlet test pressure
    a. Caution Safety Relief Valve will vent at 90 psi
4. Connect DATAQ USB to computer
5. Run WINDAQ software and launch device DI-158U
    a. Calibration is not required and settings should be saved
6. Turn on thermocouple and check for temperatures to reach steady state
7. Click File on computer then Run WINDAQ will record data for one minute
8. Click save as spreadsheet and list in comments temperatures observed
9. Change backpressure regulator and continue testing other ranges
10. Close backpressure regulator fully and then disconnect main air supply and computer