Porous Media Test Bed

Final Project Report

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DISCLAIMER

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EXECUTIVE SUMMARY

The goal of this project was to design, build, and qualify a high Reynolds number flow visualization porous media test bed to support Dr. Liburdy's research. The project must make use of existing Time Resolved 3-D Particle Image Velocimetry equipment. The paper design is engineered to achieve Reynolds numbers of greater than 200 and to minimize edge effects in the visualization region. While funding was not available to construct the paper design, construction of a proof-of-concept did take place and testing was conducted. Testing results indicate that assumptions made during the design process were correct and that the paper design has a high probability of success if implemented.

This report provides background, design requirements, a review of existing designs, potential design options, a final paper design, fabrication, testing and analysis, and a project summary including lessons learned for a 3-D porous media test bed.

The Project Description section provides background on the project, a brief justification for the project, information about the project sponsor and mentor, design requirements, and a House of Quality. Initial design requirements for this project included achieving a Reynolds number greater than 200, using Time Resolved 3-D Particle Image Velocimetry equipment, and having an index of refraction-matched imaging area. Final design requirements changed the flow rate to the inertial flow regime. However, the paper design presented in later sections is still designed for the original design requirements.

The Existing Designs section reviews current designs from budget to state-of-the-art. The current state-of-the-art system employs an MRI machine to directly image pore flow without the need for optical access, index of refraction-matched materials, cameras, seeding particles, or lasers. Budget systems often use electrodes with salt water being injected as a tracer to collect diffusion data.

The Possible Designs section reviews two potential designs, one of which relies on sealant to bond different parts of the test section together while the other uses a series of bolts and gaskets.

The Design Selected section includes all relevant engineering data on the design selected, a bolt-and-gasket flow section with inlayed borosilicate windows, and provides detailed design and fabrication drawings to construct a flow channel which meets the original design requirements.

The Cost Reduction section outlines several potential avenues for additional cost reduction that were not followed in the paper design. Cost versus performance tradeoffs are briefly discussed.

The Fabrication section describes the budgetary problems encountered, a false proof-of-concept start, and the final proof of concept fabrication. Details of materials used during fabrication are included.

The Testing section includes the original testing plan, potential design modifications, and final testing plan. It also reviews the testing data and shows analysis of collected data. Due to time constraints, the quantity of data taken was not enough to achieve statistical significance.

The Conclusion section reviews team interaction, lessons learned, mistakes made, major issues encountered during design, construction, and testing, and includes the final budget and balance sheet.

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ACKNOWLEDGEMENTS

The project team would like to thank Dr. Liburdy for his time, effort, extreme patience, and flexibility throughout the fall of 2006 and the winter of 2007. Without him, this project would have never been finished. The team would also like to thank Dr. Parmigiani who was accommodating, kind, and always ready with an idea to keep the project on-target. Additionally, the team would like to thank Dr. Wood who donated his expertise, flow valves, and dye. Of course, the team must extend a heartfelt "we're sorry!" to the graduate students in the lab who were periodically disturbed from their research to help a motley crew of undergraduates complete a senior design project. The wives and girlfriends of the three team members must also be thanked for the patience and understanding they showed toward the many long nights and weekends the team spent in the lab rather than with them.

To everyone who helped us, THANK YOU!

- The Porous Media Team

1. PROJECT DESCRIPTION

1.1. Background

The goal of this project was to design, build, and qualify a high Reynolds number flow visualization porous media test bed to support Dr. Liburdy's research in this field. As part of the design task, the design team worked closely with Dr. Liburdy to fully define the critical design requirements and guarantee that the end product would suit the research needs of the university.

Being able to visualize flow through porous media is an important part in the process of developing equations to simulate flows through porous media beds. Porous media beds have many applications in a variety of industries. For instance, the water treatment world uses porous media in the slow sand water filtration process. In the chemical industry, many chemical reactors use porous media beds as catalyst chambers. In the automotive industry, catalytic converters are porous media beds.

High Reynolds number flow regimes might become particularly important to the chemical engineering world in the form of more efficient reactor beds and higher throughput. There is a particularly interesting region of flow regime which Dr. Liburdy wants to investigate using the to-be-designed porous media test bed in the Re=200 range.

1.2. Design Requirements

1.2.1. Description of Requirements

The primary function of this porous media test bed is to take visual images of flow through porous media at Reynolds numbers greater than 200. While there are many ways to visualize flow through a porous media bed, the Mechanical Engineering Department at Oregon State University already owns a Time Resolved Three Dimensional Particle Image Velocimetry (TR 3-D PIV) rig which, due to a variety of factors ranging from budget to in-house familiarity with the system, has been identified as the visualization method for this project. TR 3-D PIV works by shining a laser through a porous media bed filled with moving fluid impregnated with small glass beads filled with dye that fluoresces when struck by laser light. The two cameras (two cameras allow for 3-D imagery) have filters on their lenses which only allow the specific wavelength of light that the fluorescing dye emits through to the CCD's.

To minimize distortions, all materials must have as close to the same refractivity indices as possible. This means that the porous media, fluid, and test bed walls all must be refractivity matched. Because of this, the design team will most likely have to mix their own fluids to develop an inexpensive fluid to meet the project budget (commercially available fluids with refractive indices matched to Plexiglas, Pyrex, or Lexan are generally extremely expensive). In a departure from classical porous media flow regime studies, this test bed will use randomly packed porous media. This means that this particular test bed will not have carefully cut half and quarter spheres glued (with matching refractivities) to the test bed walls. Additionally, the entire test rig must have good control over other factors, such as pressure and flow rate, which directly affect the Reynolds number and, thus, make the test bed adjustable for different flow regimes. This also means that the system must have good measurement equipment attached at the correct points to monitor things like head loss and flow rate. Finally, the test bed system must be safe and easy to use for Professor Liburdy and his research assistants to operate.

1.2.2. Changing Design Requirements

Due to issues of funding, discussed in later sections of this document, the original design requirements were modified to meet requirements of the second half of the course for which this document was prepared. Both original and final design requirements are presented here. The largest change between the two sets of design requirements is item 7 on the original list or item 6 on the final list. The flow regime was changed from above Reynolds numbers of 200 to the inertial flow regime.

1.2.2.1. List of Original Design Requirements

1. The test bed shall consist of a porous media bed, a closed flow loop with appropriate pumping apparatus, measurement and control equipment, and appropriate diffuser plates to guarantee uniform flow through the bed.
2. The porous media bed shall be of sufficient depth and width to make edge effects negligible. Literature indicates that between 3.5 and 10 diameters of porous media from the edge generally are sufficient to negate edge effects.
3. The test bed shall be able to take appropriate direct and indirect measurements potentially included but not limited to pressure, temperature, flow rate, samples of liquids from different locations within the media bed, etc... These measurement abilities will be appropriate to quantify the flow in the media bed.
4. The test bed shall have sufficient optical access to take desired measurements and images using the TR 3-D PIV equipment available in the OSU mechanical engineering department.
5. The test bed, media, and fluid shall be designed to optimize flow visualization in conjunction with the TR 3-D PIV. This means that everything must have matched indices of refraction.
6. The test bed shall be vibrationally isolated from its surroundings and the porous media bed shall be isolated from any sources of vibration within the machine (i.e.: pump) that could adversely affect the critical measurements in the system.
7. The test bed shall operate in the Re>200 range. This requirement helps set many of the design parameters.
8. The test bed shall be designed with safety and integrity of the system in mind based on the system operating parameters.
9. The test bed shall have adequate flow loop control with some or all of the following elements being controlled: pressure, flow rate, temperature, etc.

1.2.2.2. List of Final Design Requirements

1. The design shall consist of a porous media bed, a flow loop with appropriate pumping apparatus, measurement and control equipment.
2. The flow cell shall be of sufficient depth and width to make edge effects negligible.
3. The flow cell shall be able to take appropriate direct and indirect measurements potentially included but not limited to pressure, temperature, flow rate, etc… These measurement abilities will be appropriate to quantify the flow in the media bed.
4. The flow cell shall have sufficient optical access to take desired measurements and images using the TR 3-D PIV equipment available in the OSU mechanical engineering department.
5. The material of the flow cell, media, and fluid must have matching indices of refraction.
6. The flow cell shall operate into the porous media inertial flow regime.

7. The flow cell shall be designed to withstand operating conditions, such as pressure, temperature, and flow rate.

1.2.3. House of Quality

The House of Quality (Figure 1) and Dependency Chart (Figure 2) presented below represent an analysis of the original design requirements. Because row number 10 on the Original House of Quality has changed in name only but not in importance, only the original graphics are presented here as updated graphics would be redundant.

Figure 2, the Dependency Chart, indicates which design requirement is dependent on another. The House of Quality (Figure 1) shows customer requirements versus design requirements with correlations, customer importance, and competition benchmark data included.

Whats vs. Hows
X = strong positive
/ = medium positive
Blank = no relationship
/ = medium negative
X = strong negative

Row Number	Direction of Improvement / Customer Requirements	Customer Importance (Scale 1-5)	Professor Liburdy	Students	Manufacturing	1 height of porous media	2 width of porous media	3 depth of porous media	4 index of refractions of materials	5 Renold's number	6 PH of fluid	7 head loss	8 velocity of fluid	9 size of media (spheres)	10 porosity
1	no edge effects		5	5	5										
2	ability to measure pressure		3	3	4										
3	ability to measure flow rate		3	3	4	/ (+)	/ (+)	/ (+)				/ (+)	X (+)	X (+)	
4	ability to maintain temperature		3	4	4										
5	use existing camera equipment		5	5	1				X (−)						
6	minimal light distortion		5	5	5				X (−)						
7	minimal vibration from apparatus		2	4	4	/ (−)	/ (−)	/ (−)		X (−)		X (−)	/ (−)	/ (−)	
8	safety		4	3	1						/ (−)		/ (+)		
9	control of flow rate		3	3	3										
10	reach upper flow regimes		5	3	3										
11	inexpensive		5	5	1										
	Competition's Benchmarks														
	Stohr, Roth, Jahne Experiment					5cm	10cm	5cm	1.46					0.8mm	
	Suekane, Yokouchi, Hirai Experiment					28mm	28mm	168mm	n/a	205		.24T/m		28mm	0.48
	Target Values					min	min	min	match	>200	7	0	Re	min	0.3

Figure 1: Original House of Quality

	hieght of porous media	width of porous media	depth of porous media	Reynolds number	head loss	velocity of fluid	size of media shperes	porosity of media
hieght of porous media	-			X	X	X	X	
width of porous media		-		X	X	X	X	
depth of porous media			-	X	X	X	X	
Reynolds number				-				
head loss	X	X	X		-	X	X	X
velocity of fluid		X	X	X	X	-	X	X
size of media shperes		X	X				-	
porosity of media								-

Figure 2: Dependency Chart

2. EXISTING DESIGNS AND DEVICES

2.1. Laser Anemometry Experiment

Dybbs and Edwards [1] researched the Darcy to turbulent flow regime in porous media. They used laser anemometry to conduct flow visualization studies. The researchers chose to visualize the flow regime in 3-D. The bed was designed to have two different porous media setups. One was comprised of Plexiglas spheres in a hexagonal packing arrangement and the other was made up of a complex three dimensional Plexiglas rod matrix.

The researchers used a variety of liquids including water, silicone oils, Sohio MDI-57 oil, and mineral seal oil. The final working fluid had a matched refraction index with the Plexiglas and test section components. A dye solution of potassium permanganate was injected at a point source into the fluids to help visualize the flow. The researchers reported some small problems with the dye having slight negative buoyancy but they didn't believe it adversely affected their results [1].

2.2. Probe - Dispersion Experiment

Another research group, Han, Bhakta, and Carbonell, [2] constructed a Plexiglas column with a square test section. The spherical particles composing the porous media test bed were made of urea and formaldehyde and were hollow. The particles were approximately 0.25, 0.35, 0.45, and 0.55 cm in diameter and were randomly packed. The test section had an effective packing height of 150 cm and a cross-sectional width of 27 cm. The system had a dispersion plate at the top to divide the flow evenly through the bed. The system also had an outlet distributor to prevent any disturbance in the visualization area.

The system used a solution of de-ionized water doped with sucrose to closely match the density of the tracer used to aid in flow visualization. The tracer was a solution of de-ionized water and salt [2].

To visualize the flow, the researchers inserted a series of five probes into the column at different heights and with the ability to adjust lateral placement of the probes. The probes measured conductivity in the solution. The salt tracer solution allowed the probes to accurately measure dispersion in the bed. The system required new de-ionized water to constantly flow through the system. The used water was discarded. This was an open loop test system [2].

2.3. Electromechanical Microprobe Experiment

Seguin, Montillet, and Comiti [3] ran an experiment similar to what was discussed in section 1.3.2. They visualized flow regimes beyond the Darcy regime using electromechanical microprobes inserted into the bed. The researchers used a variety of porous media including beds packed with spheres, stratified and reticulated media, and square parallelpipedal plates. Various packing strategies and media sizes were tested.

The test section was constructed of altuglass. A centrifugal pump was used to feed liquid to the column. The flow rate was measured with rotameters. The temperature of the liquid was held between 25 and 30˚C. The tracer solution, in this paper called it an electrolyte solution, was a mixture of potassium ferricyanide and sodium hydroxide. The electrolyte solution created was detected with a series of platinum electrode probes spread throughout the column [3].

2.4. Electrode Probes and Pipedal Plate Experiment

Seguin, Montillet, Comiti, and Huet [4] researched the hydrodynamics of porous media beds in much the same manner that the researchers in sections 1.3.2 and 1.3.3 of this document conducted their studies. These researchers used electrode probes inserted into packed beds filled with either 5 or 8 mm diameter spheres. The researchers also used parallel pipedal plates much like the researchers in section 1.3.3. In addition, these researchers used several different types of open cell foam as porous media. This particular research group did not explain their system well enough to reproduce their experimental setup.

2.5. PIV Experiment

Stohr, Roth, and Jahne [5] employed the planar laser-induced fluorescence technique to visualize 3-D pore-scale flow of two immiscible liquids in a porous media bed. They used an argon ion laser operating at 488 nm to excite the fluorescent dye. The PIV system used two CCD cameras mounted at angles to the test bed to provide 3-D imaging. The porous media bed tank was built out of Plexiglas and filled with Plexiglas or silica beads. The Plexiglas beads had some problems with air bubbles trapped inside the beads but the researchers were able to separate the solid beads from the hollow beads by floating them in a solution of salt water.

Several different fluids were used including a family of Dow Corning chemicals and zinc chloride. The paper did not indicate if the system were open or closed loop but an educated guess says that it was open loop [5].

2.6. MRI Experiment

Suekane, Yokouchi, and Hirai [6] conducted porous media flow visualizations using an MRI machine. Water was used as the fluid and porous media consisting of spheres of unknown material were packed into the test bed and loaded vertically into the MRI. The visualization process relied on the MRI equipment. Due to the MRI not needing match refractivity indexes, fluids, such as water, can be used. For research teams with large budgets, this technique appears to be state-of-the-art.

3. POSSIBLE DESIGNS

Two primary designs were considered for the porous media test bed system. The two designs differed mainly in the porous media test bed section of the system. Other components in the system were largely independent of the test bed design and are reviewed following the test bed designs.

It should be noted that any apparent lack of creativity on the project group's part is due in large part to the restrictive nature of the original design requirements. Due to the nature of the experiments that the project sponsor wishes to perform, all major elements of the design are fixed. Figure 3 shows a generic porous media test bed system for use with generic PIV equipment. Generic systems usually contain the following major design components: test bed, pump, tank, diffuser & nozzle, cameras, and laser. Additionally, the generic test bed pictured in Figure 3 has a heating element that is occasionally included when heating of the working fluid is desired.

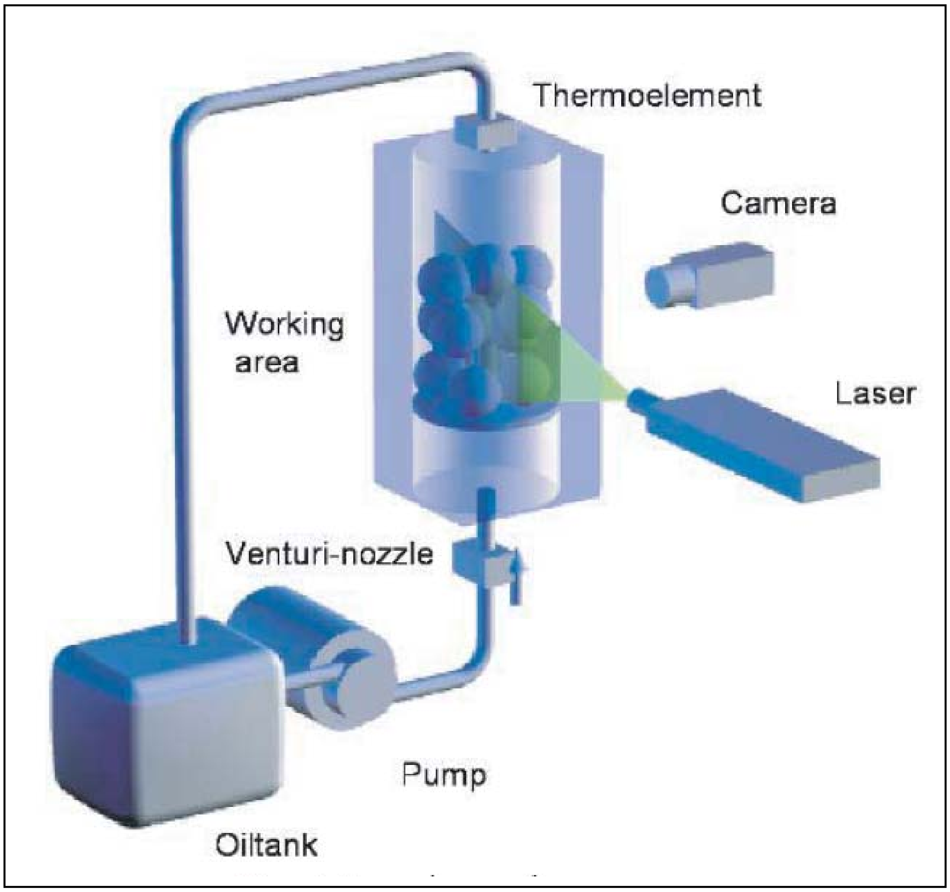


Figure 3: Generic Porous Media Test Bed System [7]

3.1. Test Bed Design #1

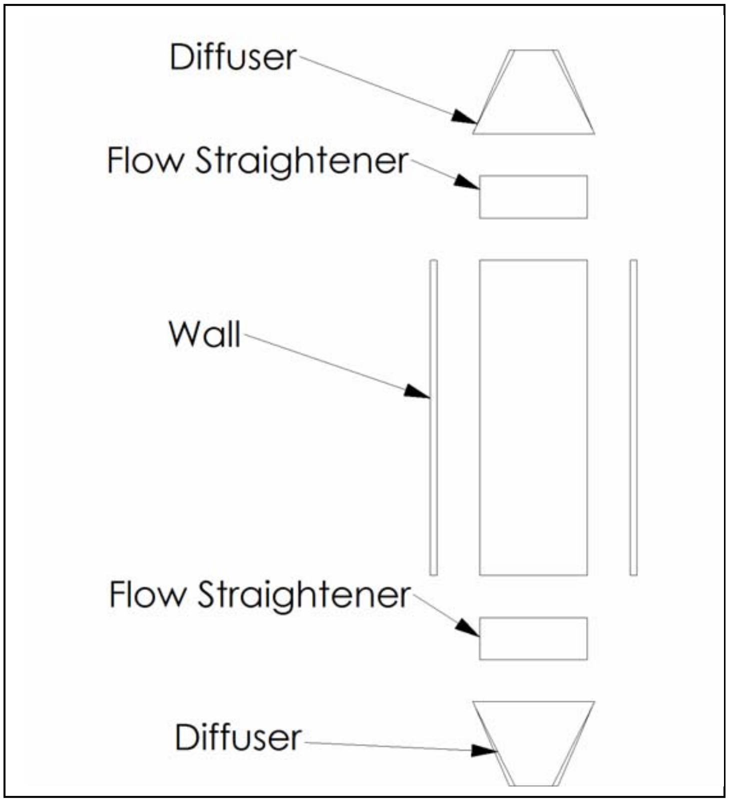


Figure 4: Test Bed Design #1 Potential Configuration

Initially, the project team considered making a test bed with a square cross section, with all four sides constructed solely of polycarbonate plastic or borosilicate glass. Figure 4 shows a potential test bed configuration under this design scheme. Both the top and bottom of the test section have diffusers and flow straighteners with the test section containing the porous media sandwiched in the middle. Four walls make up the test section. The motivations for using this design concept are: camera alignment and laser positioning would be easier and more versatile as compared with the test bed design considered in section 3.2 and the inside of the test bed walls would be smoother than the design discussed in section 3.2 which would aid in minimizing the depth of penetration of edge effects into the porous media bed. This, in turn, would help to decrease the required cross-sectional area of the porous media bed to minimize edge effects, as discussed in original design requirement #2 in section 1.2.2.

In spite of the benefits to a test bed completely made of a transparent material, there are some drawbacks to this approach. When flow rates were analyzed to achieve the desired pore Reynolds number, the developed pressure at the upstream side of the porous media test section was found to be relatively high, as can be seen in Appendix 9.1. There was some concern using a conventional sealant to adhere the test bed sides together would not stand up to the expected pressures and would develop leaks over time, or, in the worst case, experience catastrophic failure. This fear is based on holding the sealant in tension which, in general, is not as strong as holding a sealant in compression. Issues specifically pertaining to sealant are discussed in more detail in section 1.2.2.1.

3.2. Test Bed Design #2

The project team considered another design solution for the porous media test section which, much like the design discussed in section 3.1 is, at its core, a square cross section flow bed. This design calls for the four sides to be built out aluminum, stainless steel, Hastelloy C, or polycarbonate. The sides would be fitted with an appropriately sized piece of polycarbonate or borosilicate glass, symmetrically inlayed, to serve as the viewing window for the imaging equipment. The viewing window would be sealed with a sealant, such as silicone caulking or rubber gaskets, which is discussed more in depth in section 3.3.5, and would be kept under compression, and the test bed would then be assembled with machine screws with the edges of the sides sealed. If additional support was needed to maintain a positive seal along the wall edges, banding or other methods would be used to support the machine screws. Figure 5 shows a potential configuration for this design which includes diffusers and flow straighteners at the top and bottom of the test bed, four walls, inner and outer window gaskets, a window made out of a transparent material such as borosilicate or polycarbonate, an inner window retaining wall, and a wall gasket to prevent leaks between the walls.

Like with the design discussed in section 3.1, there are several concerns and benefits inherent in this design. Using a sealant for the viewing window and the test bed necessitates the chosen sealant to withstand the same pressures as mentioned in section 3.1 but under compressive loading. This means the seals must simply hold under compression rather than tension. Designing using sealant under compression is far easier than under tension. Additionally, the reactivity of the working fluid to the sealant and the metal must be considered to assure an unexpected breach of the test bed does not occur. This issue is discussed more in depth in sections 3.3.3, 3.3.5, and 4.3. Finally, the restriction on the field of view and ease of reconfiguration of the TR 3-D PIV system must be considered. This is discussed more in depth in section 3.3.7.

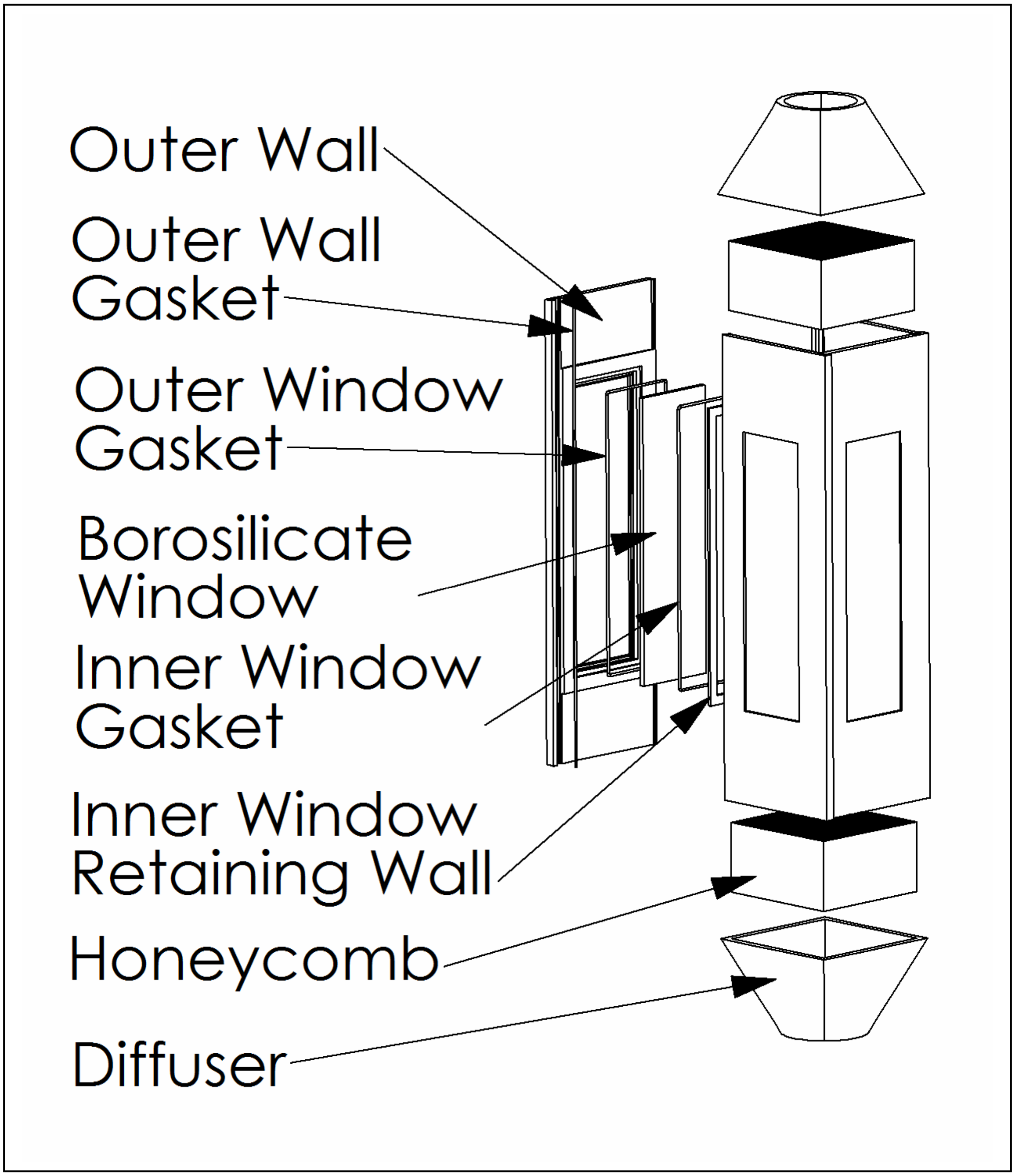


Figure 5: Test Bed Design #2 Potential Configuration

3.3. Common Design Features

There are several design features that are common to both designs and, therefore, can be considered individual designs areas. They are presented below.

3.3.1. Pump Selection

Pump selection is based upon the pump's ability to overcome the cumulative head losses through the pipe, across the porous media, through the flow straighteners, and to develop the required flow. The required flow must be free of cavitations, non-pulsing, and as "steady-state" as required to produce results of a desired accuracy from the TR 3-D PIV equipment. These parameters have still not been fully defined.

Once an approximate head loss value is determined, the selection of the pump becomes a matter of pump operation. Several types of pumps are under consideration including centrifugal, positive displacement, and peristaltic pumps.

3.3.2. Bead Selection

There are a multitude of bead types to choose from. The primary criteria to base bead selection on are material composition, the index of refraction, and bead size. Polycarbonate and borosilicate are the two primary material types being considered which have ranges of indices of refraction from 1.58 to 1.59, and 1.47 to 1.53, respectively. These two materials are the primary candidates because of their optical properties, availability, and the availability of sheets of both of these materials to build viewing windows out of in the test bed. The bead size, as defined by the bead diameter, will be determined by whichever yields an appropriate pressure drop in the porous media and is readily available.

3.3.3. Working Fluid

The working fluid for the porous media test bed must match the index of refraction of the beads and viewing glass. After researching relevant literature, the fluids under consideration are silicone oils, and zinc chloride solutions. Silicone oils can achieve a range of indices of refractions from 1.375 to 1.533. Zinc chloride solutions can produce a wide range of indices of refraction which encompass the indices of refraction of both polycarbonate and borosilicate. Most silicone oils on the market today vary in cost from $50 to $250 per 500 grams [8]. Silicone oils have a low reactivity and are considered safe to use with a wide range of materials including polycarbonate and borosilicate [9].

Zinc chloride solutions are fairly easy to make in standard university laboratories, as has been demonstrated by Dr. Brian Wood [10], and are relatively inexpensive, ranging in price from $50 to $150 per 500 grams [11]. However, zinc chloride solutions have significant health, safety, and design issues as is attested to in the MSDS in Appendix 9.2. A typical well-known zinc chloride solution application is in the production of batteries. Zinc chloride solutions that produce an index of refraction around 1.47 generally have Ph's in the range of 2 [12].

Two other considerations that should be taken into account are viscosity and volatility of the working fluid. The less viscous the fluid is, the easier it is for that fluid to move through the test bed and the less head loss there is across the test bed. Some silicone oils have a very low vaporization point. Some fluids investigated have vaporization points below 0°C [8]. Working with fluids with vaporization points below room temperature is not desirable.

3.3.4. Ductwork

Several materials have been considered for use in the ductwork for the system including steel, PVC, and nylon pipe. The primary decision factors, in order of importance, are reactivity with the working fluid, availability, cost, and surface roughness.

3.3.5. Sealing Method

Several methods of sealing the test bed have been considered which fall under two broad categories of using gaskets and using adhesives to form a seal. Gaskets made out of materials such as rubber and silicone, work well under compression and are used in a wide variety of high-pressure applications such as deep water simulation aquariums and deep ocean pressure vessels with viewing windows [13]. Adhesives, such as silicone, are well suited to join two similar materials together. Consumer-grade fish tanks and private marine boat repair are two good examples of applications of adhesives [14]. One consideration that must be made when dealing with adhesives is index of refraction matching. If any adhesive finds its way into the TR 3-D PIV system's field of view, that adhesive must be index of refraction matched to minimize distortion of the image data [5].

An additional variable that must be considered when selecting sealing methods is the potential corrosion effects of the working fluid. With relatively reactive substances like zinc chloride, this becomes especially important.

3.3.6. Imaging Equipment

The imaging equipment to be used in this project was predetermined by the project sponsor and will be TR 3-D PIV. Please see the Original Design Requirement List (section 1.2.2.1 items # 4 and 5 for more information on this design requirement.

3.3.7. Sizing the Test Bed

The test bed must be sized properly to meet the design requirements listed in items # 2 and 4 from the Original Design Requirements List (section 1.2.2.1). This means that the field of view of the cameras and the entrance and exit points of the laser sheet in the TR 3-D PIV system are at the core of the parameters governing the sizing of the test bed.

An additional design requirement of the test bed, as listed in item # 2 in the Design Requirements List (section 1.2.2.1), is minimization of edge effects. Several sources indicate that the appropriate distance one must be from the edge of the test bed to find flow with minimal edge effects ranges from 3 to 10 bead diameters [15].

3.3.8. Flow Straightening

To create a well-developed porous media bed flow with minimal edge effects flow straighteners are often employed. Effective flow straighteners for the range of velocities in which the test bed is expected to operate generally fall into the "honeycomb" category [16]. Other flow straightening techniques, such as diffuser plates, are inappropriate for the expected volumetric flow rates of the flow loop and will produce a high pressure drop affecting pump selection. See Appendix 9.1 for flow rate calculations.

When selecting a honeycomb flow straightener one must keep in mind the diameter and length of the honeycomb, the cell geometry, and the material of construction. The velocity entering the honeycomb, the honeycomb length, and diameter of the cells determine whether or not the flow will be fully developed and laminar. See Appendix 9.3 for appropriate length and cell size equations and calculations.

Aside from determining how laminar of a flow can be expected on the downstream side of a flow straightener, the cell size is also important when considering retention of the beads. A cell size must be chosen that will not unduly restrict the flow and will support the beads without allowing the beads to clog the flow straightener. This consideration is more important on the downstream side of the test bed as the beads will be pushed in this direction by the fluid flow. Depending on the orientation of the test bed, either the downstream or upstream side will be called upon to support the mass of the beads as well. See Appendix 9.3 for cell sizing, material sizing, and other related equations.

3.3.9. Diffuser

A flow diffuser is needed to convert the flow through the flow loop pipes to a flow with an even volumetric flow distribution. Without a proper diffuser, flow separation in the diffuser is expected to develop. As with all systems, no diffuser can ever create a perfectly even volumetric flow distribution. Dr. Liburdy recommended a diffuser with an angle of 30° [17]. Diffusers will be used at both the top and bottom of the test bed to help minimize edge effects and reduce head loss in the flow loop.

3.3.10. Seeding Particles

To characterize flow through the porous media, seeding particles will be used to trace the flow. There are several different types commercially available including the following: polyamide, hollow glass spheres, silver coated hollow glass spheres, and fluorescent polymer particles with homogenous distribution. Several criteria must be taken into consideration when selecting seeding particles including: reactivity with working fluid, size of seeding particles, fluorescing wavelength, tendency to adhere to porous media and other surfaces, decay rate of the seeding particle usefulness (i.e.: when a particle no longer fluoresces brightly enough to be detected by the PIV equipment), availability, and cost.

3.3.11. Measurement

Appropriate measurement systems will be used to measure pressure drop, temperature, and flow rate across the porous media test bed. These are defined by the required variables to define a pore Reynolds number as shown in Appendix 9.1. Some considerations when selecting these instruments are: corrosive resistance, desired level of accuracy, and instrumentation mounting. Temperature measurements can be taken using a thermocouple. Pressure can be monitored by using a pressure transducer. Since there are many different configurations of the same type of pressure transducer the primary design considerations compatibility with the working fluid and with appropriate mounting capabilities. Lastly, the volumetric flow rate can be monitored by a flow meter. There are many different methods in measure flow rate which include: bubble, Doppler, transit-time, vortex, and magnetic methods. The selection criteria of the flow rate meter depends primarily on the fluid choice, disruption of fluid flow, and accuracy desired.

4. DESIGN SELECTED

The design group decided to proceed with Test Bed Design #2. This is a more robust test bed design which is expected withstand higher pressures than the alternative design. A complete drawing package and fabrication Bill of Materials (BOM) (see Figure P1) can be found in Appendix 11.1. A purchased part BOM can be found in Appendix 10.1. Specific components of the design are discussed below.

4.1. Hydraulic Design

4.1.1. Flow Loop Operation

The final design of the flow loop is depicted in the following figure (see Figure 6 below), and will have the following characteristics:

1. Reservoir will be positioned to keep pump flooded at all times.
2. Pump centerline will be below the working fluid level of the reservoir to ensure that pump is in a flooded suction state.
3. Flow rate will be controlled by the throttling valve, downstream of the test bed.
4. Discharge of the pipe will be above the working fluid level of the reservoir, ensuring free fall conditions to avoid the extra work required to pump against the reservoir surface elevation.
5. Pipe lengths are to be as short as possible that equipment locations will allow, in order to minimize the frictional head losses in the pipe.
6. The total change in elevation that the pump is to see is to be less that 10-ft, the maximum lift the pump can do.

With these conditions being met, the system should operate successfully without cavitation (see Appendices 9.4 and 9.5 for AFT Fathom output for results) within the flow rates.

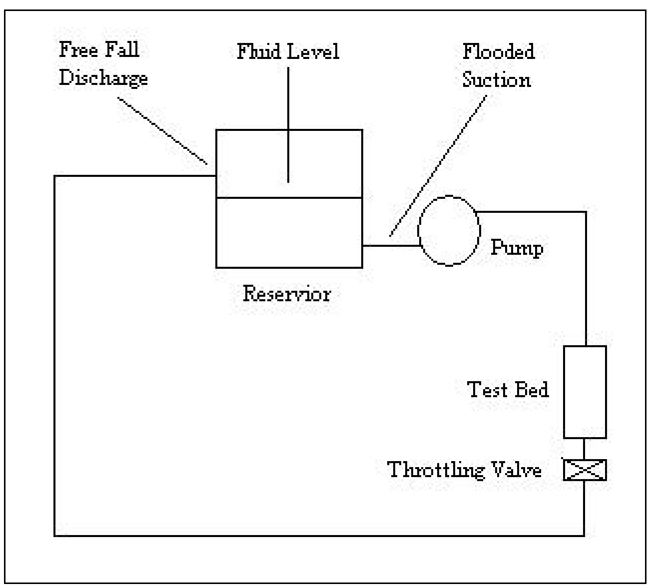


Figure 6. Flow Loop Layout

4.2. Pump Selection

From the Original Design Requirement listed in 1.2.2.1, Requirement 7, and subsequent discussions with Dr. Liburdy [17], the test bed has been designed to operate for Reynolds number between 200 and 400. Corresponding flow rates to these Reynolds number have been determined to be between 12.2-gpm and 24.5-gpm (see Appendix 9.6 for calculations), which are the flow rates that pump selection is based on.

To determine the required amount of pressure head (dynamic head) that is required by the pump, and the discharge pressure (maximum system pressure), AFT Fathom, a hydraulic computation program, was used (see AFT Fathom output in Appendices 9.4 and 9.5). A summary of the required pump pressure, and discharge pressure from the Fathom output, can be seen in Table 1.

AFT Fathom Pump Operating Points		
Flow Rate, gpm	Dynamic Head, ft	Pump Discharge Pressure, psi
9.9	46	34.1
31.2	24.3	16.7

Table 1: Pump Operating Points

As indicated in Table 1, the total head that the pump must deliver is 46-ft, and the maximum pressure of the system is 34.1-psig. Therefore the flow channel must be designed to withstand this pressure, and the pump must be able to deliver this pressure head. As is implied by the flow rates presented in Table 1, the target Reynolds numbers will be met.

Another needed piece information to properly select a pump is required horsepower. The horsepower requirement for this pumping system was determined using two methods: an application of Bernoulli's equation (see Appendix 9.6), and, alternatively, from AFT Fathom (see Appendices 9.4 and 9.5). As stated in Appendix 9.8, the horsepower calculations based on Bernoulli's equation is not believed to be accurate. The ATF Fathom output is a much more reasonable number for the hydraulic system presented in this document. From the Fathom output, the required horsepower was determined approximately 0.25-hp.

The selected pump, based on the above criteria, will be a 0.5- to 1.0-hp, magnetic drive, centrifugal pump, operating between 10- and 40-gpm, delivering a pressure head of 10- to 50-ft; with the pump head material being polypropylene for chemical compatibility. The pump was oversized to provide a factor of safety in the pumping system.

4.3. Bead Selection

Based on several factors including pressure drop calculations (Appendix 9.1), availability of materials, and reaction of the working fluid to the beads and other index of refraction matched components, the project group selected 6 mm diameter borosilicate beads with an expected index of refraction of approximately 1.47. This decision is partially in response to Dr. Wood having 6-mm beads available for the project group's use which will realized a cost savings to the project. Due to slight variations in the production process of borosilicate beads, the index of refraction is expected to vary somewhat between different production runs but is not expected to cause insurmountable problems [10].

4.4. Working Fluid

The working fluid selected for this design is a solution of zinc chloride and water (60 wt% zinc chloride, 40 wt% water) that produces an index of refraction of 1.47, the same as the expected index of refraction for borosilicate [10]. However, zinc chloride solutions are acidic and highly corrosive to traditional engineering materials. The effects on the materials inside of the flow loop have been considered in the design process. Additional concerns, as listed in section 3.3.3, have also be taken into account.

4.5. Ductwork

The ductwork of the system shall be PVC pipe. This decision was driven by the design criteria listed in section 3.3.4, and by the selection of zinc chloride as the working fluid. PVC is inexpensive, readily available, and resistant to corrosion by zinc chloride [19].

4.6. Imaging Equipment

The imaging equipment to be used in this design, as discussed in section 3.3.6, was predetermined by the project sponsor and is TR 3-D PIV.

4.7. Sizing the Test Bed

The final cross section of the flow channel is 0.139-mm by 0.139-mm. This sizing was driven by the required number of bead diameters away from the imaging area and by pressure, flow rate, and head loss calculations. Back calculating the number of bead diameters needed for negligible edge effect places the number of bead diameters at 7.5. This number is well within Original Design Requirement #2. The length of the porous media bed is 280mm. This is as a result of conversations with Dr. Liburdy [17] and Dr. Wood [28] where it was indicated that a test section length of at least 250mm was desired.

Flow channel wall thickness is 30mm. This sizing is based on the ASME pressure vessel code [29, 30]. A large factor of safety was added to the final wall thickness to guard against failure will occurring through the walls. Appendix 9.9 details this calculation.

Bolt spacing and proper gasket design were driven by the ASME pressure vessel code [29, 30] and was conservatively determined to be 15mm based on discussions in the literature.

4.8. Flow Straightening

An ideal minimum length of honeycomb was calculated to be 17-mm (see Appendix 9.2 for calculation) to straighten the flow and reduce macroscopic flow disturbances, but consideration also had be given to the mass of the beads and the force that the pressure drop exerts on the honeycomb when the test bed is vertically oriented with flow traveling in a downward direction (see Appendix 9.9 for calculations). From these calculations, the honeycomb must support a final weight of 200-lbs. A potential supplier was contacted and it was determined that this load can be supported by the honeycomb if the thickness is greater than one inch. Therefore the thickness presented in this design was set at 30-mm. Additionally, polycarbonate was selected to be the honeycomb material for its strength and resistance to corrosion.

4.9. Sealants

Several sealants were reviewed by the design team including the following adhesives and gasket materials: Silicone, Neoprene, SBR, EPDM, Santoprene, Kalrez, Viton and PVC. The design team has selected neoprene as the gasket material for the design presented in this document. However, several other materials can be substituted. Selection of Neoprene was based on its chemical comparability with zinc chloride [27], its behavior as a gasket material, and its relatively low cost.

4.10. Window Sizing and Design

Many considerations had to be taken into account in the design of the viewing windows. The material selection of borosilicate glass was predetermined to be the same as the beads discussed in section 3.3.2. The sizing of the window height and width came from the constraints discussed in sections 3.3.5 and 3.3.6. The main factor that determined the width was that the TR 3-D PIV system requires a 100mm viewing area of the porous media to properly set up the camera view angles [31]. The thickness was determined using brittle plate theory, as shown in Appendix 9.10. A large safety factor was used in specifying the final thickness because the glass is believed to be the weakest component of the structure and the worst component to have catastrophic failure occur. Considerations of the working fluid hazards shown in Appendix 9.2 were also a reason in choosing the large safety factor.

4.11. Diffuser

As mentioned in section 3.3.9, the diffuser will have a 30° angle to mate the porous media test section with the rest of the flow loop. Appendix 11.1 includes drawings of the diffuser design. The diffuser will connect with the flow loop using a pipe flange and will bolt to the test section, being sealed with a neoprene gasket. This facilitates easy access to the test section for cleaning and other needs.

4.12. Seeding Particles

Although the seeding particles are an integral part of the TR 3D PIV experiment, the designs of the flow loop and test bed are not dependent on selecting a specific seeding particle. The project group has researched fluorescent dyes used in seeding particles to gain a general understanding of the design considerations for selecting a seeding particle. The concern of pump interference was considered but dismissed because the size of the particles is negligible to the functionality of the pump selected. Chemical compatibility of the seeding particles with the working fluid were considered and it was determined that particles made with glass should have no reaction with the fluid.

4.13. Measurement

Using the criteria of corrosion resistance (to materials equivalent to 316 stainless steel), 0 to 100°F operating temperature, 0 – 50 PSI, and differential measurement capabilities, a pressure transducer was selected with adequate capabilities. The selection of the thermocouple was limited by the ability to mount the temperature probe to an appropriate location on the flow loop. Based on this consideration, a simple pipe plug probe thermocouple was selected. Finally, since the flow rate measurements can be taken after the test section a rotometer with sufficient flow rate ranges, as discussed in section 2.1, and chemical resistance was selected.

4.14. Flow Loop Material Selection

As discussed in sections 3.3.3, 3.3.4, 3.3.5, and 3.3, all of the materials within the test section must be selected with the reactivity of the zinc chloride solution in mind. This eliminates using aluminum as it decays when in contact with zinc chloride. The chemical reactivity of steels with zinc chloride solutions is minimal but it is not impervious to the effects the fluid. Over time, discoloration or slight corrosion may occur. Most non-metal pipe materials such as ABS, High Density Polyethylene, UHMW, Nylon, Teflon, polycarbonate and polypropylene have excellent compatibility with zinc chloride and can be used over extended periods of time with no effects to the material properties [19]. Another factor in material selection is the water absorption of the previously mentioned plastics over time. Swelling of the plastics can cause structural instability, sealing issues, and change the ratio zinc chloride to water of the working fluid which would un-match the index of refraction. Strength of the material, availability of sizes, and cost were other factors used in the selection process. When all of the above were considered, two materials were selected for the test section. The project group chose to manufacture the test section walls using ABS plastic. ABS plastic has the highest strength of the plastics with no water absorption, and has no chemical reactivity with zinc chloride [27]. UHMW was selected to make the diffusers on the top and bottom of the test section. Selection of UHMW was driven by size availability. Because it comes in larger thicknesses, it can be machined to accommodate smaller ductwork sizes instead of using reducers to step the sizes down to the required ductwork size. UHMW plastic does not have the tensile strength of ABS plastic but it has the same chemical resistance and does not absorb water [27]. Since the diffusers have the largest wall thickness of the test section and are only tapped for large diameter bolts, UHMW will be adequate for use in the design presented in this paper.

4.15. Working Fluid Reservoir

The same decision criteria were followed for the reservoir as for the flow loop materials discussed in section 4.13. The size of the reservoir was determined to be five gallons. This will allows for the fluid level to be high enough to avoid dry suction conditions in the pump and be able to hold all of the fluid needed for the system. The reservoir selected has fittings preinstalled to easily attach to the system, and prevent leaking. In addition, the orientation of the reservoir should be such that the pump is always in a flooded state regardless of pumping status. This will prevent cavitation in the pump during operation.

5. COST REDUCTION

Several possible design modifications were considered by the project team to modify the design to reduce budgetary pressure. The design modifications discussed in the below sections were never implemented in the paper design due to a lack of funding. While the measures discussed below will certainly reduce cost, they can not be expected to drive costs to zero. Several additional design modifications are also discussed in this section which, while not being strictly within either the Original Design Requirements or Final Design Requirements, are potentially desirable for a more functional device.

5.1. Increased Bolt Pattern Spacing

The overall cost of the system can be reduced by increasing bolt spacing on the pressure seals. The current design spacing of 15mm was selected to conservatively guarantee good seals in the test section. Bolt spacing can potentially be increased but this must be investigated further to assure that the system will still maintain a positive seal.

5.2. Remove Intro-Serts

Intro-Serts (see Appendix 9.12 Figure 9.12.23 for datasheet) are included in the design presented in this document to give the design the ability to robustly withstand repeated assembly and disassembly. Intro-Serts are threaded metal inserts designed to be thermally welded into plastic to replace directly threaded holes in plastic. Removing the Intro-Serts from the design will save a significant amount of money but will also significantly limit the number of times the test section can be assembled and disassembled before threads begin to fail. The cost of the Intro-Serts can be seen in Appendix 10.1.

5.3. Use Permanent Chemical Seals

Rather than using removable gaskets and bolts, the entire system might be reasonably glued together using chemical solvent welding techniques. Doing this will save significant machining time and will negate the need for Intro-Serts and gaskets. However, this will also make the test section significantly harder to access for cleaning and maintenance.

5.4. Machine Borosilicate Window

As can be seen in the drawings presented in Appendix 11.1, the interior of the test section does not have an entirely flat and smooth surface. The flatness of the surface is disrupted by the inset borosilicate windows. It is possible to get borosilicate glass machined, within reason, to whatever pattern one desires. A potential pattern that was investigated but discarded as too expensive by the project team was to machine a piece of borosilicate so that the window would come flush with the inside of the test section. Aside from an increase in expense, a minor redesign of the wall sections containing the windows will be necessary. While the redesign is minor, it absolutely must be done prior to machining of the walls. This modification has the potential to significantly improve the quality of data from experiments conducted on the test section.

5.5. Select Alternative Pump

As additional Reynolds numbers of interest make themselves apparent, the pump presented in this document may prove inadequate for the job. When this occurs, a pump properly sized for the new desired Reynolds numbers will be selected.

5.6. Use In-House Measurement Equipment

The Mechanical Engineering Department at Oregon State University has a small inventory of used measurement equipment which might become available for this project. A survey of the potentially available equipment has yet to be completed. The same selection criteria as presented earlier in this document will apply when qualifying existing measurement equipment for use on this project.

5.7. Select Alternate Throttling Valve

An alternate valve can be selected against the high density polyethylene diaphragm valve. One alternative is an all-brass or all-bronze ball valve commercially available at hardware stores. This will significantly reduce cost but, as is noted in several other sections of this document, metal, when in contact with zinc chloride, can be expected to corrode over time.

5.8. Drainage Valve and Tank

If complete drainage of the flow loop is to occur on a regular basis, a drainage valve and catchments tank may be necessary to properly drain and store the zinc chloride solution. This will be a relatively low-cost and easy modification to make if such a system is desired.

6. FABRICATION

Due to a grant not coming through as expected, the team was left without funding at the beginning of the second half of the course for which this project was conducted. The following sections present the team's original fabrication plan, cost reductions which were created in an attempt to construct a prototype with reduced funding, initial proof-of-concept plans, modified proof-of-concept plans, and the final proof-of-concept plans which were carried out. This section concludes with a re-design analysis for further cost reduction based on fabrication information.

6.1. Original Fabrication Plan

The following Original Fabrication Plan sections are presented as they originally appeared in the Design Proposal report. Because nothing was constructed, this section remains relevant and has been kept without modifications.

6.1.1. Cost Vs. Budget

6.1.1.1. Cost

The maximum cost of the entire flow loop, test bed, porous media, and working fluid is approximately $6800.00. A full layout of the estimated cost of materials is shown in Appendix 9.8. This cost does not include labor required to manufacture the test section's walls, gaskets, or diffusers. The cost of the media and fluid has been included in the amount shown above. Since these resources may be available from other Oregon State Universities departments the cost has also been totaled with out these components. The total cost without the media and fluid is approximately $3,500.00. In addition to the two totals shown above, another set of costs is shown in Appendix I with the same criteria as above except without the cost of the Intro-Sert (see Appendix 9.11, Figures 9.11.10 and 9.11.11 for more information on Intro-Serts) inserts used to fasten the test section walls together. These inserts are expensive but with the pressure and material considerations mentioned throughout this document, they will help to ensure secure connections of the sides and diffusers over many assemblies and disassemblies. These costs would be approximately $5,900.00 and $2,600.00, respectively. The table presented in Appendix 10.1 also shows the cost of various components grouped into the categories of: test section, flow loop, measurement equipment, and media and fluid.

6.1.1.2. Budget

Since the project was never given an official budget, the project team attempted to select components that are sufficient to make a quality test section that can be used thoroughly and without complication. Also, in considering component selections, cost effective parts that are adequate for their intended uses were selected over higher-priced but more feature-rich substitutes. Appendix 9.12 shows other options for test bed materials so that, in case a budget is given at a future date, alternative materials can be selected if desired. In addition to the vendors listed in Appendix 9.12 and 10.2, others were research but not included due to excessively high prices or poor quality of the products and services offered. Additional vendors have been contacted but at the time of publication of this document, quotes had not yet been received. Due to the slow response of some potential vendors, some material and component costs may decrease.

6.1.2. Purchased Components

The purchased components of the test section are shown in Appendix 10.2. The test section sidewall cost is the least expensive combination of available materials and sizes from the lowest cost of three suppliers. The material selection of the test section walls and diffusers were analyzed extensively in respect to properties, availability of size, and cost as shown in Appendix 9.12 and discussed in multiple sections of this document. Some minor items needed for assembly have been left out of the spreadsheet in Appendix 10.1 such as glues, clamps, and extra sealant that will be needed for assembly. These items are relatively inexpensive and, for the most part, available to the project group through the Department of Mechanical Engineering at Oregon State University's machine shop.

6.1.3. Fabricated Components

The main manufacturing operations in the construction of the test bed will be the milling of the four test section walls, and the diffusers which mount on each end of the test section. To machine these complicated components a CNC milling program to create the code needed for the CNC mill will be used. This should reduce the time needed for manufacture dramatically and greatly reduce the chance for error in machining. Also, the gaskets will need to be cut out of raw gasket stock. This will be done by creating stencils of the desired shapes and cutting the outlines into the gasket stock. The holes in the gasket will then be cut using a punch. The Intro-Sert holes will need to be drilled on a mill for accuracy (possibly with another CNC milling operation) and then installed using a thermal installation kit, such as the one presented in Figure 9.11.23 of Appendix 9.11. Assembly of the test section can proceed once the aforementioned components have been manufactured, and the rest of the purchased parts have arrived. The assembly of the flow loop will require a layout of the area in which the testing will occur. Installation of the flow loop will require minor drilling, cutting and assembly of the pipe sections into the flow loop.

6.1.4. Sourcing and Lead Times

All component sourcing information is given in Appendix 10.2. Vendors were selected by product line, availability of components needed, and price. Multiple vendors were found for as many items as possible, but only the most qualified vendors appear on the list. Also, the vendors listed in the Appendix 10.2 were the ones that were able to confirm lead times and quoted prices. Product codes and inquiry numbers are also listed in Appendix 10.2 to facilitate quick ordering for the next stage of the project. In evaluating the lead times required for the project it was determined that ordering of the parts would have to occur six weeks prior to assembly of the test section. The viewing window glass, the storage tank, flow straightener, and plastic sheeting would require longer than a week lead times. The viewing window is the critical path item because it has to be manufactured to design specifications. This process, combined with shipping, can take up to six weeks. If orders are placed prior to the second week of December, all purchased parts and raw material is expected to be received on-time to allow for completion of fabrication and testing by March.

6.2. Fabrication Outcome

6.2.1. Fabrication Cost Reduction

At the beginning of the second half of the course for which this report was prepared, the team was not sure if a prototype would be able to be built due to lack of funding. The money that was going to fund the project would have come from federal grants. Since these grants did not materialized, the team continued on by analyzing the paper design for additional cost reductions to make the prototype inexpensive enough to build. The team started by analyzing the bill of materials to see if there were any components that could be changed to lower cost. One such component was the borosilicate window. Originally, the cost for the two windows was $380.00. Some of the cost of the window came from the machining associated with specifying a thickness of 20mm. After changing the wall design to fit a more standard window thickness, the group was able to reduce the cost of the two windows down to $270.00. Another way the group found to reduce the cost was by eliminating the insert fasteners that securely hold a bolt into plastic. Eliminating this saved an additional $860.00. The group looked for more avenues of cost reduction but was only able to come up with the reductions above. Even with the $970.00 cost reduction, the prototype still cost $5,787.00. This was still too much for the project sponsor to support, so the group turned to a proof-of-concept model that could allow the team to fulfill the requirements for the second half of the senior project course.

6.2.2. Proof of Concept Considerations

Since the team could not construct the original 3D flow cell, the team began to look at ways to prove that the design of the 3D flow cell satisfied the Original Design Requirements given by the sponsor. Most of the requirements were satisfied by putting the components stated by the requirement into the design. The sponsor informed the team that there was a 2D flow cell recently constructed (shown in Figure 7) and that we could use the flow cell to verify remaining requirements.

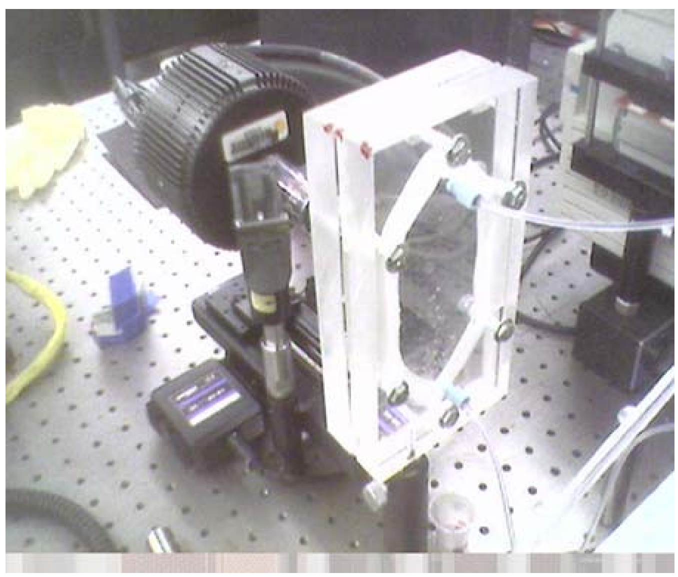


Figure 7: 2D Flow Channel

The requirement involving the boundary conditions was the main focus of the team's proof-of-concept experiment since the 3D flow cell design compensated for boundary effects by using pre-existing literature recommendations on previous experiments done of similar nature. There were no concrete formulas on which to base the paper design so the team followed what had been done in the past. The other requirement tested was the field of view that is required for adequate optical access. Both of these requirements could be tested during the same experiment as the team planned to use the same camera during their experiment as the one that would be used with a 3-D flow cell in a TR-3D-PIV experiment.

6.2.3. Proof of Concept 1

To prove that the team's design would meet the requirements that could be tested, the team and the sponsor devised a dispersion experiment involving a dye injection system that emitted a pulse of dye into the flow cell. This pulse could then be tracked through the flow cell and the team could determine the area increase of dye as it flowed through the cell. The goal was to see where, after a certain percentage of growth, the outer horizontal boundaries of the dye would be affected by edge effects from the walls of the flow cell. To modify the 2D flow cell the team would have to drill a hole into the flow channel an inch below the inlet. The drawing for this modification is shown in Appendix 11.2.

To be able to modify the 2D flow cell the group was asked to provide a modification plan and procedure which is presented below.

1. Carefully disassemble the 2D flow channel.
2. Remove all components and clean front polycarbonate window.
3. Drill and tap window as shown in Figure 3.
4. Insert adaptor and attach back check valve.
5. Reassemble 2D flow channel and fill with water.
6. Attach pump and test flow channel for leaks (modify if necessary).
7. Check flow rates and test run of dye in flow channel.
8. Drain water and refill with zinc chloride solution.

Also, the team was asked to create a parts list of the plumbing necessary to inject the dye into the flow cell (shown below in Table 2). The team researched methods and materials for injecting the dye. The below design includes all materials necessary to construct a dye injection system for the existing 2-D test setup. It should be noted that the price quotes for parts coming from Value Plastic are for quantities of 100. In all but one case, only one part was needed. Value Plastic does not sell in quantities fewer than 100 however; one team member had access to almost all of the required components through contacts at HP. Additionally, some parts might have been available within the mechanical engineering department and Value Plastic could have been convinced to provide samples. McMaster also stocks these parts on an individual basis.

The design (shown in figure 8: dye injection system) is the safest and least expensive design the team created to prevent the potential of backflow of zinc chloride into the syringe. If funds or parts could not have been attained in a timely manner, a less desirable system consisting of a brass or stainless steel 10-32 thread to male hose barb, which can be found in the mechanical engineering machine shop, some 1/8" ID hose also found in the mechanical engineering machine shop, and a syringe acquired from Student Health Services, would have been used. This system was not recommended, however, as the metal hose barb fitting will corrode when in contact with zinc chloride and no check valve would have been present to prevent backflow of zinc chloride into the syringe. The less-than-desirable system could have been closed off by simply pinching the hose to prevent fluid backflow. However, again, this was not ideal.

Table 2: Dye Injection System Parts List

Ref. Number	Name	Vendor	Part Number	Price
1	10-32 Male hose barb (white nylon)	Value Plastic	B-1	$14.00 / 100 parts
2	1/8" ID ¼"OD PVC hose	Value Plastic	PV00-3062C	$13.86 / 100 ft
3	Female Lure 200 Series to male hose barb (Polycarbonate)	Value Plastic	FTL230-9	$16.00 / 100 parts
4	Check-valve rated to 30PSI back pressure (Polycarbonate)	Value Plastic	VPS5401068N	$73.00 / 100 parts
5	Male Lure 200 series to male hose barb (Polycarbonate)	Value Plastic	MTLL230-9	$18.00 / 100 parts
6	6cc Syringe with Lure fitting	McMaster-Carr	7510A652	$7.15 / 10 parts

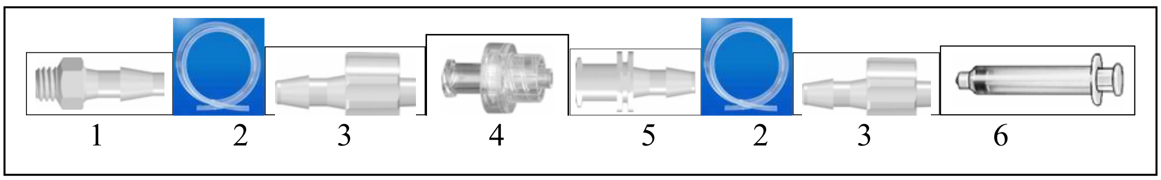


Figure 8: Dye Injection System (test loop not show but assumed left of item 1)

6.2.4. Proof of Concept 2

The evening before the modification of the 2D flow cell was to take place concerns were raised about the usefulness of the 2D flow cell after the team had drilled a hole into it and had finished experimentation. Also, the procedure the team proposed included the disassembly of the flow cell which raised another issue. The flow cell was constructed with an expensive Teflon gasket that is not reusable. If the team were to take the cell apart, it would be expensive to put back together. After some discussion, it was decided to not do the modifications described in section 6.2.3 but to instead make a dye loop and inject the dye directly into the inlet tube. This would be less intrusive on the flow cell and give the similar result. Since there was no time to order parts and no budget to do so, the Environmental Engineering department offered to lend the team the necessary equipment to make a dye loop, and anything extra that was needed would be provided by the sponsor.

The new Proof of Concept model was relatively simple. The fluid would be pumped through the system from a reservoir, to the flow cell and into a discharge bottle. The tubing in between the pump and the flow cell was modified to incorporate a dye loop controlled by two valves. In one position, the fluid would move normally through the system but in the other position a tube filled with dye would become part of the flow loop. This dye would then move into the flow cell and allow the team to take pictures of how the fluid moves through the flow cell. Lastly, the fluid would then continue out of the flow cell and into a discharge bottle. Since the fluid would then be contaminated by the dye, it could no longer be reused. The setup of the new proof of concept is shown below in Figure 9.

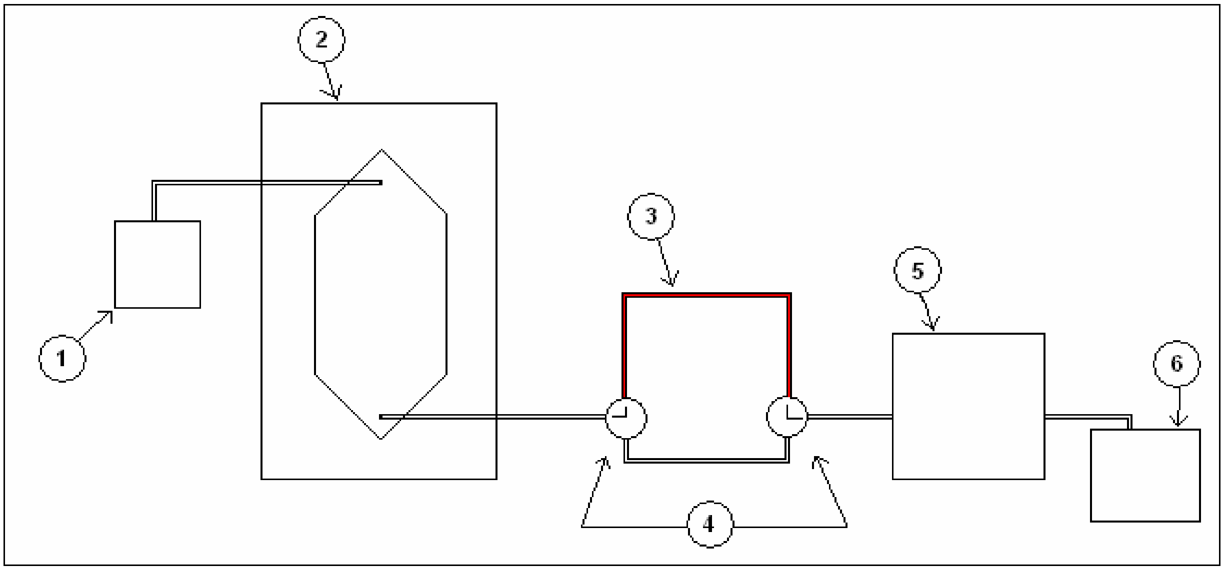


Figure 9: Proof of Concept 2 Diagram

The materials for the loop are shown below in Table 3. The team used 1/8" plastic tubing. Each of the components was connected using ¼ x 20 screw fittings with camp rings. The valves, fittings, and clamp rings were made of high-pressure PVC plastic.

Table 3: Proof of Concept 2 Components

Item #	Description	Qty.
1	discharge - 150 mL media bottle	1
2	2D - flow cell	1
3	dye loop (1/8" tubing - 0.5 mL volume)	1
4	3 way L valves	2
5	peristaltic pump	1
6	reservoir - 150 mL media bottle	1

6.2.4.1. Construction Issues

The main issues that arose during construction of the proof of concept were that there was little time and money to get a proof of concept completed. The construction and testing plan was not finalized and agreed to by the project sponsor until the very end of the period dedicated for the aforementioned activities. As the proof-of-concept evolved into the final version, the team had to adapt very quickly in order to stay on top of new proof-of-concept iterations. In regards to time, there was only a small window in which the team was allowed access to the lab to conduct the experiment. The team, understandably, low in priority for lab access considering there were multiple graduate students conducting experiments in the same area. Because of this, the setup and assembly of the experiment had to be completed quickly.

Another unexpected issue was that the team had originally intended the direction of flow in the flow cell to be from the top to the bottom. The team had set up the flow cell with this orientation and quickly noticed that the flow cell was not filling with fluid. The group had tried to raise the discharge reservoir above the flow cell in hope that it would fill but it remained unchanged. To correct the problem, the team modified the setup to change the flow of the fluid from bottom to top. This corrected the problem and the team was able to continue.

6.2.5. Cost vs. Budget

Most of the components in Proof of Concept 2 were given to the team to use or were already available in the lab due to previous experiments with the 2D flow cell. The expense incurred was as a result of the team assuming that there would be a reservoir and discharge bottles available in the lab. Since all the bottles had seeded particles in them, the team had to come up with alternate containers. The team considered some inexpensive, basic containers but after a few test runs with water, it was apparent that the team would need some secure way of getting the fluid into the bottle without any spillage occurring. The team approached the sponsor with this problem and was granted the appropriate funds, discussed in section 8, to procure two media bottles. With this being the team’s only expense, the team was able to complete construction of the proof of concept and gather the needed data.

6.2.6. Re-Design Analysis

Due to the limited scope of the proof-of-concept, and the fact that no major fabrication issues directly related to the design were encountered, the team assumes that there will be no major redesigns required of the paper design before a prototype can be built in the future. To the best of the team’s knowledge, the paper design and proof-of-concept fulfill all of the Final Design Requirements, listed in section 1.2.2.2. A complete analysis of design requirements is given in section 7. The 3D flow cell and flow loop will do what is expected of it to best of the team’s knowledge. The testing of the requirements confirmed this. However, since the cost of the 3D flow cell is substantial, the reevaluated cheaper version of the flow cell, presented in earlier sections, could be used. The original version of the 3D flow cell was designed to be structurally sound and durable in a variety of rigorous conditions. A reduced cost version may accomplish a TR-3D-PIV test but not near the upper Reynolds numbers of the original paper design. According to the team’s understanding, the higher the Reynolds numbers that could be achieved would result in more substantial research that can be done. Therefore, any significant redesign should only occur with this in mind.

7. TESTING

Due to previously discussed budgetary issues, the original testing plan had to be altered to cope with no prototype being available. The Original Testing Plan, as presented in the preliminary design report, is given without major edits with the hope that, when this project is actually constructed, the plan will be of use. Modified testing plans are provided with the original modified plans and the final modified plans presented for completeness. Data analysis and conclusions are found at the end of this secetion.

7.1. Original Testing Plan

7.1.1. Evaluation of Requirements

The following sections contain the plans to evaluate the Original Design Requirements laid out in section 1.2.2.1 of this document. Many of the design requirements can be tested either by a portion of the design being present or not. Other requirements are more subjective while others can be objectively judged and qualified. The evaluations listed below are for the Original Design Requirements but are also applicable to the Final Design Requirements.

7.1.1.1. Evaluation of Design Requirement #1

Proper design can be considered upon final assembly by performing functionality tests on the system, for leakage, flow loop functionality, and measurement equipment functionality.

If this test fails, appropriate modifications to the faulty subsystems will be made.

7.1.1.2. Evaluation of Design Requirement #2

Proper design can be considered upon final assembly by performing functionality tests on the system, for leakage, flow loop functionality, and measurement equipment functionality.

If this test fails, appropriate modifications to the faulty subsystems will be made.

7.1.1.3. Evaluation of Design Requirement #3

This requirement can be determined upon final assembly, by confirming that the appropriate equipment for all measurements of interest have been calibrated and installed correctly.

If this test fails, major redesign and remachining of the test bed will have to take place.

7.1.1.4. Evaluation of Design Requirement #4

Evaluation of the optical access of the TR 3D PIV equipment will have to come from the direct results of the experiment. The cameras and laser will have to be positioned in the best location that the section will allow. If this is not adequate then a major redesign of the test section will have to occur.

If this test fails, major redesign and remachining of the test bed will have to take place.

7.1.1.5. Evaluation of Design Requirement #5

Due to availability of index of refraction testing equipment that is currently owned by Oregon State University the project team will be able to measure the index of refraction of the viewing window to make sure it was properly manufactured. Also, the project team will be able to evaluate the glass beads to check for air bubbles and unusable indexes. The project team expects a 20% drop out ratio of bad beads from similar experiments done with the same manufacturer of beads [28]. Lastly, index-matching equipment can be used to accurately mix the zinc chloride solution to the same index of refraction as that of the viewing window and beads. If this test fails, replacement viewing windows, borosilicate beads, or working fluid will be required.

If the root cause is determined to be the working fluid, close attention will have to be paid to likely sources of contamination in the flow loop. If any sources of contamination are found, they will be removed and the fluid replaced.

7.1.1.6. Evaluation of Design Requirement #6

Testing for vibrational isolation of the test section from the pump will have to occur after the flow loop has been setup. A separate structure for the pump with isolators to reduce vibration has been considered in the preliminary designs of a support structure for the pump, flow loop, and test bed. The only complication in having a separate pump structure would be that the height sequence of the reservoir above the pump would have to be maintained. A complete support structure design will have to wait until the area of the experiment can be laid out with the placement of the test section clearly defined.

If this test fails, additional vibration damping equipment will be selected and installed.

7.1.1.7. Evaluation of Design Requirement #7

Testing the flow loop for operation in the quoted range of Reynolds numbers requires that the flow rate and differential pressure transducers have all been calibrated against instruments of known error, or by appropriate calibration method, e.g. catch and weigh procedure for flow rate, and that the porosity of the porous media, working fluid viscosity, etc. have all been experimentally determined as well. Subsequently, appropriate flow rate measurements can be taken at different settings and Reynolds number calculations can be performed to compare against the theoretical calculations for accuracy.

If this test fails, the entire flow loop will have to be reevaluated for the source of the error and either remanufactured, replaced, or repaired to provide the correct designed-for Reynolds number.

7.1.1.8. Evaluation of Design Requirement #8

Testing the safety of the test bed requires that the bed brought up to pressure and run through several cycles of pressurization and depressurization to check for leaks and catastrophic failure. Initially, this will be done with pressurized air. Once a positive seal has been demonstrated, the test section and flow loop will be loaded with water and run through several cycles. Pressure checking with zinc chloride will only be performed after seal integrity has been confirmed using air and water. Additionally, zinc chloride will not be introduced into the system until all of the materials used in flow loop construction have been physically checked with zinc chloride to confirm that material compatibility indicated on material datasheets matches the real world.

If this test fails, a root failure cause analysis will be performed and replacement, remanufacture, or redesign of the failed component(s) will be conducted as appropriate.

7.1.1.9. Evaluation of Design Requirement #9

Control of the pressure and flow rate of the system can be tested by changing the pump speed and operating the throttling valve. This can be verified by reading the pressure and flow rate meters. Temperature is not controlled in the design presented in this document beyond natural cooling present in the system. Temperature change will be monitored with the thermocouple over a period of time to determine if excess heat is introduced into the system by the pump or other sources. If this is the case, an appropriate thermal control scheme will be selected and installed in the flow loop.

If this test fails, reanalysis of the flow loop control will be performed and deficient components will be modified or replaced.

7.2. Modified Testing Plans

Due to previously discussed issues, the testing plan was modified to be conducted on a 2-D flow cell. The information presented below reflects the two iterations of the modified testing plan and also includes relevant data on dye testing.

7.2.1. Dye Testing

Before any testing was performed by the team, verification of an appropriate dye had to be determined. The different types of dispersion that are expected to occur are molecular and turbulent. The turbulent dispersion of the dye should be minimal before the dye enters the porous media because the inlet is located in the media. Molecular dispersion rates were controlled by the type of dye the team selected. The dye must be insoluble in water yet viscous enough for the team's needs. The team researched this and found a category of dyes called "lake dyes" that are used to color fats and oils. This would have been ideal but the dye could not be acquired prior to testing due to long lead-times out of India. Since it was not available, the team found multiple dyes that appeared reasonable to test. A static test was conducted to determine if the dyes would meet the needs of the experiment. This was done by placing a drop of dye in a container of water and measuring dye spread (difference in area) vs. time. With this information, the team could measure how much effect molecular dispersion would have on the experiment.

The three types of dye that the group tested were a standard green food coloring, a water insoluble paint, and the same paint mixed with a thinner mixed in. The food coloring was the best substitute for the "lake dye" but is for more general purposes. The oil paint was selected because of its insolubility in water. The reasoning for the paint with thinner mix was that the paint might be too viscous to flow through the media properly.

In each experiment the dyes were dropped into a container of water and pictures took every 8 seconds. Figure 9 shows the food coloring entering into the water and forming a slightly growing cloud. Since the time between pictures was approximately as long as the time it took a particle to travel though the 2D test cell, the group really only focused on the first two pictures. The difference between them seemed minimal, since there was some dispersion effect by the droplet entering the water.

Figure 9: Food Coloring Dye Test (8 second time intervals from left to right)

The second dye experiment was done using the oil paint shown in Figure 10. The paint was less dense than the water since it floated on top and could cause an additional force to act on the dye in the experiment. The paint had another problem that occurred that showed up while testing. It stained the cup heavily and could not be rinsed out even though it had only been in the container for less than a minute. If the paint were to be used in the experiment, it may stain the entire flow cell and render it useless for further experimentation.

Figure 10: Oil Paint Dye Test (8 second time intervals from left to right)

The third dye experiment was done using the dye and thinner mix shown in Figure. It was apparent as soon as the dye hit the water that it would not be adequate for the experiment. The dye instantly spread over the top of the water and again stained the container. The thinner lowered its viscosity dramatically but did not reduce the paint's ability to stain the container.

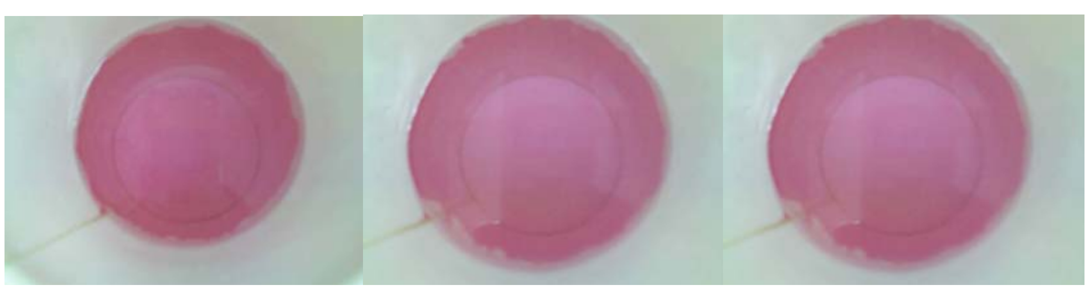


Figure 11: Oil Paint with Thinner Dye Test (8 second time intervals from left to right)

The food coloring was the best choice after looking at the results of the testing. Even though there was some molecular dispersion taking place, the time it took for a significant dispersion to occur was larger than the time for the dye to pass through the flow cell. Therefore the molecular dispersion of the food coloring was inconsequential and will be used in the experiment.

7.2.2. Intermediate Testing Plan

The below testing plan was presented to the project sponsor and is included in this document for completeness. While modifications were made to this testing plan, which are discussed later in this section, the majority of Intermediate Testing Plan was adapted and used in the Final Testing Plan. Tenses have not been changed to reflect the original testing proposal.

7.2.2.1. Abstract of Testing Plan

The design team has designed a 3D flow channel to exhibit flow characteristics inside of porous media based on the most current porous media literature; however, since construction of the 3D flow cell is not feasible at this time, an existing 2D flow cell will be used to establish validation of select design requirements.

7.2.2.2. Background

In the design phase of the project, the design team proposed a flow cell design to facilitate the TR-3D-PIV equipment to construct 3D images of fluid flow in porous media. One of the main constraints that the team chose was that for edge effects to not affect the data collection area in the porous media; the viewing area had to be 3-10 bead diameters away from the edges of the flow channel. This assumption constrained multiple areas of our design and the verification of the proper data collection needed will justify the paper design and will be adequate for its intended purpose.

7.2.2.3. Experiment Design

To provide a quantifiable result that will provide an area away from the walls in which pictures can be taken, with no edge effects present, the team purposes to do a flow channel-dye experiment. In this experiment the design team will insert dye into the flow channel and observe the dispersion effects. The goal is to measure the amount of dispersion that takes place at different Reynolds numbers and record when and how edge effects occur in the flow. In doing this the team hopes to provide an area that can be used to characterize flow characteristics in the flow channel without edge effects. Once this information about the 2D flow channel is obtained the team can then extrapolate the edge effects to the 3D design. This should either valid our design or show the team how and where mistakes were made.

To record the data the team will need to use a camera to take pictures of how the dispersion is taking place and measure its rate before edge effects take place. With the pictures the team can then determine the lateral dispersion verses the flow direction. There are two different insertion methods the team wants to test. One is to use a continuous stream of dye to see the general flow characteristics and record an overall rate of dispersion. The other method would be to use a pulse of dye to see how a particle like fluid would move through flow channel. The team would then measure the lateral expanding area vs. the flow velocity to get an area increase vs. time. Once these rates of dispersion are mapped for different values of Reynolds numbers the team can determine an area where the observations should be taken.

7.2.2.4. Experiment Procedures

Once the hardware is in place and ready for testing, the will then begin the experiment. During the experiment the team needs to gather a series of pictures taken at different rates as we increase the Reynolds numbers. Table 4 outlines the flow and picture rates per Reynolds number.

Table 4: Estimated Rates for Experiment

Re#	Q (m^3/s)	Q (mL/min)	Vpore (m/s)	Tpore	Picture Rate (pic/s)	Vmacro (m/s)	Tmacro	Picture Rate (pic/s)
100	8.60E-06	516	0.0667	1.14	8.75	0.02001	3.81	2.6
150	1.30E-05	780	0.1	0.76	13.12	0.03	2.54	3.9
200	1.70E-05	1020	0.133	0.57	17.45	0.0399	1.91	5.2
250	2.20E-05	1320	0.1667	0.46	21.88	0.05001	1.52	6.6
300	2.60E-05	1560	0.2	0.38	26.25	0.06	1.27	7.9
350	3.00E-05	1800	0.233	0.33	30.58	0.0699	1.09	9.2
400	3.40E-05	2040	0.2667	0.29	35.00	0.08001	0.95	10.5

Using Table 4, the design team can set the injection pump to deliver 0.5 mL of dye at half of the picture rate per Reynolds number. The picture rate was calculated to give the team ten pictures of the dye as it passes through the working area of the flow channel. This area is located below the delivery hole down to the section where the channel begins to narrow.

7.2.2.5. Materials

The below design (Figure 12, Table 5) includes all materials necessary to construct a dye injection system for the existing 2-D test setup. It should be noted that the price quotes for parts coming from Value Plastic are for quantities of 100. In all but one case, only one part is needed. Value Plastic doesn’t sell in quantities fewer than 100 however; one team member most likely has access to almost all of the required components through contacts at HP. Additionally, some parts might be available within the mechanical engineering department and Value Plastic might be convinced to provide samples. McMaster also stocks these parts on an individual basis.

The below design is the safest design to prevent the potential of backflow of zinc chloride into the syringe. If funds or parts cannot be attained in a timely manner, a less desirable system consisting of a brass or stainless steel 10-32 thread to male hose barb, which can be found in the mechanical engineering machine shop, some 1/8” ID hose also found in the mechanical engineering machine shop, and a syringe acquired from Student Health Services. This system is not recommended, however, as the metal hose barb fitting will corrode when in contact with zinc chloride and no check valve will be present to prevent backflow of zinc chloride into the syringe. The, less-than-desirable, system can be closed off by simply pinching the hose to prevent fluid backflow. However, again, this is not ideal.

Table 5: Dye Injection System Parts List

Ref. Number	Name	Vendor	Part Number	Price
1	10-32 Male hose barb (white nylon)	Value Plastic	B-1	$14.00 / 100 parts
2	1/8" ID ¼"OD PVC hose	Value Plastic	PV00-3062C	$13.86 / 100 ft
3	Female Lure 200 Series to male hose barb (Polycarbonate)	Value Plastic	FTL230-9	$16.00 / 100 parts
4	Check-valve rated to 30PSI back pressure (Polycarbonate)	Value Plastic	VPS5401068N	$73.00 / 100 parts
5	Male Lure 200 series to male hose barb (Polycarbonate)	Value Plastic	MTLL230-9	$18.00 / 100 parts
6	6cc Syringe with Lure fitting	McMaster-Carr	7510A652	$7.15 / 10 parts

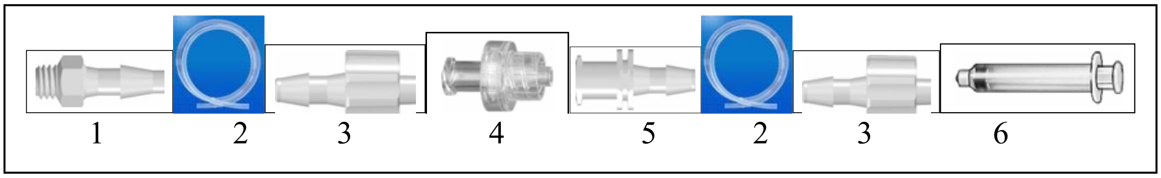


Figure 12: Dye Injection System (test loop not show but assumed left of item 1)

7.2.2.6. Data Collection

During the experiment, pictures will be taken, as outlined in the procedures section. After the pictures are taken the team can then gather the dispersion into quantifiable rates. The data that will be gathered are a series of ten pictures per Reynolds number. These will be taken with the existing digital camera equipment in the lab. The team will attach an appropriate scaling in the field of view of the camera so that size can be analyzed. Since the team doesn't know exactly how the dye will interact in the porous media, the team will test the expected injection rates during the modification test noted in the hardware modification section. During this the team will check for spacing of the dye between injections so that a dispersion effect can be seen in the direction of the flow channel when the pictures are taken.

7.2.2.7. Analysis

Once the team has the pictures from the experiment we can measure the amount of dispersion that occurs in the direction of the flow and the direction perpendicular to the flow. The team can take the average growth of the dye in each direction and compare it with the previous pulse. This data can give the team a dispersion rate in each direction as it progresses through the media with time. The team can show the details of how this dispersion takes place by graphing the velocity of the flow vs. the perpendicular dispersion distance. Another graph that would be useful is the flow rate vs. the velocity in the perpendicular direction. This would show how the increase in Reynolds numbers affects dispersion in the media. Also, during this experiment we can see where edge effects are occurring by observation of different flow characteristics. Once all of the dispersion rates are clear the team can then evaluate the proper viewing area that is in the dispersion range with no edge effects.

7.2.2.8. Conclusion

This experiment will show that the design requirements for the team's 3D flow channel were met and that, if it were built, the data gathered would be in accordance with what was intended. By interpolating the results of the 2D experiment into the team's 3D design for a porous media flow channel, the team will be able to show the paper design is able to gather the information needed for the TR-3D-PIV experiment. One way it will prove the team met requirements is if the selected viewing area falls in the dispersion region of the 3D flow channel then it must be in the inertial flow regime. The team will also be able to classify the boundary effects and show that the paper design viewing window is within them. Lastly, by doing this experiment the team will be able to see the abilities of the camera and if the paper design can accommodate them.

7.2.3. Final Testing Plan

The testing plan outlined in section 7.2.2 was rejected on the premise that the hardware modifications were too extensive, and that the cost to reassemble the flow cell would incur a cost of a new gasket that was deemed unnecessary. Therefore the testing plan was modified yet again in order to minimize the physical modifications of the flow cell and cost.

However since the testing plan has been modified numerous times and was redesigned to be performed on an existing 2D flow cell, the number of design requirements that can be validated through testing are minimal. The actual design requirements that can be validated by testing are Design Requirements #2 and #4 of section 1.2.2.2. Also, due to equipment limitations, Reynolds numbers of 200 and above could not be achieved, thus Design Requirement #6 of section 1.2.2.2 was born and the desired flow regime was changed to the inertial realm. Other design requirements, as can be seen in section 1.2.2, were dropped from the list of Final Design Requirements (section 1.2.2.2) due to only a 2-D flow cell being available.

7.2.3.1. Experiment Design

The motivation behind this test is to provide validation of the 3D flow cell designed around the design requirements as outline in section 1.2.2.2. As stated before, the numerous changes to the original testing plan has limited the scope of testing to two design requirements (see section 7.2.3).

The data for this test is gathered non-intrusively, but injecting the dye into a bypass line in parallel with the main flow line, with images captured by a commercially available camera. In this test the existing 2D flow cell was modified according to section 6.2.4 *Proof of Concept 2*. Pictures were captured at a rate 1 picture per second and analysis for a limiting value of horizontal dispersion.

7.2.3.2. Procedure and Data Collection

In order to gather the relevant data to verify design requirement #2 and #4 of section 1.2.2.2, the following procedure was executed:

- Modify flow cell loop according to section 6.2.4
- Fill the bypass line with 0.5-mL of dye, and install on bypass valves.
- Assign the pump to the first flow rate of Table 6 below, and start pump.
- Ready the digital camera and start pictures sequencing.
- Actuate valves to bypass line with dye.
- Once dye has sufficiently dispersed in flow cell stop camera, pump and return bypass valve to original position.
- Download pictures to local computer.
- The above procedure was repeated for each subsequent flow rate shown in Table 6.

Table 6: Flow Rate Testing Plan

Q (mL/min)	Q (m^3/s)	Reynold's # pore	Velocity pore (m/s)	Time pore (sec)	Pore Picture Rate (pic/sec) [max]	Velocity macro (m/s)	Time macro (sec)	Macro Picture Rate (pic/sec) [min]
70	1.17E-06	13.6	9.04E-03	8.43	1.19	2.71E-03	28.10	0.4
90	1.50E-06	17.4	1.16E-02	6.56	1.53	3.49E-03	21.86	0.5
110	1.83E-06	21.3	1.42E-02	5.36	1.86	4.26E-03	17.88	0.6
130	2.17E-06	25.2	1.68E-02	4.54	2.20	5.04E-03	15.13	0.7
150	2.50E-06	29.1	1.94E-02	3.93	2.54	5.81E-03	13.11	0.8
170	2.83E-06	32.9	2.20E-02	3.47	2.88	6.59E-03	11.57	0.9

7.2.3.3. Equipment and Hardware Modifications

The materials needed to make modification to the existing flow cell are outlined in section 6.2.4. Images were captured using a Canon Powershot Digital Camera. Images were imported, scaled, and dimensioned in AutoCAD 2007. An example of the setup can be seen in Figure 13.

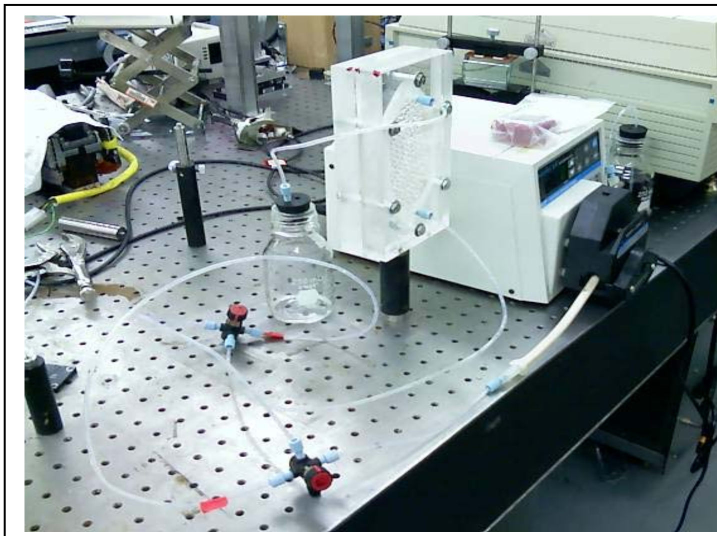


Figure 13: Equipment Setup

7.2.3.4. Analysis

The images were downloaded, scaled, and dimensioned in AutoCAD 2007. The parameters of interest collected were based on how the flow developed through the flow cell. As subsequent images were observed, it was immediately recognized that the flow pattern developed into a right, center, and left region; and an overall leading and trailing edge was noticeable as well (see Figure 14). From this, the average vertical lengths of the leading and trailing edges, and horizontal lengths, of each region were measured and recorded in an Excel table (see Figure 15 and Table 7).

Figure 14 Flow Developing Into Right, Center, and Left Regions

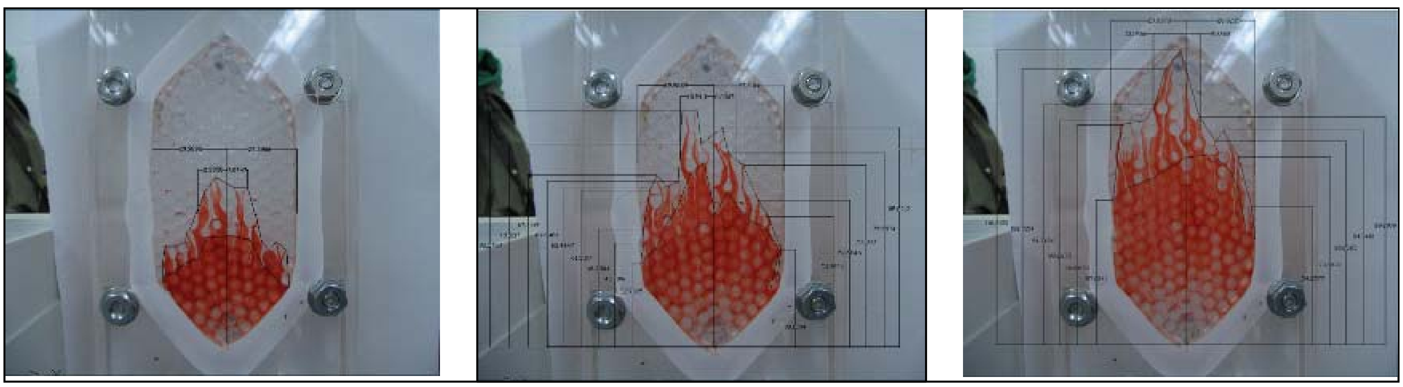


Figure 15: Developed Flow Regions Dimensioned in AutoCAD 2007

Table 7: Image Data Summary per Flow Rate

Dispersion Experiment Picture Data						
pic time interval	2	Picture #	1	2	3	Average Time Rate of Change
pic time			0	2	4	
mL/min		Area	912	971	1406	123.5
170	Horizontal Region	L	18.1	13.7	15.8	-0.575
		M	21.8	26.5	24.4	0.65
		R	17.6	17.3	16.9	-0.175
	Upper Vertical Boundary	L	50.4	49.3	70.1	4.925
		M	72	80.7	94.5	5.625
		R	46.8	61.7	64	4.3
	Lower Vertical Boundary	L	37.9	43.5	58.8	5.225
		M	45.3	57.6	62.7	4.35
		R	35.5	45	55.2	4.925
pic time interval	2	Picture #	1	2	3	Average Time Rate of Change
pic time			0	2	4	
mL/min		Area	841	1023	1657	204
150	Horizontal Region	L	22.8	16.4	16.1	-1.675
		M	16.6	22.2	24.1	1.875
		R	18.2	17.3	16.7	-0.375
	Upper Vertical Boundary	L	32.1	51.7	68.4	9.075
		M	60.9	79.7	95.5	8.65
		R	42	55	58.4	4.1
	Lower Vertical Boundary	L	29.3	37.2	50.3	5.25
		M	33.6	49.6	57.6	6
		R	27.7	40.5	46.2	4.625
pic time interval	2	Picture #	1	2	3	Average Time Rate of Change
pic time			0	2	4	
mL/min		Area	701	1014	1376	168.75
130	Horizontal Region	L	18.4	17.4	16.9	-0.375
		M	20	22.6	23	0.75
		R	18.9	17.3	17.5	-0.35
	Upper Vertical Boundary	L	38.6	55.4	78.7	10.025
		M	56.7	75.9	96.6	9.975
		R	35.4	48.2	68.3	8.225
	Lower Vertical Boundary	L	26.5	31.7	50.6	6.025
		M	33	45.7	60.3	6.825
		R	26.1	35.2	50.6	6.125
pic time interval	4	Picture #	1	2	3	Average Time Rate of Change
pic time			0	4	8	
mL/min		Area	768	956	1246	59.75
110	Horizontal Region	L	19.2	16.7	16.7	-0.3125
		M	19.4	21.5	18.6	-0.1
		R	19.3	19	21.6	0.2875
	Upper Vertical Boundary	L	39.4	57.2	81.7	5.2875
		M	62.5	83.4	102.3	4.975
		R	40.7	54.4	76.5	4.475
	Lower Vertical Boundary	L	28.1	44	61.9	4.225
		M	42.8	63.3	71.4	3.575
		R	31.5	40	58.3	3.35
pic time interval	4	Picture #	1	2	3	Average Time Rate of Change
pic time			0	4	8	
mL/min		Area	581	734	1082	62.625
90	Horizontal Region	L	11.7	17	16.6	0.6125
		M	27.1	21.8	17.3	-1.225
		R	19.6	18.1	22.7	0.3875
	Upper Vertical Boundary	L	39.7	53.4	76.2	4.5625
		M	54.8	74.7	96.8	5.25
		R	38	47.9	63.7	3.2125
	Lower Vertical Boundary	L	33.5	47.4	63.9	3.8
		M	42.6	53.2	71.3	3.5875
		R	30.4	39.3	58.5	3.5125
pic time interval	4	Picture #	1	2	3	Average Time Rate of Change
pic time			0	4	8	
mL/min		Area	761	918	761	0
70	Horizontal Region	L	17.7	15.8	16.9	-0.1
		M	20.6	22.5	25.7	0.6375
		R	18.7	18.6	14.3	-0.55
	Upper Vertical Boundary	L	44.4	72.7	81.2	4.6
		M	66.8	81.9	96.1	3.6625
		R	39.8	59.6	71.4	3.95
	Lower Vertical Boundary	L	39.5	57.7	73.5	4.25
		M	50.7	47.2	79.1	3.55
		R	35.9	48.4	62.8	3.3625

From the data collected, presented in Table 7 above, the behavior of the horizontal dispersion could be plotted. In Figures 16 and 17, it can be seen that as the flow develops in the main part of the flow cell (around 4 seconds), that horizontal dispersion maintains an average limiting value of approximately 17.2-mm.

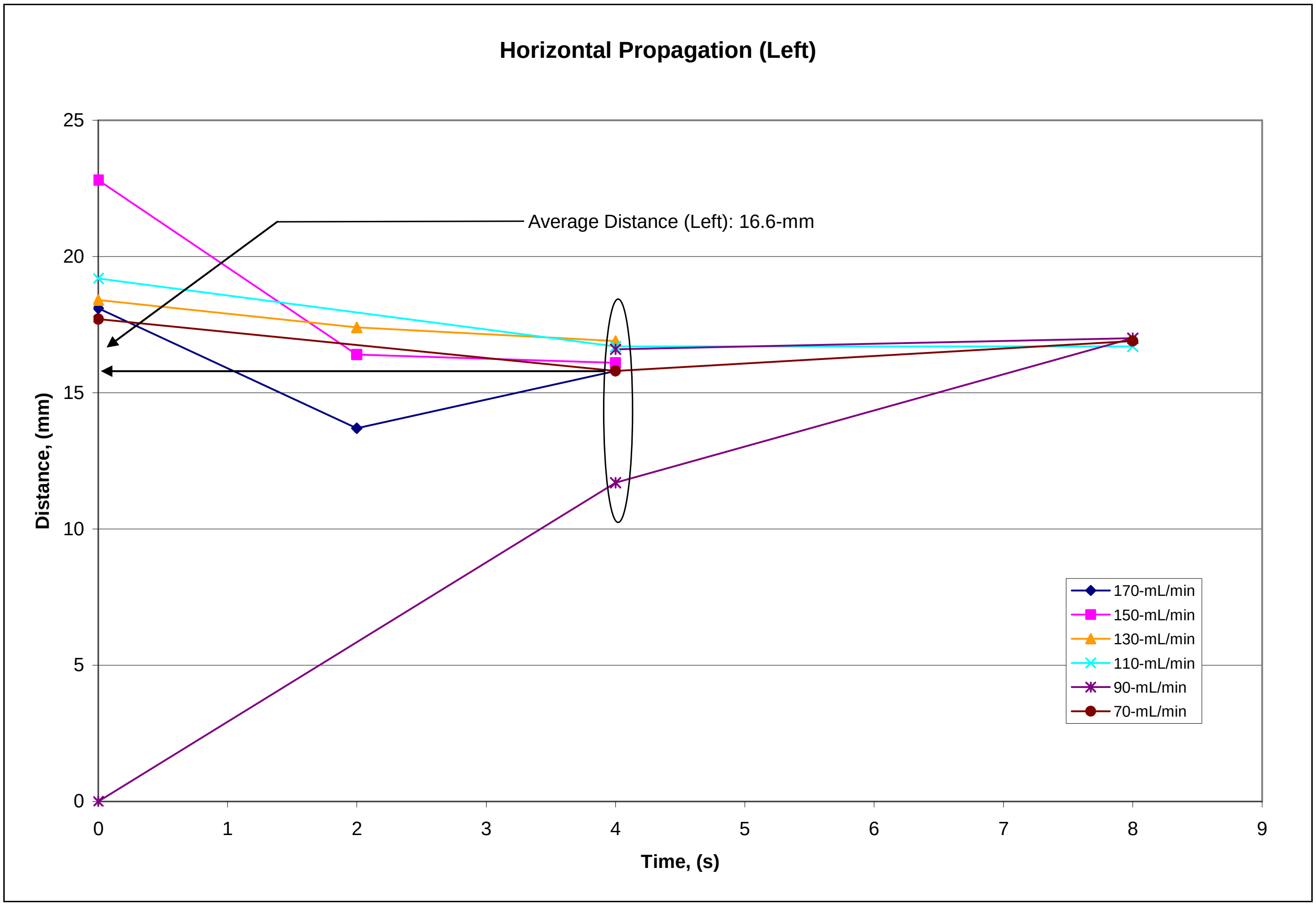


Figure 16: Horizontal Development (Left Region)

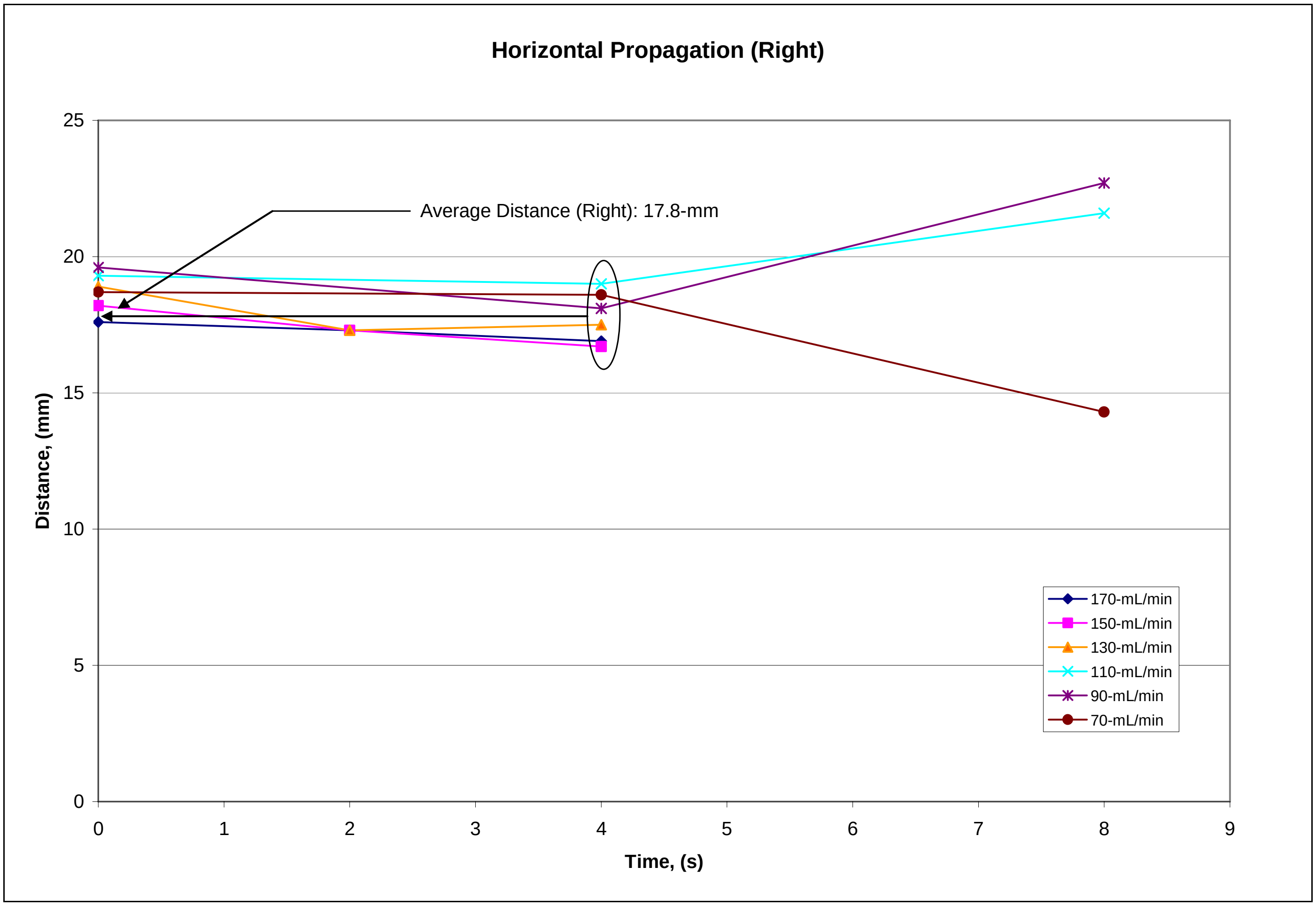


Figure 17: Horizontal Development (Right Region)

7.2.3.5. Conclusion

It can be concluded from the above data that as the flow enters the middle portion of the main part of the flow cell, the minimum distance from the wall in which edge effects will be detected is approximately 17.2 mm. In the paper design, the distance from the edge of the inside of the wall to the viewing window is 25 mm; therefore, if imaging is performed within the dimensions of the viewing window, and at the flow rates used in these experiments, edge effects are expected to be negligible.

Furthermore is can be deduced that the imaging equipment has sufficient optical access. As can be seen in Figure 11.3.2 in Appendix 11.3, the 100 mm square optical viewing area is situated 25 mm from each adjacent wall. Considering that, at most, 40 mm by 40 mm of viewing area will be used at any given time; the 100 mm square viewing window is more than adequate to provide sufficient optical access in a region with negligible edge effects. Thus, optical access for image collection is maximized. Therefore, both Design Requirement #2 and Design Requirement #4 are satisfied.

7.3. Design Requirements Analysis

Table 8, below, lists each of the Final Design Requirements, the status of the validation of the requirements, and the method by which that requirement was verified. As can be seen, all design requirements were verified and met, thus, the paper design meets the requirements as laid out in section 1.2.2.2.

Table 8: Final Design Requirement Validation

Design Requirement	Status of Validation	Method of Validation
The design shall consist of a porous media bed, a flow loop with appropriate pumping apparatus, measurement and control equipment.	Passed	Verified by final paper design as presented in this document.
The flow cell shall be of sufficient depth and width to make edge effects negligible.	Passed	Verified by experimentation as outlined in section 7.
The flow cell shall be able to take appropriate direct and indirect measurements potentially included but not limited to pressure, temperature, flow rate, etc. These measurement abilities will be appropriate to quantify the flow in the media bed.	Passed	Verified by paper design as presented in this document. Appropriate equipment was selected to collect data on all relevant measurements.
The flow cell shall have sufficient optical access to take desired measurements and images using the TR 3-D PIV equipment available in the OSU mechanical engineering department.	Passed	Verified by experimentation as outlined in section 7.
The material of the flow cell, media, and fluid must have matching indices of refraction.	Passed	Verified by final paper design as presented in this document.
The flow cell shall operate into the porous media inertial flow regime.	Passed	Verified by final paper design as presented in this document and also by experimentation as outlined in section 7.
The flow cell shall be designed to withstand operating conditions, such as pressure, temperature, and flow rate.	Passed	Verified by final paper design as presented in this document. Additional testing should be performed if a prototype is constructed.

8. PROJECT SUMMARY

8.1. Group Interactions

The original formation of the project team, like many other groups, was somewhat random. Prior to the day the team formed, none of the members had worked together or knew each other. As with most project groups, after the initial Forming period of the Team Cycle there was a Storming phase where the members of the group tested each other, established ground rules for interaction, and got to know one another [32]. The Norming phase found the group making the transition from being a group to a true team [32]. A one-for-all and all-for-one mentality formed with all team members working toward the common goal of meeting the design requirements and succeeding as a team on the project. Finally, the latter half of fall term saw the team enter the Performing phase where they have been at ever since [32].

Typical group interactions were characterized by loud and boisterous meetings, long work sessions in the labs, and strong camaraderie. When one team member couldn't complete something due to other obligations, after the requisite jovial ribbing, the other team members would pick up the slack knowing full well that when something came up for them, they too could count on the team to pull together and help them out. The team truly was a team.

As the team is writing this report they find themselves entering the Adjourning phase [32]. Looking back on their time together, they are happy with their working relationships, proud of their accomplishments and have even become friends. In spite of the major hurtles and setbacks that the project faced, the team stayed together and persevered. They ironed out their differences, became a cohesive group, and made the leap to become a true team.

8.2. Technical Knowledge Gained

As seems to be the case with most educational endeavors the team has thus far faced, the further they got into the project, the more they realized the less they knew. Certainly, technical knowledge was gained through the background research phase where the team chewed through hundreds of pages of journal articles, textbooks, and other secondary sources. The design phase saw the team processing the ASME pressure vessel codes and applying a multitude of formulae from literature and their extra-scholastic jobs to the design to assure safety and ensure that design criteria would be fully met. Knowledge was specifically gained in material selection for caustic environments, pressure vessels and proper pressure vessel sealing and bolt patterns, borosilicate manufacture and machining, caustic fluid pump selection, and a myriad of pressure and flow calculations.

The construction phase saw the team run against some major obstacles which resulted in even more background research and more formulae to design a proof-of-concept experiment that would test the major design requirements. Technical knowledge was gained in pressure fitting selection, and dye injection and imaging techniques.

Analyzing the proof-of-concept experimental data proved a valuable learning opportunity. The team gained hands-on experience with the difficulties of manually interpreting imaging data. Additional skills were gained in effective data presentation and explanation.

Writing this report significantly benefited the team's technical writing abilities. Specifically, the team improved their written technical communication and presentation skills through a multitude of rough drafts, referring to the ASME writing standard and citation guides, and learned to take advantage of peer editing within the team. Certainly, the final report, when compared to initial reports, shows marked improvement in the aforementioned areas.

8.3. Mistakes Made

This project was not without its mistakes. Some of the largest originated in communication. One in particular stands out in the team's mind with the discontinuity between expected funding and actual funding. Due to communication issues, the project sponsor was not informed that a financial outlay at the beginning of December would be expected to construct a viable prototype per the course syllabus. The team assumed that the project sponsor knew that a prototype would be constructed and that the sponsor was to provide the necessary funds. The project sponsor assumed that this senior project would follow past projects that didn't require a prototype but could instead conduct further analysis to fulfill course requirements. The course instructor assumed that the requirements of a built prototype and funds with which to construct had been relayed to the project sponsor. Because of false assumptions, the project sponsor was surprised to learn that the team expected funding, the team was surprised when the funding didn't appear, and the course instructor was surprised when the team wasn't able to build a prototype. Luckily, the team was able to continue with the project by revising their testing plan to use existing equipment. This communication blunder taught the team a valuable lesson about clarifying expectations and responsibilities at the onset of a project.

Another mistake common throughout the project was the team's underestimation of time required to complete key tasks. Because of poor time estimation skills, many late nights and weekends were spent in the labs pouring over data, designs, presentations, and project reports. Fall term's rush to complete all required work in a quality manner was quite stressful as many very long days and nights were pulled in order to meet expectations. Naturally, the team would have preferred a more balanced work load.

A particularly regrettable and unavoidable mistake came during data collection to confirm that all design requirements were met. Due to time limitations, the team was not able to conduct enough experimental runs to achieve statistical significance. Instead, the team had to conduct one run at each of the flow rates of interest before they had to return the equipment to the normal configuration and the lab to the graduate students. The team was aware of this mistake going into testing but was not able to avoid it due to the aforementioned time constraints.

8.4. Major Issues Encountered During Design Phase

Especially during the initial design phase, the team suffered from a dearth of knowledge on the subject of flow through porous media. While a great deal of background research was conducted, the team learned the most valuable information pertaining to the project when talking with the project mentor and other parties with an interest in the project. Knowing which questions to ask and the appropriate words with which to ask them turned into a large headache for the team.

Difficulty was encountered when working with the ASME pressure vessel codes. Being that this was the team's first encounter with the tomes of ASME codes, a significant amount of time was consumed even trying to navigate the index system to find the relevant codes. Once the appropriate codes had been found, additional time was required to adapt codes designed for metal pressure vessels for use with plastics as found in the team's design.

8.5. Major Issues Encountered During Build Phase

The single major issue the team encountered during the build phase was a near complete lack of funds. Rather than build the paper design as presented in this document to use in the testing phase, the team

was forced to design a new testing procedure to use existing laboratory equipment, as outlined in section 6 of this document. Had the team
No Money

8.6. Major Issues Encountered During Testing and Analysis Phase

The largest issue faced during the testing phase was the absence of a prototype. Due to the troubles with funding mentioned earlier, a prototype was not fabricated and, as mentioned earlier, a new testing scheme had to be created. The new testing scheme called for modifications to be made to the 2-D flow cell which was made available to the team. The night before the team was to make irreversible modifications to the flow cell, the project sponsor informed the team that the previously approved modifications could not be made and a non-intrusive testing method would instead have to be substituted. The team scrambled to pull together appropriate equipment and create new procedures for testing. While the team was successful in the testing endeavor, there were several tense hours as the team composed new testing procedures the night before testing was to commence.

Another major issue encountered, discussed in section 6 of this document, was a lack of time on the 2-D porous media bed. The team was only able to run one set of experiments before the lab equipment had to be returned to the graduate students who normally conduct research on said equipment. Due to a lack of data, all conclusions drawn from the testing phase are not statistically significant and, due to this, no conclusions of any weight can be drawn from the testing data. However, in spite of the dearth of experiment runs and corresponding data points, the results are instructive and suggest important areas that should be further investigated.

When analyzing the test data, the team found that it had to spend a significant amount of time analyzing the data by hand. This was due to the data coming in photographic form. Because no program that the team was familiar with could conduct the data analysis without a significant investment of time by the team into coding an analysis routine, the team chose to analyze all of the data by hand using AutoCAD as a geometric referencing tool. While this method did work well, a software program with the ability to analyze photographic data without requiring lengthy setup would have been a great benefit and time-saver for the group. Had the team acquired a larger set of data, such as would have been generated with running enough repeated experiments to achieve statistical significance, time would have been invested in creating an algorithm to automatically analyze the data.

8.7. Final Budget

Due to a lack of funding, as discussed in several earlier sections, the final project budget came to a total of $14. The lack of funding, as discussed earlier, was a significant hindrance but did not derail completion of the senior design course. Table 9, below, lists the funds available, final budget, expenditures, and final account balance. In spite of going over-budget by $14, the project sponsor approved of the cost overrun.

Table 9: Final Balance Sheet and Budget

Funds Available:	$0.00
Expenditures:	
Media Bottles, 150 ml (x 2)	$7.00/each
Final Budget:	($14.00)

8.8. Conclusion

This project, in light of the paper design and testing results, is quite promising but was limited due to a lack of funding. The project team believes that the paper design presented in this document will work as designed and will meet all original design criteria. As is evidenced by section 7, the paper design and analogous testing proved that the project meets the modified design requirements. Indications from the project sponsor point to a future implementation of the design once adequate funding has been secured.

The team is glad to have participated in this project and proud of the team's accomplishments, especially in light of the setbacks experienced. This report is the culmination of twenty weeks worth of work on this project. As is evidenced in this document, the team went from a layman's knowledge of porous media flow apparatuses, to a more advanced knowledge state. Not only did they learn how a flow bed and flow loop work, but they also designed a 3-D porous media bed and flow loop intended to push into Reynolds numbers of 400 and higher. The design not only allows for safety and a core flow free of edge effects but it also provides easy optical access for the TR 3-D PIV equipment in the possession of the project sponsor and gives relatively easy access for cleaning of the porous media between experiment runs.

All in all, the team feels that they worked well together, acquired a great deal of useful knowledge, produced a good and worthwhile final product in spite of the difficulties encountered, and are proud of their work.

Thanks for the memories,

The Porous Media Team
David Chadwick, Travis Wilhelm, Douglas Van Bossuyt

9. APPENDIX SECTION 1: ENGINEERING CALCULATIONS AND DATA

9.1. Porous Media Test Bed Pressure Drop Calculations

The pressure drop per unit length across the porous media test bed can be calculated by the following formula, [22]

$$\frac{\Delta P}{L} = \frac{\rho V_o^2(1-\varepsilon)}{D\varepsilon^3}\left[\frac{180(1-\varepsilon)}{\text{Re}} + 1.8\right] \quad \text{(Eqn. 9.1.1)}$$

where,

$$\text{Re} = \frac{\rho V_o D}{\mu} = \text{Pore Reynolds Number} \quad \text{(Eqn. 9.1.2)}$$

ε = Porosity of a Randomly Packed Bed

V_o = Volumetric Flow/Cross Sectional Area of Flow Channel.

Dr. Liburdy's [18] research interest lies in characterizing the flow in porous media for pore Reynolds numbers that range from 200 to 400. A typical calculation to determine the pressure per unit length for a flow channel cross sectional are 19.3(10-3)-m^2, volumetric flow rate of 1.55(10-3)-m^3/s, and a Re_{Pore} = 400 is as follows:

$$\frac{\Delta P}{L} = \frac{1700(0.08^2)(1-0.3)}{0.006(0.3)^3}\left[\frac{180(1-0.3)}{400} + 1.8\right] = 85849 - Pa \quad \text{(Eqn. 9.1.3)}$$

and in pressure and feet of water for a flow channel that is 0.25-m in length [23],

$$\frac{\Delta P}{L} = 3.11 - psi = 7.2 - ft \quad \text{(Eqn. 9.1.4)}$$

A spreadsheet was set up in Excel to expedite the calculations for other Reynolds numbers of interest and understand the influence that certain parameters had on it. A summary of the test bed pressure drop at for the Reynolds number range is in Table 9.1, and a spreadsheet for general calculations is presented Table 9.2.

Table 9.1: Porous Media Test Bed Pressure Drop

Flow Rate and Pressure Drop for 6mm Beads and 8 Bead Diameters beyond FOV w/ Flow Channel Length 0.280-m			
Re(Pore)	Pressure Drop, ft	Pressure Drop, psi	Flow Rate, gpm
200	1.82	0.786	12.2
400	8.04	3.48	24.5

Table 9.2: Spreadsheet for Flow Calculations and Flow Channel Sizing

"Knowns"			**"Calculated"**		
	Value	Units		Value	Units
Porocity	0.3		Vel (Macro)	0.08	m/s
Bead Diameter	0.006	m	Vel (Pore)	0.2666667	m/s
Length	0.28	m	Re (Macro)	5560	
Width	0.139	m	Re (Pore)	400	
Height	0.139	m	Pressure Drop	85687.61	Pa/m
Area	0.019321	m^2	Minmum Pressure	23992.531	Pa
Volume	0.00540988	m^3		3.4798287	psi
Density	1700	kg/m^3		8.0384042	ft
Viscocity	6.80E-03	N-s/m^2			
Viscocity (kenimatic)	4.00E-06	m^2/s			
Flow Rate	24.49960374	gpm			
	0.00154568	m^3/s			
Hydraulic Radius	0.139	m			
Cammera Calculations			**Assumptions**		
	Value	Units	1. Square Cross		
Pixel Height (Length?)	1040	pixels			
Pixel Width	1300	pixels	2		
Pixels/Bead Diameter	160	pixels/bead diameter			
FOV (Height)	6.5	bead diamters	3		
FOV (Width)	8.125	bead diamters			
Additional Bead Diamters for Boundry Effects	7.520833333	bead diamters	4		
Minimum Height (Length?)	0.12925	m			
Minimum Width	0.139	m			
Minimum Height (Length?)	5.0885725	in			
Minimum Width	5.47243	in			

9.2. MSDS Sheets for Working Fluid

MSDS - Zinc Chloride Solution Page 1 of 4

MATERIAL SAFETY DATA SHEET

Common Name	**ZINC CHLORIDE SOLUTION**
Manufacturer	Madison Industries, Inc.
	P.O. Box 175
	Old Bridge, New Jersey 08857
Telephone	(732) 727-2225
Emergency Telephone	1(800) 275-3924

This document is prepared pursuant to the OSHA Hazard Communication Standard (29 CFR 1910.1200).

SECTION I. MATERIAL IDENTIFICATION

Common Name	Zinc Chloride
Molecular Formula	$ZnCl_2$ in water
CAS Number	7646-85-7

SECTION II. PHYSICAL DATA

Physical State	Liquid
Boiling Point	120° to 150° C
	248° to 315°F
Melting Point	NA
Freezing Point*	40° to -70° F
Vapor Pressure	Ca. 3mm.
Vapor Density*	Vapor is water
Volitiles %*	29 to 50
Specific Gravity	1.57 to 2.0
Solubility in H_2O	100%
Evaporation Rate	Less than 1 (Butyl Acetate = 1)
Color	Colorless
Appearance	Clear liquid

msdszncl2.doc Madison Industries, Inc.

Figure 9.2.1: MSDS for Zinc Chloride – Page 1 [12]

MSDS - Zinc Chloride Solution | Page 2 of 4

Odor	Odorless
pH	2.0

* See Section X for specific grades and percentage

SECTION III. FIRE AND EXPLOSION DATA

Flash Point	Will not burn
Extinguishing Media	Not applicable
Special Fire Fighting Instructions	Not applicable
Fire and Explosion Hazards	May release Zinc Chloride and Zinc Oxide fumes and Hydrogen Chloride gas in a fire.

SECTION IV. REACTIVITY DATA

Stability	Very stable at high temperatures.
Incompatibility	Cyanide - may release toxic HCN
	Sulfides - may release toxic Hydrogen Sulfide
Decomposition	Will not occur except at high temperatures.
Polymerization	Will not occur.

SECTION V. HEALTH AND HAZARD INFORMATION

Exposure Limits	OSHA 8 hour Time Weighted Average (TWA) and ACGIH TLV-TWA for Zinc Chloride (fume) are one mg. Per cubic meter.
Swallowing	May cause burns of mouth and throat.
Skin	May cause severe skin burns.
Eyes	May cause severe cornea injury and result in permanent impairment of vision or even blindness.
Inhalation	Dusts, mists or vapors, may cause severe irritation to upper respiratory tract. Severe exposure may cause pulmonary edema. Metal fume fever may result from inhaling Zinc Oxide, which is a possible decomposition product at high temperatures.
Carcinogenicity	None as per NTP, OSHA, and IARC.

msdszncl2.doc | Madison Industries, Inc.

Figure 9.2.2: MSDS for Zinc Chloride – Page 2 [12]

MSDS - Zinc Chloride Solution | Page 3 of 4

SECTION VI. FIRST AID PROCEDURES

Swallowing	Give large amounts of milk or water. Do not Induce vomiting. Call Poison Control Center or a physician. Do not give anything by mouth to an unconscious person.
Skin	Immediately flush skin with plenty of water for 15 minutes. Remove contaminated clothing and shoes. Call a physician. Wash contaminated clothing before reuse.
Eyes	Immediately flush eyes with plenty of water for 15 minutes. Hold eyelids apart during irrigation. Call a physician.
Inhalation	If dusts, mists or vapors are inhaled, immediately remove person to fresh air and call a physician.
Carcinogenicity	None

SECTION VII. HANDLING PRECAUTIONS

Personal Protective Equipment	Chemical safety goggles. Rubber gloves. When needed: rubber apron, rubber shoes and transparent face shield.
Ventilation	Maintain good general ventilation to keep mists below exposure guidelines.

SECTION VIII. SPILL OR LEAK PROCEDURES

Spills and Leaks	Comply with Federal, State and local regulations on reporting spills. Flush with plenty of water to an approved chemical sewer.
Waste Disposal	Comply with Federal, State and local regulations. Zinc Chloride can be carefully reacted with Sodium Carbonate to from an insoluble Zinc Carbonate solid that can be scooped up and sent to a disposal contractor.

SECTION IX. SPECIAL PRECAUTIONS

Storage	Do not store in a steel container. Plastic or plastic lined or rubber lined containers or storage tanks should be used.

SECTION X. PHYSICAL PROPERTIES CONTINUED FROM SECTION II

Properties	50.0%	62.5%	65.0%	70.0%	72.0%
Weight per Gallon (lbs.)	13.08	14.83	15.33	16.33	16.74
Specific Gravity	1.57	1.78	1.84	1.96	2.01

msdszncl2.doc | Madison Industries, Inc.

Figure 9.2.3: MSDS for Zinc Chloride – Page 3 [12]

Properties	**50.0%**	**62.5%**	**65.0%**	**70.0%**	**72.0%**
Boiling Point °F	239	253	259	275	283
Freezing Point °F	-70	-50	-40	38	40
Volitiles %	50.0	37.5	35.0	30.0	28.0
Viscosity Centipoise 70°F	3.6	9.0	14.0	40.0	41.0
Zinc Content (SARA 313)	**24%**	**30%**	**31.2%**	**33.6%**	**34.6%**

SECTION XI. REGULATORY INFORMATION

NOTICE: The information herein is presented in good faith and believed to be accurate. However, no warranty, expressed or implied, is given. Regulatory requirements are subject to change and may differ from one location to another. It is the buyer's responsibility to ensure that its activities comply with Federal, State and local laws.

U.S. REGULATIONS: SARA 313 Information. This product contain the following substance subject to the reporting requirements of Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 and 40 CFR Part 372: **ZINC COMPOUND** See Section X for concentrations.

SARA HAZARD CATEGORY: This product has been reviewed according to the EPA "Hazard Categories" promulgated under Sections 311 and 312 of the Superfund Amendments and Reauthorization Act of 1986 (SARA Title III) and is considered, under applicable definitions, to meet the following category: **AN IMMEDIATE HEALTH HAZARD**.

SECTION XII. SHIPPING INFORMATION

ZINC CHLORIDE SOLUTION, 8, UN1840, PGIII, RQ, ERG 154

SECTION XIII. MSDS PREPARATION INFORMATION

Prepared by	Joel L. Goldschmidt, Vice President
Updated	March 16, 1999

Figure 9.2.4: MSDS for Zinc Chloride – Page 4 [12]

The above Figures 9.2.1-4 display the Material Safety Data Sheet for Zinc Chloride solutions. Specific attention should be paid to toxilogical data and reactivity data.

9.3. Honeycomb Flow Straightener Length Determination

To determine the length of honeycomb to straighten the flow entering the porous media test bed, a few assumptions need to be made. As a first assumption, the velocity profile must uniform and fully developed before entering the honeycomb. Next, it is assumed that the flow is evenly distributed over the channels of the honeycomb. From this it can be written that the flow rate of the channel is equal to the sum of the flow rates of the individual channel, that is [24],

$$Q_c = nQ_h \qquad \text{(Eqn. 9.3.1)}$$

and from the definition of volumetric flow rate [24],

$$\left(AV\right)_c = n\left(AV\right)_h \qquad \text{(Eqn. 9.3.2)}$$

Solving for the honeycomb velocity and estimating the ratio of the areas to be 1.11 then the velocity in a single flow channel has the value of,

$$V_h = \left(\frac{A_c}{nA_h}\right)V_c = 1.11V_c = 1.11(0.04\frac{m}{s}) = 0.044\frac{m}{s} \qquad \text{(Eqn. 9.3.3)}$$

From this the Reynolds number can be calculated for a single channel in the honeycomb for a channel diameter of 5-mm (smaller than the bead diameter), and has the value,

$$\mathrm{Re}_h = \frac{Vd}{\upsilon} = \frac{\left(0.044\frac{m}{s}\right)\left(0.005m\right)}{4\left(10^{-6}\right)\frac{m}{s}} = 55 \qquad \text{(Eqn. 9.3.4)}$$

A Reynolds number of 55 places the flow within the laminar flow region for pipe flow. By substituting in known values and from F. M. White's *Fluid Mechanics,* [24] the length for fully developed flow in the laminar flow region can be determined from,

$$L \approx 0.06\left(\mathrm{Re}\right)\left(d\right) = 0.06\left(55\right)\left(0.005m\right) = 0.0165m \qquad \text{(Eqn. 9.3.5)}$$

It can be concluded that the minimum length of honeycomb to ensure fully developed laminar flow into the test bed is to be 17-mm.

9.4.ATF Fathom Output (Low Flow Rate)

AFT Fathom 6.0 Output (1 of 2) 12/2/2006
CH2M HILL
AFT Fathom Model

General

Title: AFT Fathom Model
Analysis run on: 12/2/2006 9:16:52 AM
Application version: AFT Fathom Version 6.0 (2006.04.12)
Input File: C:\Documents and Settings\dchadwic\Desktop\David Chadwick\Homework Dead Week\Porous Media Test Loop.fth
Scenario: Base Scenario/Flooded State C-72009-00/Flooded State C-72009-00 (Small Diameter Pipe)

Execution Time= 0.11 seconds
Total Number Of Head/Pressure Iterations= 0
Total Number Of Flow Iterations= 34
Total Number Of Temperature Iterations= 0
Number Of Pipes= 8
Number Of Junctions= 8
Matrix Method= Gaussian Elimination

Pressure/Head Tolerance= 0.0001 relative change
Flow Rate Tolerance= 0.0001 relative change
Temperature Tolerance= 0.0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Constant Fluid Property Model
Fluid Database: Unspecified
Fluid= Zinc Chloride
Density= 1700 kg/m3
Viscosity= 0.0068 kg/sec-m
Vapor Pressure= Unspecified
Viscosity Model= Newtonian

Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Total Inflow= 3.691E-07 gal/min
Total Outflow= 3.691E-07 gal/min
Maximum Pressure is 49.27 psia at Junction 8 Inlet
Minimum Pressure is 15.05 psia at Junction 2 Inlet

Pump Summary

Jct	Name	Vol. Flow (gal/min)	dH (feet)	Overall Power (hp)
2	Pump	9.912	46.05	0.1962

Valve Summary

Jct	Name	Valve Type	Vol. Flow (gal/min)	Mass Flow (lbm/sec)	dP Stag. (psid)	dH (feet)	P Inlet Static (psia)	Cv	K	Valve State
8	Valve	REGULAR	9.912	2.344	31.63	42.92	49.27	2.299	204.0	Open

Reservoir Summary

Jct	Name	Type	Liq. Height (feet)	Liq. Elevation (feet)	Surface Pressure (psia)	Liquid Volume (feet3)	Liquid Mass (lbm)	Net Vol. Flow (gal/min)	Net Mass Flow (lbm/sec)
1	Reservoir	Infinite	N/A	6.000	14.70	N/A	N/A	0	0

Pipe Output Table

AFT Fathom 6.0 Output (2 of 2) 12/2/2006
CH2M HILL
AFT Fathom Model

Pipe	Name	Pipe Nominal Size	Vol. Flow Rate (gal/min)	Velocity (feet/sec)	dH (feet)	P Static In (psig)	P Static Out (psig)
1	Pipe	2 inch	9.912	0.9477	0.003117	0.3531	0.3508
2	Pipe	1 inch	9.912	3.6794	0.080641	34.1468	34.0874
3	Pipe	1 inch	9.912	3.6794	0.040320	34.0167	34.3555
4	Pipe	1 inch	9.912	3.6794	0.080641	34.2633	34.5724
5	Pipe	1 inch	9.912	3.6794	0.302403	2.9406	5.4814
6	Pipe	1 inch	9.912	3.6794	0.161281	5.4107	5.2919
7	Pipe	1 inch	9.912	3.6794	0.443524	5.2211	0.8408
8	Pipe	1 inch	9.912	3.6794	0.044862	0.7701	0.0000

All Junction Table

Jct	Name	dP Static Total (psid)	P Static In (psig)	P Static Out (psig)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Reservoir	N/A	0.0000	N/A	N/A	N/A	1.5000
2	Pump	-33.79605	0.3508	34.1468	9.912	2.344	0.0000
3	Bend	0.07072	0.8408	0.7701	9.912	2.344	0.4561
4	Bend	0.07072	5.2919	5.2211	9.912	2.344	0.4561
5	Bend	0.07072	5.4814	5.4107	9.912	2.344	0.4561
6	General Component	0.09211	34.3555	34.2633	9.912	2.344	4.1588
7	Bend	0.07072	34.0874	34.0167	9.912	2.344	0.4561
8	Valve	31.63185	34.5724	2.9406	9.912	2.344	204.0000

Junction Loss Table

Jct	Pipe #	Pipe Dir.	Loss Factor (K)
1	P1	Out	0.5000
	P8	In	1.000

9.5.AFT Fathom Output (High Flow Rate)

AFT Fathom 6.0 Output (1 of 2) 12/2/2006
CH2M HILL
AFT Fathom Model

General

Title: AFT Fathom Model
Analysis run on: 12/2/2006 9:18:27 AM
Application version: AFT Fathom Version 6.0 (2006.04.12)
Input File: C:\Documents and Settings\dchadwic\Desktop\David Chadwick\Homework Dead Week\Porous Media Test Loop.fth
Scenario: Base Scenario/Flooded State C-72009-00/Flooded State C-72009-00 (Small Diameter Pipe)

Execution Time= 0.10 seconds
Total Number Of Head/Pressure Iterations= 0
Total Number Of Flow Iterations= 16
Total Number Of Temperature Iterations= 0
Number Of Pipes= 8
Number Of Junctions= 8
Matrix Method= Gaussian Elimination

Pressure/Head Tolerance= 0.0001 relative change
Flow Rate Tolerance= 0.0001 relative change
Temperature Tolerance= 0.0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Constant Fluid Property Model
Fluid Database: Unspecified
Fluid= Zinc Chloride
Density= 1700 kg/m3
Viscosity= 0.0068 kg/sec-m
Vapor Pressure= Unspecified
Viscosity Model= Newtonian

Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Total Inflow= 1.511E-06 gal/min
Total Outflow= 1.511E-06 gal/min
Maximum Pressure is 31.38 psia at Junction 2 Outlet
Minimum Pressure is 14.89 psia at Junction 2 Inlet

Pump Summary

Jct	Name	Vol. Flow (gal/min)	dH (feet)	Overall Power (hp)
2	Pump	31.19	24.31	0.3259

Valve Summary

Jct	Name	Valve Type	Vol. Flow (gal/min)	Mass Flow (lbm/sec)	dP Stag. (psid)	dH (feet)	P Inlet Static (psia)	Cv	K	Valve State
8	Valve	REGULAR	31.19	7.374	0.3224	0.4374	24.54	71.65	0.2100	Open

Reservoir Summary

Jct	Name	Type	Liq. Height (feet)	Liq. Elevation (feet)	Surface Pressure (psia)	Liquid Volume (feet3)	Liquid Mass (lbm)	Net Vol. Flow (gal/min)	Net Mass Flow (lbm/sec)
1	Reservoir	Infinite	N/A	6.000	14.70	N/A	N/A	0	0

Pipe Output Table

AFT Fathom 6.0 Output (2 of 2) 12/2/2006
CH2M HILL
AFT Fathom Model

Pipe	Name	Pipe Nominal Size	Vol. Flow Rate (gal/min)	Velocity (feet/sec)	dH (feet)	P Static In (psig)	P Static Out (psig)
1	Pipe	2 inch	31.19	2.982	0.02371	0.2157	0.1983
2	Pipe	1 inch	31.19	11.578	0.59660	16.6811	16.2414
3	Pipe	1 inch	31.19	11.578	0.29830	15.5413	15.6899
4	Pipe	1 inch	31.19	11.578	0.59660	9.9175	9.8463
5	Pipe	1 inch	31.19	11.578	2.23724	9.5239	10.6388
6	Pipe	1 inch	31.19	11.578	1.19320	9.9387	9.0593
7	Pipe	1 inch	31.19	11.578	3.28129	8.3591	1.8873
8	Pipe	1 inch	31.19	11.578	0.61083	1.1872	0.0000

All Junction Table

Jct	Name	dP Static Total (psid)	P Static In (psig)	P Static Out (psig)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Reservoir	N/A	0.0000	N/A	N/A	N/A	1.5000
2	Pump	-16.4829	0.1983	16.681	31.19	7.374	0.0000
3	Bend	0.7002	1.8873	1.187	31.19	7.374	0.4561
4	Bend	0.7002	9.0593	8.359	31.19	7.374	0.4561
5	Bend	0.7002	10.6388	9.939	31.19	7.374	0.4561
6	General Component	5.7724	15.6899	9.918	31.19	7.374	4.1201
7	Bend	0.7002	16.2414	15.541	31.19	7.374	0.4561
8	Valve	0.3224	9.8463	9.524	31.19	7.374	0.2100

Junction Loss Table

Jct	Pipe #	Pipe Dir.	Loss Factor (K)
1	P1	Out	0.5000
	P8	In	1.000

9.6. Flow Rate Calculations

The ranges of Reynolds numbers dictate the flow rate of the system. Based on the design requirements the flow loop is to operate between Reynolds numbers of 200 and 400. The flow rates associated with this range can be found by the making the following assumptions and calculations. The quoted Reynolds number is the average Reynolds number through the pore of the porous media. If D is the bead diameter, V_{pore} is the average velocity through the pore of the porous media, and the working fluid has a viscosity of ν, then the pore Reynolds number has the following form:

$$\mathrm{Re}_{pore} = \frac{DV_{pore}}{\nu}. \quad \text{(Eqn. 9.6.1)}$$

Solving for the pore velocity, and recognizing that the average pore velocity can be estimated by dividing the macroscopic velocity by the porosity of the porous media, the above equation becomes,

$$V_{pore} = \frac{V}{\varepsilon} = \frac{\nu\,\mathrm{Re}_{pore}}{D} \quad \text{(Eqn. 9.6.2)}$$

Upon making appropriate substitutions for the macroscopic flow rate, the flow rate for the system can be solved and determined by,

$$Q = \frac{\varepsilon \nu A \mathrm{Re}_{pore}}{D} \quad \text{(Eqn. 9.6.3)}$$

See Table 9.6.1 below for a summary of the flow rates the flow loop is designed for.

Table 9.6.1: Flow Rate Final Calculations

Flow Rate Final Calculations							
Reynolds Number		Porosity	Viscosity (m^2/s)	Flow Channel Dimension (m)	Area (m^2)	Bead Diameter (mm)	Flow Rate (gpm)
MIN	200	0.3	4.00E-06	0.139	0.019321	6	12.25
MAX	400						24.5

9.7. Pump Horsepower Preliminary Calculation

A maximum estimate of horsepower for the pump can be determined by analyzing the flow loop. From the schematic in Figure 9.7.1, the system is a closed loop drawing and delivering to the same reservoir.

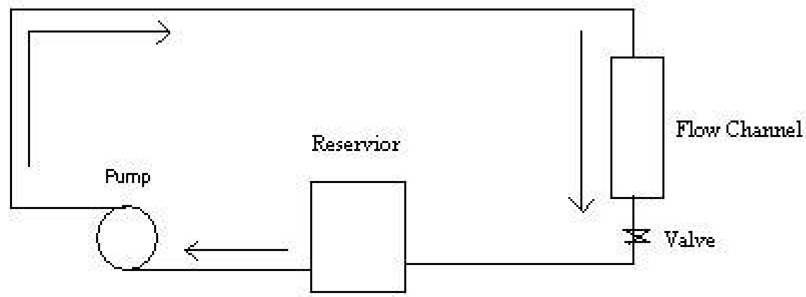


Figure 9.7.1: Porous Media Flow Channel Schematic

The steady flow energy equation (Bernoulli's equation) applies. And also accounting frictional head losses in the pipe, minor losses in the elbows and valves, and the head loss across flow channel, the equation then becomes [24],

$$(\frac{p_1}{\rho g}+\frac{V_1^2}{2g}+z_1)=(\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+z_2)+h_f+h_m-h_p \quad \text{(Eqn. 9.7.1)}$$

Observing the fact that the reservoir is the same for both states, the pump head then becomes,

$$h_p = h_f + h_m \quad \text{(Eqn. 9.7.2)}$$

The pump head then can be determined from any appropriate source. Here the source, Ingersoll-Rand Cameron Hydraulic Data, was used. The head loss can be calculated from their appropriate tables. In this preliminary calculation steel pipe was chosen as the material, an appropriate estimated length of pipe and fittings were decided upon, and "worst case" flow rate was used (24-gpm). From Cameron Hydraulic Data [23], the pump head becomes,

$$h_p = L(h_{100})+\left(\sum K_i\right)\left(\frac{V^2}{2g}\right)+h_{FC} \quad \text{(Eqn. 9.7.3)}$$

where,

h_{100} = head loss per 100 feet
K_i = resistance coefficient
h_{fc} = flow channel head.

The above equation was implemented into a spreadsheet and as a first pass a value was determined for the horsepower (see Table 9.7.1).

Table 9.7.1: Pump Horsepower Spreadsheet

Pump Horsepower Spreadsheet			
Pipe Data:			
Pipe Diameter	1		
Flow Rate	24		
Velocity	8.904		
Velocity Head	1.23264		
Head Loss/100-ft	35.8		
Frictional Pipe Losses		Head Loss	
Length of Pipe	20	7.16	
Minor Losses			
Effect	No.	K	Total K
Entrance and Exits	2	1	2
Elbows	6	0.57	3.42
Valves	1	7.8	7.8
Enlargement (in)	1	2.5835613	2.58356126
Enlargement (out)	1	0.7949419	0.79494193
Grand Total K			16.5985032
Total Minor Losses			20.459979
Losses Due to Porous Media at 20-gpm	ft		
Porous Media	8.04		
Honeycomb			
Pump Head	35.65998		
hp	7.362037		
1.5*hp	11.04306		

Unfortunately, this number seemed to be on the extreme high side. It is presumed that this difference lays in the fact that the roughness coefficient of steel is 2 orders of magnitude larger that PVC. However a much more efficient way to determine an estimate for the horsepower of the pump is to employ the uses of AFT Fathom (see Appendices E and F for output). This program provided a more reasonable estimate for horsepower at 1-hp maximum.

9.8. Wall Thickness Calculations

The ASME pressure vessel code gives the following formulas to determine wall thickness for non-circular plates and flat covers which is analogous to the wall design of the test section presented in this document [29,30].

$$t = d\sqrt{(ZCP/(SE)} \quad \text{(Eqn. 9.8.1)}$$

where,

$$Z = 3.4 - (2.4d/D) \leq 2.5 \quad \text{(Eqn. 9.8.2)}$$

where the variables are defined as:

d = effective diameter of the flat plate (in)
C = corner detail coefficient (chosen to be 0.2 as a conservative estimate)
P = design pressure (psi)
S = allowable stress at the design temperature and pressure (psi)
E = butt-welded joint efficiency of the joint within the flat plate (E=1 in this design)
t = minimum required thickness of the flat plate (in)

For ABS plastic, it was determined that wall thickness should be at least 0.244 in to meet pressure vessel standards. With a conservative factor of safety of 2, wall thickness comes to approximately 0.5 in. The final design thickness was approximately 1 in which was largely dictated by the Intro-Serts. Details of the calculations can be seen in Table 9.8.1.

Table 9.8.1: Wall Thickness Spreadsheet

		Finding Plate Thickness for a Pressure Vessel				
Plate Dimensions						
Width (m)	0.15	d (small length) (in)	5.905512			
Length (m)	0.31	D (large length) (in)	12.20472			
		C (corner detail coefficient, referenced from page 99)	0.2		Z (non-uniform membrane correction factor)	2.23871
		P (design pressure) (psi)	30		t (minimum plate thickness) (in)	0.245
		S (allowable stress at design temperature & psi) (psi)	7830		Thickness with factor of safety (in)	0.489
		E (joint efficiency of the joint within the flat plate - if no	1		Tickness with factor of safety (m)	0.012
		N factor of safety	2			

9.9. Cumulative Force Calculations on Honeycomb Flow Straightener

As depicted in Figure 9.7.1, the flow channel will be oriented vertically, with the direction of flow along the component of gravity. The flow straighteners will be oriented perpendicular to the flow, and thus the downstream flow straightener will be supporting the weight of the beads and the force created by the pressure drop across the beads of the porous media. Consideration must be given to the magnitude of the resultant force that is supported on the honeycomb flow straightener.

The total weight of the beads in the porous media test bed can be approximated by,

$$W_{GB} = g(1-\varepsilon)V_T\rho_{GB} = \left(9.8\frac{m}{s}\right)(0.7)\left(0.280\left(0.139^2\right)m^3\right)\left(2.23\left(10^3\right)\frac{kg}{m^3}\right) = ... = 18.5 - lbs\,.$$

(Eqn. 9.9.1)

Where V_T is the total volume of the test section, p_{GB} is the density of borosilicate glass beads, and epsilon is the porosity.

The resulting force due to the pressure drop across the glass beads of the porous media can be approximated by,

$$F_{dP} = dPA_C = (21.4kPa)(0.139m)^2 = ... = 93.0 - lbs\,. \quad \text{(Eqn. 9.9.2)}$$

Where A_c is the cross-sectional area of the flow channel and the dP is the pressure drop at maximum flow.

The total force that the flow straightener is support is 111.5-lbs. Invoking a safety factor of two, the total approximate weight is thus 200-lbs. An applications engineer for the flow straightener was contacted to see if this force could be supported by polycarbonate flow straightener, and it was determined that a minimum of one inch should be used. The design presented in this paper uses a 30 mm flow straightener.

9.10. Viewing Window Thickness Calculations and Spreadsheet

Table 9.10.1: Brittle Plate Theory

Conversion		Properties		(units)
(psi)	(Mpa)	E =	64000	MPA
30	0.20684271	σ =	3.5	MPA
		Po =	0.41368542	MPA
Formula Components		**Window Size**		**(units)**
Moment =	212.2206205	height	100	(mm)
safety factor	2	width	100	(mm)
		thickness	19.07371956	(mm)
		conversion	0.75	(in)

Equations in Spreadsheet

Brittle Plate Theory [26]:

$$M = 0.0513\left(nP_o\right)a^2 \qquad \text{(Eqn. 9.10.1)}$$

$$\sigma = \frac{\left(6M\right)}{h^2} \qquad \text{(Eqn. 9.10.2)}$$

where:

σ = max tensile stress
P_o = pressure applied to surface
a = length of sides
M = moment caused by bending
n = factor of safety

9.11. Component Source Datasheet

Figure 9.11.1: ABS Plastic Source Data Sheet

Figure 9.11.2: UHMW Plastic Source Data Sheet

SPECIALTY GLASS PRODUCTS, INC.

2885 TERWOOD RD., WILLOW GROVE, PA 19090 USA

PHONE (215) 659-8400 FAX (215) 659-7217

Email: sales@sgpinc.com www.sgpinc.com

November 30, 2006

Inquiry #I06112904 (1), #I06112806 (2)

Travis Wilhelm

Oregon State University

1942 Madras Street SE

Salem, OR 97306

Ph: 503-459-3599

wilhelmt@engr.orst.edu

Dear Travis:

Thank you for the opportunity to support your specialty glass requirements. In response to your recent request, SGP is pleased to propose the following:

1. Schott Borofloat Square; 120mm+-.25mm square; 20mm+-.25mm thick; 4 corners approximately 7.5mm radius; seamed edges; top and bottom surfaces polished finish.

Figure 9.11.3.1: Viewing Window Source Data Sheet

Quantity	1 piece	Price	$275.00 each
	2 pieces		$190.00 each
	5 pieces		$155.00 each

Ship Start 4 weeks ARO

2. Schott Borofloat Square; 120mm+-.25mm square; 25mm standard thickness; 4 corners approximately 7.5mm radius; seamed edges.

Quantity	1 piece	Price	$175.00 each
	2 pieces		$139.00 each
	5 pieces		$ 95.00 each

Ship Start 3 weeks ARO

Terms FOB Willow Grove, PA. Net 30 days.

or

Terms Credit Card, FOB Willow Grove, PA.

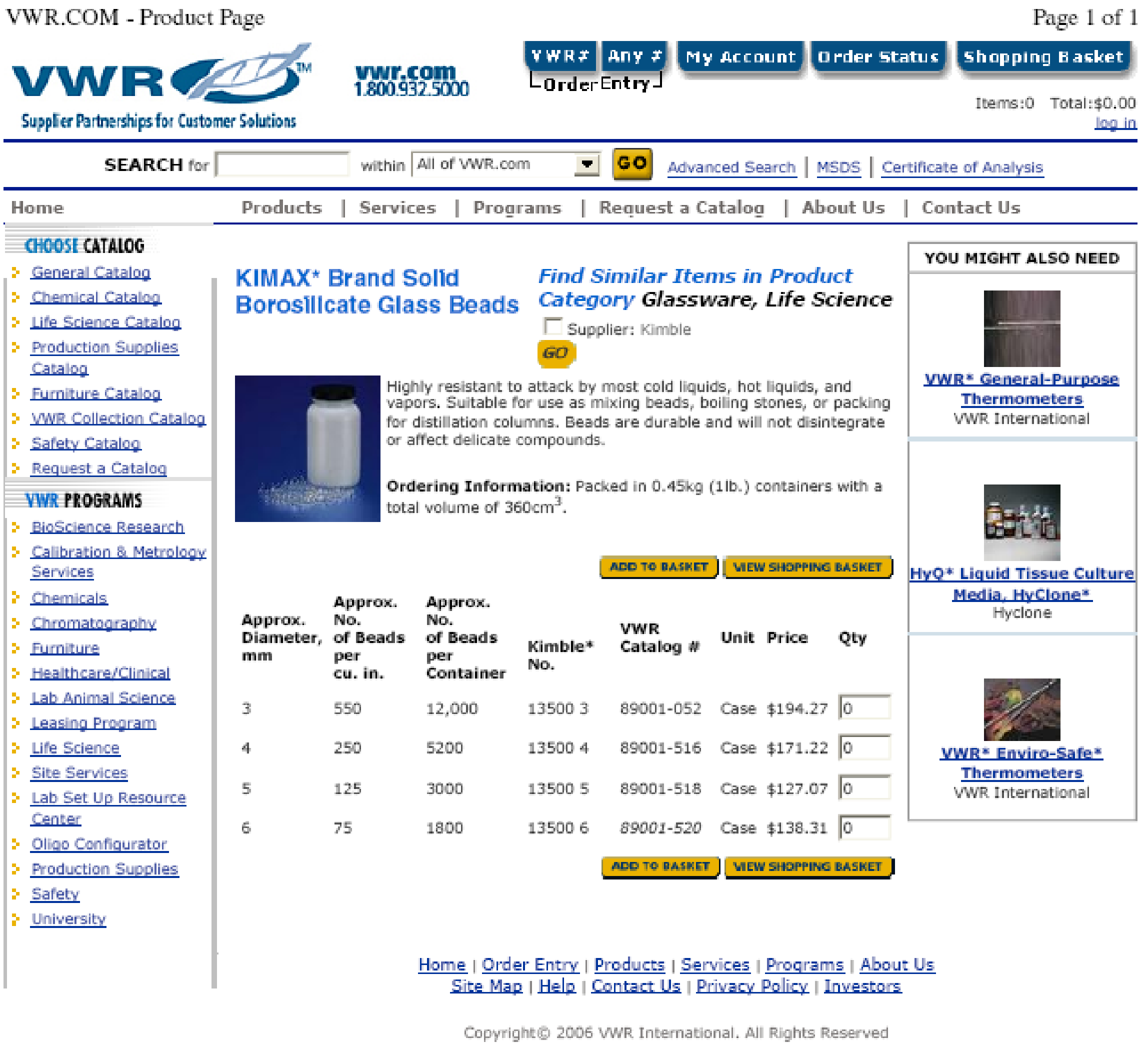
Travis, if you have any questions concerning this quotation, or if you would like to place an order, please contact Ursula Leslie, Customer Service/Support (ursula@sgpinc.com).

Best regards,

Beau Harrington

Sales Engineer

Figure 9.11.3.2: Viewing Window Source Data Sheet



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- University

KIMAX* Brand Solid Borosilicate Glass Beads

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Highly resistant to attack by most cold liquids, hot liquids, and vapors. Suitable for use as mixing beads, boiling stones, or packing for distillation columns. Beads are durable and will not disintegrate or affect delicate compounds.

Ordering Information: Packed in 0.45kg (1lb.) containers with a total volume of 360cm³.

ADD TO BASKET | VIEW SHOPPING BASKET

Approx. Diameter, mm	Approx. No. of Beads per cu. in.	Approx. No. of Beads per Container	Kimble* No.	VWR Catalog #	Unit	Price	Qty
3	550	12,000	13500 3	89001-052	Case	$194.27	0
4	250	5200	13500 4	89001-516	Case	$171.22	0
5	125	3000	13500 5	89001-518	Case	$127.07	0
6	75	1800	13500 6	89001-520	Case	$138.31	0

ADD TO BASKET | VIEW SHOPPING BASKET

YOU MIGHT ALSO NEED
- VWR* General-Purpose Thermometers — VWR International
- HyQ* Liquid Tissue Culture Media, HyClone* — Hyclone
- VWR* Enviro-Safe* Thermometers — VWR International

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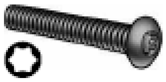
Figure 9.11.4: Glass Beads Source Data Sheet

Socket Head Cap Screws

Technical drawings and 3-D models available for items with this symbol CAD

Black-Oxide Alloy Steel Torx Button Head



Drive offers improved driveability and reduced bit slippage. Screws offer a wider bearing surface and low head height. Because of the head configuration, these screws are not recommended for use in high strength applications where socket head cap screws should be used. Finish offers mild rust resistance and some lubricity. Class 3A thread fit. Rockwell hardness is C39-C44. Min. tensile strength is 145,000 psi. Length is measured from under head. Fully threaded.

For Torx tools, see pages 2683-2684 and 2698-2699. For head dimensions, see page 2978.

Lg.	Pkg. Qty.		Per Pkg.
4-40			*Torx Key: T8*
¼"	100	96452A106	$11.92
⅜"	100	96452A108	12.57
½"	100	96452A110	12.89
6-32			*Torx Key: T10*
¼"	100	96452A144	$12.43
⅜"	100	96452A146	12.57
½"	100	96452A148	13.16
⅝"	100	96452A150	13.97
8-32			*Torx Key: T15*
¼"	100	96452A190	$13.59
⅜"	100	96452A192	13.76
½"	100	96452A194	14.38
¾"	100	96452A197	14.95
10-24			*Torx Key: T25*
¼"	100	96452A238	$13.89
½"	100	96452A242	14.51
¾"	100	96452A245	14.95
1"	50	96452A246	10.30
10-32			*Torx Key: T25*
⅜"	100	96452A311	$14.05
½"	100	96452A314	14.51
⅝"	50	96452A319	8.53
1"	50	96452A331	11.01
¼"-20			*Torx Key: T27*
⅜"	100	96452A535	$14.86
½"	100	96452A537	14.70
¾"	100	96452A540	14.93
1"	50	96452A542	10.47
5/16"-18			*Torx Key: T40*
½"	50	96452A578	$9.61
¾"	50	96452A581	10.84
1"	25	96452A585	6.84
⅜"-16			*Torx Key: T45*
½"	25	96452A619	$7.50
¾"	25	96452A622	8.60
1¼"	25	96452A628	10.63

Metric Button Head—Hex Socket

Use for a wider bearing surface and low head height. Not for use in high strength applications. Length is measured from under head. Screws indicated with a ♣ are always fully threaded. ***18-8 stainless steel*** offers excellent corrosion resistance. May be mildly magnetic. Not tested for Rockwell hardness. Min. tensile strength is 101,000 psi. Class 6g thread fit. ***Class 10.9 black-oxide steel*** is comparable to Grade 8. Finish provides mild rust resistance. Rockwell hardness is C32-C39. Minimum tensile strength is 145,000 psi. Class 5g/6g thread fit.

Also Available: Screws in high-visibility blue-coated Class 10.9 steel in sizes marked with ■. Please ask for 94722A200 and specify thread size and length.

Hex Key and Head Dimensions, mm									
Screw Size	M2	M2.5	M3	M4	M5	M6	M8	M10	M12
Key Size	1.3	1.5	2	2.5	3	4	5	6	8
Head Ht.	1.3	1.5	1.65	2.2	2.75	3.3	4.4	5.5	6.6
Head Dia.	3.5	4.5	5.7	7.6	9.5	10.5	14	17.5	21
Min. Thread Lg.	Full	Full	18	20	22	24	28	32	36

Lg., mm	Pkg. Qty.		Per Pkg.
18-8 Stainless Steel—ISO 7380-A2			
M3			*Pitch: 0.5 mm*
5	100	92095A177♣	$10.37
6	100	92095A179♣	3.72
8	100	92095A181♣	6.50
10	100	92095A182♣	8.28
12	100	92095A183♣	11.87
14	50	92095A168♣	5.00
16	100	92095A184♣	13.34
20	100	92095A185	8.09
25	100	92095A186	7.98
30	100	92095A187	8.05
35	25	92095A201	4.79
40	25	92095A203	6.60
M4			*Pitch: 0.7 mm*
6	100	92095A188♣	$7.62
8	100	92095A189♣	7.90
10	100	92095A190♣	8.09
12	100	92095A192♣	9.93
14	50	92095A193♣	6.90
16	100	92095A194♣	9.05
20	50	92095A196♣	5.48
25	100	92095A197	11.90
30	50	92095A198	8.14
35	25	92095A199	4.68
40	25	92095A200	6.18
45	25	92095A205	5.85
50	10	92095A209	3.61
M5			*Pitch: 0.8 mm*
8	100	92095A207♣	$10.48
10	100	92095A208♣	10.48
12	100	92095A210♣	11.90
14	50	92095A211♣	12.05
16	100	92095A212♣	13.34
20	50	92095A214♣	7.81
25	25	92095A216♣	4.88
30	25	92095A218♣	5.95
35	25	92095A220	6.43
40	25	92095A222	8.57
45	25	92095A223	7.42
50	25	92095A228	9.76
60	10	92095A225	6.48
M6			*Pitch: 1 mm*
8	25	92095A239♣	$6.99
10	50	92095A224♣	7.38
12	50	92095A226♣	8.10
M6 (Cont.)			
14	25	92095A227♣	$9.31
16	25	92095A238♣	4.76
20	25	92095A240♣	5.48
25	25	92095A242♣	6.26
30	25	92095A244♣	7.26
35	25	92095A246	8.22
40	25	92095A248	9.64
45	10	92095A250	4.75
50	10	92095A252	6.24
55	10	92095A253	6.29
60	10	92095A254	6.72
M8			*Pitch: 1.25 mm*
10	25	92095A256♣	$11.63
12	25	92095A258♣	9.89
16	25	92095A260♣	9.38
20	25	92095A284♣	10.55
25	10	92095A286♣	5.05
30	10	92095A290♣	5.72
35	10	92095A292♣	6.19
40	10	92095A294♣	6.48
45	10	92095A296	9.28
50	5	92095A298	4.90
55	5	92095A299	8.21
60	5	92095A300	5.86
M10			*Pitch: 1.5 mm*
16	10	92095A408♣	$8.95
20	10	92095A410♣	7.62
25	10	92095A413♣	9.14
30	10	92095A416♣	9.52
40	10	92095A420♣	10.48
50	10	92095A424	12.38
55	5	92095A426	10.24
60	5	92095A429	11.43
M12			*Pitch: 1.75 mm*
20	10	92095A428♣■	$10.71
25	5	92095A427♣■	5.90
30	5	92095A431♣■	6.55
35	5	92095A432♣	9.24
40	5	92095A434♣	10.78
45	5	92095A435♣	10.76
50	5	92095A437♣	11.88
55	5	92095A440	14.88
60	5	92095A442	13.93
Class 10.9 Black-Oxide Steel—ISO 7380			
M2			*Pitch: 0.4 mm*
3	10	91239A700♣	$5.92
4	10	91239A703♣	8.29
M2 (Cont.)			
6	25	91239A704♣	$12.16
12	25	91239A707♣	13.93
Class 10.9 Black-Oxide Steel—ISO 7380 (Cont.)			
M2.5			*Pitch: 0.45 mm*
3	10	91239A752♣	$5.83
6	25	91239A755♣	10.63
12	25	91239A758♣	13.13
M3			*Pitch: 0.5 mm*
5	50	91239A110♣	$8.56
6	100	91239A111♣	5.60
8	100	91239A113♣■	5.24
10	100	91239A115♣■	5.60
12	100	91239A117♣■	6.40
14	100	91239A118♣	9.43
16	100	91239A120♣■	7.39
20	100	91239A122■	9.00
25	100	91239A126	13.21
M4			*Pitch: 0.7 mm*
6	100	91239A138♣	$6.35
8	100	91239A140♣■	7.39
10	100	91239A144♣■	7.39
12	100	91239A148♣■	7.25
14	100	91239A149♣	11.07
16	100	91239A150♣■	8.26
20	100	91239A152♣■	8.40
25	100	91239A154■	10.43
30	100	91239A156	10.40
35	50	91239A158	9.94
40	25	91239A160	6.84
M5			*Pitch: 0.8 mm*
6	100	91239A220♣	$10.22
8	100	91239A222♣	10.00
10	100	91239A224♣■	6.96
12	100	91239A228♣■	6.25
14	100	91239A230♣	14.00
16	100	91239A232♣■	7.83
18	100	91239A241♣	14.95
20	100	91239A233♣■	8.00
22	100	91239A242♣	14.79
25	100	91239A234♣■	8.80
30	100	91239A236♣■	10.00
35	50	91239A238	8.36
40	10	91239A240	8.12
45	10	91239A244	4.61
M6			*Pitch: 1 mm*
8	100	91239A314♣	$9.91
10	100	91239A316♣■	9.13
12	100	91239A318♣■	8.46
14	100	91239A319♣	14.09
16	100	91239A321♣■	10.43
M6 (Cont.)			
18	50	91239A323♣	$8.59
20	100	91239A326♣■	11.30
22	50	91239A324♣	7.93
25	100	91239A327♣■	13.04
30	100	91239A328♣■	14.00
35	25	91239A330■	5.73
40	25	91239A332	6.84
45	25	91239A334	8.44
50	25	91239A336	11.34
55	10	91239A337	5.41
60	5	91239A340	2.74
M8			*Pitch: 1.25 mm*
10	25	91239A414♣■	$5.55
12	25	91239A416♣■	5.42
14	50	91239A417♣	12.93
16	25	91239A418♣■	4.94
18	50	91239A420♣	14.91
20	25	91239A426♣■	5.54
25	25	91239A427♣■	5.70
30	25	91239A428♣■	6.40
35	25	91239A438♣■	7.20
40	25	91239A442♣■	7.90
45	10	91239A444	4.90
50	25	91239A448	8.70
55	10	91239A450	6.96
60	10	91239A453	7.24
70	10	91239A455	10.33
80	10	91239A457	7.93
M10			*Pitch: 1.5 mm*
16	25	91239A512♣■	$10.50
18	5	91239A511♣	9.83
20	25	91239A513♣■	8.10
25	25	91239A514♣■	8.42
30	25	91239A515♣■	10.00
35	10	91239A518♣	4.78
40	10	91239A521♣■	5.64
45	10	91239A523	6.61
50	5	91239A525■	5.79
M12			*Pitch: 1.75 mm*
16	5	91239A610♣	$5.04
20	10	91239A612♣■	7.16
25	10	91239A614♣■	6.08
30	10	91239A616♣■	7.52
35	5	91239A618♣	4.16
40	5	91239A620♣	4.76
45	5	91239A621♣	5.76
50	5	91239A622♣	5.04

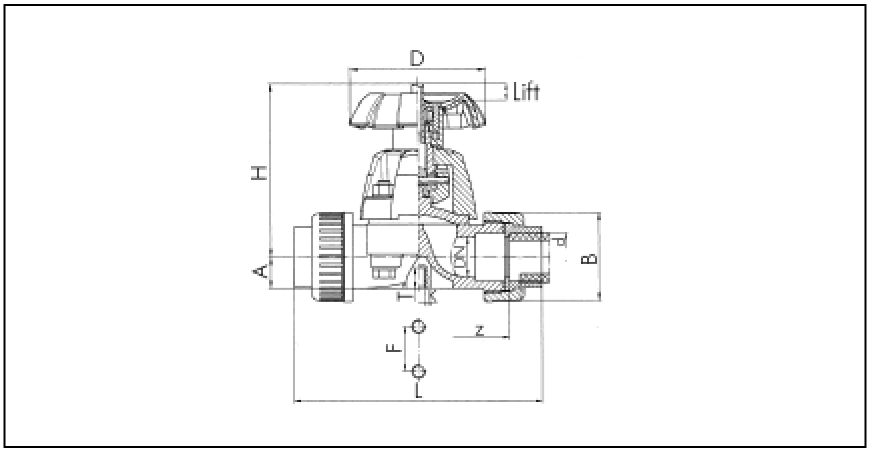
ISO 7380 250-Pc. Assortment—Has 25 each: M4 × 8, 10, 12, 16; M5 × 16, 20. 10 each: M5 × 25, 30; M6 × 16, 20, 25, 30; M8 × 20, 25, 30, 40. Includes 8 hex keys—2 each of 2.5, 3, 4, and 5 mm. Furnished in a 10⅝" Lg. × 6½" Wd. × 1¾" Dp. compartmented plastic case with lid chart.

90115A032 .... Each $45.13

2980 McMASTER-CARR

Figure 9.11.5: Cap Screw Source Data Sheet

Dimensions for Type 314 True Union Diaphragm Valve PVC (solvent cement socket ends)



Inch size	A Inch	B Inch	D Inch	F Inch	K mm	H Inch	L Inch	T Inch	Z Inch	Lift Inch	Weight lbs.
1/2	0.55	1.69	3.15	0.98	M6	3.54	5.04	.47	3.78	0.32	0.88
3/4	0.69	2.09	3.15	0.98	M6	4.02	5.98	.47	4.49	0.43	1.32
1	0.83	2.36	3.70	0.98	M6	4.67	6.54	.47	4.80	0.51	1.98
1-1/4	1.00	2.91	4.61	1.77	M8	4.96	7.56	.59	5.51	0.63	2.65
1-1/2	1.28	3.27	4.61	1.77	M8	5.47	8.74	.59	6.30	0.83	3.53
2	1.54	4.06	5.98	1.77	M8	6.77	10.47	.59	7.48	1.10	6.17

Figure 9.11.6: Diaphragm Valve Source Data Sheet

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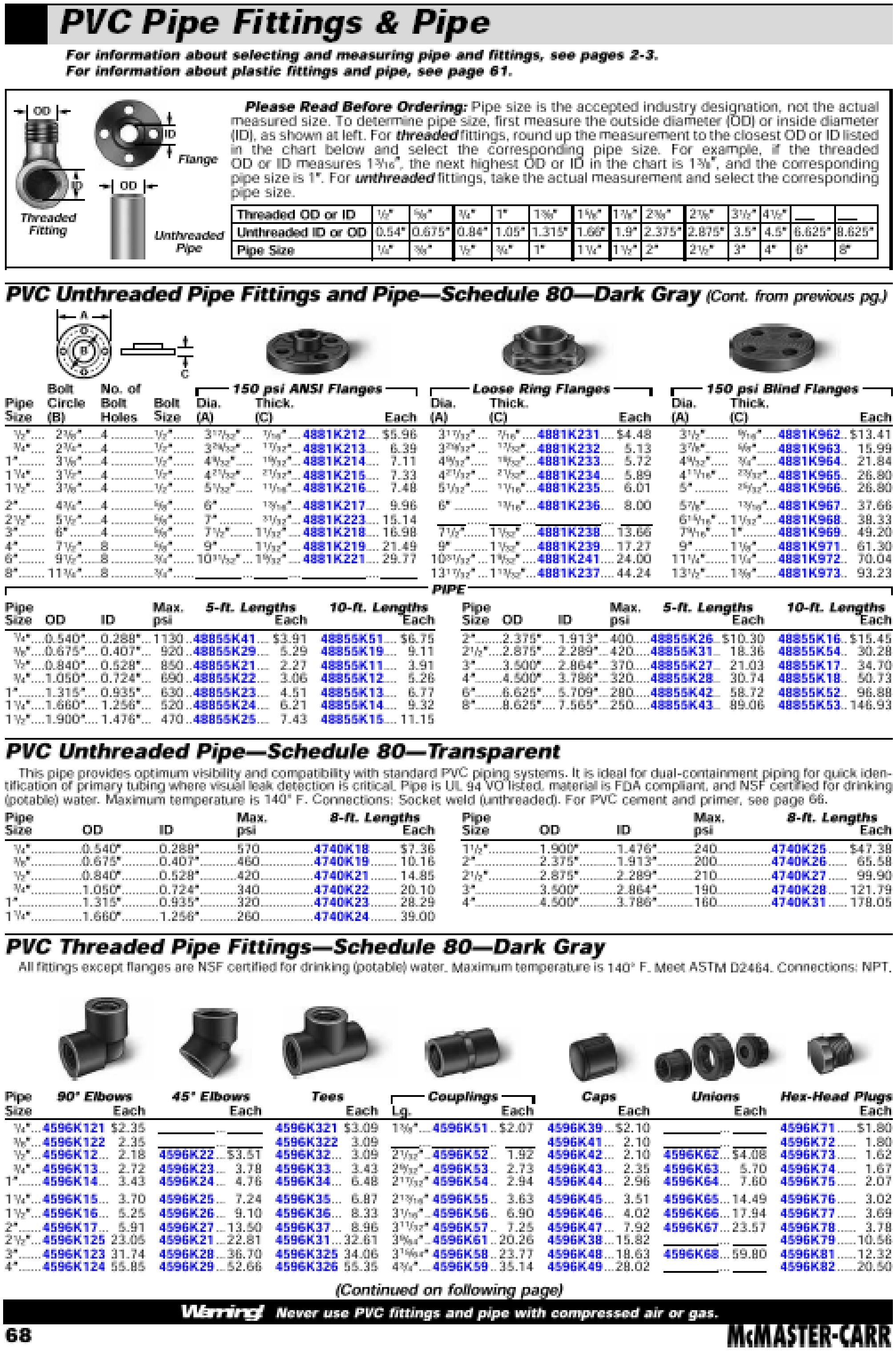
OMEGA's PX26 Series pressure sensors feature state-of-the-art silicon technology which permits both sides of the diaphragm to handle liquids. A unique conductive seal between the silicon diaphragm and the plastic housing allows for wet/wet applications and lower production costs than typical gold wire silicon sensors. This new construction has a larger diaphragm than traditional silicon sensors, resulting in increased long-term stability.

SPECIFICATIONS
Excitation:10 Vdc, 16 Vdc max @ 2 mA
Output (@ 10 Vdc):1 psi = 16.7 mV, 5 psi = 50 mv; >5 psi = 100 mV; 250 psi = 150 mV
Linearity:±0.25% FS BFSL Typical
(±1% maximum) P2>P1
Hysteresis and Repeatability:0.2% FS
Zero Balance:±1.5 mV
Span Tolerance:±3.0 mV
1 Year Stability:0.5% FS
Operating Temperature:-40 to 85°C (-40 to 185°F)
Compensated Temperature:0 to 50°C (32 to 122°F)
Thermal Effects:
Zero: 1 mV Span: 1% Rdg
Proof Pressure:20 psi for ≤5 psi;
45 psi for 15 psi ; 60 psi for 30 psi
200 psi for 100 psi range
Input Resistance:7.5kΩ
Output Resistance:2.5kΩ
Response Time:1 ms
Gage Type: Silicon sensor
Wetted Parts: Polyethimide, silicon, fluorosilicone
Mating Connector:CX136-4, ($2.50), not included
Weight:2 g (0.07 oz)

Figure 9.11.7: Pressure Transducer Source Data Sheet



PVC Pipe Fittings & Pipe

For information about selecting and measuring pipe and fittings, see pages 2-3.
For information about plastic fittings and pipe, see page 61.

Please Read Before Ordering: Pipe size is the accepted industry designation, not the actual measured size. To determine pipe size, first measure the outside diameter (OD) or inside diameter (ID), as shown at left. For *threaded* fittings, round up the measurement to the closest OD or ID listed in the chart below and select the corresponding pipe size. For example, if the threaded OD or ID measures 1 3/16", the next highest OD or ID in the chart is 1 3/8", and the corresponding pipe size is 1". For *unthreaded* fittings, take the actual measurement and select the corresponding pipe size.

Threaded OD or ID	1/2"	5/8"	3/4"	1"	1 3/8"	1 5/8"	1 7/8"	2 3/8"	2 7/8"	3 1/2"	4 1/2"	—	—
Unthreaded ID or OD	0.54"	0.675"	0.84"	1.05"	1.315"	1.66"	1.9"	2.375"	2.875"	3.5"	4.5"	6.625"	8.625"
Pipe Size	1/4"	3/8"	1/2"	3/4"	1"	1 1/4"	1 1/2"	2"	2 1/2"	3"	4"	6"	8"

PVC Unthreaded Pipe Fittings and Pipe—Schedule 80—Dark Gray (Cont. from previous pg.)

Pipe Size	Bolt Circle (B)	No. of Bolt Holes	Bolt Size	150 psi ANSI Flanges Dia. (A)	Thick. (C)		Each	Loose Ring Flanges Dia. (A)	Thick. (C)		Each	150 psi Blind Flanges Dia. (A)	Thick. (C)		Each
1/2"	2 5/8"	4	1/2"	3 17/32"	7/16"	4881K212	$5.96	3 17/32"	7/16"	4881K231	$4.48	3 1/2"	9/16"	4881K962	$13.41
3/4"	2 3/4"	4	1/2"	3 29/32"	17/32"	4881K213	6.39	3 29/32"	17/32"	4881K232	5.13	3 7/8"	5/8"	4881K963	15.99
1"	3 1/8"	4	1/2"	4 9/32"	19/32"	4881K214	7.11	4 9/32"	19/32"	4881K233	5.72	4 9/32"	3/4"	4881K964	21.84
1 1/4"	3 1/2"	4	1/2"	4 21/32"	21/32"	4881K215	7.33	4 21/32"	21/32"	4881K234	5.89	4 11/16"	23/32"	4881K965	26.80
1 1/2"	3 7/8"	4	1/2"	5 1/32"	11/16"	4881K216	7.48	5 1/32"	11/16"	4881K235	6.01	5"	25/32"	4881K966	26.80
2"	4 3/4"	4	5/8"	6"	13/16"	4881K217	9.96	6"	13/16"	4881K236	8.00	5 7/8"	13/16"	4881K967	37.66
2 1/2"	5 1/2"	4	5/8"	7"	31/32"	4881K223	15.14	—	—	—	—	6 15/16"	1 1/32"	4881K968	38.33
3"	6"	4	5/8"	7 1/2"	1 1/32"	4881K218	16.98	7 1/2"	1 1/32"	4881K238	13.66	7 9/16"	1"	4881K969	49.20
4"	7 1/2"	8	5/8"	9"	1 1/32"	4881K219	21.49	9"	1 1/32"	4881K239	17.27	9"	1 1/8"	4881K971	61.30
6"	9 1/2"	8	3/4"	10 31/32"	1 9/32"	4881K221	29.77	10 31/32"	1 9/32"	4881K241	24.00	11 1/4"	1 1/4"	4881K972	70.04
8"	11 3/4"	8	3/4"	—	—	—	—	13 17/32"	1 13/32"	4881K237	44.24	13 1/2"	1 3/8"	4881K973	93.23

PIPE

Pipe Size	OD	ID	Max. psi	5-ft. Lengths	Each	10-ft. Lengths	Each
1/4"	0.540"	0.288"	1130	48855K41	$3.91	48855K51	$6.75
3/8"	0.675"	0.407"	920	48855K29	5.29	48855K19	9.11
1/2"	0.840"	0.528"	850	48855K21	2.27	48855K11	3.91
3/4"	1.050"	0.724"	690	48855K22	3.06	48855K12	5.26
1"	1.315"	0.935"	630	48855K23	4.51	48855K13	6.77
1 1/4"	1.660"	1.256"	520	48855K24	6.21	48855K14	9.32
1 1/2"	1.900"	1.476"	470	48855K25	7.43	48855K15	11.15
2"	2.375"	1.913"	400	48855K26	$10.30	48855K16	$15.45
2 1/2"	2.875"	2.289"	420	48855K31	18.36	48855K54	30.28
3"	3.500"	2.864"	370	48855K27	21.03	48855K17	34.70
4"	4.500"	3.786"	320	48855K28	30.74	48855K18	50.73
6"	6.625"	5.709"	280	48855K42	58.72	48855K52	96.88
8"	8.625"	7.565"	250	48855K43	89.06	48855K53	146.93

PVC Unthreaded Pipe—Schedule 80—Transparent

This pipe provides optimum visibility and compatibility with standard PVC piping systems. It is ideal for dual-containment piping for quick identification of primary tubing where visual leak detection is critical. Pipe is UL 94 VO listed, material is FDA compliant, and NSF certified for drinking (potable) water. Maximum temperature is 140° F. Connections: Socket weld (unthreaded). For PVC cement and primer, see page 66.

Pipe Size	OD	ID	Max. psi	8-ft. Lengths	Each
1/4"	0.540"	0.288"	570	4740K18	$7.36
3/8"	0.675"	0.407"	460	4740K19	10.16
1/2"	0.840"	0.528"	420	4740K21	14.85
3/4"	1.050"	0.724"	340	4740K22	20.10
1"	1.315"	0.935"	320	4740K23	28.29
1 1/4"	1.660"	1.256"	260	4740K24	39.00
1 1/2"	1.900"	1.476"	240	4740K25	$47.38
2"	2.375"	1.913"	200	4740K26	65.58
2 1/2"	2.875"	2.289"	210	4740K27	99.90
3"	3.500"	2.864"	190	4740K28	121.79
4"	4.500"	3.786"	160	4740K31	178.05

PVC Threaded Pipe Fittings—Schedule 80—Dark Gray

All fittings except flanges are NSF certified for drinking (potable) water. Maximum temperature is 140° F. Meet ASTM D2464. Connections: NPT.

Pipe Size	90° Elbows	Each	45° Elbows	Each	Tees	Each	Couplings Lg.		Each	Caps	Each	Unions	Each	Hex-Head Plugs	Each
1/4"	4596K121	$2.35	—	—	4596K321	$3.09	1 3/8"	4596K51	$2.07	4596K39	$2.10	—	—	4596K71	$1.80
3/8"	4596K122	2.35	—	—	4596K322	3.09	—	—	—	4596K41	2.10	—	—	4596K72	1.80
1/2"	4596K12	2.18	4596K22	$3.51	4596K32	3.09	2 1/32"	4596K52	1.92	4596K42	2.10	4596K62	$4.08	4596K73	1.62
3/4"	4596K13	2.72	4596K23	3.78	4596K33	3.43	2 9/32"	4596K53	2.73	4596K43	2.35	4596K63	5.70	4596K74	1.67
1"	4596K14	3.43	4596K24	4.76	4596K34	6.48	2 11/32"	4596K54	2.94	4596K44	2.96	4596K64	7.60	4596K75	2.07
1 1/4"	4596K15	3.70	4596K25	7.24	4596K35	6.87	2 13/16"	4596K55	3.63	4596K45	3.51	4596K65	14.49	4596K76	3.02
1 1/2"	4596K16	5.25	4596K26	9.10	4596K36	8.33	3 1/16"	4596K56	6.90	4596K46	4.02	4596K66	17.94	4596K77	3.69
2"	4596K17	5.91	4596K27	13.50	4596K37	8.96	3 11/32"	4596K57	7.25	4596K47	7.92	4596K67	23.57	4596K78	3.78
2 1/2"	4596K125	23.05	4596K21	22.81	4596K31	32.61	3 [illegible]/64"	4596K61	20.26	4596K38	15.82	—	—	4596K79	10.56
3"	4596K123	31.74	4596K28	36.70	4596K325	34.06	3 [illegible]/64"	4596K58	23.77	4596K48	18.63	4596K68	59.80	4596K81	12.32
4"	4596K124	55.85	4596K29	52.66	4596K326	55.35	4 3/4"	4596K59	35.14	4596K49	28.02	—	—	4596K82	20.50

(Continued on following page)

Warning! *Never use PVC fittings and pipe with compressed air or gas.*

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Figure 9.11.8: Flange Half Coupling Pipe Fitting Source Data Sheet

Viton Rubber & Foam Rubber

For more information about rubber and durometer scales, see page 3316.

Corrosion-Resistant Viton Rubber

A fluoroelastomer often designated as FKM, Viton is ideal for use in harsh and corrosive environments. It has exceptional resistance to heat, aging, weather, ozone, oxygen, and sunlight, as well as a broad range of fuels, solvents, and chemicals. It is also more flame resistant than other rubbers.

Sheets, Sheeting, and Strips—Smooth Finish

- Color: Black
- Temp. Range: –20° to +400° F
- Excellent recovery from compression
- Cut with scissors or shears

Width and length tolerances are ±1/16" for sheets, ±1" for sheeting, and +1" for strips.

Durometer Hardness ±5	75A
Tensile Strength, psi	1000
Stretch Limit %	225
Density, lbs./cu. ft.	97

		Sheets						36" Wide Sheeting			36" Long Strips			
		6" × 6"		12" × 12"		12" × 24"		Max.			2" Wide		4" Wide	
Thick.	Thick. Toler.		Each		Each		Each	Lg., ft.		Per Ft.		Each		Each
1/32"	±0.012"	86075K21	$6.27	86075K31	$21.79	86075K51	$37.20	100	86075K71	$46.79	8297K11	$13.27	8297K12	$24.12
1/16"	±0.016"	86075K22	8.85	86075K32	31.89	86075K52	55.68	100	86075K72	68.49	8297K14	18.77	8297K15	34.11
3/32"	±0.016"	86075K23	13.15	86075K33	45.95	86075K53	79.92	65	86075K73	102.50	8297K17	28.00	8297K18	50.90
1/8"	±0.020"	86075K24	15.66	86075K34	54.50	86075K54	95.61	50	86075K74	120.70	8297K21	33.21	8297K22	60.38
3/16"	±0.031"	86075K25	23.16	86075K35	80.53	86075K55	141.04	30	86075K75	179.14	8297K24	49.10	8297K25	89.27
1/4"	±0.031"	86075K26	29.95	86075K36	104.23	86075K56	182.39	25	86075K76	231.23	8297K27	63.55	8297K28	115.55
5/16"	±0.047"	86075K27	36.11	86075K37	125.54	86075K57	218.48	3	86075K77	273.13	—	—	—	—
3/8"	±0.047"	86075K28	43.87	86075K38	152.56	86075K58	265.31	3	86075K78	332.02	—	—	—	—
1/2"	±0.047"	86075K29	52.03	86075K39	180.98	86075K59	314.74	3	86075K79	394.28	—	—	—	—

High-Strength Corrosion-Resistant Viton Rubber

Get the high performance of Viton with even greater strength. Ideal for use in harsh and corrosive environments, Viton has exceptional resistance to heat, aging, weather, ozone, oxygen, and sunlight, as well as to a broad range of fuels, solvents, and chemicals.

Sheets, Sheeting, Strips, and Cord—Smooth Finish

- Color: Black
- Temp. Range: 0° to 400° F
- Good recovery from compression
- Cut with scissors or shears

Sheets, sheeting, and strips meet ASTM D2000 HK and MIL-R-83248A, Type 2, Class 1. Cord meets MIL-R-83248C, Type 2, Class 1. Adhesive is acrylic and has a temperature range of 0° to 220° F. Width and length tolerances are ±1/4" for sheets and strips and ±1" for sheeting. Cord has a length tolerance of +1/2".

Durometer Hardness ±5	75A
Tensile Strength, psi	1500
Stretch Limit %	125
Density, lbs./cu. ft.	112-114

		Plain Back									Adhesive-Back Sheets			
		Sheets						36" Wide Sheeting						
		6" × 6"		12" × 12"		12" × 24"		Max.			12" × 12"		12" × 24"	
Thick.	Thick. Tolerance		Each		Each		Each	Length		Per Ft.		Each		Each
1/32"	±0.012"	8625K11	$11.68	8625K21	$34.87	8625K41	$57.07	50 ft.	8625K61	$86.20	8625K31	$41.60	8625K51	$74.90
1/16"	±0.016"	8625K12	19.03	8625K22	64.47	8625K42	105.51	50 ft.	8625K62	130.76	8625K32	69.75	8625K52	120.60
3/32"	±0.016"	8625K13	26.41	8625K23	83.63	8625K43	158.30	50 ft.	8625K63	189.71	8625K33	88.63	8625K53	153.20
1/8"	±0.020"	8625K14	33.18	8625K24	105.62	8625K44	183.69	50 ft.	8625K64	223.96	8625K34	109.45	8625K54	191.25
3/16"	±0.031"	8625K15	46.62	8625K29	152.04	8625K45	264.42	25 ft.	8625K69	344.90	8625K35	203.60	8625K55	272.38
1/4"	±0.031"	8625K16	58.91	8625K25	185.70	8625K46	321.22	25 ft.	8625K65	418.98	8625K36	273.86	8625K56	329.65

		Plain-Back 36" Long Strips						Adhesive-Back 36" Long Strips					
		2" Wide		4" Wide		6" Wide		2" Wide		4" Wide		6" Wide	
Thick.	Thick. Tolerance		Each		Each		Each		Each		Each		Each
1/32"	±0.012"	8999K11	$19.20	8999K31	$34.76	8999K51	$47.40	8999K21	$20.40	8999K41	$36.85	8999K61	$51.20
1/16"	±0.016"	8999K12	33.15	8999K32	57.65	8999K52	75.20	8999K22	34.52	8999K42	59.70	8999K62	79.45
3/32"	±0.016"	8999K13	48.08	8999K33	83.63	8999K53	109.08	8999K23	50.44	8999K43	85.98	8999K63	112.95
1/8"	±0.020"	8999K14	60.72	8999K34	105.62	8999K54	137.76	8999K24	62.20	8999K44	107.86	8999K64	141.55
3/16"	±0.031"	8999K15	87.35	8999K35	151.92	8999K55	198.15	8999K25	88.96	8999K45	154.23	8999K65	202.38
1/4"	±0.031"	8999K16	106.20	8999K36	184.70	8999K56	240.92	8999K26	107.68	8999K46	186.88	8999K66	244.67

36" Long Cord

Dia.	Dia. Tol.		Each
1/8"	±0.006"	9029K11	$6.76
1/4"	±0.010"	9029K12	$12.03
3/8"	±0.013"	9029K13	$27.40
1/2"	±0.018"	9029K14	$41.95

Tight-Tolerance Balls—Smooth Finish

- Color: Black
- Temp. Range: 0° to 400° F
- Excellent recovery from compression

Material meets ASTM D2000 HK. Balls are seamless.

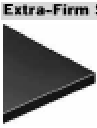
Dia.	Dia. Tolerance		Each
3/16"	±0.003"	3645K1	$2.38
1/4"	±0.003"	3645K2	2.58
5/16"	±0.003"	3645K3	2.58
7/16"	±0.004"	3645K4	2.75
1/2"	±0.005"	3645K5	5.06
5/8"	±0.005"	3645K6	7.63
3/4"	±0.006"	3645K7	8.04

Durometer Hardness ±5	70A
Tensile Strength, psi	1800
Stretch Limit %	230
Density, lbs./cu. ft.	116

Corrosion-Resistant Viton Foam Rubber

This foam version of Viton is closed cell, which means each cell is completely closed, restricting water, air, and gas from passing through. Ideal for use in harsh and corrosive environments. Viton has exceptional resistance to heat, aging, weather, ozone, oxygen, and sunlight, as well as to a broad range of fuels, solvents, and chemicals.

Extra-Firm Sheets—Smooth Finish



- Color: Black
- Temp. Range: –10° to +400° F
- Good recovery from compression
- Cut with shears

Material has a skin on all sides. Width and length tolerances are ±1/32" for 6" × 6" sheets and ±1/4" for all others.

		6" × 6"		12" × 12"		12" × 24"	
Thick.	Thick. Tolerance		Each		Each		Each
1/8"	±0.060"	3156T33	$27.60	3156T13	$82.48	3156T23	$148.46
1/4"	±0.060"	3156T34	43.07	3156T14	134.54	3156T24	239.30
3/8"	±0.080"	3156T35	59.93	3156T15	199.77	3156T25	332.96
1/2"	±0.125"	3156T36	79.55	3156T16	265.15	3156T26	441.92

Firmness (25% Deflection), psi	10-19
Durometer Hardness	Not rated
Tensile Strength, psi	Not rated
Stretch Limit %	Not rated
Density, lbs./cu. ft.	3.5-6.5

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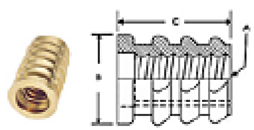
Figure 9.11.9: Gasket Source Data Sheet

Yardley Products Corporation
10 West College Avenue P.O. Box 357 Yardley, PA 19067-8357
Toll Free: (800) 457-0154 Telephone: 215-493-2723 Fax: 215-493-6796
E-Mail: info@yardleyproducts.com Web site: www.yardleyproducts.com

All Categories > Intro-Sert > INTRO-SERT Ultrasonic Insert - Metric Threads > Item # 3005H6-8SS

Item # 3005H6-8SS, INTRO-SERT Ultrasonic Insert - Metric Threads
$2.22 (quantity discount available)



larger image

INTRO-SERT Ultrasonic Insert - Metric Threads
Yardley INTRO-SERT Ultrasonic Inserts offer plastic molders and users, impressive benefits in lower cost production and better quality assemblies. In addition, they offer a choice of installation methods with conventional high frequency ultrasonic production equipment or the Yardley Thermal Inserter for low volume work.
Advantages:
-Self-tapping, self-locking
-Provide stronger, more durable permanent threads in soft metals and plastics
-Supply permanent threads in cast iron that will not gall, seize, corrode or strip
-Offer strong resistance to rotation and pull-out
-Lead on both ends simplifies installation
-Ideal for automated production

NOTE: For Quantities Over 50,000 Please Call 1-800-457-0154

Specifications

Series	Regular
Construction	Stainless Steel
Metric Thread Size (A)	M3.0 x 0.5
Outside Diameter (+/- .005) (B)	.187
Length (+/- .005) (C)	.250
Starting Hole Size ABS	.154
Starting Hole Size Polycarbonates	.150
Base Materials	Thermoplastics, ABS, Polycarbonates
Installation Methods	Ultrasonic, Thermal

Print Back

Figure 9.11.10: Regular Insert Source Data Sheet

YARDLEY® PRODUCTS CORP A DVCC, INC. COMPANY

Unique Solutions For Your Fastening Needs

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Selection Guide

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By Part Number [GO]

All Categories   INTRO-SERT Ultrasonic Insert - Metric Threads

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Shopping Cart	0 Items	Shipping
Request for Quote	0 Items	Tax
		Terms

All Categories > Intro-Sert > INTRO-SERT Ultrasonic Insert - Metric Threads > Item # 3005HR6-7SS

Request Information | Add to Cart | Request Quote

Item # 3005HR6-7SS, INTRO-SERT Ultrasonic Insert - Metric Threads
$2.2230 (quantity discount available)

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INTRO-SERT Ultrasonic Insert - Metric Threads
Yardley INTRO-SERT Ultrasonic Inserts offer plastic molders and users, impressive benefits in lower cost production and better quality assemblies. In addition, they offer a choice of installation methods with conventional high frequency ultrasonic production equipment or the Yardley Thermal Inserter for low volume work.
Advantages:
-Self-tapping, self-locking
-Provide stronger, more durable permanent threads in soft metals and plastics
-Supply permanent threads in cast iron that will not gall, seize, corrode or strip
-Offer strong resistance to rotation and pull-out
-Lead on both ends simplifies installation
-Ideal for automated production

NOTE: For Quantities Over 50,000 Please Call 1-800-457-0154

Specifications	
Series	Short
Construction	Stainless Steel
Metric Thread Size (A)	M3.0 x 0.5
Outside Diameter (+/- .005) (B)	.187
Length (+/- .005) (C)	.219
Starting Hole Size ABS	.154
Starting Hole Size Polycarbonates	.150
Base Materials	Thermoplastics, ABS, Polycarbonates

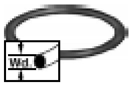
Figure 9.11.11: Short Insert Source Data Sheet

O-Rings—AS568A Dash Nos. 031-149

For information about O-ring materials, see page 3271.

Don't see the O-ring you need? Just tell us what you're looking for and we'll get it for you.

Buna-N, Viton, Silicone, and EPDM O-Rings *(Continued from previous page)*



Buna-N (nitrile) is used in oil applications. Temperature range is -35° to +250° F. Durometer hardness is A70. Meets SAE J200. Color is black.

Viton has excellent chemical and oil resistance. Temperature range is -15° to +400° F. Durometer hardness is A75. Meets SAE J200. Color is black.

Silicone has good low and high temperature resistance. Temperature range is -65° to +450° F. Durometer hardness is A70. Meets FDA 21CFR.177. Color is red-orange.

EPDM (ethylene propylene) is used in applications requiring weather resistance. Temperature range is -65° to +212° F. Durometer hardness is A70. Meets SAE J200. Color is black.

AS568A Dash No.	Fractional Size, ID × OD	Actual Inch Size, ID × OD	Buna-N Pkg. Qty.	Buna-N	Buna-N Per Pkg.	Viton Pkg. Qty.	Viton	Viton Per Pkg.	Silicone Pkg. Qty.	Silicone	Silicone Per Pkg.	EPDM Pkg. Qty.	EPDM	EPDM Per Pkg.
Width: 1/16" Fractional (0.070" Actual) (Cont.)														
031	1 3/4" × 1 7/8"	1.739" × 1.879"	100	9452K118	$8.76	25	9464K311	$8.18	25	9396K111	$8.30	100	9557K123	$12.89
032	1 7/8" × 2"	1.864" × 2.004"	100	9452K119	9.27	25	9464K321	10.14	25	9396K112	10.36	100	9557K469	13.00
033	2" × 2 1/8"	1.989" × 2.129"	100	9452K121	9.78	25	9464K331	10.55	25	9396K113	10.50	50	9557K124	10.09
034	2 1/8" × 2 1/4"	2.114" × 2.254"	100	9452K122	10.32	25	9464K341	10.73	25	9396K114	10.71	40	9557K125	7.10
035	2 1/4" × 2 3/8"	2.239" × 2.379"	100	9452K123	10.83	10	9464K351	5.40	25	9396K115	14.12	50	9557K126	11.14
036	2 3/8" × 2 1/2"	2.364" × 2.504"	100	9452K124	11.84	10	9464K361	5.65	10	9396K116	6.03	50	9557K69	10.31
037	2 1/2" × 2 5/8"	2.489" × 2.629"	100	9452K125	12.16	10	9464K371	5.83	10	9396K117	5.39	50	9557K127	12.86
038	2 5/8" × 2 3/4"	2.614" × 2.754"	100	9452K126	12.38	10	9464K381	6.28	10	9396K118	6.44	50	9557K71	10.83
039	2 3/4" × 2 7/8"	2.739" × 2.879"	100	9452K127	12.40	10	9464K391	6.35	10	9396K119	6.45	50	9557K128	14.82
040	2 7/8" × 3"	2.864" × 3.004"	100	9452K128	12.45	10	9464K401	6.84	10	9396K121	6.70	25	9557K131	8.38
041	3" × 3 1/8"	2.989" × 3.129"	100	9452K129	12.50	10	9464K411	7.05	10	9396K122	7.07	20	9557K132	8.75
042	3 1/4" × 3 3/8"	3.239" × 3.379"	100	9452K131	13.24	10	9464K421	7.38	10	9396K123	7.42	25	9557K133	9.07
043	3 1/2" × 3 5/8"	3.489" × 3.629"	50	9452K132	7.94	10	9464K431	7.88	10	9396K124	7.63	15	9557K134	8.83
044	3 3/4" × 3 7/8"	3.739" × 3.879"	50	9452K133	8.11	10	9464K441	7.88	10	9396K125	7.78	12	9557K135	7.20
045	4" × 4 1/8"	3.989" × 4.129"	50	9452K134	8.50	10	9464K451	8.55	10	9396K126	8.42	10	9557K136	7.56
046	4 1/4" × 4 3/8"	4.239" × 4.379"	50	9452K135	11.00	10	9464K461	8.98	10	9396K127	8.81	10	9557K137	8.00
047	4 1/2" × 4 5/8"	4.489" × 4.629"	10	9452K312	4.48	10	9464K106	9.11	10	9396K128	9.09	10	9557K138	6.93
048	4 3/4" × 4 7/8"	4.739" × 4.879"	10	9452K313	4.97	2	9464K511	3.36	10	9396K129	12.43	10	9557K139	7.29
049	5" × 5 1/8"	4.989" × 5.129"	10	9452K314	5.40	2	9464K512	3.77	10	9396K131	13.18	10	9557K141	7.31
050	5 1/4" × 5 3/8"	5.239" × 5.379"	10	9452K315	5.56	2	9464K513	4.28	10	9396K132	13.94	10	9557K142	7.05
Width: 3/32" Fractional (0.103" Actual)														
102	1/16" × 1/4"	0.049" × 0.255"	100	9452K316	2.00	50	9464K107	4.98	25	9396K133	2.74	100	9557K143	7.31
103	3/32" × 9/32"	0.081" × 0.287"	100	9452K317	2.00	50	9464K514	4.98	50	9396K134	4.81	100	9557K144	7.60
104	1/8" × 5/16"	0.112" × 0.318"	100	9452K318	2.00	50	9464K108	5.06	50	9396K135	5.08	100	9557K145	7.75
105	5/32" × 11/32"	0.143" × 0.349"	100	9452K167	2.00	50	9464K515	5.14	100	9396K136	9.60	100	9557K146	7.88
106	3/16" × 3/8"	0.174" × 0.380"	100	9452K168	2.00	50	9464K109	5.14	100	9396K73	9.72	100	9557K147	6.40
107	7/32" × 13/32"	0.206" × 0.412"	100	9452K169	2.00	50	9464K112	5.14	50	9396K137	4.89	100	9557K72	7.14
108	1/4" × 7/16"	0.237" × 0.443"	100	9452K171	2.20	50	9464K113	5.14	100	9396K138	9.83	100	9557K148	7.31
109	5/16" × 1/2"	0.299" × 0.505"	100	9452K172	2.24	50	9464K44	5.21	100	9396K74	9.93	100	9557K149	7.43
110	3/8" × 9/16"	0.362" × 0.568"	100	9452K22	2.43	50	9464K23	5.98	100	9396K23	10.11	100	9557K471	9.48
111	7/16" × 5/8"	0.424" × 0.630"	100	9452K23	2.77	50	9464K24	6.31	100	9396K24	11.42	100	9557K472	9.67
112	1/2" × 11/16"	0.487" × 0.693"	100	9452K24	2.89	50	9464K25	6.63	100	9396K25	12.14	100	9557K473	10.49
113	9/16" × 3/4"	0.549" × 0.755"	100	9452K25	2.90	50	9464K26	6.95	100	9396K26	12.40	100	9557K474	10.82
114	5/8" × 13/16"	0.612" × 0.818"	100	9452K26	2.94	50	9464K27	7.07	100	9396K27	13.33	100	9557K475	11.15
115	11/16" × 7/8"	0.674" × 0.880"	100	9452K27	3.06	50	9464K28	7.81	50	9396K28	7.78	50	9557K476	5.70
116	3/4" × 15/16"	0.737" × 0.943"	100	9452K28	3.61	50	9464K29	8.54	50	9396K29	8.55	50	9557K477	6.26
117	13/16" × 1"	0.799" × 1.005"	100	9452K81	3.71	50	9464K81	9.56	50	9396K139	8.73	50	9557K73	6.55
118	7/8" × 1 1/16"	0.862" × 1.068"	100	9452K82	3.93	50	9464K82	9.99	50	9396K75	9.40	50	9557K151	7.58
119	15/16" × 1 1/8"	0.924" × 1.130"	100	9452K83	4.00	50	9464K83	10.63	50	9396K141	10.54	50	9557K152	7.58
120	1" × 1 3/16"	0.987" × 1.193"	100	9452K84	4.54	50	9464K84	11.41	50	9396K142	11.87	50	9557K153	7.58
121	1 1/16" × 1 1/4"	1.049" × 1.255"	100	9452K85	4.84	50	9464K85	11.70	50	9396K76	11.51	50	9557K154	7.58
122	1 1/8" × 1 5/16"	1.112" × 1.318"	100	9452K86	5.10	50	9464K86	11.77	25	9396K143	6.41	50	9557K155	8.92
123	1 3/16" × 1 3/8"	1.174" × 1.380"	100	9452K87	5.43	25	9464K87	6.82	25	9396K144	7.17	50	9557K156	8.92
124	1 1/4" × 1 7/16"	1.237" × 1.443"	100	9452K88	5.66	25	9464K88	6.94	25	9396K77	7.24	50	9557K157	8.92
125	1 5/16" × 1 1/2"	1.299" × 1.505"	100	9452K89	6.03	25	9464K89	7.08	25	9396K145	7.31	50	9557K158	10.36
126	1 3/8" × 1 9/16"	1.362" × 1.568"	100	9452K91	6.42	25	9464K91	7.85	25	9396K146	8.24	50	9557K159	10.36
127	1 7/16" × 1 5/8"	1.424" × 1.630"	100	9452K92	6.54	25	9464K92	8.03	25	9396K147	8.43	50	9557K161	10.36
128	1 1/2" × 1 11/16"	1.487" × 1.693"	100	9452K93	6.90	25	9464K93	8.57	25	9396K148	8.94	50	9557K162	10.36
129	1 9/16" × 1 3/4"	1.549" × 1.755"	100	9452K94	7.35	25	9464K94	9.20	25	9396K149	9.42	50	9557K163	11.61
130	1 5/8" × 1 13/16"	1.612" × 1.818"	100	9452K95	7.72	25	9464K95	9.74	25	9396K151	9.57	50	9557K164	11.61
131	1 11/16" × 1 7/8"	1.674" × 1.880"	100	9452K136	8.73	10	9464K131	5.17	25	9396K152	10.42	50	9557K165	12.07
132	1 3/4" × 1 15/16"	1.737" × 1.943"	100	9452K137	9.05	10	9464K132	5.44	25	9396K153	11.12	50	9557K166	12.07
133	1 13/16" × 2"	1.799" × 2.005"	100	9452K138	9.05	10	9464K133	5.61	25	9396K154	12.39	50	9557K167	9.50
134	1 7/8" × 2 1/16"	1.862" × 2.068"	100	9452K139	9.05	10	9464K134	5.64	10	9396K155	5.87	50	9557K168	12.83
135	1 15/16" × 2 1/8"	1.925" × 2.131"	100	9452K141	9.37	10	9464K135	5.95	10	9396K156	5.96	50	9557K169	9.88
136	2" × 2 3/16"	1.987" × 2.193"	100	9452K142	9.37	10	9464K136	6.12	10	9396K157	6.15	40	9557K3	8.50
137	2 1/16" × 2 1/4"	2.050" × 2.256"	100	9452K143	9.51	10	9464K137	6.15	10	9396K158	6.23	25	9557K171	6.14
138	2 1/8" × 2 5/16"	2.112" × 2.318"	50	9452K144	7.38	10	9464K138	6.18	10	9396K159	6.43	25	9557K172	6.14
139	2 3/16" × 2 3/8"	2.175" × 2.381"	50	9452K145	7.38	10	9464K139	6.20	10	9396K78	6.52	25	9557K173	6.14
140	2 1/4" × 2 7/16"	2.237" × 2.443"	50	9452K146	7.54	10	9464K151	6.20	10	9396K161	6.70	40	9557K174	13.21
141	2 5/16" × 2 1/2"	2.300" × 2.506"	50	9452K147	7.54	10	9464K141	6.45	10	9396K79	6.72	25	9557K175	8.31
142	2 3/8" × 2 9/16"	2.362" × 2.568"	50	9452K148	7.94	10	9464K142	6.45	10	9396K162	6.78	25	9557K74	7.94
143	2 7/16" × 2 5/8"	2.425" × 2.631"	50	9452K149	7.94	10	9464K143	6.45	10	9396K163	6.78	25	9557K177	8.72
144	2 1/2" × 2 11/16"	2.487" × 2.693"	50	9452K151	8.17	10	9464K144	6.85	10	9396K164	6.91	35	9557K178	13.13
145	2 9/16" × 2 3/4"	2.550" × 2.756"	50	9452K152	8.33	10	9464K145	7.21	10	9396K165	7.12	35	9557K179	9.54
146	2 5/8" × 2 13/16"	2.612" × 2.818"	50	9452K153	8.33	10	9464K146	7.44	10	9396K166	7.33	35	9557K181	14.00
147	2 11/16" × 2 7/8"	2.675" × 2.881"	50	9452K154	8.49	10	9464K147	8.15	10	9396K167	8.05	35	9557K182	14.09
148	2 3/4" × 2 15/16"	2.737" × 2.943"	50	9452K155	9.52	10	9464K148	8.24	10	9396K168	8.15	30	9557K183	12.08
149	2 13/16" × 3"	2.800" × 3.006"	50	9452K156	9.52	10	9464K149	9.92	10	9396K169	9.32	25	9557K184	8.82

(Continued on following page)

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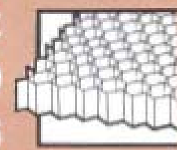
Figure 9.11.12: O- rings Source Data Sheet

PLASCORE

Plastic Honeycomb Cores



PC Polycarbonate Honeycomb

Description:

Plascore polycarbonate honeycomb core exhibits a unique cell structure. The core has 3 orientations vs. the 2 orientations common with other cores, making its properties more uniform. Each cell has a tubular form and is inherently stable.

Features:

- Excellent dielectric properties
- Good thermal and electric insulator
- Conductive grades available
- Fire resistant
- Corrosion resistant
- Fungi resistant
- Sandwich skins can be melted to core
- Use temperatures below 200°F
- Small cell sizes at high densities
- Available transparent and in colors

Applications:

Wind tunnels — Grilles
Sandwich cores
Radomes — Antennae
Skylights
Sound absorbing structures

Availability:

Plascore polycarbonate honeycomb is available in the following standard dimensions:

Cell Sizes:	3/32", 1/8", 1/4" (other cell sizes on request)	
Densities:	3 to 20 pcf	
Sheet length:	150" max	
Sheet width:	49" max	
Sheet thickness:	13" max, .120" min	
Tolerances:	Length:	± .060"
	Width:	± .060"
	Thickness:	± .008"
	Density:	± 10%

Special colors, cell sizes, shapes, dimensions, tolerances and mechanical properties can be provided.

PLASCORE®

Figure 9.11.13: Honeycomb Flow Straightener Source Data Sheet

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PGUF-25B-100PSI/7BAR

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- Dual Scales in PSI and BAR Standard
- Economically Priced
- 2.5% Full Scale Accuracy
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- Center Back or Lower Mount Fittings

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OMEGA's PGUF series liquid fillable utility gauges are designed for a wide range of applications on pumps, compressors, hydraulic systems, machine tools and petrochemical processing equipment.

For high shock and vibration applications the PGUF can be liquid filled in the field to dampen the gauge pointer movement. The PGUF Series liquid filled gauges come in ranges of (PSI/BAR) 0-30/2, 60/4, 100/7, 160/11, 300/20, 600/40 and 1000/70 (63 mm (2 1 /2 ") gauge is also available in 2000/140 and 3000/200). Rated accuracy is ± 2.5% of span.

Gauges feature a corrosion resistant 304 stainless steel case and ring, and a durable polycarbonate window. Phosphor bronze bourdon tubes with brass movement, socket and NPT connections are standard. PGUF gauges are available in 38 mm (1 1 /2 "), 50 mm (2") and 63 mm (2 1 /2 ") designs with center back or lower mount NPT connections.

SPECIFICATIONS
Ranges: From 30PSI/2BAR to 1000PSI/70BAR (2000PSI/140BAR and 3000PSI/200BAR ranges on 63 mm (2 1 /2 ") models only)
Accuracy: ±2.5% full scale
Bourdon Tube: Phosphor bronze
Window: Polycarbonate
Dial: Galvalume white background with blue and black markings
Pointer: Galvalume black finish
Movement: Brass

Figure 9.11.14: Pressure Gauge Source Data Sheet

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Pressure Snubbers, models PS-2, PS-4 and PS-8

PS Series

MADE IN USA

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- Protects Transducers, Gauges and Switches from Pessure Spikes, Surges and Water Hammer
- Available in 1/8, 1/4, or 1/2 NPT Fittings
- Three Different Porosity Ratings Suitable for Most Media
- All Stainless Steel Construction

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PRESSURE SNUBBER - for dampening and filtering. The snubber has a porous metal disc available in three standard grades of porosity. Due to the large filter surface, the snubber has less tendency to clog than orifice type devices. The housing is 303SS and the filter disc is 316SS with a maximum PSI rating of 10,000 at 25°C. (PS-8 series 5000 PSI)

To Order (Specify Model Number) Add to Cart

Part Number	Availability	Price	Description	Qty.
PS-8D	In Stock	$10.00	1/8" NPT pressure snubber for oils (>225 SSU viscosity)	0
PS-8E	In Stock	$10.00	1/8" NPT pressure snubber for water and light oils (<225 SSU viscosity)	0
PS-8G	In Stock	$10.00	1/8" NPT pressure snubber for air, steam and gases	0
PS-4D	In Stock	$10.00	1/4" NPT pressure snubber for oils (>225 SSU viscosity)	0
PS-4E	In Stock	$10.00	1/4" NPT pressure snubber for water and light oils (<225 SSU viscosity)	0
PS-4G	In Stock	$10.00	1/4" NPT pressure snubber for air, steam and gases	0
PS-2D	In Stock	$24.00	1/2" NPT pressure snubber for oils (>225 SSU viscosity)	0
PS-2E	In Stock	$24.00	1/2" NPT pressure snubber for water and light oils (<225 SSU viscosity)	0
PS-2G	2 Weeks	$24.00	1/2" NPT pressure snubber for air, steam and gases	0

Figure 9.11.15: Pressure Snubber Source Data Sheet

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High Efficiency Polypropylene or Fluoroplastic Magnetic Drive Pumps - Product Detail

Back To List

C-72009-00

High Efficiency Polypropylene or Fluoroplastic Magnetic Drive Pumps

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C-72009-00
High Efficiency Polypropylene Pump, 40 GPM, 1/2 hp, 115/208-230 VAC

Qty: 1 Add To Cart

$692.00 / each (USD)

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- **Search through our large selection of Pumps!**
- **Split volute casing forms a volute chamber to increase pump efficiency, reduce horsepower and energy usage**
- Pumps can run dry for up to one hour.
- To reduce maintenance, bearings are kept cool with heat dissipation vent holes and a large flush groove.
- Use in production processes such as filtering, spraying, washing, and etching.

Pumps are set up for hard-wiring; cord and plug are not included.

Application Assistance
Need help from our experts, use this form.

Literature
07-08 Catalog
05-06 Catalog

More Info
(click to view)
Flow curve for 72009-series

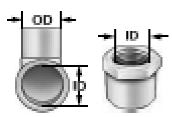
Specifications

Max flow rate		40 GPM
Max fluid temp		176°F (80°C)
Max system pressure		36 psi
Max head (ft)		52
Duty cycle		Continuous
Motor phase		1
Run dry		up to one hour
Wetted materials		glass-reinforced PP pump head, carbon bearing, alumina ceramic spindle, Viton ® O-ring
Dimensions		20"L x 6-1/3"W x 10"H
Connections	outlet	1" NPT(M)
	inlet	1" NPT(M)
	type	TEFC
	rpm	3500
	VAC	115/208-230

Figure 9.11.16: Pump Source Data Sheet

PVC Pipe Fittings

For information about selecting and measuring pipe and fittings, see pages 2-3.
For information about plastic fittings and pipe, see page 61.



Unthreaded *Threaded*

Please Read Before Ordering: Pipe size is the accepted industry designation, not the actual measured size. To determine pipe size, first measure the outside diameter (OD) or inside diameter (ID), as shown at left. For ***unthreaded*** fittings, take the actual measurement and select the corresponding pipe size. For ***threaded*** fittings, round up the measurement to the closest ID listed in the chart below and select the corresponding pipe size. For example, if the threaded pipe fitting ID measures 1 3/16", the next highest ID in the chart is 1⅜", and the corresponding pipe size is 1".

Unthreaded OD or ID	—	0.675"	0.840"	1.050"	1.315"	1.660"	1.90"	2.375"	2.875"	3.50"	4.50"	6.625"	8.625"
Threaded ID	½"	—	¾"	1"	1⅜"	1⅝"	1⅞"	2⅜"	2⅞"	3½"	4½"	—	—
Pipe Size	¼"	⅜"	½"	¾"	1"	1¼"	1½"	2"	2½"	3"	4"	6"	8"

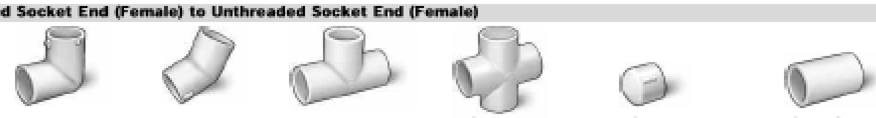
Standard-Wall (Schedule 40) White PVC Pipe Fittings

- NSF-61 certified for use with drinking (potable) water
- Maximum Temperature: 140° F
- Pipe: Use standard-wall (Schedule 40) white PVC unthreaded (see page 63)

Offering corrosion resistance, strength, and rigidity, these standard-wall PVC fittings are the most common choice for plastic fittings in low-pressure plumbing applications. They meet ASTM D1784 and D2466.

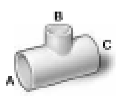
Connect fittings to pipe by cementing the pipe end (male) into the socket end (female) using a primer and cement (see page 66). The pipe end is also known as a spigot. Connections: Unthreaded socket end (female), unthreaded pipe end (male), or threaded (NPT).

Unthreaded Socket End (Female) to Unthreaded Socket End (Female)



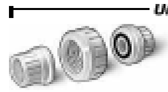
Pipe Size	90° Elbows	Each	45° Elbows	Each	Tees	Each	Crosses	Each	Caps	Each	Couplings Lg.	Couplings	Each
⅜"	4880K108	$1.54	—	—	4880K109	$1.18	—	—	—	—	1 9/32"	4880K114	$0.54
½"	4880K21	.31	4880K31	$0.51	4880K41	.38	4880K241	$1.17	4880K51	$0.28	1 21/32"	4880K71	.20
¾"	4880K22	.35	4880K32	.78	4880K42	.43	4880K242	1.94	4880K52	.32	1 11/16"	4880K72	.28
1"	4880K23	.62	4880K33	.94	4880K43	.82	4880K243	2.42	4880K53	.51	2 3/32"	4880K73	.48
1¼"	4880K24	1.10	4880K34	1.31	4880K44	1.28	4880K244	3.20	4880K54	.72	2⅝"	4880K74	.66
1½"	4880K25	1.17	4880K35	1.64	4880K45	1.55	4880K245	3.62	4880K55	.78	2⅝"	4880K75	.72
2"	4880K26	1.83	4880K36	2.14	4880K46	2.26	4880K246	5.34	4880K56	.94	2⅞"	4880K76	1.10
2½"	4880K103	5.56	4880K113	5.57	4880K123	7.45	4880K247	11.32	4880K143	2.99	4 3/32"	4880K133	2.42
3"	4880K27	6.67	4880K37	8.66	4880K47	9.78	4880K248	13.88	4880K57	3.28	4¼"	4880K77	3.78
4"	4880K28	11.92	4880K38	15.53	4880K48	17.69	4880K249	20.56	4880K58	7.45	4¼"	4880K78	5.46
6"	4880K101	25.72	4880K111	26.02	4880K121	37.43	—	—	4880K141	12.12	7 5/16"	4880K131	11.74
8"	4880K102	61.37	4880K112	58.01	4880K122	86.84	—	—	4880K142	29.10	9 5/16"	4880K132	21.90

Reducing Tees



Pipe Size, (A) × (B) × (C)		Each	Pipe Size, (A) × (B) × (C)		Each
¾" × ½" × ¾"	4880K971	$0.51	2" × 1½" × 2"	4880K978	$2.42
1" × ¾" × ¾"	4880K972	1.45	2½" × 1¼" × 2½"	4880K979	7.42
1" × ½" × 1"	4880K973	.87	2½" × 2" × 2½"	4880K981	7.42
1" × ¾" × 1"	4880K974	.94	3" × 2" × 3"	4880K982	10.62
1¼" × 1" × 1"	4880K975	1.97	4" × 3" × 4"	4880K983	17.69
1½" × ¾" × 1½"	4880K976	2.46	6" × 4" × 6"	4880K984	37.43
1½" × 1" × 1½"	4880K977	2.46	8" × 6" × 8"	4880K985	86.84

Unions



Pipe Size		Each
½"	4880K301	$2.99
¾"	4880K302	3.41
1"	4880K303	3.51
1¼"	4880K304	11.30
1½"	4880K305	11.79
2"	4880K306	15.88

Unthreaded Pipe End (Male) to Unthreaded Socket End (Female)

Hex Reducing Bushings

Pipe Size, Male × Female		Each	Pipe Size, Male × Female		Each	Pipe Size, Male × Female		Each
¾" × ½"	4880K313	$0.35	2" × ¾"	4880K337	$1.50	3" × 1½"	4880K519	$3.58
1" × ½"	4880K314	.64	2" × 1"	4880K338	1.50	3" × 2"	4880K612	3.58
1" × ¾"	4880K315	.64	2" × 1¼"	4880K339	1.50	3" × 2½"	4880K613	3.58
1¼" × ½"	4880K171	.86	2" × 1½"	4880K512	1.50	4" × 2"	4880K614	7.22
1¼" × ¾"	4880K317	.86	2½" × 1"	4880K513	2.42	4" × 2½"	4880K616	8.01
1¼" × 1"	4880K318	.75	2½" × 1¼"	4880K514	2.42	4" × 3"	4880K615	8.01
1½" × ½"	4880K319	.80	2½" × 1½"	4880K515	2.42	6" × 2"	4880K181	13.40
1½" × ¾"	4880K333	.80	2½" × 2"	4880K516	2.42	6" × 4"	4880K183	18.21
1½" × 1"	4880K334	.80	3" × 1"	4880K517	3.58	8" × 4"	4880K185	43.15
1½" × 1¼"	4880K335	.80	3" × 1¼"	4880K518	3.58	8" × 6"	4880K186	43.15
2" × ½"	4880K172	1.50						

90° Elbows

Pipe Size		Each
½"	4880K771	$0.87
¾"	4880K772	1.06
1"	4880K773	1.83
1¼"	4880K774	2.18
1½"	4880K775	2.42
2"	4880K776	4.67

Unthreaded Pipe End (Male) to Threaded End

Hex Reducing Bushings, Pipe End (A) × Female NPT (B)

Pipe Size, (A) × (B)		Each	Pipe Size, (A) × (B)		Each	Pipe Size, (A) × (B)		Each	Pipe Size, (A) × (B)		Each
½" × ¼"	4880K199	$0.66	1½" × ¾"	4880K208	$1.45	2" × 1½"	4880K216	$1.94	3" × 1½"	4880K228	$3.23
¾" × ½"	4880K201	.51	1½" × 1"	4880K209	1.45	2½" × 1"	4880K217	2.81	3" × 2"	4880K229	3.23
1" × ½"	4880K202	.82	1½" × 1¼"	4880K211	1.45	2½" × 1¼"	4880K218	2.81	3" × 2½"	4880K224	3.23
1" × ¾"	4880K203	.82	2" × ½"	4880K212	1.94	2½" × 1½"	4880K219	2.81	4" × 2"	4880K231	7.22
1¼" × ½"	4880K204	1.26	2" × ¾"	4880K213	1.94	2½" × 2"	4880K221	2.81	4" × 2½"	4880K225	7.22
1¼" × ¾"	4880K205	1.26	2" × 1"	4880K214	1.94	3" × 1"	4880K222	3.23	4" × 3"	4880K233	7.22
1¼" × 1"	4880K206	1.26	2" × 1¼"	4880K215	1.94	3" × 1¼"	4880K223	3.23	6" × 4"	4880K235	17.94
1½" × ½"	4880K207	1.45									

(Continued on following page)

Warning! ***Never use PVC fittings and pipe with compressed air or gas.***

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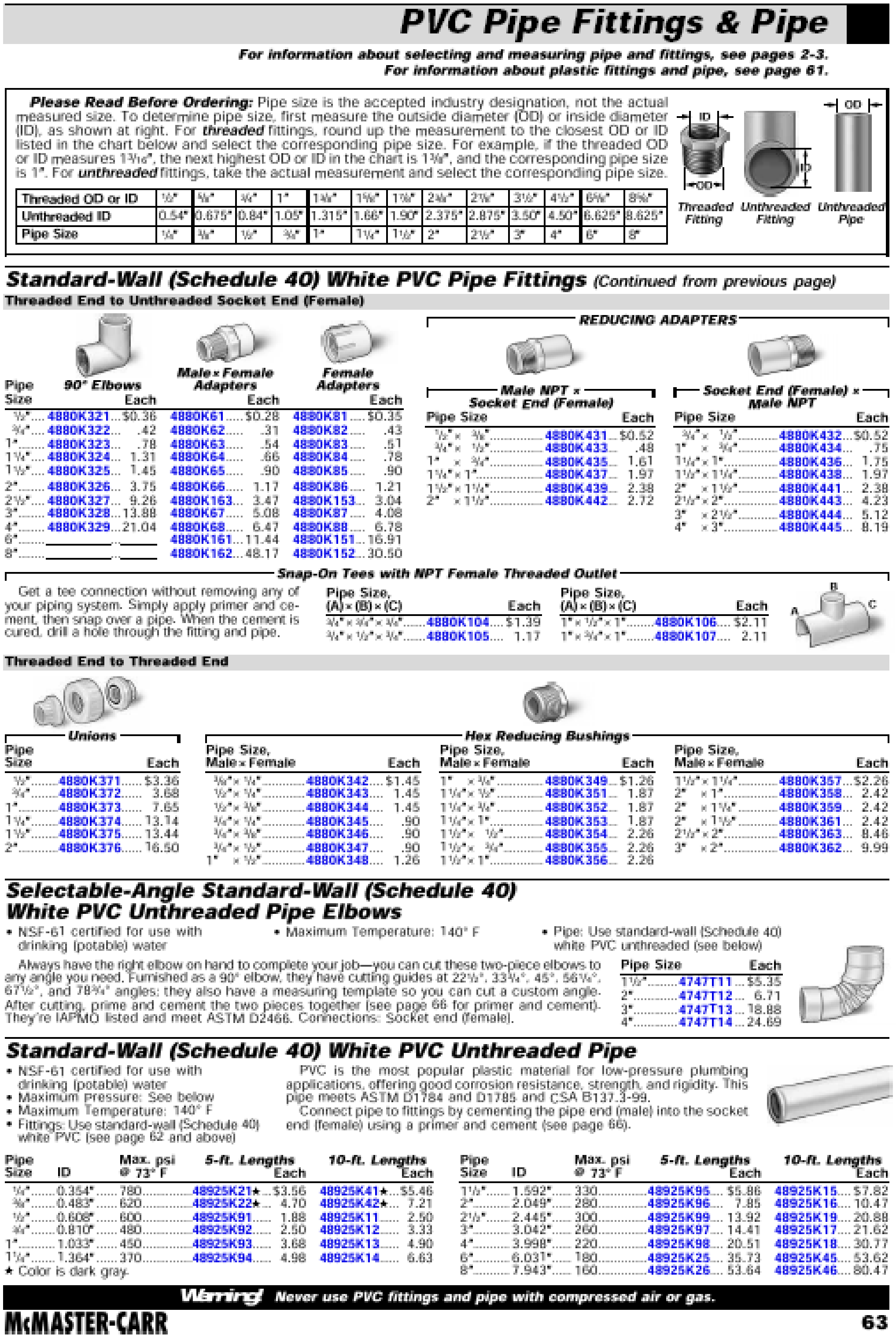
Figure 9.11.17: PVC Fittings Source Data Sheet



PVC Pipe Fittings & Pipe

For information about selecting and measuring pipe and fittings, see pages 2-3.
For information about plastic fittings and pipe, see page 61.

Please Read Before Ordering: Pipe size is the accepted industry designation, not the actual measured size. To determine pipe size, first measure the outside diameter (OD) or inside diameter (ID), as shown at right. For ***threaded*** fittings, round up the measurement to the closest OD or ID listed in the chart below and select the corresponding pipe size. For example, if the threaded OD or ID measures 1³⁄₁₆", the next highest OD or ID in the chart is 1⁵⁄₁₆", and the corresponding pipe size is 1". For ***unthreaded*** fittings, take the actual measurement and select the corresponding pipe size.

Threaded OD or ID	½"	⅝"	¾"	1"	1⁵⁄₁₆"	1⅝"	1⅞"	2⅜"	2⅞"	3½"	4½"	6⅝"	8⅝"
Unthreaded ID	0.54"	0.675"	0.84"	1.05"	1.315"	1.66"	1.90"	2.375"	2.875"	3.50"	4.50"	6.625"	8.625"
Pipe Size	¼"	⅜"	½"	¾"	1"	1¼"	1½"	2"	2½"	3"	4"	6"	8"

Standard-Wall (Schedule 40) White PVC Pipe Fittings *(Continued from previous page)*

Threaded End to Unthreaded Socket End (Female)

Pipe Size	90° Elbows	Each	Male × Female Adapters	Each	Female Adapters	Each
½"	4880K321	$0.36	4880K61	$0.28	4880K81	$0.35
¾"	4880K322	.42	4880K62	.31	4880K82	.43
1"	4880K323	.78	4880K63	.54	4880K83	.51
1¼"	4880K324	1.31	4880K64	.66	4880K84	.78
1½"	4880K325	1.45	4880K65	.90	4880K85	.90
2"	4880K326	3.75	4880K66	1.17	4880K86	1.21
2½"	4880K327	9.26	4880K163	3.47	4880K153	3.04
3"	4880K328	13.88	4880K67	5.08	4880K87	4.08
4"	4880K329	21.04	4880K68	6.47	4880K88	6.78
6"	______	______	4880K161	11.44	4880K151	16.91
8"	______	______	4880K162	48.17	4880K152	30.50

REDUCING ADAPTERS

Male NPT × Socket End (Female)

Pipe Size		Each
½" × ⅜"	4880K431	$0.52
¾" × ½"	4880K433	.48
1" × ¾"	4880K435	1.61
1¼" × 1"	4880K437	1.97
1½" × 1¼"	4880K439	2.38
2" × 1½"	4880K442	2.72

Socket End (Female) × Male NPT

Pipe Size		Each
¾" × ½"	4880K432	$0.52
1" × ¾"	4880K434	.75
1¼" × 1"	4880K436	1.75
1½" × 1¼"	4880K438	1.97
2" × 1½"	4880K441	2.38
2½" × 2"	4880K443	4.23
3" × 2½"	4880K444	5.12
4" × 3"	4880K445	8.19

Snap-On Tees with NPT Female Threaded Outlet

Get a tee connection without removing any of your piping system. Simply apply primer and cement, then snap over a pipe. When the cement is cured, drill a hole through the fitting and pipe.

Pipe Size, (A) × (B) × (C)		Each	Pipe Size, (A) × (B) × (C)		Each
¾" × ¾" × ¾"	4880K104	$1.39	1" × ½" × 1"	4880K106	$2.11
¾" × ½" × ¾"	4880K105	1.17	1" × ¾" × 1"	4880K107	2.11

Threaded End to Threaded End

Unions

Pipe Size		Each
½"	4880K371	$3.36
¾"	4880K372	3.68
1"	4880K373	7.65
1¼"	4880K374	13.14
1½"	4880K375	13.44
2"	4880K376	16.50

Hex Reducing Bushings

Pipe Size, Male × Female		Each	Pipe Size, Male × Female		Each	Pipe Size, Male × Female		Each
⅜" × ¼"	4880K342	$1.45	1" × ¾"	4880K349	$1.26	1½" × 1¼"	4880K357	$2.26
½" × ¼"	4880K343	1.45	1¼" × ½"	4880K351	1.87	2" × 1"	4880K358	2.42
½" × ⅜"	4880K344	1.45	1¼" × ¾"	4880K352	1.87	2" × 1¼"	4880K359	2.42
¾" × ¼"	4880K345	.90	1¼" × 1"	4880K353	1.87	2" × 1½"	4880K361	2.42
¾" × ⅜"	4880K346	.90	1½" × ½"	4880K354	2.26	2½" × 2"	4880K363	8.46
¾" × ½"	4880K347	.90	1½" × ¾"	4880K355	2.26	3" × 2"	4880K362	9.99
1" × ½"	4880K348	1.26	1½" × 1"	4880K356	2.26			

Selectable-Angle Standard-Wall (Schedule 40) White PVC Unthreaded Pipe Elbows

- NSF-61 certified for use with drinking (potable) water
- Maximum Temperature: 140° F
- Pipe: Use standard-wall (Schedule 40) white PVC unthreaded (see below)

Always have the right elbow on hand to complete your job—you can cut these two-piece elbows to any angle you need. Furnished as a 90° elbow, they have cutting guides at 22½°, 33¾°, 45°, 56¼°, 67½°, and 78¾° angles; they also have a measuring template so you can cut a custom angle. After cutting, prime and cement the two pieces together (see page 66 for primer and cement). They're IAPMO listed and meet ASTM D2466. Connections: Socket end (female).

Pipe Size		Each
1½"	4747T11	$5.35
2"	4747T12	6.71
3"	4747T13	18.88
4"	4747T14	24.69

Standard-Wall (Schedule 40) White PVC Unthreaded Pipe

- NSF-61 certified for use with drinking (potable) water
- Maximum pressure: See below
- Maximum Temperature: 140° F
- Fittings: Use standard-wall (Schedule 40) white PVC (see page 62 and above)

PVC is the most popular plastic material for low-pressure plumbing applications, offering good corrosion resistance, strength, and rigidity. This pipe meets ASTM D1784 and D1785 and CSA B137.3-99.

Connect pipe to fittings by cementing the pipe end (male) into the socket end (female) using a primer and cement (see page 66).

Pipe Size	ID	Max. psi @ 73° F	5-ft. Lengths	Each	10-ft. Lengths	Each
¼"	0.354"	780	48925K21★	$3.56	48925K41★	$5.46
⅜"	0.483"	620	48925K22★	4.70	48925K42★	7.21
½"	0.608"	600	48925K91	1.88	48925K11	2.50
¾"	0.810"	480	48925K92	2.50	48925K12	3.33
1"	1.033"	450	48925K93	3.68	48925K13	4.90
1¼"	1.364"	370	48925K94	4.98	48925K14	6.63
1½"	1.592"	330	48925K95	$5.86	48925K15	$7.82
2"	2.049"	280	48925K96	7.85	48925K16	10.47
2½"	2.445"	300	48925K99	13.92	48925K19	20.88
3"	3.042"	260	48925K97	14.41	48925K17	21.62
4"	3.998"	220	48925K98	20.51	48925K18	30.77
6"	6.031"	180	48925K25	35.73	48925K45	53.62
8"	7.943"	160	48925K26	53.64	48925K46	80.47

★ Color is dark gray.

Warning! *Never use PVC fittings and pipe with compressed air or gas.*

McMASTER-CARR 63

Figure 9.11.18: PVC Pipe Source Data Sheet

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- Cistern (Water) Tanks

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- Low Profile Water Hauling Tanks
- OIL TANKS (Used Oil Only)
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- Drum Spill Pallets & Containment
- FUEL TANKS (Be Prepared!!)
- Pick Up Truck Tanks
- ***PRESSURE WASHER TANKS*** (auto detail industry)
- Doorway Tanks (29" wide)
- Small Sprayer Tanks

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Part Number:	B268
Capacity:	5 gallons
Size:	12 1/4"L x 12 1/4"W x 8 1/4"H
USD Price:	65.00
USD Shipping:	**

** Oversized item. Shipping will be billed separately.
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This is a 3/8th wall heavy duty marine grade tank. It can be used for many other applications outside the marine industry. This tank is of the highest quality in the business.
It's a blank (no fittings or holes) tank and you can turn it anyway you choose to fit your needs. We will install any fittings you ask for. The process works with us sending you a blank drawing to fill out. Once you send it back to us we give you a call to go over it revising any corrections needed. Once you are comfortable enough to place an order, we get it rolling.

Fitting accessories include:
inspection plates, manways, hose barbs, female npt (threaded), slip, uniseal

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Figure 9.11.19: Reservoir Source Data Sheet

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FL30000

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FL-30000 Series flow meters use a pitot tube pickup and a hard-edged float design to provide a convenient and economical means of measuring water flow in a closed pipe system. A one-piece, impact-resistant machined acrylic body offers the strength and long service required in most commercial and industrial applications. Ten low flow rate models are ideal for applications where flowrates are typically low, such as in solar-heated pools and spas, electronics, and irrigation.

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Part Number	Availability	Price	Description	RoHS	Qty.
FL-30001	In Stock	$70.00	5-40 GPM Rotometer 1" pipe size	✓	0

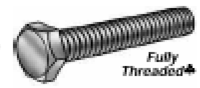
Figure 9.11.20: Flow Meter Source Data Sheet

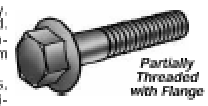
CAD Technical drawings and 3-D models available for items with this symbol.

Hex Head Cap Screws

For information about cap screw head and thread dimensions, see page 2982. For nuts, see pages 3025-3050.

Nonmetallic





All screws are made to a Class 2A thread fit. Length is measured from under head or flange where applicable. Fully threaded screws are also known as tap bolts.

Nylon 6/6—This nonconductive material resists chemicals and solvents, except mineral acids. Temperature range is –40° to +185° F. Rockwell hardness is R105. Minimum tensile strength is 11,000 psi. Color is off-white. **Also Available:** Black color. Please ask for 91970A222 and specify thread size and length.

Note: Since nylon absorbs moisture from the environment, changes in moisture content will affect the screw's dimensions and properties.

PVC—Provides excellent corrosion resistance against weak acids, alkalies, and alcohols. Withstands temperatures up to 120° F. Rockwell hardness is R70. Minimum tensile strength is 5,000 psi. Color is gray.

Reinforced Polyurethane—Made of polyurethane reinforced with fiberglass for greater strength than nylon screws. Great in corrosive environments. Material is nonconductive and resistant to many chemicals. Temperature range is –40° to +150° F. Not rated for Rockwell hardness. Minimum tensile strength is 27,000 psi. Color is gray.

Screws with flange provide a grip on the bearing surface when the screw is tightened. No loose washers needed.

Kynar (PVDF)—Possesses excellent corrosion and chemical resistance. Also known as PVDF (polyvinylidene fluoride), it's a tough and durable material. Withstands temperatures up to 285° F. Rockwell hardness is R109. Minimum tensile strength is 6,200 psi. Color is off-white.

PTFE—Has high dielectric properties, so it's perfect for electrical applications. Resists moisture and chemicals, and has excellent mechanical properties. Temperature range is –100° to +500° F. Rockwell hardness is R58. Minimum tensile strength is 3,000 psi. Color is white.

Nylon 6/6

Lg.	Pkg. Qty.		Per Pkg.
1/4"-20 Head: Wd. 7/16"; Ht. 5/32"			
3/8"	100	91244A535♣	$10.92
1/2"	100	91244A537♣	11.08
3/4"	100	91244A540♣	11.25
1"	100	91244A542♣	11.42
1 1/4"	100	91244A544	11.59
1 1/2"	100	91244A546	11.75
2"	100	91244A550	12.09
5/16"-18 Head: Wd. 1/2"; Ht. 13/64"			
1/2"	50	91244A579♣	$9.97
3/4"	50	91244A581♣	10.11
1"	50	91244A583♣	10.25
1 1/4"	25	91244A585	5.60
1 1/2"	25	91244A587	5.68
2"	25	91244A591	5.84
2 1/2"	25	91244A593	6.00
3"	25	91244A595	6.16
3/8"-16 Head: Wd. 9/16"; Ht. 15/64"			
1/2"	25	91244A620♣	$5.71
1"	25	91244A624♣	5.37
3/8"-16 (Cont.)			
1 1/4"	50	91244A626	$11.84
1 1/2"	25	91244A628	6.67
2"	25	91244A632	7.15
2 1/2"	25	91244A634	7.79
3"	25	91244A638	7.96
1/2"-13 Head: Wd. 3/4"; Ht. 5/16"			
1/2"	10	91244A708♣	$4.59
3/4"	10	91244A710♣	4.72
1"	10	91244A712♣	4.84
1 1/4"	10	91244A714♣	4.96
1 1/2"	10	91244A716	5.09
2"	10	91244A720	5.34
2 1/2"	10	91244A722	5.40
3"	10	91244A724	6.38
5/8"-11 Head: Wd. 15/16"; Ht. 25/64"			
1/2"	10	91244A751♣	$5.31
1"	10	91244A753♣	5.63
2"	10	91244A755	6.38

PVC

Lg.	Pkg. Qty.		Per Pkg.
1/4"-20 Head: Wd. 7/16"; Ht. 11/64"			
1/2"	10	95841A538♣	$4.39
3/4"	10	95841A540♣	4.70
1"	5	95841A542♣	2.58
1 1/2"	5	95841A546	3.48
2"	5	95841A550	4.24
3"	1	95841A554	2.27
5/16"-18 Head: Wd. 1/2"; Ht. 13/64"			
1"	10	95841A583♣	$6.36
1 1/4"	5	95841A585	4.39
1 1/2"	5	95841A587	5.00
2"	5	95841A589	6.36
3/8"-16 Head: Wd. 9/16"; Ht. 1/4"			
1/2"	10	95841A623♣	$6.82
1"	5	95841A624♣	3.64
3/8"-16 (Cont.)			
1 1/4"	5	95841A626	$5.00
1 1/2"	5	95841A628	4.55
2"	5	95841A632	6.36
3"	1	95841A636	2.42
1/2"-13 Head: Wd. 3/4"; Ht. 11/32"			
1"	1	95841A712♣	$1.67
1 1/2"	1	95841A716	2.17
2"	1	95841A720	2.50
3"	1	95841A724	3.83
4"	1	95841A726	9.00
5/8"-11 Head: Wd. 7/8"; Ht. 27/64"			
1 1/2"	1	95841A800	$4.00
2"	1	95841A802	4.83
3"	1	95841A806	4.67
4"	1	95841A810	10.27

Reinforced Polyurethane

Lg.	Pkg. Qty.		Per Pkg.
1/4"-20 Head: Wd. 7/16"; Ht. 0.19"			
1/2"	25	91345A552♣	$11.48
3/4"	25	91345A554♣	12.22
1"	25	91345A556♣	12.98
1 1/4"	25	91345A558	14.53
1/4"-20 (Cont.)			
1 1/2"	25	91345A560	$12.95
5/16"-18 Head: Wd. 1/2"; Ht. 0.205"			
1 1/2"	25	91345A582	$13.62
2"	25	91345A584	14.68
3/8"-16 Head: Wd. 9/16"; Ht. 0.25"			
1 1/2"	25	91345A628	$14.66
2"	25	91345A632	14.91
2 1/2"	10	91345A634	7.40
3"	10	91345A636	7.74
5/8"-11 Head: Wd. 15/16"; Ht. 0.40"			
1 1/2"	5	91345A640	$7.25
2"	5	91345A642	8.00
2 1/2"	5	91345A644	9.20
3"	5	91345A646	9.47
3 1/2"	5	91345A648	11.27
5/8"-11 (Cont.)			
4"	1	91345A650	$2.34
5"	1	91345A655	4.86
3/4"-10 Head: Wd. 1 1/8"; Ht. 0.465"			
1 1/2"	5	91345A660	$10.11
2"	5	91345A662	11.91
2 1/2"	1	91345A664	2.49
3"	1	91345A666	2.83
3 1/2"	1	91345A668	2.92
4"	1	91345A670	3.22
5"	1	91345A675	5.12

Reinforced Polyurethane with Flange

Lg.	Pkg. Qty.		Per Pkg.
1/4"-20 Head: Wd. 3/8"; Ht. 0.280" Flange Dia.: 0.560"			
1/2"	25	91345A680♣	$11.66
5/8"	25	91345A682♣	13.09
3/4"	25	91345A684♣	13.60
7/8"	25	91345A686♣	13.66
1"	25	91345A688♣	14.53
1 1/4"	25	91345A690♣	13.97
1 1/2"	25	91345A692♣	14.73
3/8"-16 Head: Wd. 9/16"; Ht. 0.383" Flange Dia.: 0.800"			
1/2"	25	91345A694♣	$14.92
3/4"	25	91345A698♣	14.88
7/8"	10	91345A699♣	7.53
1"	10	91345A700♣	7.75
1 1/4"	10	91345A701♣	8.21
3/8"-16 (Cont.)			
1 1/2"	10	91345A702	$8.55
2"	10	91345A703	9.37
2 1/2"	5	91345A704	5.08
3"	5	91345A705	5.38
1/2"-13 Head: Wd. 3/4"; Ht. 0.500" Flange Dia.: 1.059"			
3/4"	10	91345A706♣	$7.24
1"	10	91345A707♣	8.42
1 1/4"	10	91345A714♣	9.47
1 1/2"	5	91345A716♣	5.32
2"	5	91345A720♣	6.92
2 1/2"	5	91345A722	7.66
3"	5	91345A724	9.44
3 1/2"	1	91345A726	2.45
4"	1	91345A728	2.77

Kynar (PVDF)

Lg.		Each
1/4"-20 Head: Wd. 7/16"; Ht. 11/64"		
1/2"	98046A110♣	$5.63
3/4"	98046A115♣	5.88
1"	98046A120♣	6.25
5/16"-18 Head: Wd. 1/2"; Ht. 13/64"		
3/4"	98046A150♣	$6.88
1"	98046A155♣	7.38
5/16"-18 (Cont.)		
1 1/2"	98046A160♣	$8.13
3/8"-16 Head: Wd. 9/16"; Ht. 1/4"		
1"	98046A215♣	$7.75
1 1/2"	98046A220♣	8.75
2"	98046A225♣	13.13
2 1/2"	98046A230♣	16.88

PTFE

Lg.		Each
1/4"-20 Head: Wd. 7/16"; Ht. 5/32"		
1/2"	91297A537♣	$3.84
3/4"	91297A540♣	4.22
1"	91297A542♣	4.47
5/16"-18 Head: Wd. 1/2"; Ht. 13/64"		
3/4"	91297A581♣	$4.78
1"	91297A583♣	6.25
5/16"-18 (Cont.)		
1 1/2"	91297A585♣	$6.56
3/8"-16 Head: Wd. 9/16"; Ht. 15/64"		
1"	91297A624♣	$6.94
1 1/2"	91297A628♣	7.44
2"	91297A632♣	7.97
2 1/2"	91297A634♣	8.69

♣ Always fully threaded.

Self-Sealing 18-8 Stainless Steel

A silicone rubber O-ring under the head forms a tight seal as these screws are fastened. The O-ring has a temperature range of –160° to +500° F and withstands pressures up to 6000 psi. Screws can be reused without degrading the seal. To ensure sealing performance, the hole size dimensions must be adhered to. 18-8 stainless steel offers excellent corrosion resistance; it may be mildly magnetic. Rockwell hardness is B70. Minimum tensile strength is 70,000 psi. Screws have a Class 2A thread fit. Length is measured from under head. UL recognized and CSA certified. Screws indicated with a ♣ are always fully threaded (fully threaded screws are also known as tap bolts).

Lg.		Each
1/4"-20 Hole Size: 0.265"-0.269"		
1/2"	92205A537♣	$1.86
3/4"	92205A540♣	1.86
1"	92205A542♣	1.86
1 1/4"	92205A544	1.86
1 1/2"	92205A547	2.41
2"	92205A550	2.59
2 1/2"	92205A555	2.79
5/16"-18 Hole Size: 0.332"-0.336"		
3/4"	92205A581♣	$2.93
1"	92205A583♣	2.93
1 1/4"	92205A585	2.93
1 1/2"	92205A588	3.03
2"	92205A591	3.25
2 1/2"	92205A595	3.62
3"	92205A598	3.84
3/8"-16 Hole Size: 0.395"-0.399"		
3/4"	92205A622♣	$3.24
1"	92205A624♣	3.24
1 1/4"	92205A626	3.24
1 1/2"	92205A629	3.38
2"	92205A631	3.76
2 1/2"	92205A635	4.00
3"	92205A640	4.59
1/2"-13 Hole Size: 0.530"-0.534"		
1"	92205A722♣	$4.21
1 1/4"	92205A725	4.48
1 1/2"	92205A728	4.66
2"	92205A731	5.14
2 1/2"	92205A735	5.62
3"	92205A740	6.03
3 1/2"	92205A745	6.41

♣ Always fully threaded.

McMASTER-CARR 2991

Figure 9.11.21: Hex Cap Screws Source Data Sheet

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These high pressure thermocouple plug sensors are ideal for vessel applications, pressurized containers and applications requiring mounted NPT security. The 304SS sheath has a 6.4mm (1/4") dia. that extends 1/2" from the end of the 1/4 NPT pipe plug. Other length sheaths are available. The thermocouple-grade lead wires are stranded 20 AWG, fiberglass insulated, and stainless steel overbraided with stripped leads. Connectors are attached on request. Junctions are grounded or ungrounded for a pressure rating of up to 2500 psi. Exposed junctions are available for air or gas temperature measurements at ambient pressures. To tighten mounting threads, there is a hex section that is 22mm (.56") across flats that are 5.8mm (.23") wide.

To Order (Specify Model Number) Add to Cart

Part Number	Availability	Price	Description	Qty.
TC-T-NPT-G-72	In Stock	$34.00	Type T Grounded Pipe Plug Probe	0
TC-E-NPT-G-72	In Stock	$34.00	Type E Grounded Pipe Plug Probe	0
TC-J-NPT-E-72	In Stock	$34.00	Type J Exposed Tip Pipe Plug Probe	0
TC-K-NPT-E-72	In Stock	$34.00	Type K Exposed Tip Pipe Plug Probe	0
TC-T-NPT-E-72	In Stock	$34.00	Type T Exposed Tip Pipe Plug Probe	0
TC-E-NPT-E-72	In Stock	$34.00	Type E Exposed Tip Pipe Plug Probe	0
TC-J-NPT-U-72	In Stock	$39.00	Type J Ungrounded Pipe Plug Probe	0

Figure 9.11.22: Thermocouple Source Data Sheet

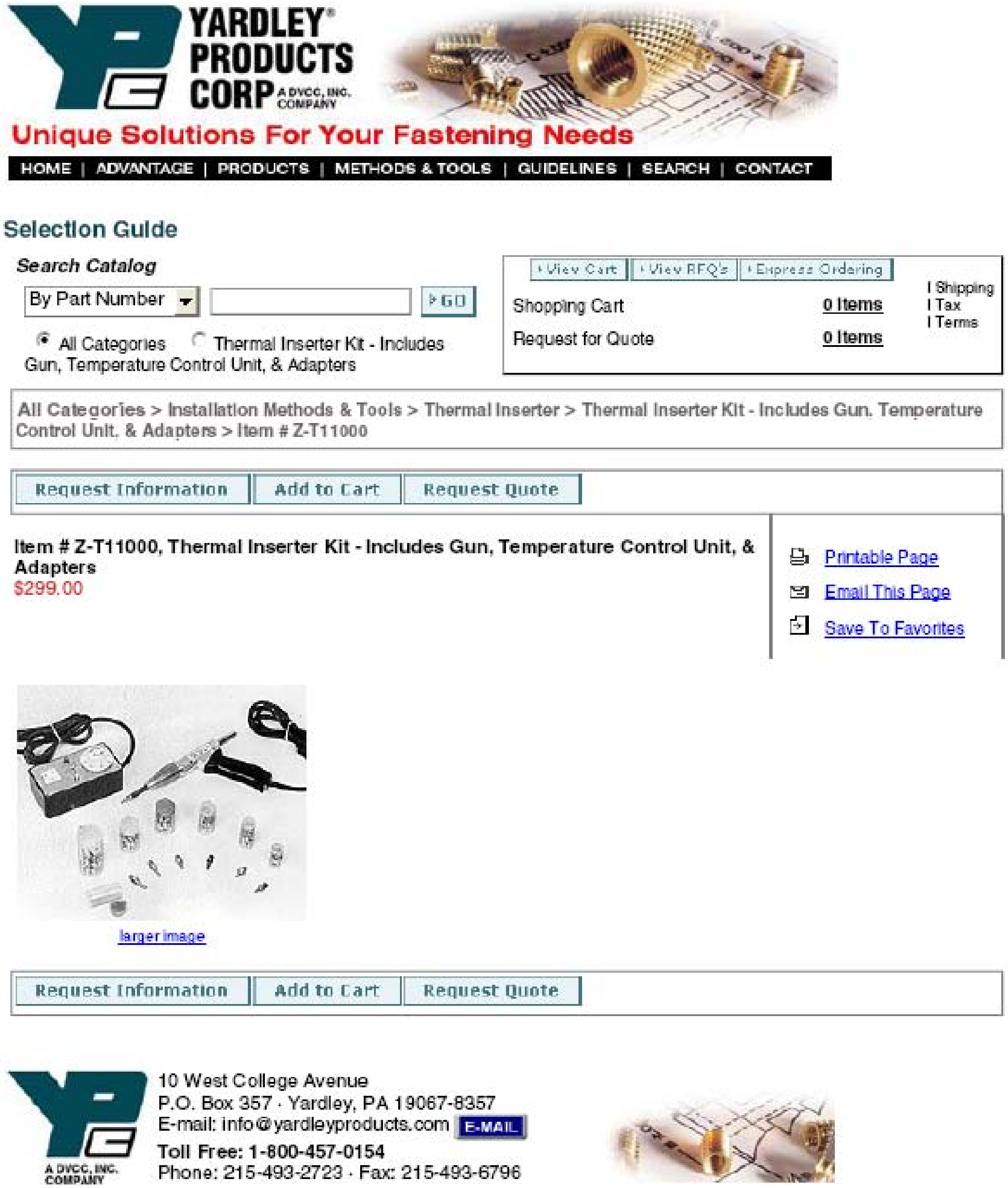

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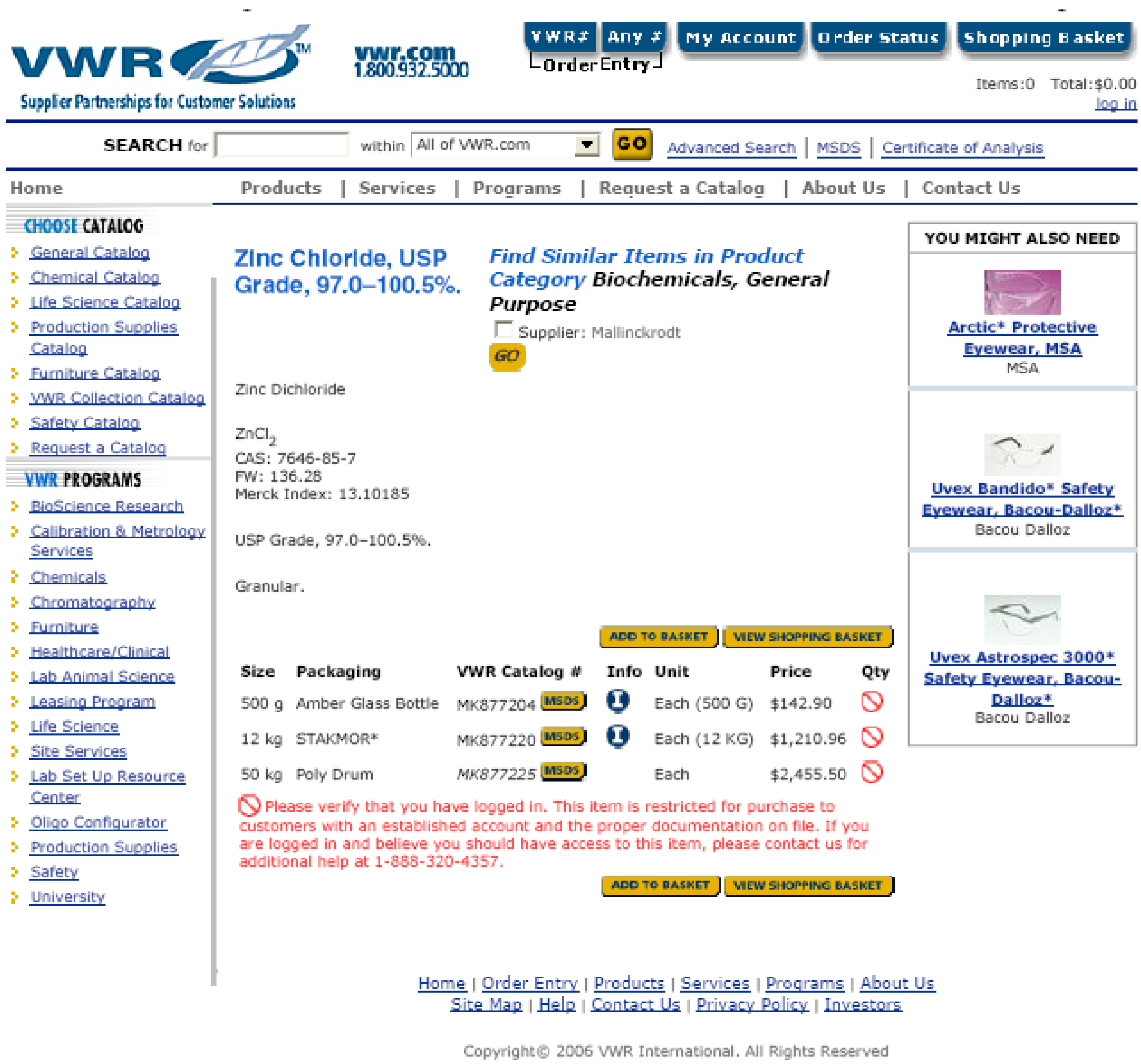
Figure 9.11.23: Thermal Insert Kit Source Data Sheet



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$ZnCl_2$

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Merck Index: 13.10185

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Figure 9.11.24: Zinc Chloride Source Data Sheet

9.12. Test Bed Material Selection Spreadsheets

						VENDORS							
SPECIFICATIONS						USPC	IPS	KMAC	ENG. INFORMATION (data from KMAC)				
Type	Color	Width	Length	Thickness	qty	Price			Mod of Elast. Tens. (PSI)	Mod of Elast. Flex. (PSI)	Tens. Str. (PSI)	H2O Abs. 24hr. (%)	React.
Acrylic	clear	12	12	1/4	1	$4.64	$5.10	$48.56	406000	11700	7830		A
Acrylic	clear	24	24	1 1/4	1			$271.40					A
Acrylic	clear	48	96	2	1			$1,972.00					A
Acrylic	**clear**	**12**	**12**	**4**	**2**			$757.50					A
HD Polyethylene	white	12	12	1/4	1		$4.25	$9.31		207200	4050		A
HD Polyethylene	white	24	24	1 1/4	1		$99.00	$158.40					A
HD Polyethylene	white	24	24	2	1		$197.00	$284.33					A
HD Polyethylene	white	24	48	1/4	1	$25.76							A
HD Polyethylene	**white**	**48**	**96**	**4**	**1**			$5,231.52					A
UHMW (PE)	white	12	12	1/4	1		$5.57	$15.31	155900	107900	3250	0	A
UHMW (PE)	white	24	24	1 1/4	1		$111.32	$160.39					A
UHMW (PE)	white	24	24	2	1		$178.08	$304.27					A
UHMW (PE)	**white**	**12**	**12**	**6**	**2**			$311.78					A
UHMW (PE)	white	24	48	1/4	1	$64.13							A
UHMW (PE)	white	24	48	1 1/4	1	$331.63							A
UHMW (PE)	white	24	48	2	1	$524.37							A
PVC	grey	12	12	1/4	1		$7.33	$13.68	410000	420000	7300		B
PVC	grey	24	24	1 1/4	1		$112.24	$238.86					B
PVC	grey	24	24	2	1		$232.36	$316.72					B
PVC	grey	24	48	1/4	1	$58.16							B
PVC	grey	24	48	1 1/4	1	$438.54							B
PVC	grey	24	48	2	1	$766.33							B
CPVC	opaic grey	12	12	1/4	1			$44.74	430000	410000	8200	0.04	A/B
CPVC	opaic grey	24	48	1 1/4	1			$1,454.61					A/B
CPVC	opaic grey	24	48	2	1			$2,038.90					A/B
CPVC	grey	24	48	1/4	1	$221.63							A/B
Acetal Delrin		12	12	1/4	1	$21.15	$19.59	$20.50	403205	382899	9572	0.65	C
Acetal Delrin		24	24	1 1/4	1		$419.64	$439.72					C
Acetal Delrin		24	24	2	1		$419.64	$685.92					C
Acetal Delrin		**12**	**12**	**4**	**2**		$661.04	$511.48					C
Acetal Delrin		24	48	1 1/4	1	$862.50	$371.12						C
Acetal Delrin		24	48	2	1	$1,343.29							C
ABS	natural	12	12	1/4	1		$5.83	$17.81	302000	314000	5800		A
ABS	natural	24	24	1 1/4	1		$182.40	$245.48					A
ABS	natural	24	24	2	1		$289.07	$376.38					A
ABS	**natural**	**12**	**24**	**4**	**1**			$841.70					A
Teflon		12	12	1/4	1	$46.76	$35.60	$75.74	72000	80000	3900	<0.01	A
Teflon		24	24	1 1/4	1		$711.92	$911.20					A
Teflon		24	24	2	1		$1,139.04	$1,448.42					A
Polypropylene	clear tint	12	12	1/4	1		5.46 x 2	$9.54	152192	183860	3466	slight	A
Polypropylene	white	24	48	1/4	1	$24.39							A
Polypropylene	clear tint	24	48	1 1/4	1		$143.36	$235.01					A
Polypropylene	clear tint	24	48	2	1		$297.04	$463.75					A
Polypropylene	**clear tint**	**48**	**120**	**4**	**1**			$5,400.00					A
Polycarbonate	tinted bronze/grey	12	12	1/4	1	$9.45	$7.63	$15.86	345000	345000	9000	0.15	A
Polycarbonate	black	24	24	1 1/4	1		$715.98	$827.23					A
Polycarbonate	black	24	24	2	1		$1,125.32	$1,026.00					A
Polycarbonate	**black**	**12**	**24**	**4**	**1**			$1,700.46					A
Nylon	white	12	12	1/4	1	$19.56	$23.06	$21.70	400000	410000	12400	1.2	A
Nylon	white	24	24	1 1/4	1		$322.66	$230.42					A
Nylon	white	24	24	2	1		$522.42	$354.07					A
Nylon	**white**	**12**	**24**	**4**	**1**			$340.40					A
Nylon	white	24	48	1 1/4	1	$643.75							A
Nylon	white	24	48	2	1	$1,079.16							A
Nylon	**white**	**12**	**12**	**4**	**2**	$251.66							A

Reactivity Key (with Zinc Chloride)	
A -	Excellent
B -	Good - Minor Effect, slight corrosion or discoloration
C -	Fair - Moderate Effect, not recommended for continous use. Softening, loss of Strength, swelling may occur.
D -	Severe Effect - not recommended for any use.

Sheet Sizes	Qty	L	W	T
Sides	2	13.4	6.9	1.25
Sides -W	2	13.4	6.9	2
Cover	2	6	6	0.25
Endcaps	2	8	8	4+

Vendor Codes	
USPC -	United States Plastic Corp.
IPS -	Industrial Plastic Supply
KMAC -	K-mac Plastics (typically more options available than others)

					Price by Vendor		
Material	**L**	**W**	**T**	**QTY**	**USPC**	**IPS**	**KMAC**
Acrylic	12	12	1/4	1	$4.64	$5.10	$48.56
	24	24	1 1/4	1			$271.40
	48	96	2	1			$1,972.00
	12	12	4	2			$757.50
HD Polyethylene	12	12	1/4	1		$4.25	$9.31
	24	24	1 1/4	1		$99.00	$158.40
	24	24	2	1		$197.00	$284.33
	24	48	1/4	1	$25.76		
	48	**96**	**4**	**1**			$5,231.52
UHMW (PE)	12	12	1/4	1		$5.57	$15.31
	24	24	1 1/4	1		$111.32	$160.39
	24	24	2	1		$178.08	$304.27
	12	**12**	**6**	**2**			$311.78
	24	48	1/4	1	$64.13		
	24	48	1 1/4	1	$331.63		
	24	48	2	1	$524.37		
PVC	12	12	1/4	1		$7.33	$13.68
	24	24	1 1/4	1		$112.24	$238.86
	24	24	2	1		$232.36	$316.72
	24	48	1/4	1	$58.16		
	24	48	1 1/4	1	$438.54		
	24	48	2	1	$766.33		
CPVC	12	12	1/4	1			$44.74
	24	48	1 1/4	1			$1,454.61
	24	48	2	1			$2,038.90
	24	48	1/4	1	$221.63		
Acetal Delrin	12	12	1/4	1	$21.15	$19.59	$20.50
	24	24	1 1/4	1		$419.64	$439.72
	24	24	2	1		$661.04	$685.92
	12	**12**	**4**	**2**		$371.12	$511.48
	24	48	1 1/4	1	$862.50		
	24	48	2	1	$1,343.29		
ABS	12	12	1/4	1		$5.83	$17.81
	24	24	1 1/4	1		$182.40	$245.48
	24	24	2	1		$289.07	$376.38
	12	**24**	**4**	**1**			$841.70
Teflon	12	12	1/4	1	$46.76	$35.60	$75.74
	24	24	1 1/4	1		$711.92	$911.20
	24	24	2	1		$1,139.04	$1,448.42
Polypropylene	12	12	1/4	1		$5.46	$9.54
	24	48	1/4	1	$24.39		
	24	48	1 1/4	1		$143.36	$235.01
	24	48	2	1		$297.04	$463.75
	48	**120**	**4**	**1**			$5,400.00
Polycarbonate	12	12	1/4	1	$9.45	$7.63	$15.86
	24	24	1 1/4	1		$715.98	$827.23
	24	24	2	1		$1,125.32	$1,026.00
	12	**24**	**4**	**1**			$1,700.46
Nylon	12	12	1/4	1	$19.56	$23.06	$21.70
	24	24	1 1/4	1		$322.66	$230.42
	24	24	2	1		$522.42	$354.07
	12	**24**	**4**	**1**			$340.40
	24	48	1 1/4	1	$643.75		
	24	48	2	1	$1,079.16		
	12	**12**	**4**	**2**	$251.66		

Price per material	**sides**	**endcaps**	**w/ max h**
Acylic	$2,248.50	$1,515.00	4
HD Polyethylene	$300.25	$5,231.52	4
UHMW (PE)	$294.97	$623.56	6
PVC	$351.93	-	-
CPVC	$3,538.25	-	-
Acetal Delrin	$1,100.27	$1,022.96	4
ABS	$477.30	$841.70	4
Teflon	$2,406.38	-	-
Polypropylene	$445.86	$5,400.00	4
Polycarbonate	$1,749.61	-	-
Nylon	$604.05	$340.40	4

9.13. Flow Channel Cross Section Maximum and Minimum Dimensions

The maximum and minimum dimensions of the flow channel are based on the maximum pixel dimension of the imaging equipment, and the maximum and minimum number of bead diameters for minimizing edge effects. For instance, if the pixel dimensions of the imaging equipment are P_l and P_w, the bead resolution is R, and the maximum and minimum number of bead diameters for negligible edge effects are N_{max} and N_{min}, with a bead diameter of D_B then a range of dimensions for the flow channel can be determined by,

$$MAX = D_B\left[\frac{MAX\left(P_l, P_w\right)}{R} + 2N_{\max}\right], \quad \text{(Eqn. 9.13.1)}$$

and,

$$MIN = D_B\left[\frac{MAX\left(P_l, P_w\right)}{R} + 2N_{\min}\right]. \quad \text{(Eqn. 9.13.2)}$$

The following table is a summary of above calculations.

Table 9.13.1: Maximum and Minimum Flow Channel Dimensions

Flow Channel Final Calculations							
Camera Dimensions (Pixels)		Resolution (Pixels/Bead Diameter)	Edge Effects Dimensions (Bead Diamters)		Bead Diameter (mm)	Flow Channel Length (m)	
Length	1300	160	MIN	3.5	6	MIN	0.16875
Width	1040		MAX	10		MAX	0.09075

The final cross section dimensions of the flow channel are 0.139-m by 0.139-m, placing the number bead diameters for minimizing edge effects at approximately 7.5.

10. APPENDIX SECTION 2: BILL OF MATERIALS

10.1. Test Bed Price Estimation

			(in)						
Purchased Parts & Materials	**Material**	**Qty**	**L**	**W**	**T**	**Cost per**	**(increment)**	**Min Buy**	**Total**
				Test Section Material Costs					
Test Section Sides	ABS		lowest cost order						$477.30
Test Section Ends	UHMW (PE)	1	12.00	24.00	6.00	$548.47			$548.47
Flanged half coupling pipe fitting	PVC	2				$6.39	ea.		$12.78
Self-Sealing Hex Cap Screws	Stainless Steel	8				$4.21	ea.		$33.68
Viewing Window	Borosilicate Glass	2				$190.00	ea.	2	$380.00
Intro-serts - Regular	Stainless Steel	216				$2.22	ea.		$480.17
Intro-serts - Short	Stainless Steel	36				$2.22	ea.		$79.92
Thermal Inserter Kit		1				$299.00	ea.		$299.00
Gasket Sheeting	Neoprene	2	24.00	24.00	0.06	$6.75	per ft.		$13.50
O-Rings	Viton Rubber	252				$4.98	per pack of	50	$24.90
Btn Sckt Hd Cap Screw(M3X0.5)	Stainless Steel	252				$8.05	per pack of	50	$40.25
Honeycomb flow staightener	Polycarbonate	2				$1.00			$2.00
								Total:	$2,391.97
							w/out inserts	Total:	$1,532.88
				Flow Loop Material Costs					
Diaphram Valve	PVC	1				$116.00	ea.		$116.00
Centerfugal Pump	PPE**	1				$692.00	ea.		$692.00
PVC Pipe	PVC	2				$4.85	per 10 ft.		$9.70
Fittings	PVC	6				$0.62			$3.72
Storage Tank	Polyethylene	1				$65.00			$65.00
								Total:	$886.42
				Measurement Equipment Cost					
Rotometer	Polysulfone	1				$70.00			$70.00
Pressure Transducer	Plastic/Silicone	1				$36.00			$36.00
Thermocouple (pipe plug probe)	Stainless Steel	1				$34.00			$34.00
Pressure Gauge	Stainless Steel	2				$16.25			$32.50
Pressure Snubber	Stainless Steel	2				$10.00			$20.00
								Total:	$192.50
				Media & Fluid Cost					
Glass Beads	Borosilicate Glass	6				$138.31	per container	1800	$829.86
ZnCl2 Powder	ZnCl2	1				$2,455.50	per	50kg.	$2,455.50
								Total:	$3,285.36

Grand Total: $6,756.25
w/out media & fluid: $3,470.89

Grand Total w/out inserts: $5,897.16
w/out media & fluid: $2,611.80

10.2. Component Source and Lead Times

Item #	Item	Vendor	Product Code	Description	Qty.	Unit Price	Per Qty.	Total Price	Lead Time (weeks)
1	Pump	Cole Parmer	C-72009-00	High Efficiency Prolypropylene Pump, 40 GPM, 1/2hp,115/208-230 VAC	1	$692.00	ea.	$692.00	1
2	Diaphragm Valve	George Fisher	161-314-680	Type 314 Manual True Union Diaphragm Valve - PVC	1	$116.00	ea.	$116.00	1
3	Storage Tank	Plastic-Mart	B268	5 gallon, 12.25"L x 12.25"W x 8.25"H 3/8"thick polyethylene tank	1	$65.00	ea.	$65.00	4
4	Viewing Glass	Specialty Glass Products	inq.#06112904	Schott Borofloat Square 120mm+-0.25mm square; 20mm thick; rnd. Corners	2	$190.00	ea.	$380.00	5 - 6
5	ABS Sheet	Industrial Plastic Supply		various sheet sizes	req'd	$477.30		$477.30	2
6	UHMW Block	K-MAC Plastics	KS-8505	6.00" x 12" x 24"- Standard Natural, UHMWPE Sheet	1	$548.70	ea.	$548.70	3
7	Intro-serts - Regular	Yardley Products Corp.	3005H6-8SS	Ultrasonic stainless steel inserts - metric threads M3.0 x 0.5	216	$2.22	ea.	$480.17	1
8	Intro-serts - Short	Yardley Products Corp.	3005HR6-7SS	Ultrasonic stainless steel inserts - metric threads M3.0 x 0.5	36	$2.22	ea.	$79.92	1
9	Thermal Inserter Kit	Yardley Products Corp.	Z-T11000	Thermal Inserter Kit - includes gun, temp. control unit, and adapters	1	$299.00	ea.	$299.00	1
10	Flanged half coupling pipe fitting	McMaster Carr	4881K213	flanged half coupling pipe fitting	2	$6.39	ea.	$12.78	1
11	Self-Sealing Hex Cap Screws	McMaster Carr	92205A722	18-8 Stainless Steel, self sealing hex cap screws	8	$4.21	ea.	$33.68	1
12	Gasket Sheeting	McMaster Carr	8625K62	Neoprene rubber sheet	2	$6.75	ft.	$13.50	1
13	O-Rings	McMaster Carr	9464K514	Viton rubber o-ring	252	$4.98	50	$24.90	1
14	Btn Sckt Hd Cap Screw(M3X0.5)	McMaster Carr	92095A187	18-8 Stainless Steel Button Socket Head Cap Screw M3.0x0.5	252	$8.05	50	$40.25	1
15	PVC Pipe	McMaster Carr	48925K13	1" sch 40 white solid PVC unthreaded	2	$4.85	10ft	$9.70	1
16	Fittings	McMaster Carr	4880K23	1" sch 40 white PVC Socket-weld x Socket-weld female 90° Elbow	6	$0.62	ea.	$3.72	1
17	Pressure Gauge	Omega	PGUF-20L-60PSI	304 Stainless Steel Case, 0-60 psi, 2" dial	2	$16.25	ea.	$32.50	1
18	Pressure Snubber	Omega	PS-4E	1/4" NPT pressure snubber for water and light oils (	2	$10.00	ea.	$20.00	1
19	Honeycomb flow staightener	Plascore		PC Polycarbonate honeycomb	2	$1.00	ea.	$2.00	4 - 5
20	Rotometer	Omega	FL30002	5-40 GPM, 316SS, FLOAT 1" FNPT	1	$70.00	ea.	$70.00	1
21	Pressure Transducer	Omega	PX26-100GV	Differential model with a range of 0 to 100 psig	1	$36.00	ea.	$36.00	1
22	Thermocouple (pipe plug probe)	Omega	TC-J-NPT-G-72	Type T grounded pipe plug probe	1	$34.00	ea.	$34.00	1
23	Kimax Borosilicate Glass Beads	WWR	13500 6	Beads,solid glass,6mm CS 1LB	6	$138.31	ea.	$829.86	3
24	ZnCl2 Powder	WWR	MK877225	50 Kg Poly Drum of ZnCL2 powder	1	$2,455.50	ea.	$2,455.50	3
							Total:	$6,756.48	

11.APPENDIX SECTION 3: PART DRAWINGS

11.1. Drawing Package

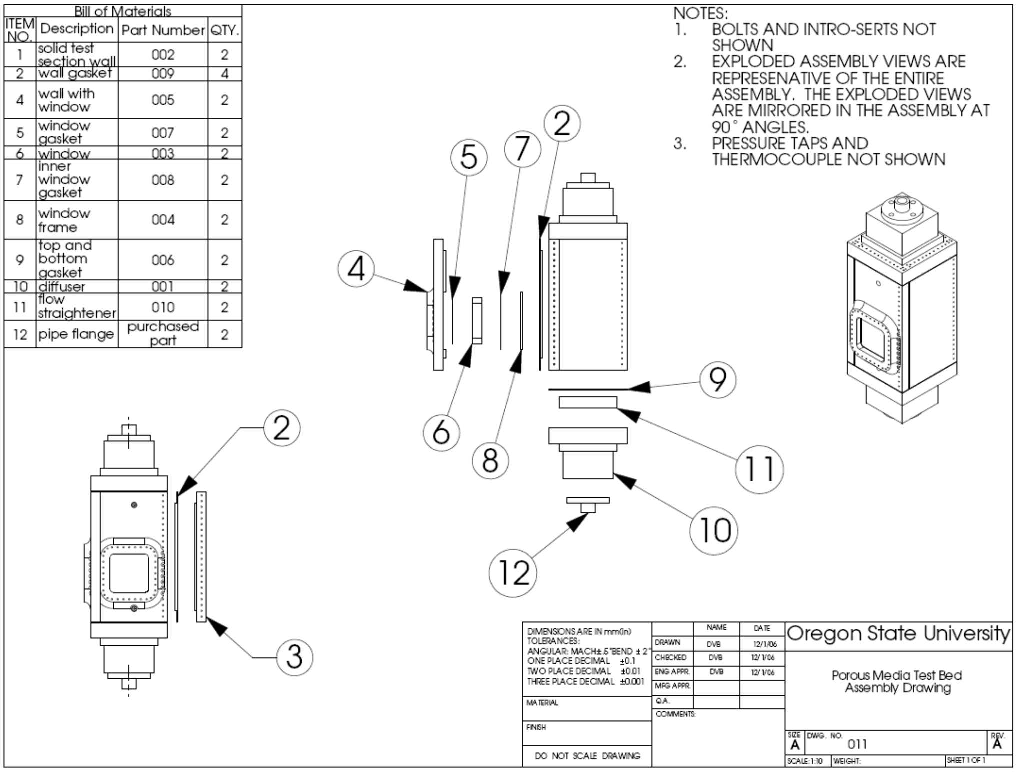

Figure 11.1: Assembly Drawing

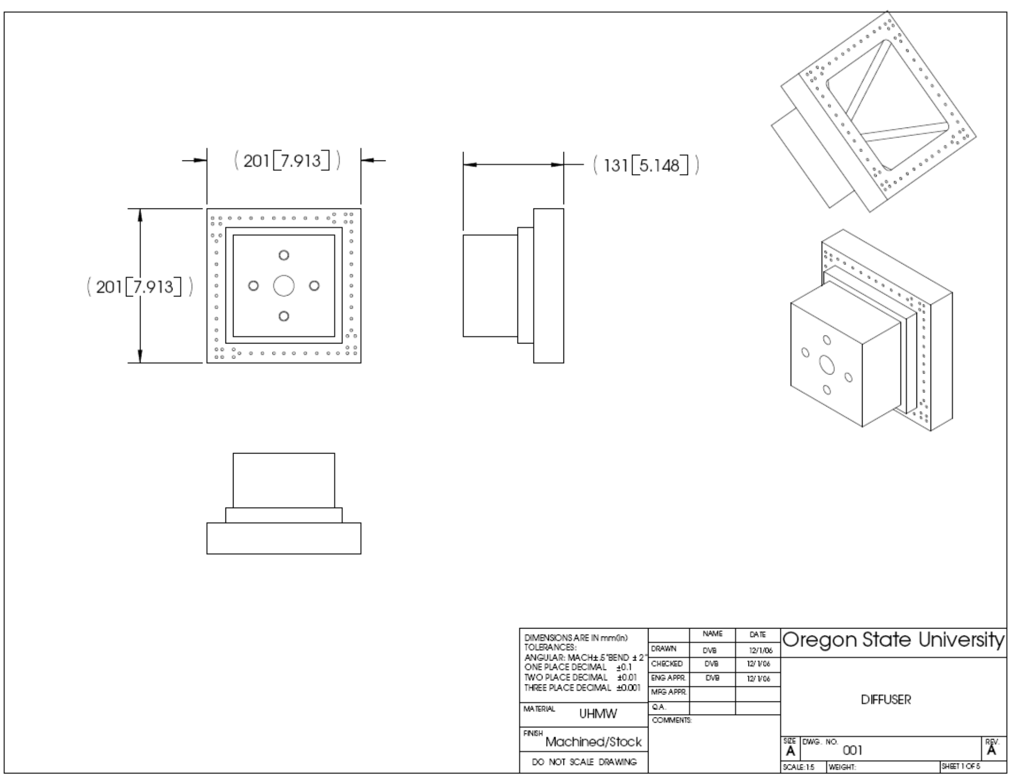

Figure 11.2.1: Diffuser Drawing

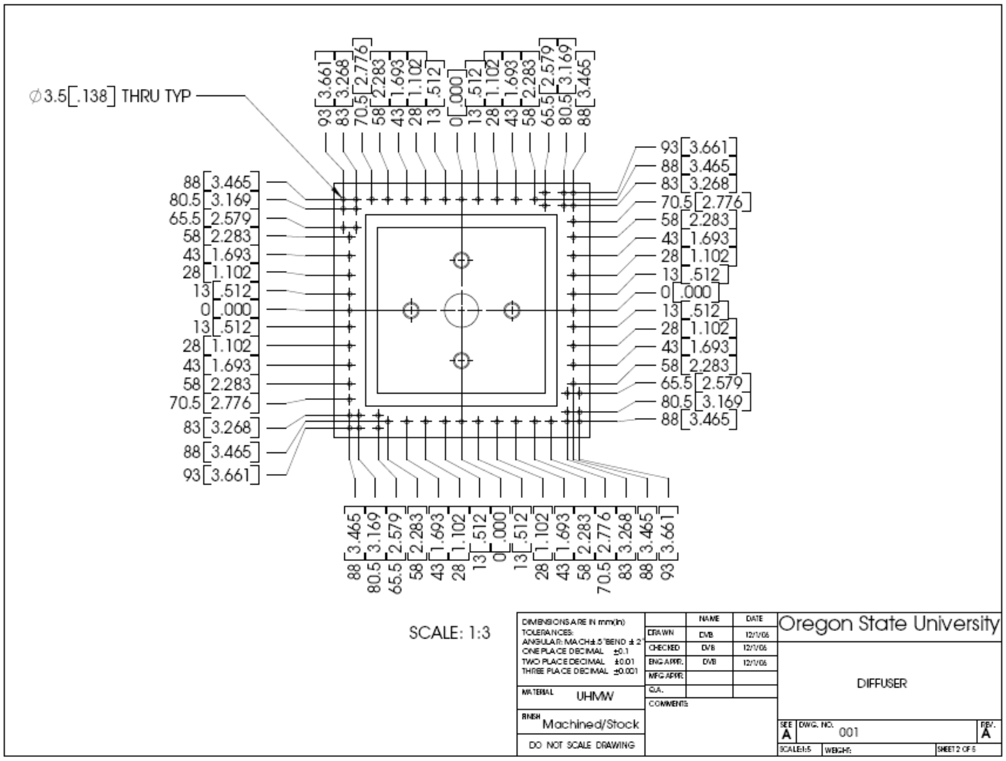

Figure 11.2.2: Diffuser Drawing

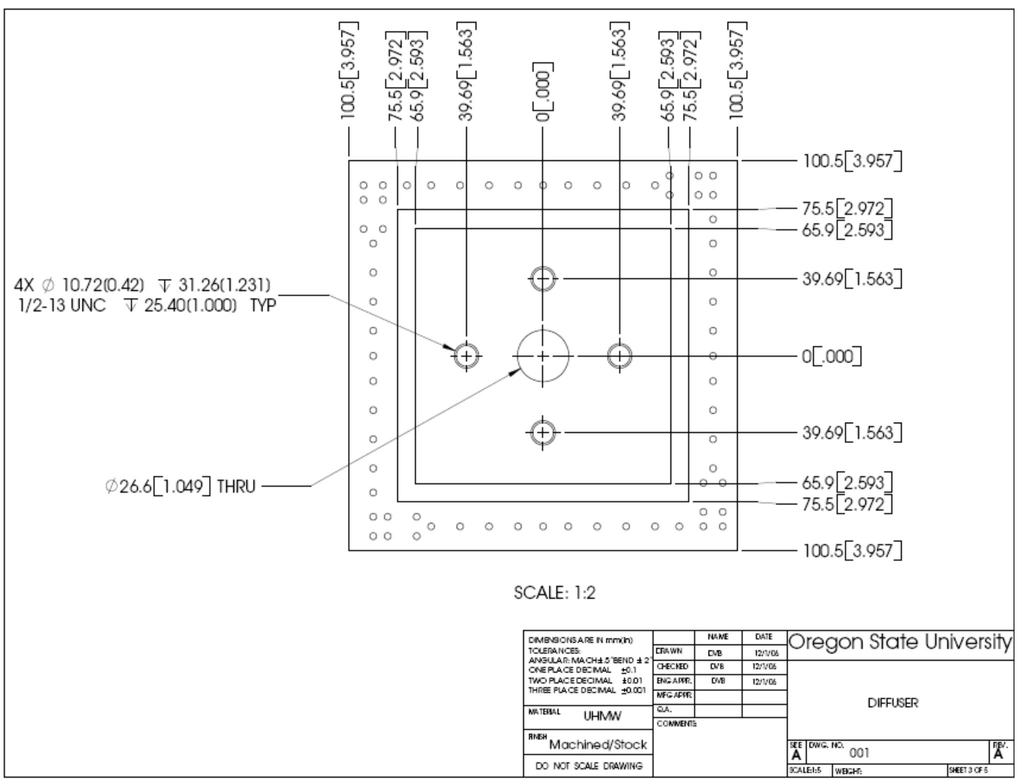

Figure 11.2.3: Diffuser Drawing

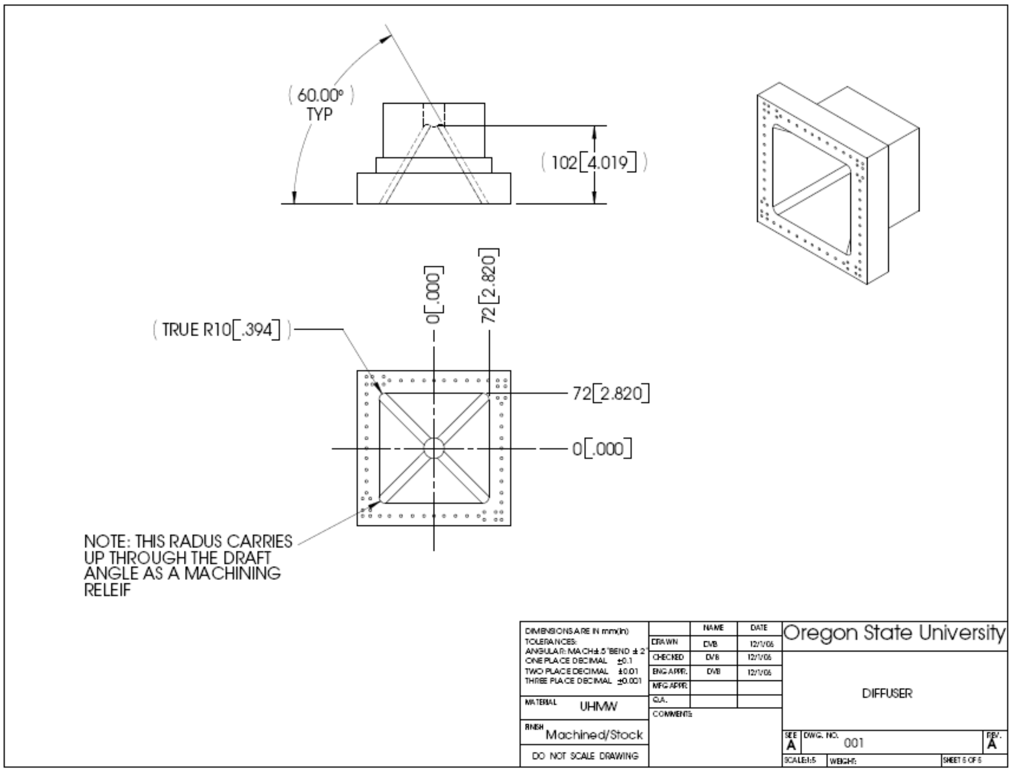

Figure 11.2.4: Diffuser Drawing

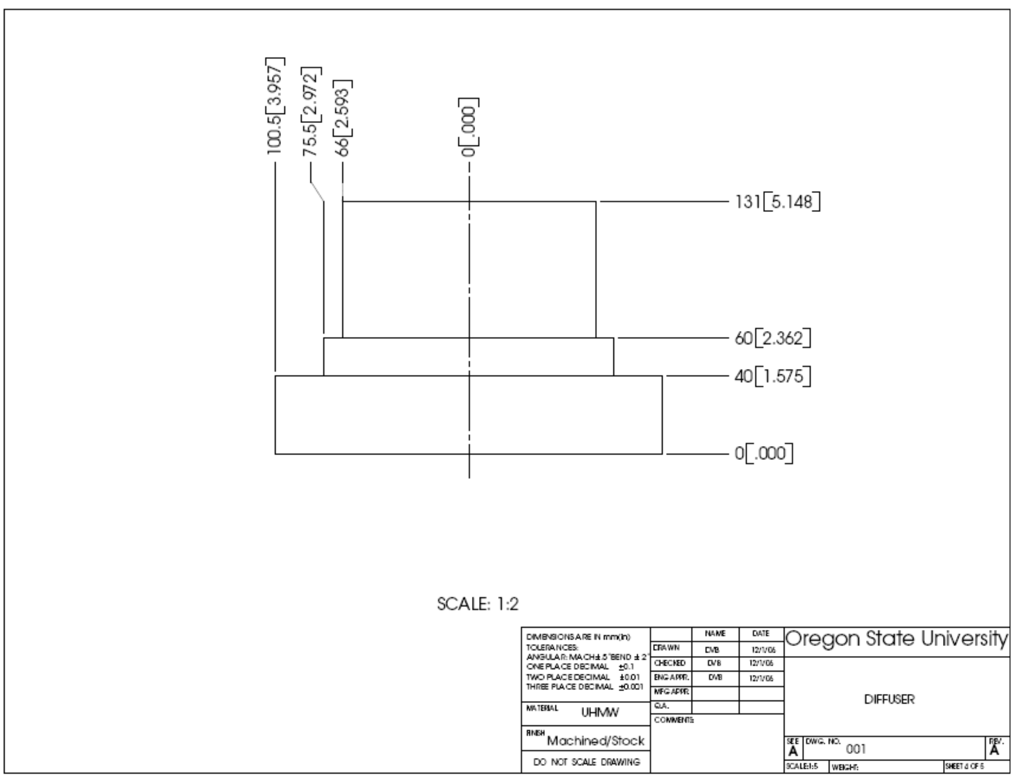

Figure 11.2.5: Diffuser Drawing

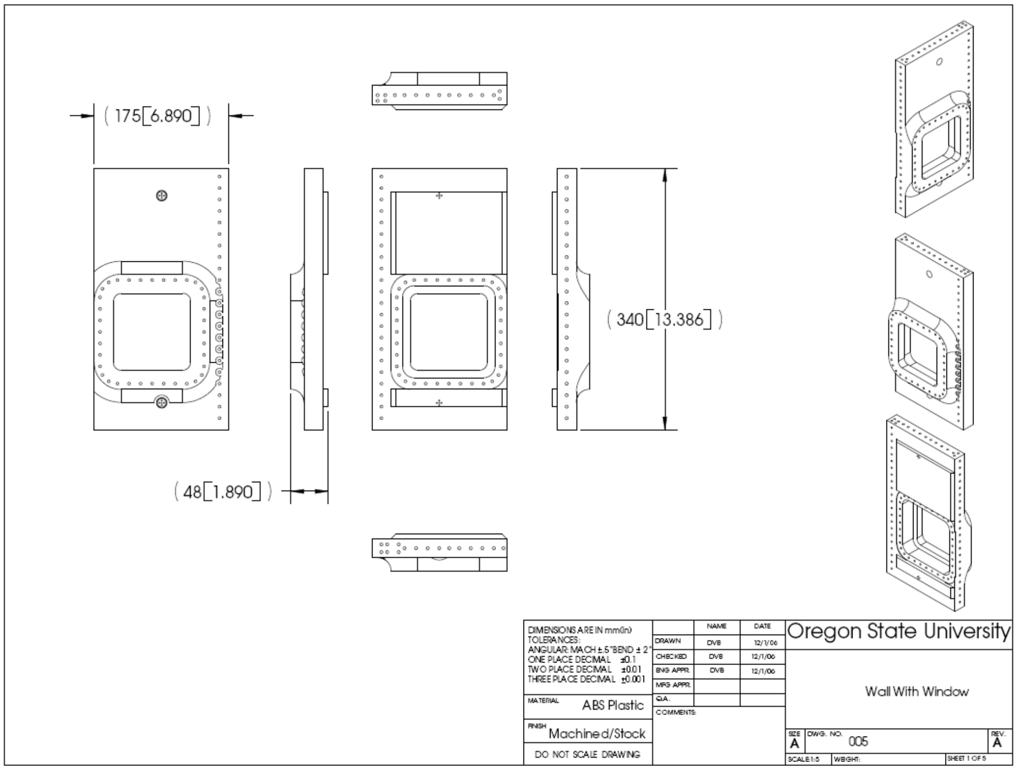

Figure 11.3.1: Window Wall Drawing

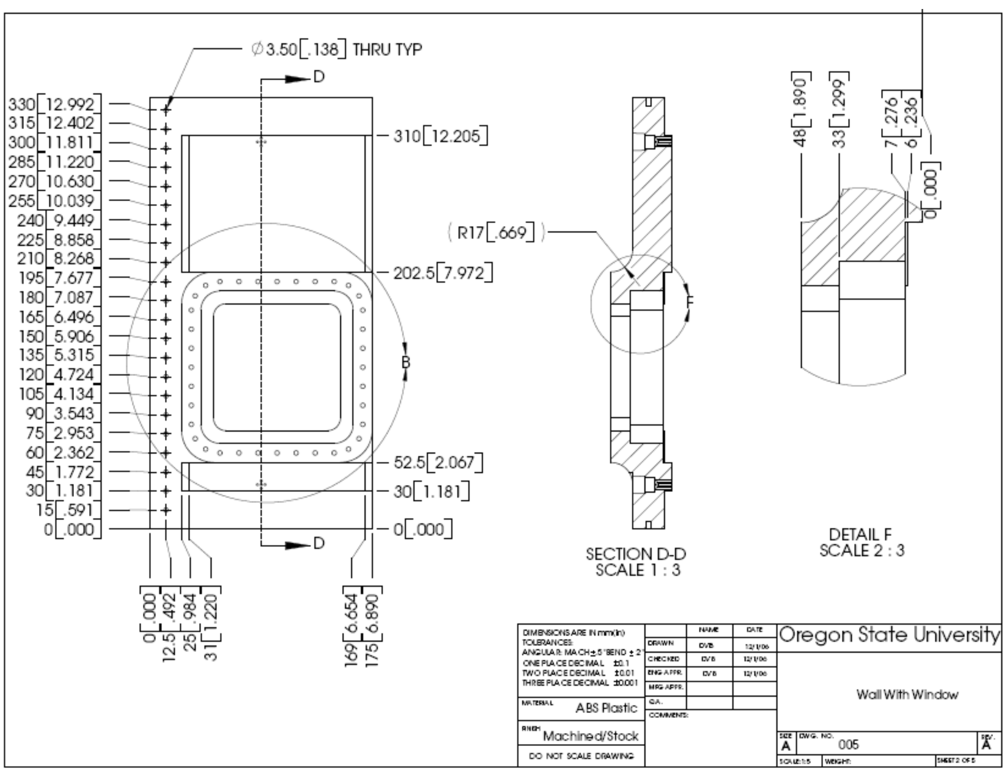

Figure 11.3.2: Window Wall Drawing

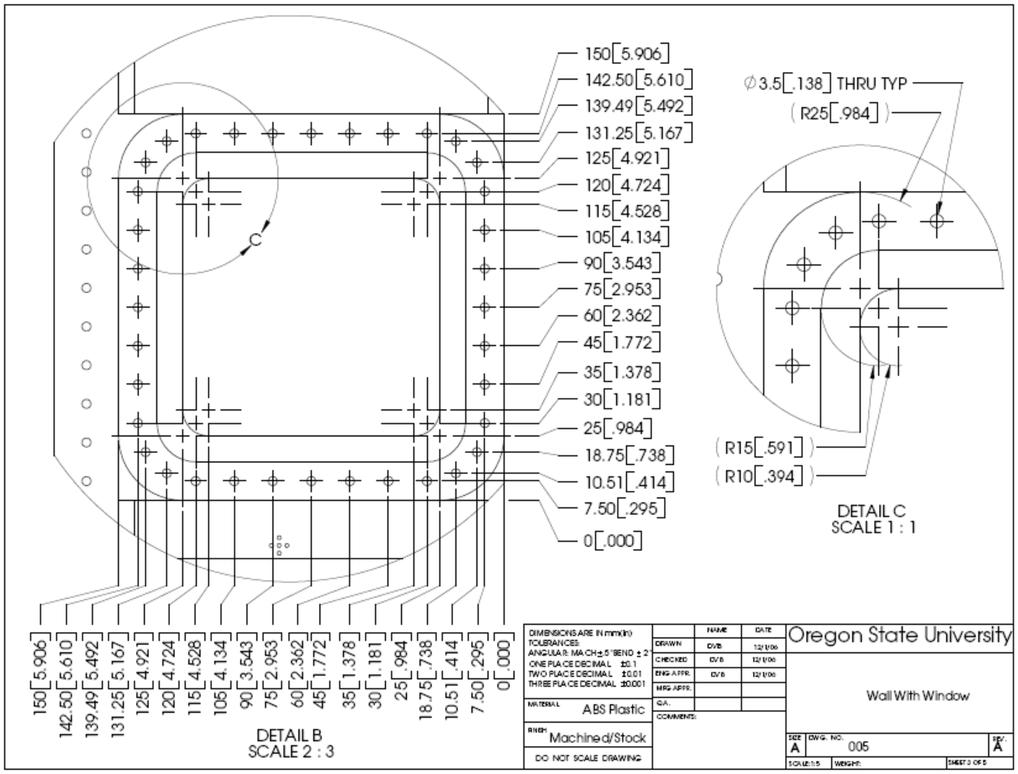

Figure 11.3.3: Window Wall Drawing

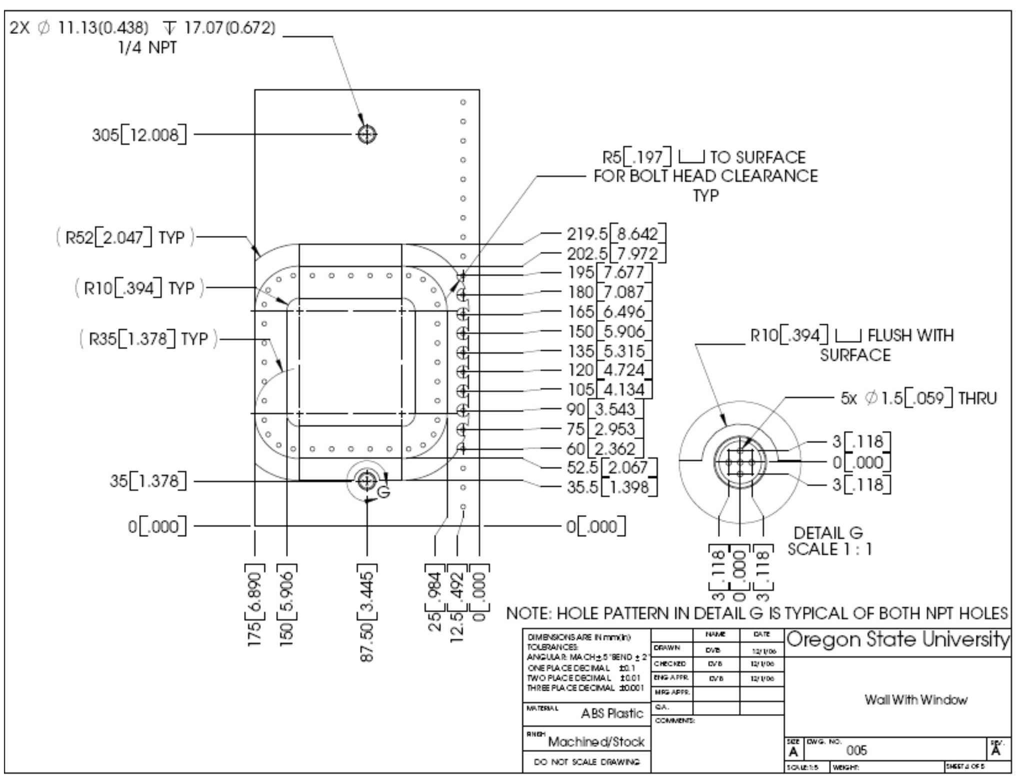

Figure 11.3.4: Window Wall Drawing

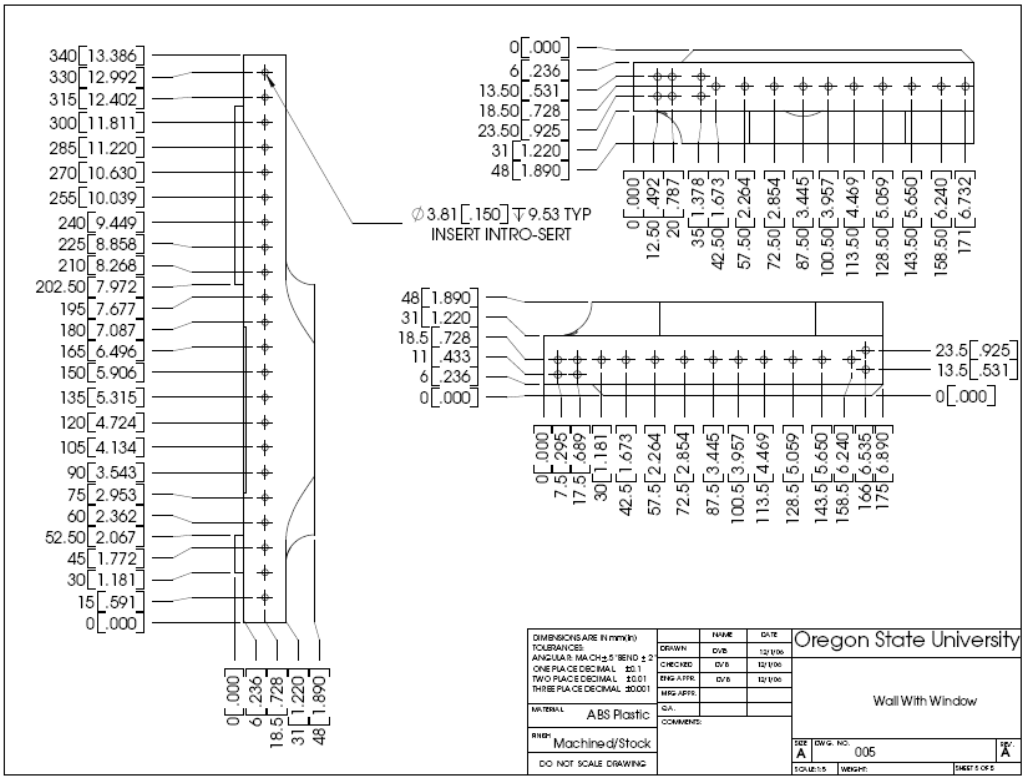

Figure 11.3.5: Window Wall Drawing

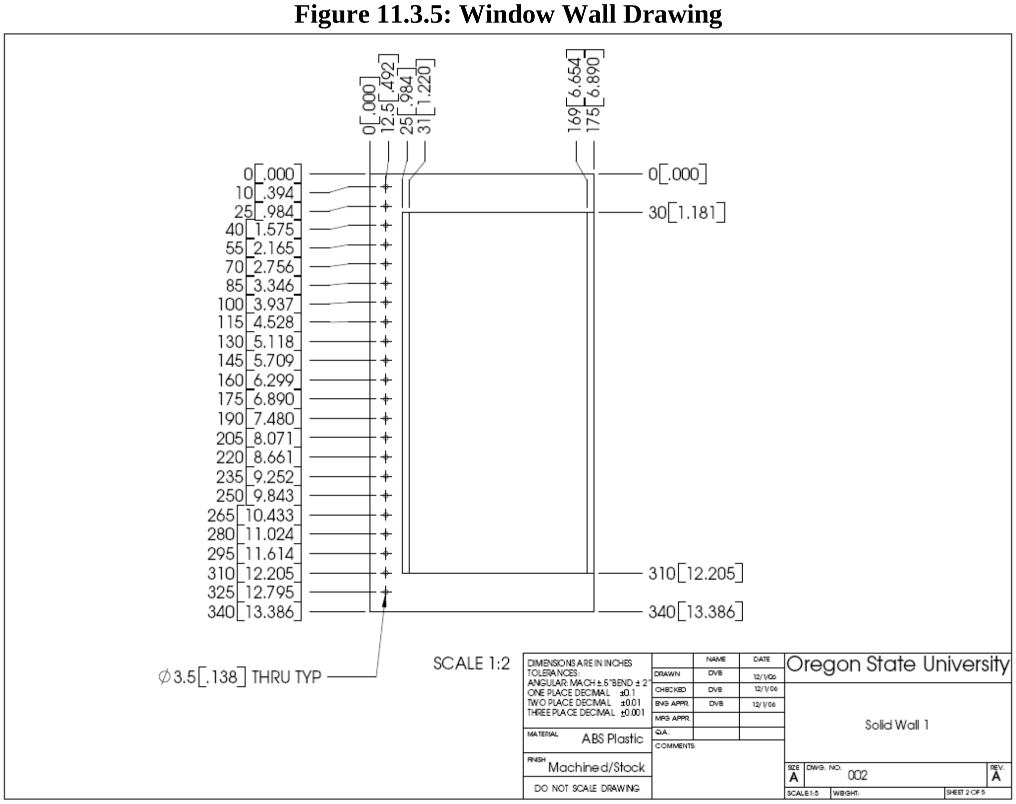

Figure 11.4: Solid Wall 1 Drawing

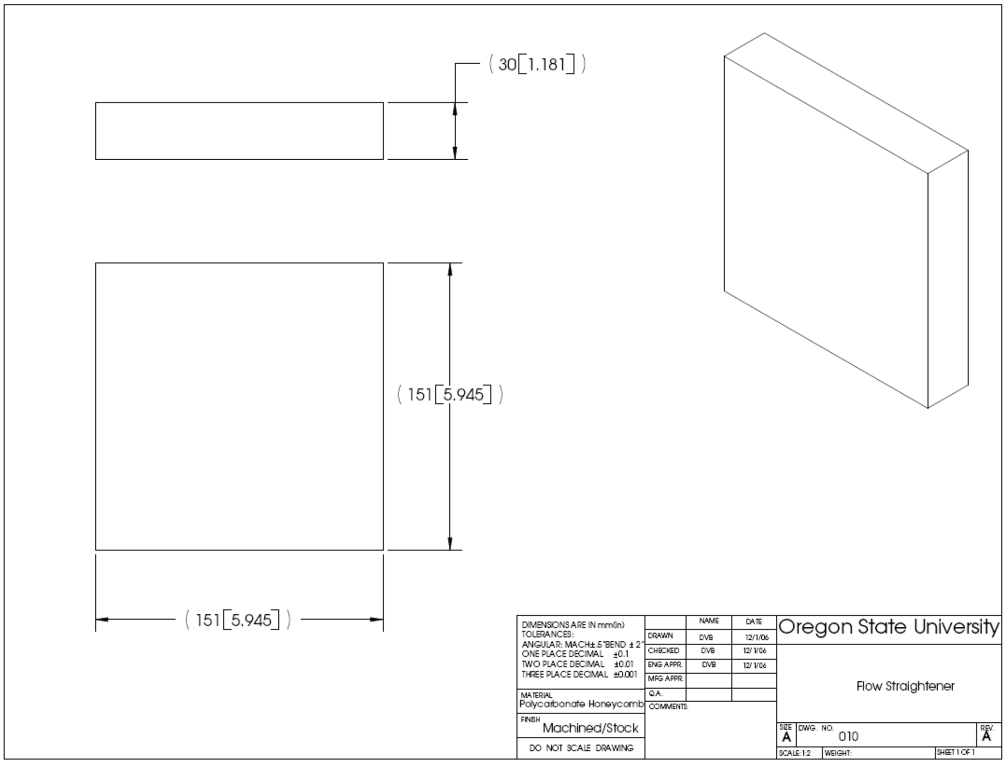

Figure 11.5: Flow Straightener Drawing

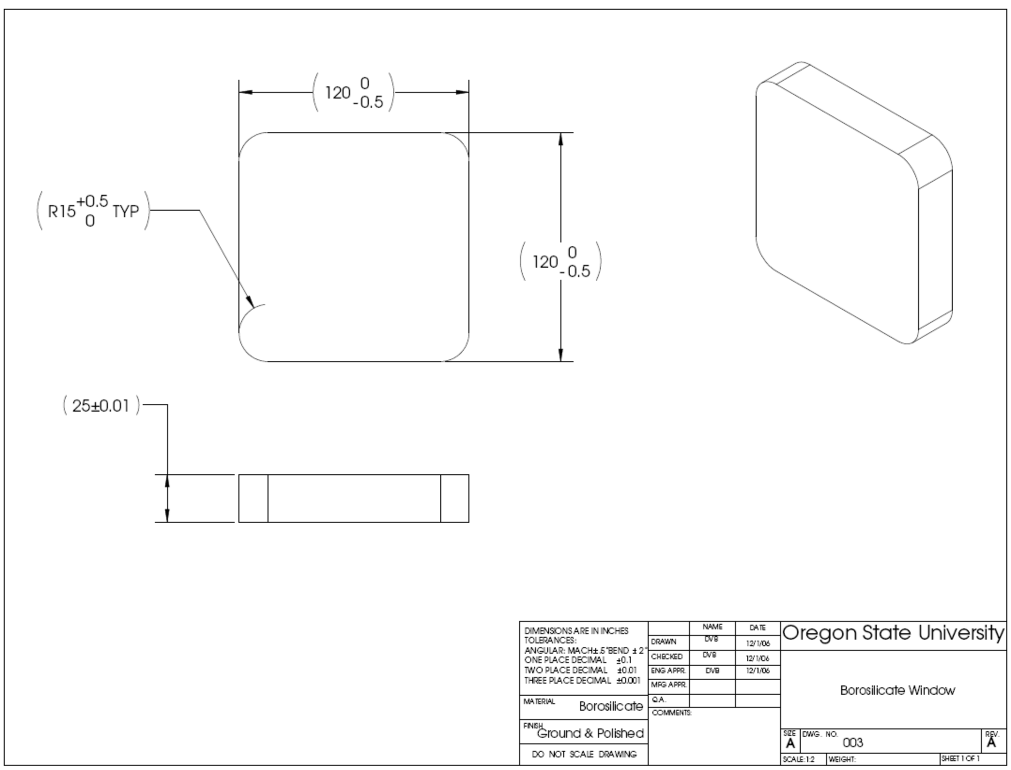

Figure 11.6: Viewing Window Drawing

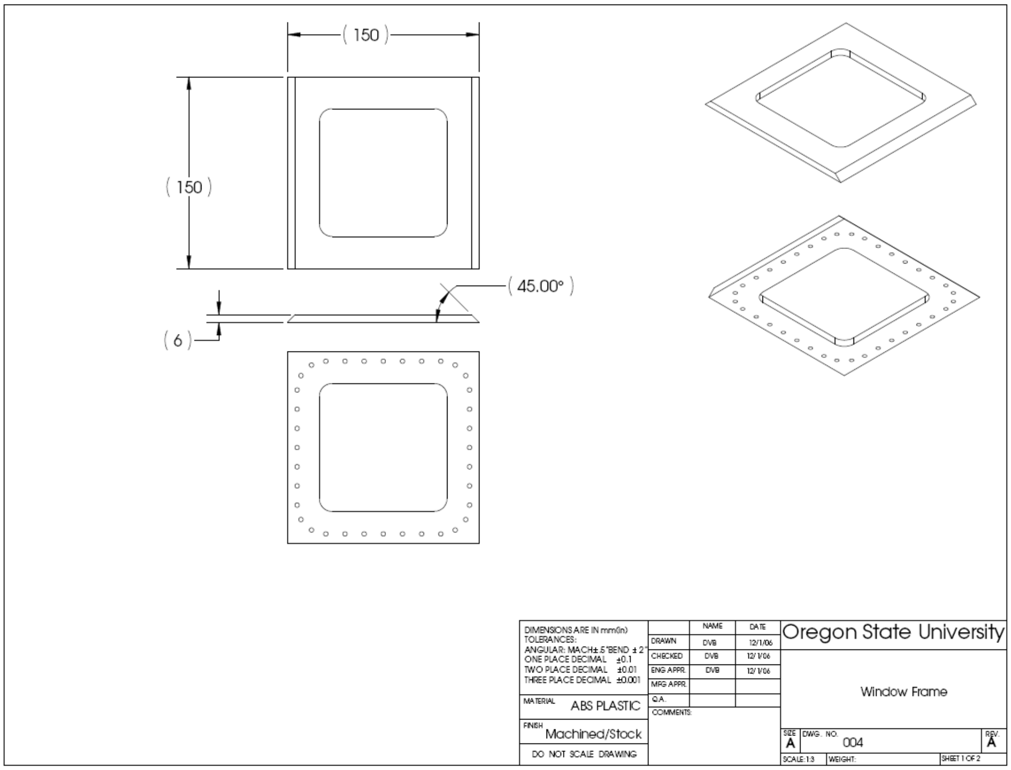

Figure 11.7.1: Window Frame Drawing

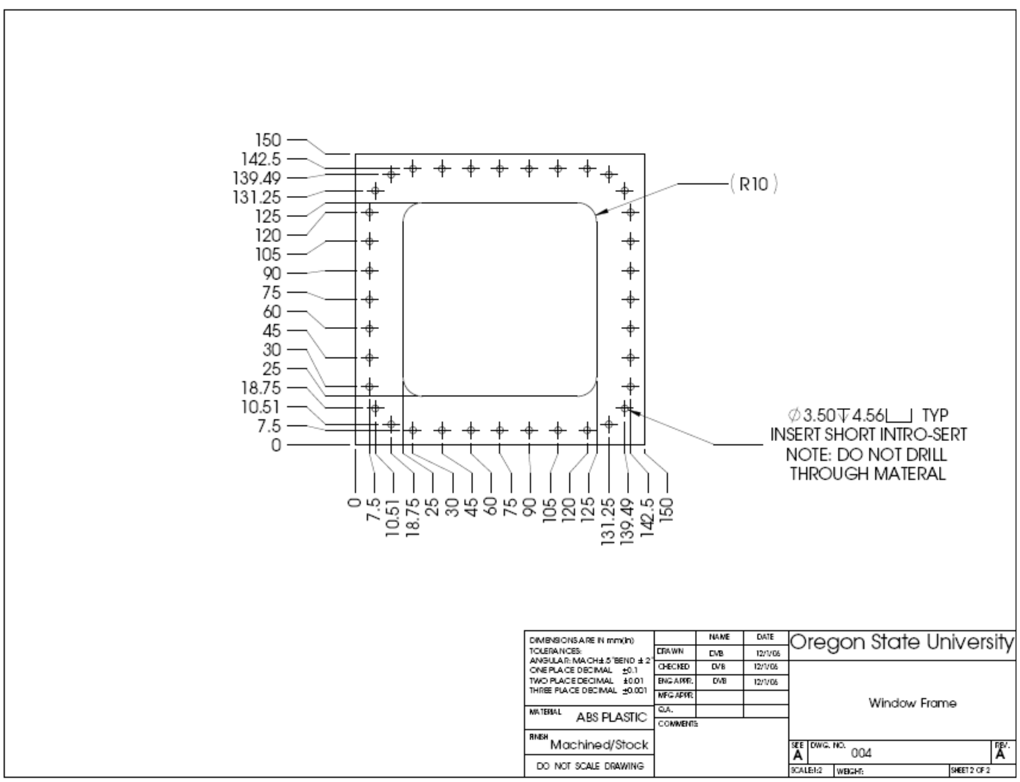

Figure 11.7.2 Window Frame Drawing

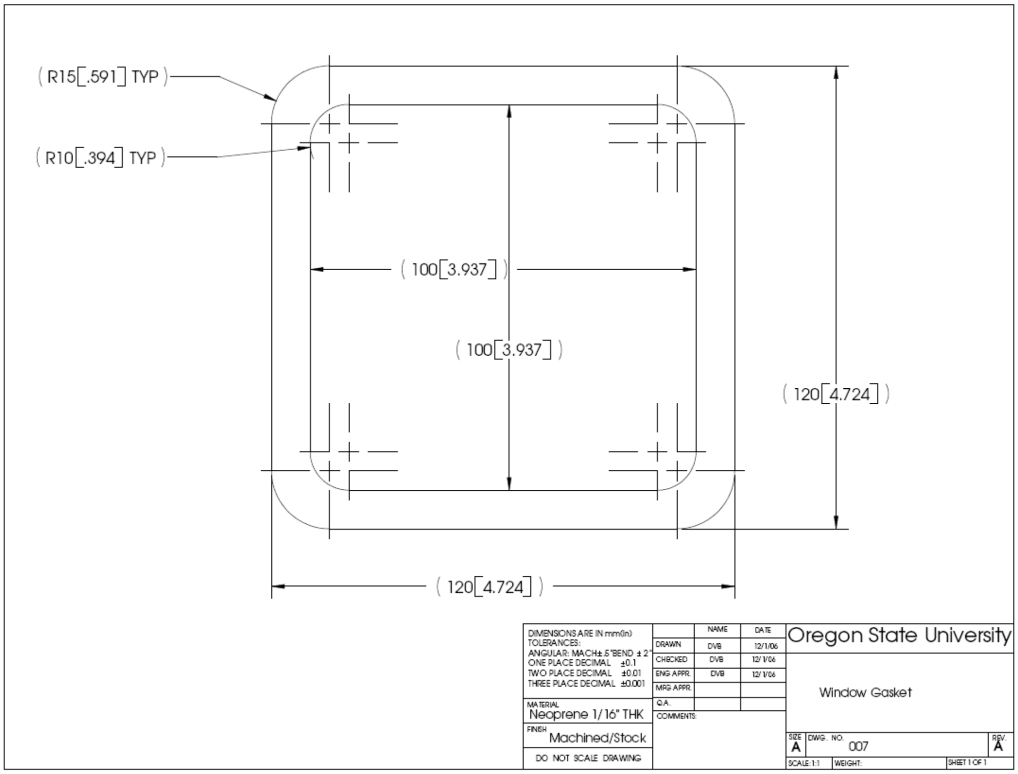

Figure 11.8: Outer Window Gasket Drawing

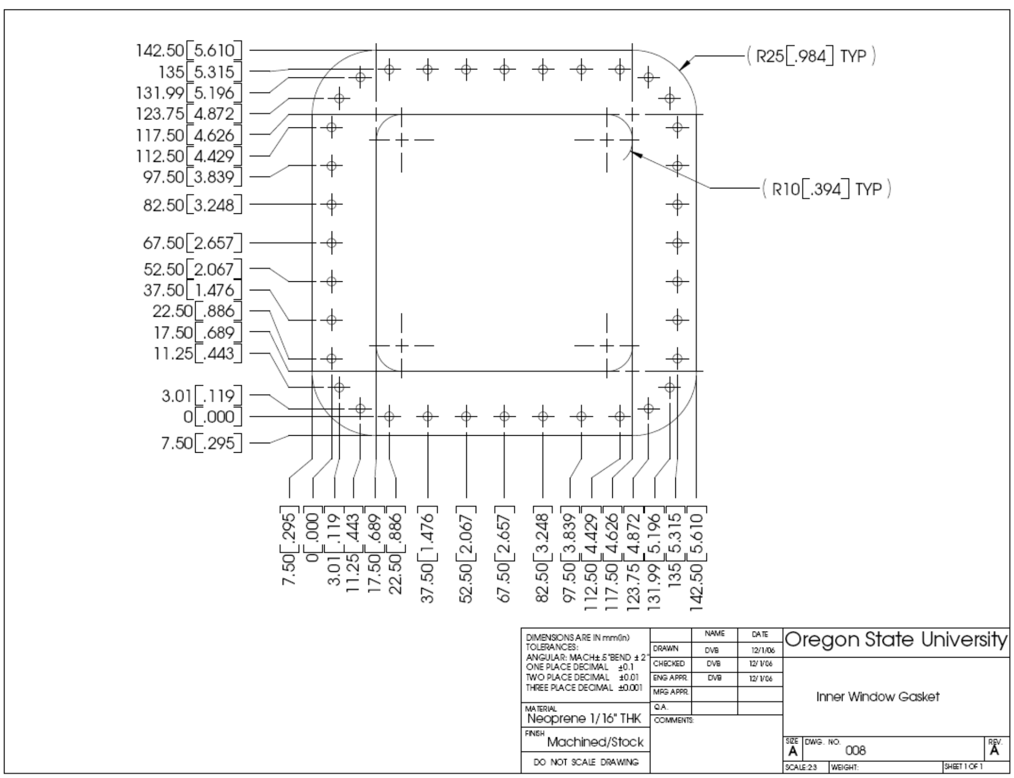

Figure 11.9: Inner Window Gasket Drawing

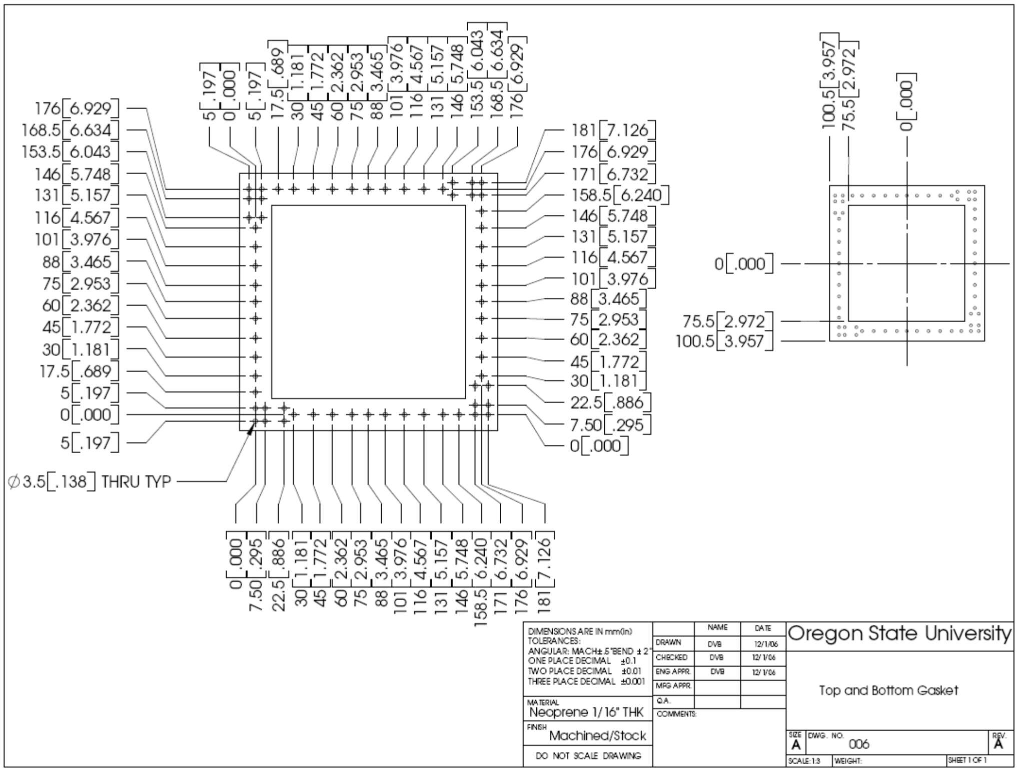

Figure 11.10: Diffuser Gasket Drawing

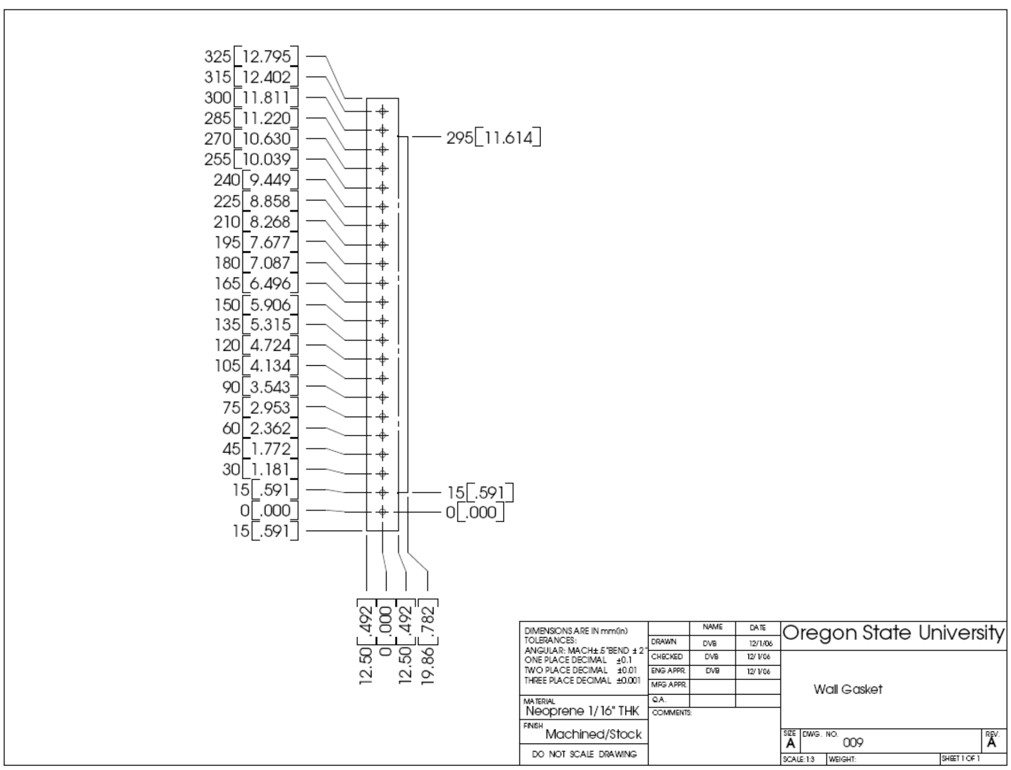

Figure 11.11: Wall Gasket Drawing

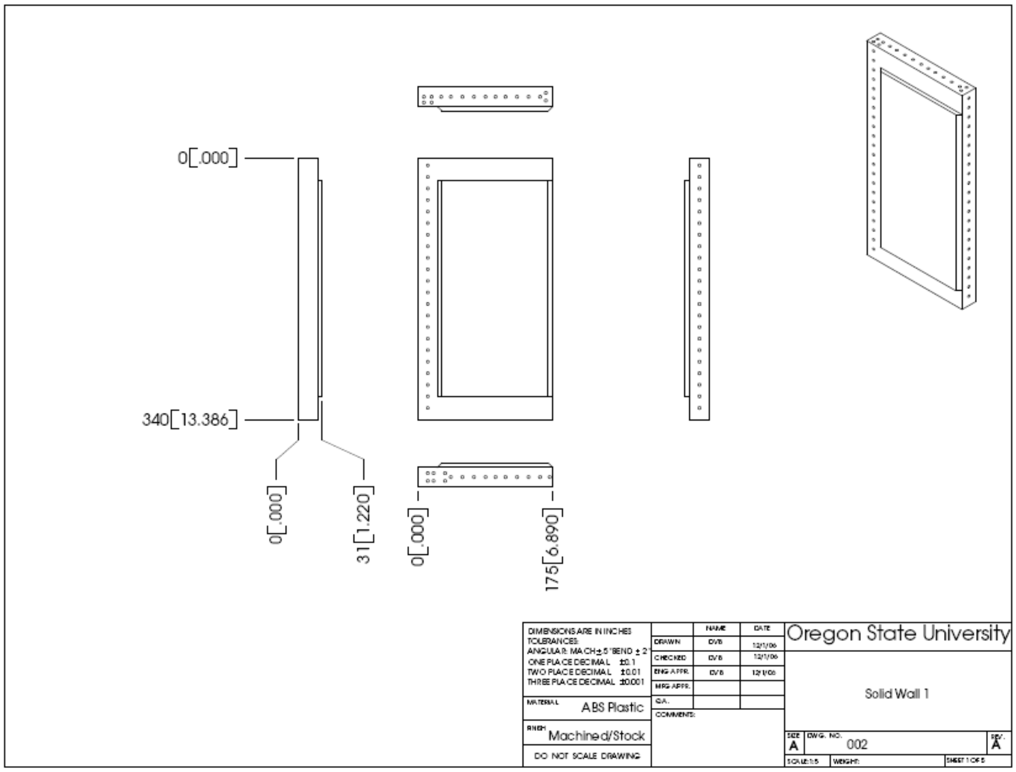

Figure 11.12.1: Solid Wall 1 Drawing

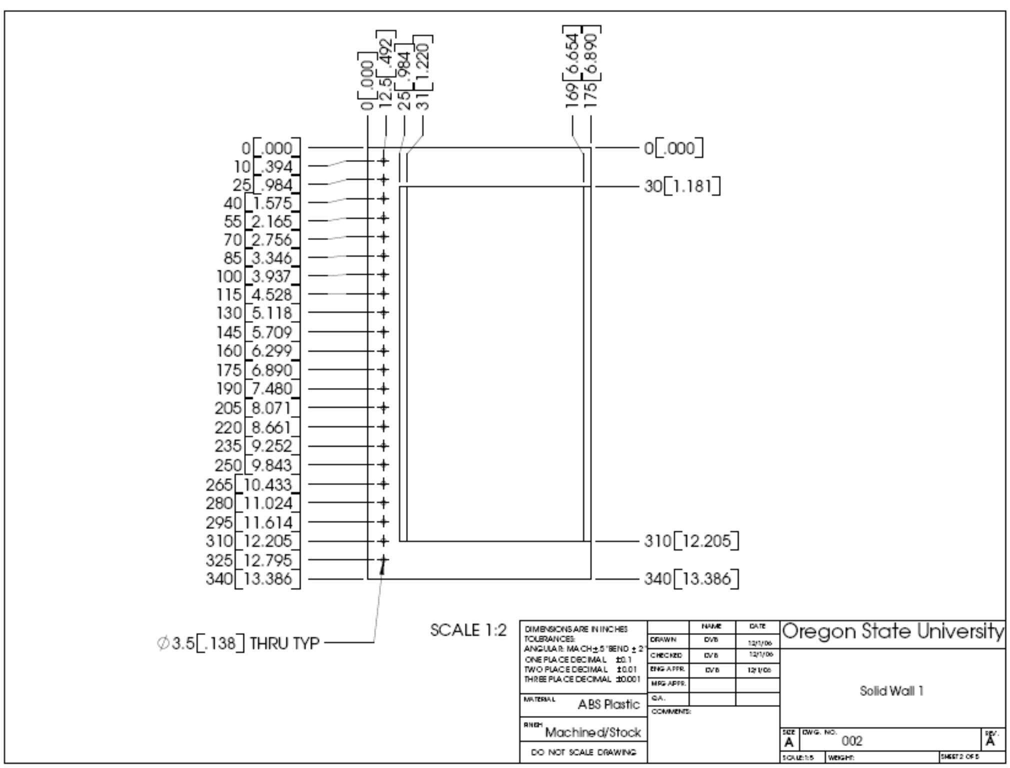

Figure 11.12.2: Solid Wall 1 Drawing

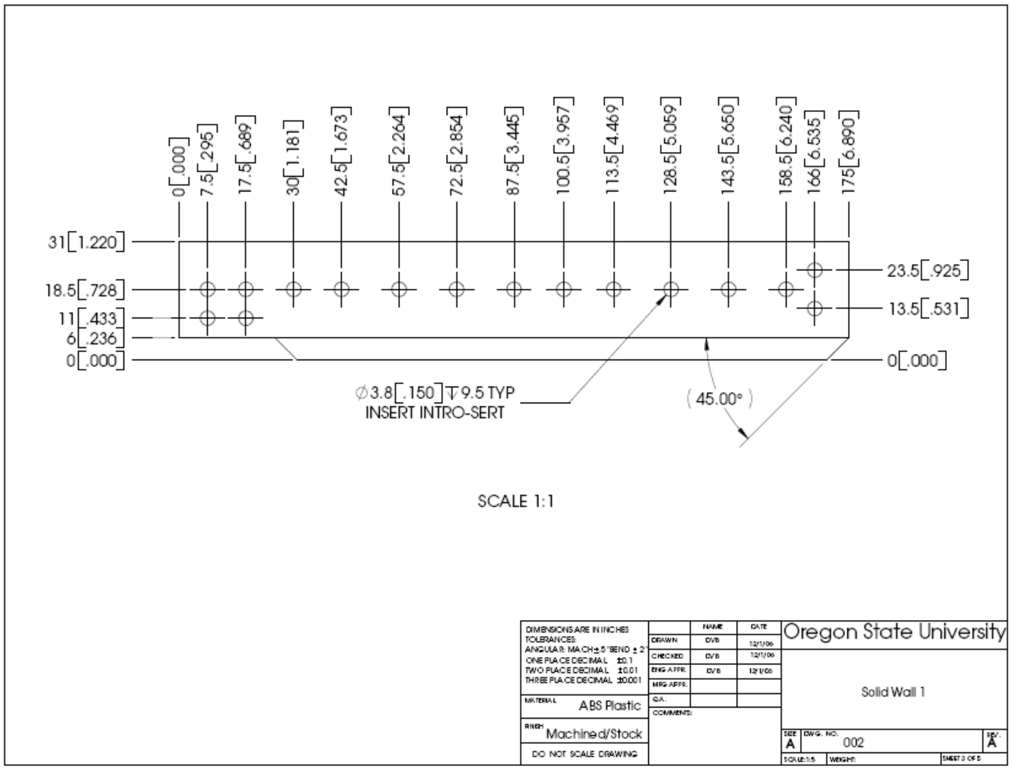

Figure 11.12.3: Solid Wall 1 Drawing

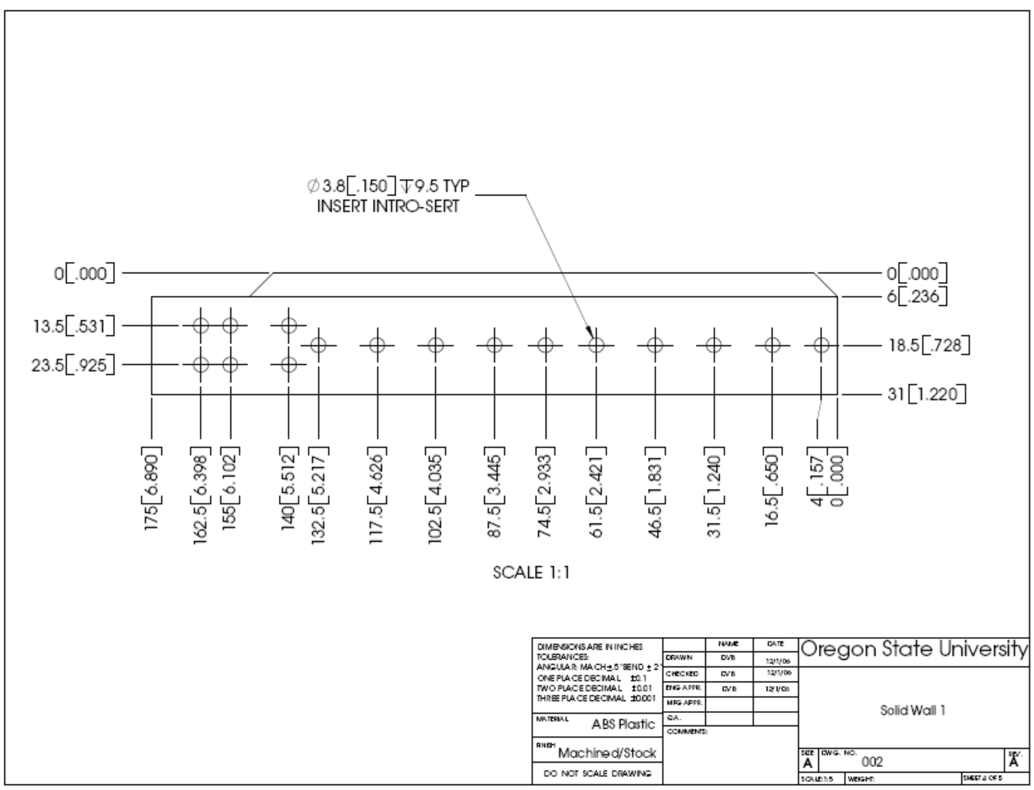

Figure 11.12.4: Solid Wall 1 Drawing

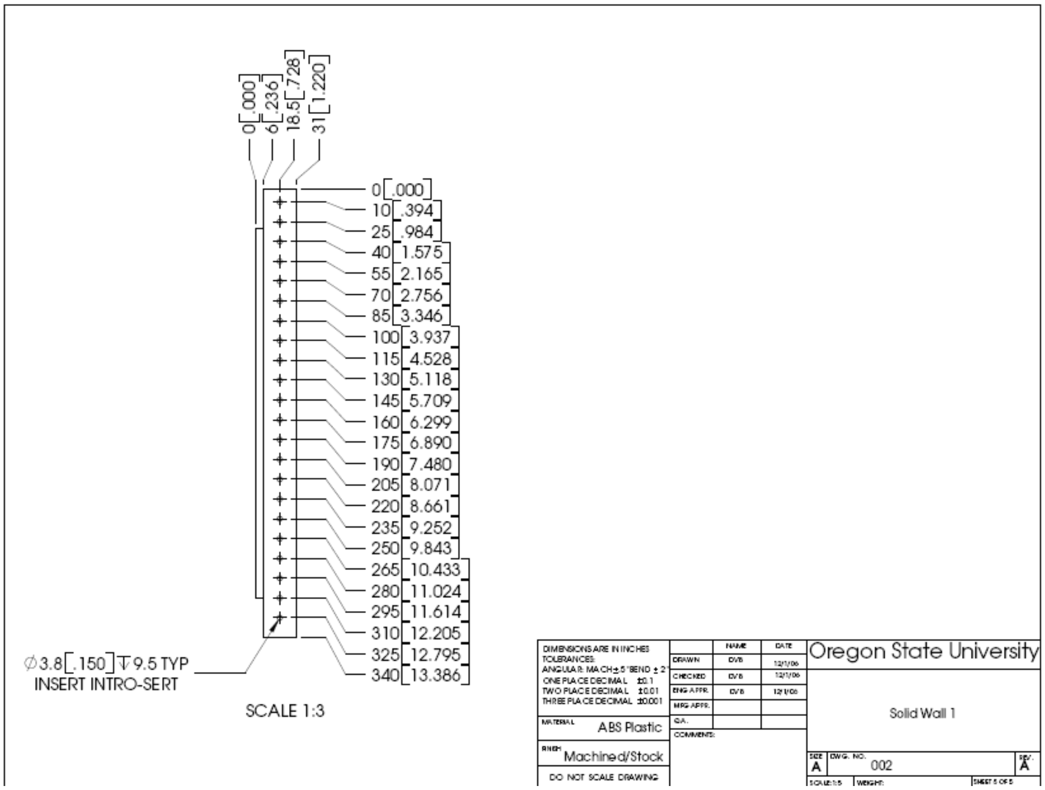

Figure 11.12.5: Solid Wall 1 Drawing

11.2. Modified Fabrication Plan Drawing

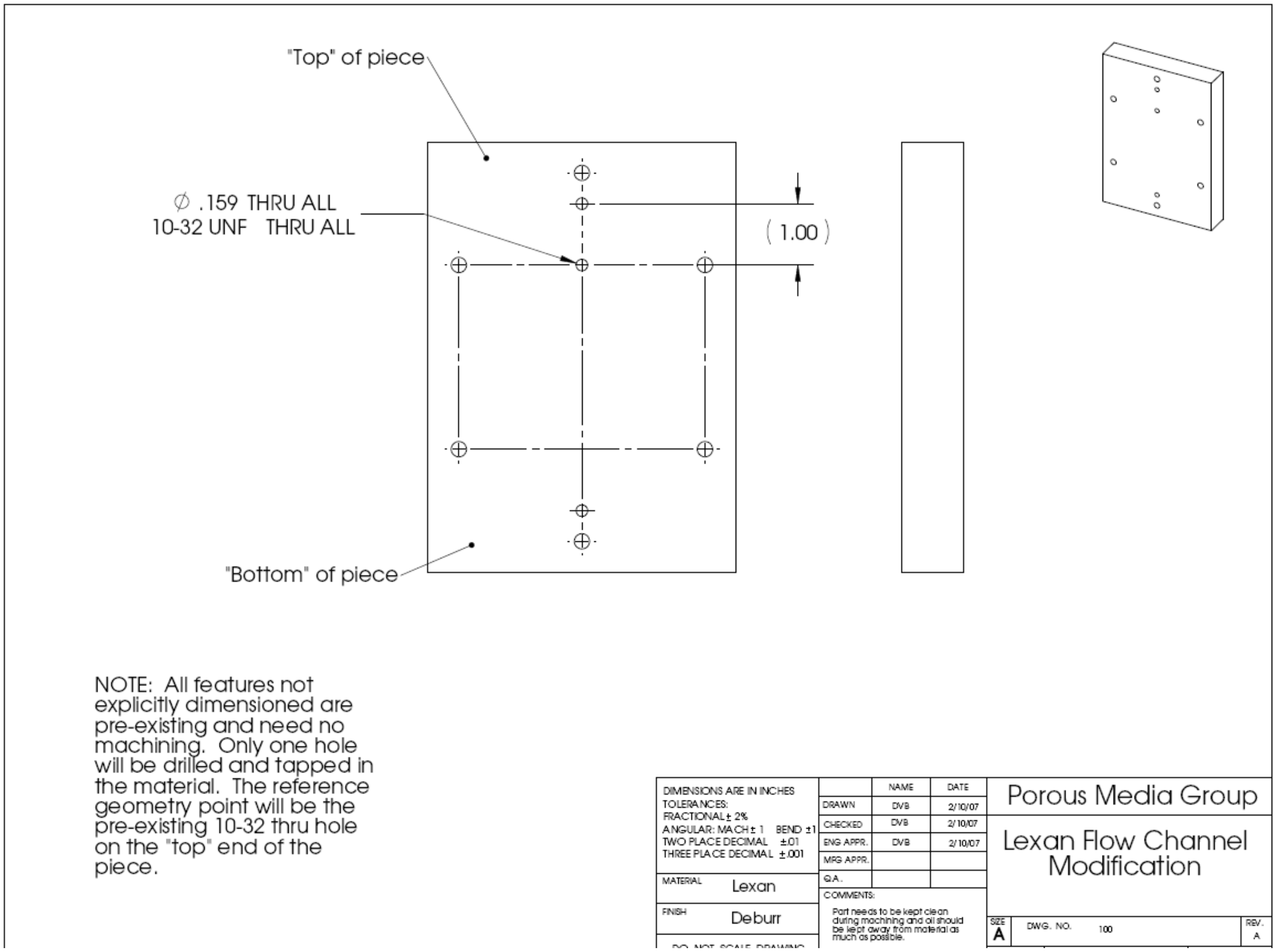

Figure 11.2.1: 2-D Flow Cell Modification Drawing

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