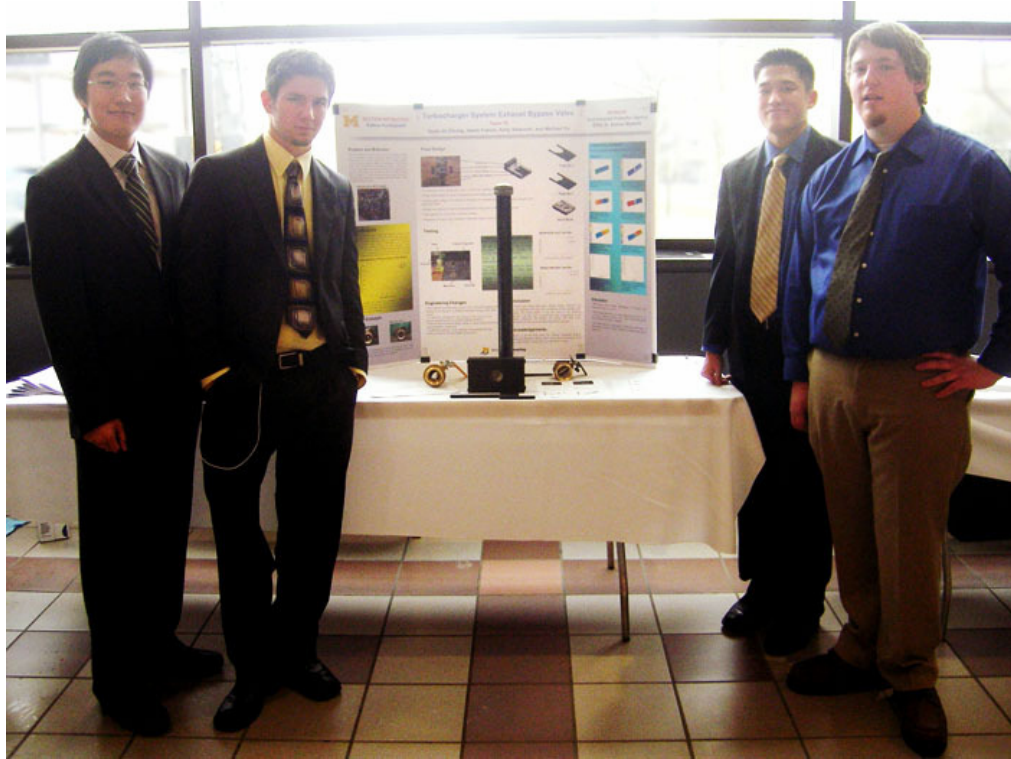


# Turbocharger System Exhaust Bypass Valve



Team #16

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## ABSTRACT

The Environmental Protection Agency (EPA) is currently developing clean homogeneous charge compression ignition (HCCI) engine technologies. This concept requires high levels of intake pressure, which is typically obtained using twin turbochargers. At high engine speeds, the low-speed turbocharger is bypassed to prevent overspeeding. Dr. Andrew Moskalik, from the EPA, has asked us to design and build an exhaust bypass valve able to function at high temperatures and pressures with high efficiency in both the open and closed position.

## TABLE OF CONTENTS

ABSTRACT.....	1
TABLE OF CONTENTS.....	1
1. INTRODUCTION .....	3
2. INFORMATION SEARCH.....	5
2.1 Patent Search.....	5
3. CUSTOMER REQUIREMENTS.....	6
4. ENGINEERING SPECIFICATION.....	7
5. CONCEPT GENERATION.....	7
5.1 Analysis of Valve Concepts.....	7
5.2. Actuator Concepts.....	9
6. CONCEPT EVALUATION AND SELECTION.....	9
6.1. Concept 4: Sliding Plate Valve with Linear Electric Actuator .....	9
6.2. Concept 1: Ball Valve with Rotary Actuator .....	10
6.3. Concept 2: Gate Valve with Rotary Actuator .....	10
6.4. Concept 5: Wedge Gate Valve with Linear Actuator .....	11
6.5. Concept 3: Butterfly Valve with Rotary Actuator .....	11
6.6. Additional Plate Valve Features .....	11
7. SELECTED CONCEPTS .....	11
8. ENGINEERING ANALYSIS.....	13
8.1 Mathematical Analysis for Sliding Plate Valve.....	13
8.2 Computational Fluid Dynamics Simulation.....	14
8.3 Bushing Analysis .....	16
8.4 Actuator Force Analysis .....	16
9. FINAL DESIGN .....	16
9.1 Final Design Plate Concept 1.....	17
9.2 Final Design Plate Concept 2.....	18
9.3 Engineering Drawings .....	18
9.4 Bill of Materials .....	18
10. MANUFACTURING AND TESTING .....	19
10.1 Manufacturing of Prototype.....	19
10.2 Testing of Prototype.....	20
11. ENGINEERING RECOMMENDATIONS.....	22
12. CONCLUSIONS.....	22
13. ACKNOWLEDGEMENTS.....	23
14. REFERENCES .....	23

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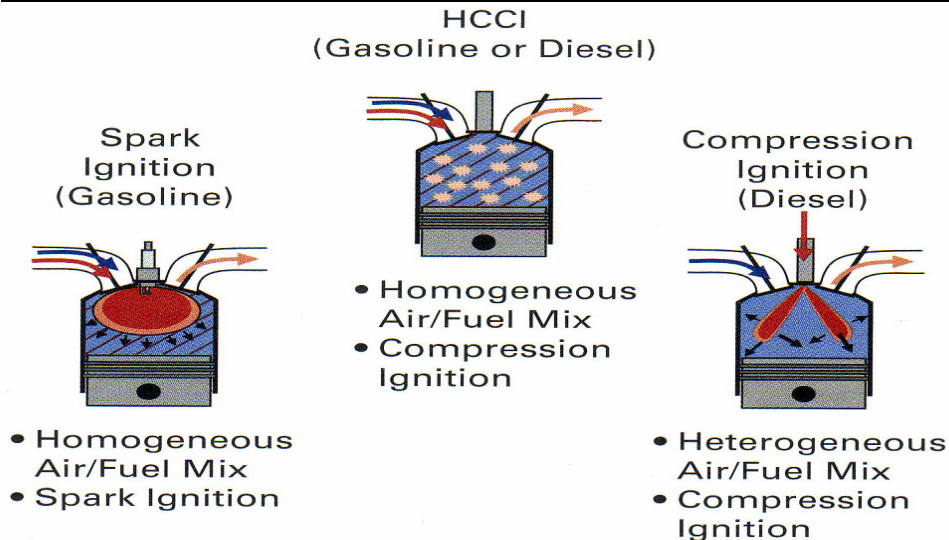
15. TEAM MEMBER BIOS.....	24
16. APPENDICES .....	25
Appendix A: Figures.....	25
Appendix B: Manufacturing Procedure .....	38
Appendix C: Testing Procedure.....	39
Appendix D: Results for computational fluid dynamics using Fluent.....	41
Appendix E: Specifications and quote for graphite bearings.....	44
Appendix F: Engineering Changes Notice .....	45

## 1. INTRODUCTION

The EPA is currently in the research and development phase of several clean automotive technologies, one of which is an HCCI engine, or homogenous charge compression ignition engine. A HCCI engine combines the principles of a traditional gasoline powered engine with those of a traditional diesel fueled engine. In an HCCI engine, fuel is homogeneously premixed with air, as in a spark ignited gasoline engine, but with a leaner air to fuel ratio. Diagrams of these engines are given in Figure 1 below.

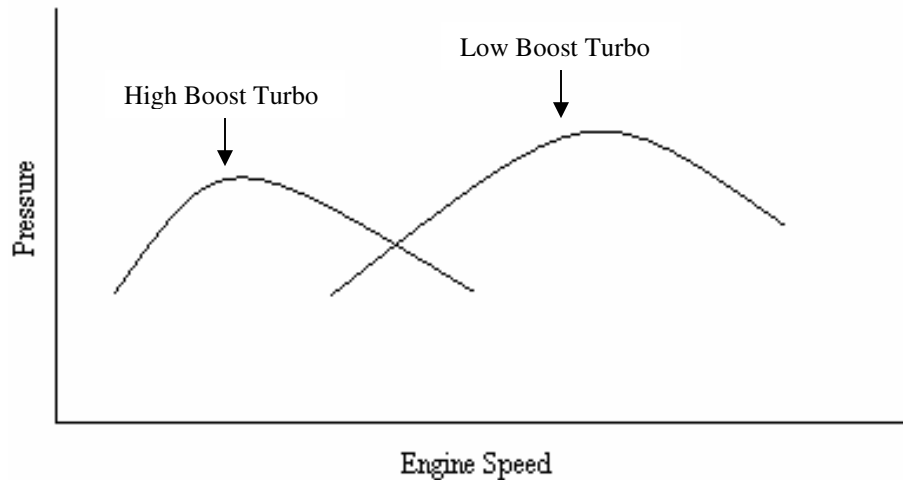
There are multiple benefits of HCCI, mainly due to the low emissions and efficiency. HCCI has the ability to obtain diesel-like fuel efficiency using gasoline. The combustion process also has very low  $\text{NO}_x$  emissions, eliminating the need for a catalyst. However, the HC and CO emissions are generally higher than that of a diesel engine, due to the lower combustion cylinder temperatures [5]. HCCI combustion is possible for full operation range of the engine with proper boost supply.

**Figure 1. HCCI combines favorable attributes of gasoline and diesel engines**

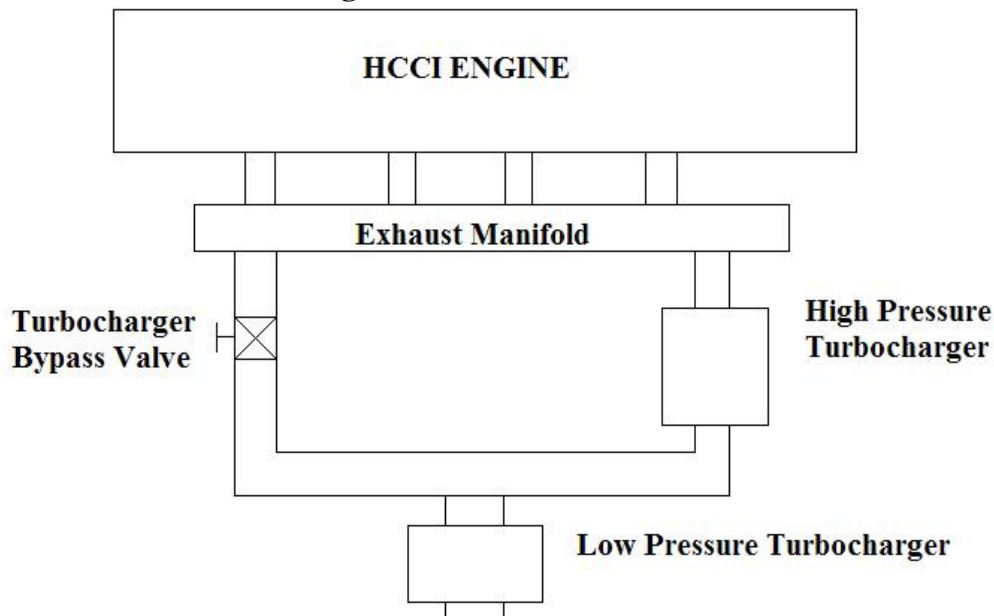


In order to control the combustion process, two turbochargers are used to provide the optimum boost for combustion at varying engine speeds. A low speed, high boost turbo is used at the lower engine speeds, while a high speed, low boost turbo is phased into operation as needed, using a bypass. Figure 2 below shows the boost supplied by the turbochargers, quantitatively. The bypass valve will be in operation at the center area between the two peaks, phasing the low boost turbo into operation. Figure 3 shows the relevant components and their relative locations of the HCCI engine. The engine exhaust from the exhaust manifold has two outlets; the high boost turbo, and a bypass valve. The exhaust gas flows through both of these components and then into the low boost turbo. Our task is to design and build a prototype of a new bypass valve, as the current valve and the previous one have several drawbacks which directly affect the turbocharger performance.

**Figure 2. Graphical representation of high and low boost turbo operations**



**Figure 3. Schematic of test engine with locations of both turbochargers and the valve that is to be redesigned.**



The EPA is currently using plate valves. The current valve has a relatively small opening, resulting in a large pressure loss of around 40 kPa when the valve is fully open. This large pressure loss is unacceptable, and needs to be reduced to around a maximum of 5 kPa. The previous valve was a poppet type, and had a tendency to open at high manifold pressures, also unacceptable. The valve needs to stay closed except when commanded to open, and the leakage across it has to be minimized. The valve should also minimize leakage when fully closed; when the valve is closed and not in operation, there should be zero leakage. Also, a linear relationship between the pressure drop across the valve and the opening of the valve is desirable.

The valve also has to open very quickly. Under normal operation, the valve should be completely open within 0.1 s. Also, the valve should be able to stop anywhere in between fully open and fully closed.

## **2. INFORMATION SEARCH**

We have collected information on several different valves already in production and use in the industry. The ball valve, the butterfly valve, and the sliding-plate valve are all possible solutions to our problem if used properly. The sliding-plate valve is currently used in exhaust systems. The ball and butterfly valves have the ability to be used in an exhaust system, but has not been implemented on a large scale [1, 2]. In fact, we could not find either of these valves on the market that would withstand the high temperature of the exhaust. Knowing that the system requires a slow opening of the valve, each of these valves can theoretically work. It is difficult to entirely invent a new valve for our application. However, benchmarking these valves allows us to expand on older ideas. We must collect data and brainstorm about how to perhaps modify or integrate some of these ideas, and our own, to create a functional valve. The information we still must collect pertains to actuators. Our design requires that the valve will be actuated when needed. The valve can be pressure or electronically actuated, however, the EPA has asked us to use an electric linear actuator. We have researched the benefits/draw-backs of actuator designs.. We have collected, and evaluated each valve for their performance in our application (high temp and high pressure exhaust).

During our information search, we also found several proportional control valves which are electronically adjusted to compensate for pressure loss. A proportional solenoid is attached to the valve, which is under pressure-compensated control. This keeps the actuator speed and flow constant when the load forces change. However, the fluid temperature range for these valves range from -20 to 80 degrees Celsius, far below the necessary temperature range for our use.

### **2.1 Patent Search**

Furthermore, we conducted a patent search for similar applications of an exhaust bypass valve in a turbocharger system:

Patent number 4492519 involves a pivoted valve which selectively controls the passage of the exhaust gas. This arrangement would use a catalytic converter and inexpensive control elements. However, our sponsor requires the specific usage of an electric actuator; thus, this benchmark was noted, but did not offer much for our design.

Patent number 6109591 is a continuous flow type proportional flow control valve with a wide range of controllable flows. It is designed with a simple cylindrical flow passage and a seat opening defined by a narrow slot a circular orifice in the form of two diverging circles. We will use this as a benchmark for our selected slide plate design.

Intellectual patent number WO2004088108, utilizes a modified butterfly valve which when closed would greatly minimize leakage. However, this system uses multiple valves, and would require a complicated machining process. This patent shows the potential abilities of

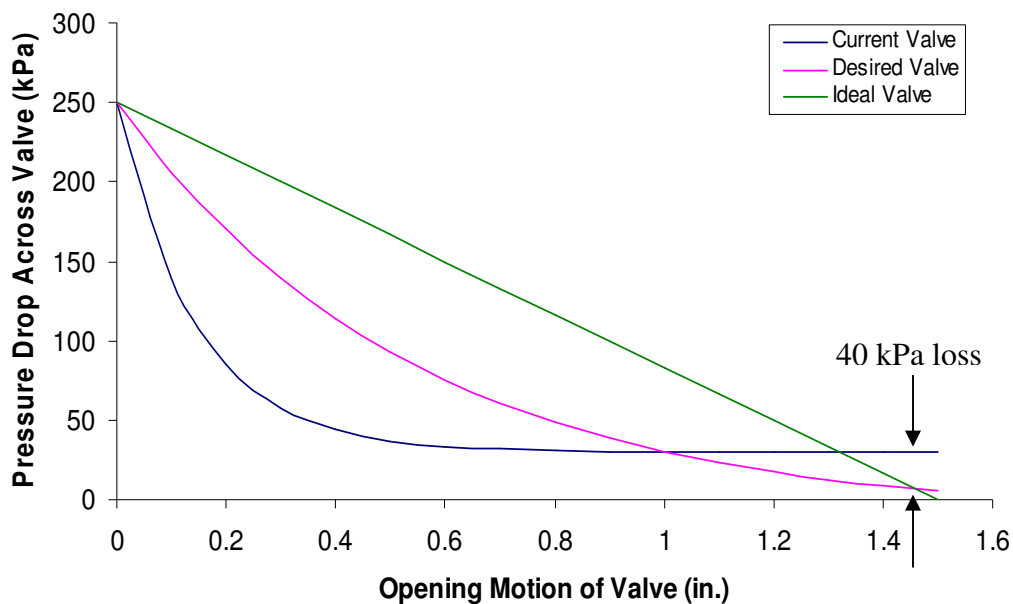
the butterfly valve, but in our concept generation process, we will be comparing the properties of standard valves in a single bypass valve system, so this particular application was also noted but did not affect our final design concept.

### 3. CUSTOMER REQUIREMENTS

The customer requirements for the turbocharger system exhaust bypass valve were based mainly on the desire for high performance. In our application, high performance will be defined as non-existent leakage when closed and very small pressure losses across the valve when fully open. Currently used plate valves have proven to have too small an opening, which leads to a large pressure loss (up to 40 kPa) when fully open. Essentially, our customer wants a valve that will function efficiently at high temperatures and pressures with minimal pressure loss and leakage in the open and closed positions, respectively.

We interviewed our sponsor, Dr. Andrew Moskalik, in order to determine the relative importance of each customer requirement. The most important requirements include maximizing efficiency and minimizing leakage, functioning at high temperatures (500° C) and pressures (250 kPa) with a minimal pressure loss (< 5 kPa) across the valve, and the ability to open slowly. Another main requirement is that the pressure drop varies linearly with the valve opening rather than making a large drop. A graphical representation of the linear relation between motion of the valve and the pressure drop is shown in Figure 4.

**Figure 4. Linear relation between motion of the valve and the pressure drop**



Our customer informed us that cost is a lower priority; our \$400 budget should not limit us in our design. Our design's compatibility with the existing testing unit was another issue that didn't have as much weight as efficiency; the valve can be scaled accordingly.

## 4. ENGINEERING SPECIFICATION

The engineering specifications were created in response to our customer requirements. These specifications are qualitative judgments that need to be made in order to fulfill the criteria laid out by the customer. The most important decisions to be made are the size and type of valve as well as the type of actuator, because they are closely related to the customer requirements. The current area of the valve is 350 mm<sup>2</sup>, and we plan to use a 1.5 in diameter valve. The volume flow rate of the exhaust, when fully open, is 0.117 m<sup>3</sup>/s. To determine target values, we researched existing technologies and valves to provide benchmarks with which to compare and better our design.

## 5. CONCEPT GENERATION

We identified several main functions our design must meet based on our customer requirements. One of the major functions is that the valve must close completely (minimize leakage). We can solve this using tight tolerance metal fittings. Plastic and rubber seals are not useful in this application due to the high temperature and moisture of the exhaust. In addition, the valve is required to function at high temperatures. For this function, we decided to use a proper metal. This metal must have low thermal expansion, and still maintain a high strength. A low carbon steel or a stainless steel would work well for our application. Also, the valve must be able to function under high pressure. This also requires a proper metal with a high strength, and also, we can design the valve with thick walls to avoid failure. Another important function of the valve is to minimize the pressure loss across the valve when fully open. We decided to maximize the area of the valve in order to maximize the flow. We felt that this was the best idea to minimize the pressure drop. The valve must function using an electric actuator. We have decided to design using an actuator that will be operated directly by the engine's onboard computer. This will ensure precise and expedient communication between the valve and the computer. The final function was for a linear opening and closing of the valve. This function will largely be dependent on which valve we use. If we use a sliding plate valve, then we will likely use a linear actuator. If we use a butterfly or ball valve, we will likely use a rotary actuator. Each respective actuator will provide the best motion for each valve.

### 5.1. Analysis of Valve Concepts

If we choose only the valve, and the sections of tubing attached to both sides of the valve, we can model it as pipe flow. Analyzing the relationship between the pressure difference across the valve while opening as compared to the opening amount of the valve is quite difficult. Therefore, we have decided to laboratory test the valve to determine this relationship. We can however determine the theoretical pressure loss across the valve while fully open, modeling it as pipe flow, and using the Bernoulli Equation [4], Eq (1):

$$\frac{P_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2 + K_L \frac{V^2}{2g} \quad \text{Eq (1)}$$

Here the subscripts denote any two points chosen in the control volume of the system. The loss coefficient,  $K_L$ , is dependent on the valve geometry [4]. Furthermore, our analysis will neglect any changes in kinetic and potential energy across the valve, as we do not have the



needed data to determine it. Using these simplifications, the pressure loss can be expressed as shown in Eq (2):

$$\Delta P = K_L \frac{\rho V^2}{2} \quad \text{Eq (2)}$$

This value,  $\Delta P$ , represents the pressure loss when the valve is fully open. In order to determine the velocity,  $V$ , across the valve, the EPA supplied us with information regarding the air and fuel mass flow rates, as well as the percentage of Exhaust Gas Recirculation (EGR) flow in the engine intake. For this analysis, we assumed perfect combustion, and used the continuity equation to determine the flow rate of engine exhaust. Figure 5 shows the relative directions of mass flow in and out of the engine.

$$\dot{m}_{air} + \dot{m}_{fuel} + \dot{m}_{EGR} = \dot{m}_{exhaust} \quad \text{Eq (3)}$$

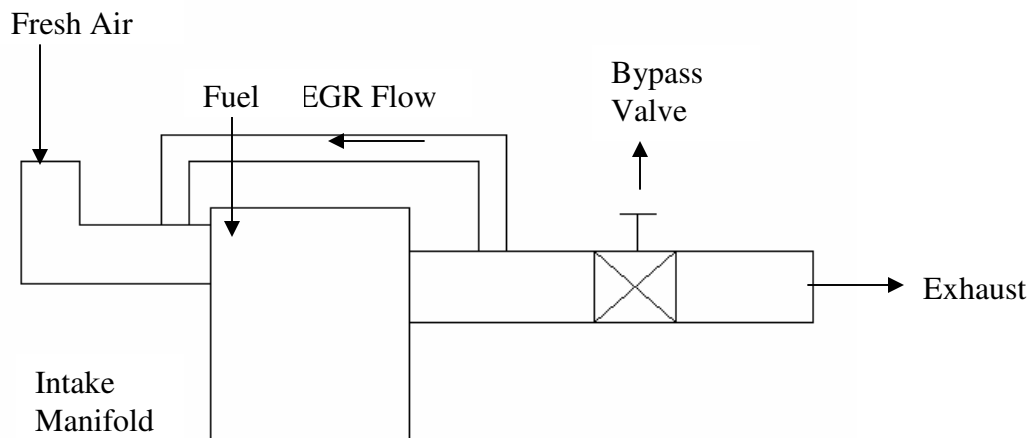
Using the specified values, the exhaust mass flow rate was determined to be 120.18 g/s using Eq (3). This calculation, along with a given temperature of 440° C and pressure of 221 kPa, gave us a volume flow rate of 0.117 m<sup>3</sup>/s. Here we assumed that the working fluid is air, as a simplification. This volumetric flow rate is valid for all of the valve concepts, and if we divide it by the specific valve area, we can determine the velocity across the valve.

**Table 1. Valve concepts with geometric properties and estimated values**

Valve	Opening Area, mm <sup>2</sup>	Velocity Across, m/s	$K_L$	Pressure Loss, kPa
Ball	1140.1	102.6	0.05	0.13
Butterfly	1094.3	106.9	0.40	2.93
Gate	1134.1	103.2	0.15	1.02
Plate	1134.1	103.2	0.25	1.70
Wedge	1134.1	103.2	0.18	1.30

The calculations used to find the pressure drop were greatly simplified. Therefore, the actual values of  $\Delta P$  will be higher. The values in Table 1 give us a relative measure of the pressure loss,

**Figure 5. Basic combustion elements. Arrows represent mass flows in engine.**



## 5.2. Actuator Concepts

An actuator is a mechanism that causes a device to be moved. For our project, actuator selection is one of the most important tasks because this is the device that will open and close the valve. There are several different types of actuators depending on the power source, but we have decided to use an electric actuator. The main advantages of an electric actuator are the high degree of stability and constant thrust available to the user. Stiffness is also far better with an electric actuator. It also allows the user to electrically control the valve. However, a big downfall to electric actuators is their relative expensive cost when compared to the more commonly used pneumatic actuator.

Depending on the valves, two types of actuator motion are available; rotary and linear. Rotary actuator is used for the rotary motion valves (rotary valves) such as ball, plug and butterfly valves that rotate through a quarter-turn (90 degrees) or more from open to close. This includes multi turn valves. Linear actuators are used for the linear motion valves (linear valves) such as gate, globe, diaphragm, pinch, and angle-style valves. These valves have a sliding stem design that pushes the closure element open or closed. The valve stem may rise while rotating (multi-turn) or may rise without rotating.

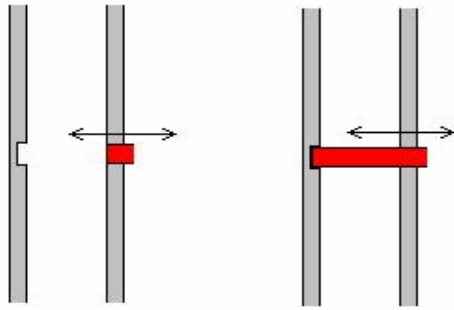
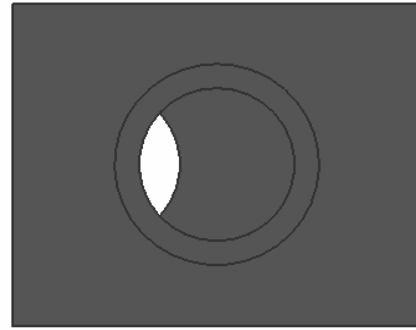
## 6. CONCEPT EVALUATION AND SELECTION

Once brainstorming and concept generation was completed, we moved on to concept selection entailing: a discussion with our sponsor, Morphological and Pugh charts, and further research. Combining those allowed us to select our five most viable options. Figure A.3 in Appendix shows sketches of all concepts.

The purpose of the Pugh chart is to evaluate our control method concepts based on our customer requirements. Customer requirements were taken directly from the QFD diagram. Weightings were also developed using the same information. Concepts were evaluated on a “-1” “0” and “1” basis for each customer requirement. For each concept the numbers of positive and negative scores were tallied along with a net score. The most crucial statistic was the weighted total, which formed the basis for rating the concepts. Using these ratings we determined our most viable concepts. Results are shown below in order of rank. The Pugh chart is shown in Figure A.5 in Appendix A.

### 6.1. Concept 4: Sliding Plate Valve with Linear Electric Actuator

One possible turbocharger bypass valve is the sliding plate valve shown in Figure 6 on the next page. It is a linear motion valve perpendicular to the process flow, which slides into the flow stream to provide shutoff. One unique design of our plate is that it has a circular end in order to maximize the area of valve and minimize the pressure drop as shown in Figure 7. Other ideas on increasing the smoothness of the plate motion included using a knife edge to reduce friction, or the use of metal bearings. However, these ideas were discarded because of the increased difficulty in manufacturing the knife. Because it is a linear motion valve, a linear electric actuator should be used.

**Figure 6. Sliding plate valve****Figure 7. Circular end plate***Advantages*

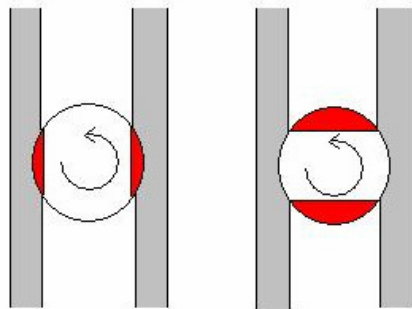
As noted before, it can be designed for full-area flow to minimize the pressure drop. When compared to the other valve concepts, this is relatively inexpensive as well as easy to install and maintain. Also, we believe that the unique opening shape will allow the pressure drop to vary linearly with valve opening area.

*Disadvantages*

A sliding plate valve presents some disadvantages. First, they have difficulty opening and closing against high pressure. An additional challenge is tight shutoff of the plate valve. We need further consideration to solve these disadvantages.

**6.2. Concept 1: Ball Valve with Rotary Actuator**

The ball valve is a quarter turn, straight-through flow valve that uses a round closure element with matching rounded elastomeric seats that permit uniform seating stress. It is shown in Figure 8. Because it is rotary motion valve, a rotary actuator should be used. This design allows the pressure drop to be minimized. However because it needs additional joint, there is another potential leak path. Also it is not easy to maintain.

**Figure 8. Ball Valve****6.3. Concept 2: Gate Valve with Rotary Actuator**

The gate valve with a rotary actuator acts very much like a swinging door. This type of valve allows for a fully open position without any obstructions, and it can be tightly shut in the closed position. A sketch of this concept can be found in Appendix A, Figure A.3.C

#### 6.4. Concept 5: Wedge Gate Valve with Linear Actuator

Wedge gate valve is similar to the plate valve; however it uses two inclined seats and a slightly mismatched inclined gate. It is shown in Figure A.3.I, in Appendix A. It allows for tight shutoff, even against higher pressure. However, when fully opened, the wedge shaped gate causes a lot of empty room in the valve housing and it might disturb the flow.

#### 6.5. Concept 3: Butterfly Valve with Rotary Actuator

Although the butterfly valve ranks low on the Pugh chart, we believe it is still a viable solution. Since the valve is always in the path of the exhaust flow, it will have a higher pressure loss than the other valves. However, unlike the other concepts, the outer walls of the butterfly valve are smooth. We found a very similar concept, US Patent 4492519, that uses a uniquely designed type of butterfly valve, as a turbocharger bypass. A sketch of this concept can be found in Appendix A, Figure A.3.D.

#### 6.6. Additional Plate Valve Features

Further concepts were considered for the sliding plate valve, including the shape of the plate, a contoured surface, angled entry, and bushings. However, due to time constraints and difficulty in machining, not all of these additional features were implemented.

**Shape of the opening.** Various different opening geometries, such as a narrow opening at the front edge plate that expands into a larger orifice when fully open can alter the relationship between pressure drop and area of the opening. We believe that the severity of the pressure drop in relation to opening is proportional to the opening area of the plate; by creating different opening shapes we hope to better control this relationship. This is our most important design consideration.

**Contoured surface.** Also, a contoured surface such as a concave spherical surface with respect to the opening or a profiled surface can affect pressure drop while opening. However, due to the difficulty in machining this complex geometry, it was not considered for our final design.

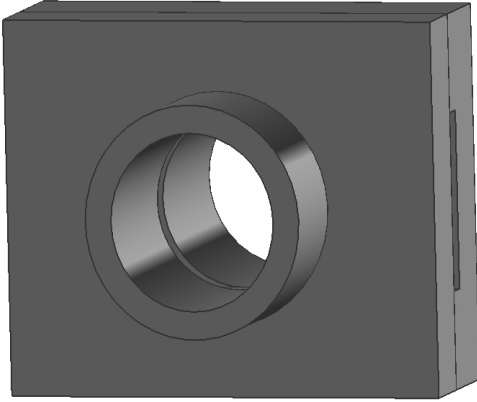
**Angled entry.** An angled entry for the plate can also affect this relationship. Our goal is to design the plate such that pressure drop is linear as the plate opens. Vortexes can be minimized due to flow separation with proper entry angle. The major disadvantage of an angled valve would be due to the opening force. The surface area will be larger than that of a valve perpendicular to the flow, and the normal force from the exhaust pressure will be higher. It would also increase the size of the valve and housing, which might lead to compatibility issues and therefore was not considered for our final design.

### 7. SELECTED CONCEPTS

We have chosen to pursue forward with three different types of valves: the ball valve, butterfly valve, and the sliding plate valve. We plan on testing these valves, and determining which one most fully meets the customer requirements. The laboratory testing will include determining a relationship for the pressure drop across the valve and valve opening, as well as the pressure difference across the valve when fully opened. We intend

to use this data, as well as the feasibility and cost of each valve to finalize our decision to one valve.

**Figure 9. CAD drawing of selected valve**



**Figure 10. CAD drawing of sliding plate valve concept.**

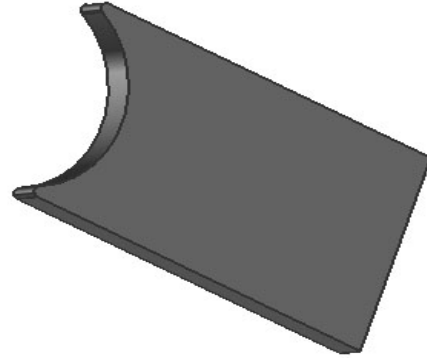
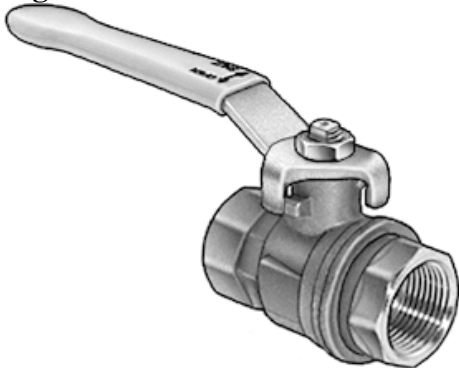


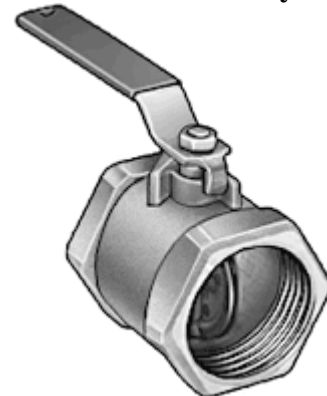
Figure 9 shows a CAD rendition of our selected concept. The circular opening is where the exhaust will flow through. This valve will be fitted inline with the exhaust pipe between the exhaust manifold and the low pressure turbocharger. The actual valve plate will have a circular end with the same radius of the valve opening, as seen in Figure 10.

Both the ball valve and the butterfly valve are purchased. The ball valve chosen has a 1.5 in diameter opening. It is a McMaster Carr P/N 47865K27, and is shown in Figure 11. This valve is mainly used on water shut off applications. The selected butterfly valve also has a 1.5 in diameter opening. It is a McMaster Carr P/N 4682K78, shown in Figure 12. This specific valve is mainly used for throttling applications.

**Figure 11. Selected ball valve**



**Figure 12. Selected butterfly valve**



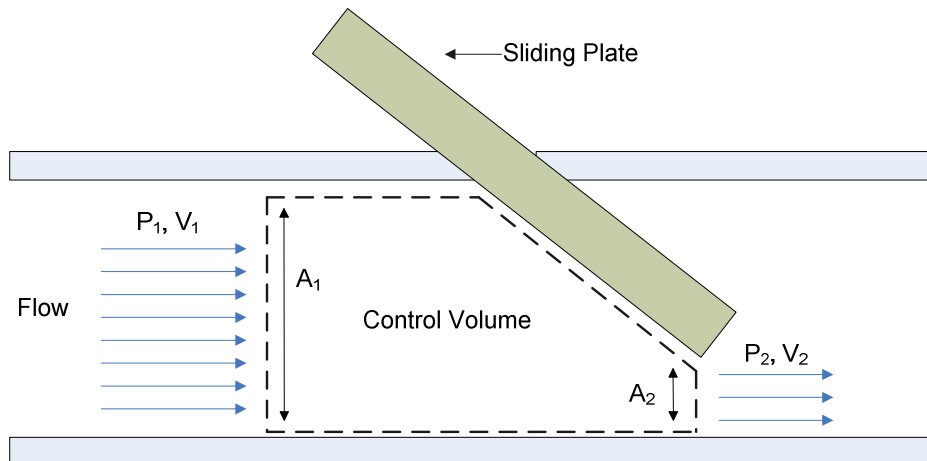
## 8. ENGINEERING ANALYSIS

An analysis was done on the selected concepts. After the valves were ordered, they were tested to determine a relationship for the pressure drop across the valve and opening, as well as the pressure difference across the valve when fully opened. We tested a sliding plate valve, a standard ball valve, and butterfly valve. Although the sliding plate valve is our final concept, the other valves were tested because they were the second and third ranked concepts in our Pugh chart, and their test values will be compared against the values for the sliding plate valve. The testing is detailed in section 10.

### 8.1 Mathematical Analysis for Sliding Plate Valve

Both shape of the opening and contoured surface ideas are directly related to the area of the outlet flow. Therefore mathematical relationship between pressure drop and area of opening for each idea are desirable in order to come up with final design and satisfy our customer requirements. A schematic diagram for one of our design is shown in Figure 13, where  $P$  is the pressure,  $V$  is the velocity of flow, and  $A$  is the area.

**Figure 13. Schematic diagram for our design**



Again, continuity and Bernoulli equation are used for this calculation. However in this case, we do not use the loss coefficient,  $K_L$  which is dependent on the valve geometry because we are just comparing our ideas under the same conditions. There are several assumptions we made for simplicity, as follows:

- The flow is steady and the frictional effects are negligible
- The weight of the gas, the pipe and the valve is negligible
- Vortex due to geometry is negligible
- No elevation between inlet and outlet

Note that angled plate, one of our valve features, is used as shown in Figure 13 to satisfy our third assumption. We take the control volume as shown in Figure 1 and designated the inlet by 1 and outlet by 2.

Starting with continuity equation,  $\dot{m}_1 = \dot{m}_2$ , we can get  $V_2$  in terms of  $V_1$ ,  $A_1$  and  $A_2$  as shown below. Noting that that  $\dot{m} = \rho AV$

$$V_2 = \frac{V_1 A_1}{A_2} \quad \text{Eq (4)}$$

With our fourth assumption, Bernoulli equation can be written as

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} \quad \text{Eq (5)}$$

Plug Eq(2) into Eq(1), and solve for pressure drop

$$\Delta P = P_2 - P_1 = \rho \frac{V_1^2 [(A_1/A_2)^2 - 1]}{2} \quad \text{Eq (6)}$$

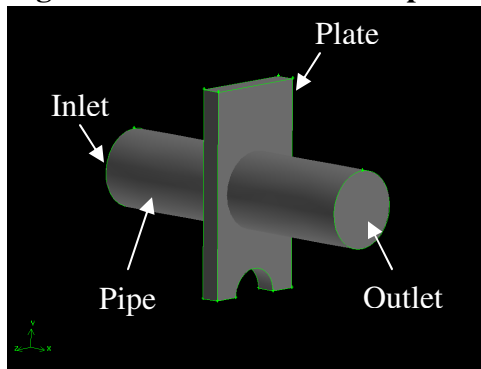
All variables are given and calculated already except for  $P_2$  and  $A_2$ . Therefore in Eq(3), pressure drop is expressed in terms of area of outlet. Relationship between pressure drop and motion of the opening also can be expressed with Eq(3) since area of the outlet is directly related to the motion of the opening. However because our ideas are too complicated to express as a equation, we decided that in order to find an accurate relation, we would need to use Fluent<sup>®</sup> computational fluid dynamics software in order to show the effect of opening motion to the pressure drop with our ideas.

## 8.2 Computational Fluid Dynamics Simulation

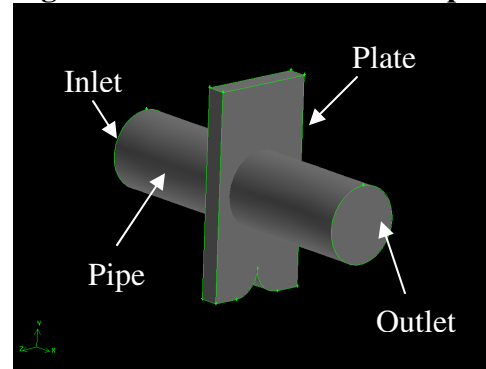
Fluent was used to validate our selected concepts. The relationship between pressure drop and motion of the plate for several plate concepts can be found using Fluent. Also, the temperature distribution, pressure distribution and velocity can be illustrated.

3-D models of two different plate concepts were set up using Gambit. Since we need to see the pressure at the several different valve opening positions, five to six different 3-D models are drawn for each plate in different positions. Two plates were chosen for the Fluent analysis based on our final design. An explanation of these final designs is presented in section 9. Fully closed valve models are shown in Figure 14 and 15 below respectively.

**Figure 14: 3-D model of first plate**



**Figure 15: 3-D model of second plate**



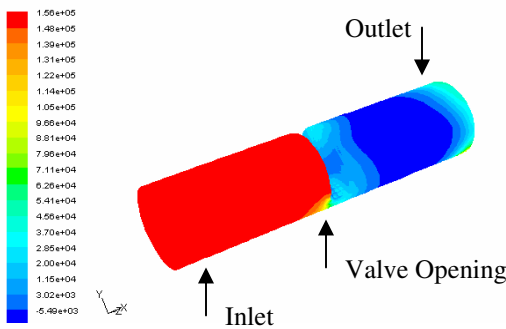
The plate part in the 3-D model is subtracted from the pipe for each of models in order to draw the mesh where fluid passes through. These CAD files were then exported to Fluent for analysis. We set up boundary conditions as shown in Table 2 on next page and then iterated to see the results.

**Table 2. Boundary conditions**

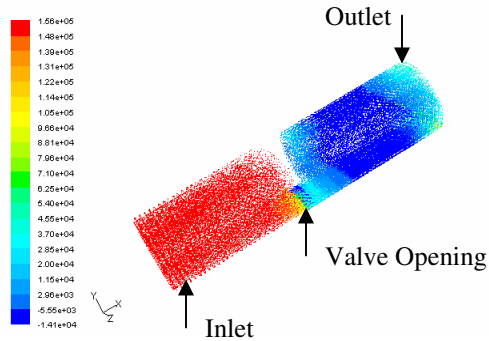
Fluid	Air	Turbulence Intensity	5%
Velocity	111.43m/s	Hydraulic Diameter	1.5 inch
Temperature	773K	Wall Material	Steel

From Fluent analysis, we found the velocity distribution, pressure distribution and temperature distribution across the valve. Selected pressure results are shown in Figure 16 and Figure 17 and most of results are in Appendix D. As we expected, it shows very high velocity at the valve opening and minor variation of temperatures across the valve. It also shows large pressure difference across the valve at the small opening and large variation of pressure as valve opens.

**Figure 16. Contour form of pressure distribution at the second opening position for the first plate**

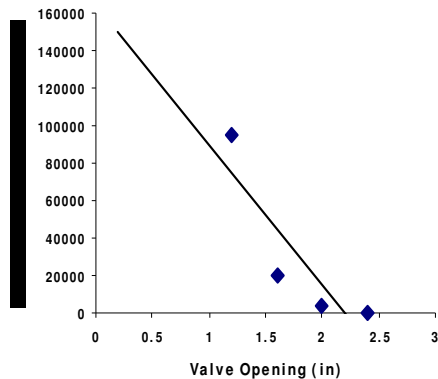


**Figure 17. Vector form of pressure distribution at the second opening position for the first plate**

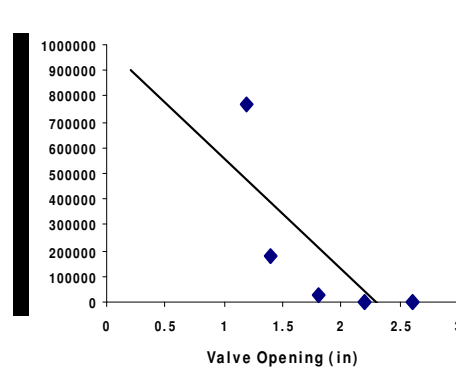


Since we could find the pressure of inlet and outlet at each opening position from Fluent, we could plot the pressure difference across the valve against valve opening. These results for the first and second plate are shown in Figure 18 and Figure 19 respectively.

**Figure 18. Pressure difference vs. valve opening of the first plate**



**Figure 19. Pressure difference vs. valve opening of the second plate**



As you can see from the graphs above, both plates show an exponential relation between pressure difference and valve opening. The linear lines drawn in figures 18 and 19 show the desired relationship. Both plates show near zero pressure loss at the completely open



state, and the second plate model shows less pressure difference at the first opening than first plate.

### 8.3 Bushing Analysis

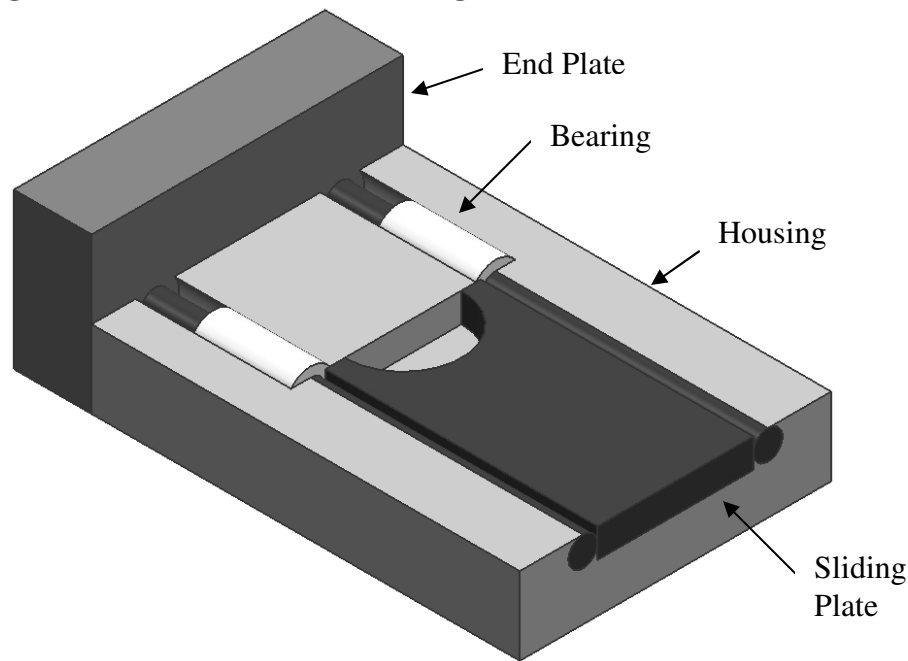
In order to accurately position the valve, guide rods and linear bearings will be used. The valve plate will use 0.375 in. steel guide rods attached to the top and bottom, and these two rods will be guided by a linear bearing on each. This will help minimize frictional effects, as well as to assist in the wanted smooth opening motion of the valve. Ideally, linear ball bearings would be used in this application. However, the high temperatures do not allow us to consider this type of bearing in our application. We have requested information pertaining to a high temperature graphite bearing; however, our time and budget constraints did not allow us to implement this type of bearing in our prototype.

### 8.4 Actuator Force Analysis

The actual force needed to move the valve at operation conditions is determined using simple force analysis. Using the maximum pressure of 250 kPa and the valve area of  $1140.1 \text{ mm}^2$ , we find the normal force to be 285 N. This is found from  $F=PA$ . The only force resisting the motion of the valve is due to friction. For a steel to steel interface, the coefficients of friction,  $\mu$ , are 0.7 and 0.6 for static and kinetic, respectively. This gives a “breakaway” force of 199.5 N to initially move the valve, and a force of 171 N to continued moving the valve. These forces are found from  $P=\mu F$ , where  $F$  is the previous calculated normal force of 285 N. This force will decrease greatly, since both the area and pressure decrease.

## 9. FINAL DESIGN

The final design for the prototype has been chosen, and a CAD model was generated. Figure 20 shows one half of the valve housing. The design utilizes linear bearings on the valve plate, represented by the white cylinders. The valve itself will move on a circular track on top and bottom of the valve, supported by the linear bearings. More detailed CAD models can be found in Appendix A.5.

**Figure 20. CAD model of final design**

Referring back to Figure 4 in the section for customer requirements, it was our goal to better linearize the relationship between pressure drop and plate motion. A Fluent analysis was used to determine this relationship and to verify our testing results; however, due to limited resources and availability, the analysis was not completed until after manufacturing had started. Therefore, a basic qualitative judgment along with a general pressure vs. motion analysis was done to justify our reason for choosing the following concepts.

Additional features such as an angled plate entry or a contoured surface were not considered for our final design; therefore, it follows that the parameters involved in manipulating the rate of pressure drop would only include a time-based motion of the plate and its opening geometry. Fluent allows us to create a 3-D pressure distribution of fluid flow; however, it cannot model time-based motion for our application.

Thus, our two final designs for our plates were generated from a variety of different concepts that could possibly achieve a more desirable relationship between pressure and motion. Our belief was that a smaller initial opening would lead to a more linear relationship. Our goal was to analyze our two shapes in Fluent and perform laboratory testing to see which plate better met our customer requirements.

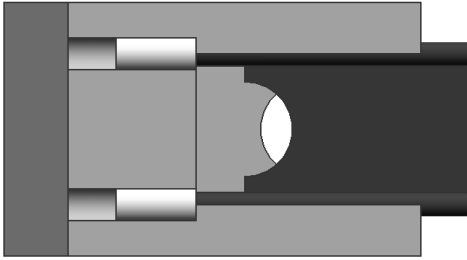
### 9.1 Final Design Plate Concept 1

Our first plate design has an opening in the shape of a convex half-circle with a 1.5 in. diameter, as illustrated in Figure 21. The opening shape resembles an eclipse as the opening begins, and allows unimpeded flow at the fully open position.

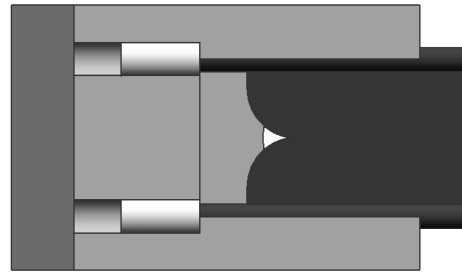
## 9.2 Final Design Plate Concept 2

Our second plate design has an opening described as two adjacent circles converging to a narrow opening. With a smaller opening at the beginning of the plate's movement, we hope to better control pressure loss with respect to plate opening. This concept should serve to linearize the pressure drop during valve opening. A CAD drawing of this valve is shown in Figure 22.

**Figure 21. CAD drawing of final design concept 1.**



**Figure 22. CAD drawing of final design concept 2.**



## 9.3 Engineering Drawings

Figure 23 shows one of the engineering drawings of our final concept. This figure gives the important dimensions, mainly of the housing. Additional dimensioned drawings can be found in Appendix A.6

## 9.4 Bill of Materials

The only major component that still needs to be purchased is the actuator. However, in order to meet the engineering specifications, a linear computer controlled digital actuator is needed. The price for one of these precisely controlled, high resolution actuators ranges from several hundred to several thousand dollars. Therefore, the EPA will purchase this item. We have already purchased comparison valves, low carbon steel for prototype, and miscellaneous hardware items. A quote for the graphite bearings, not able to be purchased in time for the design expo, can be found in Appendix E. The bill of materials is listed in Table 3. Also, the pipe and pipe fittings used in the testing of the valve can be found in the bill of materials. An electric actuator was not needed at this time, due to the high cost of a suitable actuator.

**Table 3. Bill of materials**

Quantity	Part Description	Purchased From	Part Number	Price (each)	Price (Total)
1	1.5" Butterfly Valve	McMaster-Carr	4682K78	\$39.41	\$39.41
1	1.5" Ball Valve	McMaster-Carr	47865K27	\$28.68	\$28.68
1	1" x 7" x 12" Low Carbon Steel Plate	ASAP Metals	n/a	\$15.95	\$15.95
1	3/8" x 24" Low Carbon Steel Rod	ASAP Metals	n/a	\$5.95	\$5.95
1	2" x 6" x 1/4" Low Carbon Steel Plate	ASAP Metals	n/a	\$4.89	\$4.89
1	2" x 6" x 1/8" Low Carbon Steel Plate	ASAP Metals	n/a	\$3.48	\$3.48
1	2" x 12" x 3/8" Low Carbon Steel Plate	ASAP Metals	n/a	\$9.81	\$9.81
2	Linear Bearing	McMaster-Carr	5986K23	\$18.22	\$36.44
1	Graphite Seal	McMaster-Carr	13125K76	\$16.10	\$16.10
6	M10 x 1.5 Bolt	Carpenter Hardware	n/a	\$0.98	\$5.90
8	1/4"-20 x 3/8" Bolt	McMaster-Carr	91255A551	\$0.13	\$1.04
4	1.5 in. Diameter Pipe (feet)	Home Depot	669423	\$2.67	\$10.68
2	Pipe Flange	Home Depot	32888407176	\$3.40	\$6.80
1	Pipe Cap	Home Depot	32888406797	\$1.55	\$1.55
				<b>Total</b>	<b>\$186.68</b>

## 10. MANUFACTURING AND TESTING

The fabrication and testing of the valve was performed ourselves. We machined the valve in the College of Engineering machine shop. The testing of the valve took place in the Auto Lab ME 395 laboratory.

### 10.1 Manufacturing of Prototype

We fabricated the sliding plate valve prototype with low carbon steel due to the metal's ability to withstand high temperature. Clearances between moving parts of the prototype will be the thermal strain of the given component, as well as an additional 0.002 in. to take into account natural variations.

The maximum temperature is around 500° C, as provided by the EPA, and we use a minimum temperature 0° C. Therefore, the thermal strain can be expressed as  $\epsilon = \alpha \Delta T$ , where  $\alpha$  for AISI 1005 carbon steel, at 500° C, is equal to  $16.6 \cdot 10^{-6}/^{\circ}\text{C}$ . We use a strain of  $8.3 \cdot 10^{-3}$  in our design. This strain multiplied by the specific part dimensions gives us the amount of clearance needed for thermal expansion.

The housing of the valve is made in two major parts. The splitting occurs at the plate slot. These two pieces are bolted together using 6 bolts to complete the housing assembly. Linear bearings, or bushings, are pressed into the housing to provide a precise track for the plate assembly. The actual plate assembly has two guide rods, mounted at the top and bottom of the plate as seen in Figure 14 on page 14.

In order to minimize friction, high quality tooling is used. All moving parts have a very smooth surface, obtained using sanding and other abrasives.

Currently, HCCI engines are not mass produced, but still in the research and development phase. Therefore, our concept will not be mass produced, and we do not offer any changes to our valve as such.

The exact machining procedure can be found in appendix B.

## 10.2 Testing of Prototype

In order to get the most accurate information on the pressure loss, sealing ability when closed, and pressure drop while opening, laboratory testing was performed. Our prototype, as well as the butterfly and ball valve was tested, in order to provide a comparison of different types of valves. The lab setup consists of a 1.5 in. pipe that is 18 in. long attached to each side of the valve. One section of pipe is closed off at all times, and the other allows the air to vent to atmosphere. This section of pipe has compressed air flowing through a pressure regulator. Two manometers or pressure transducers are attached to the setup, placed 6 in. on either side of the valve.

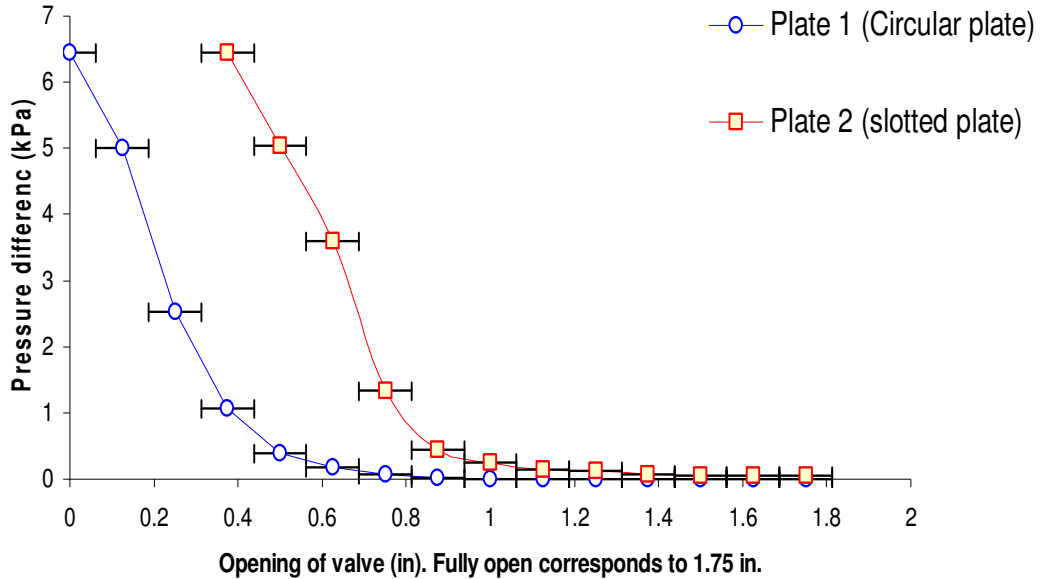
The first testing procedure was used to determine the pressure loss across the valve. With the valve in the fully open position, compressed air at a range of 300 to 600 kPa was allowed to enter the pipe. The manometer readings were recorded before and after the valves to provide the pressure loss of the specific valve.

The second testing procedure was run at the maximum pressure of the regulator. The valves were opened in equal intervals in order to determine the relationship between the valve opening and the pressure drop across. For the ball and butterfly valve, the angle of opening was used to relate the actual valve opening. For the sliding plate valve, the total travel of each specific plate was used.

The third and final testing procedure was used to test the sealing of the valve. Using the maximum air pressure, the sealing of the valve was tested. We believed any leakage will be far too small to measure, but any leakage at this pressure would be easily heard. The exact testing procedure can be found in appendix C.

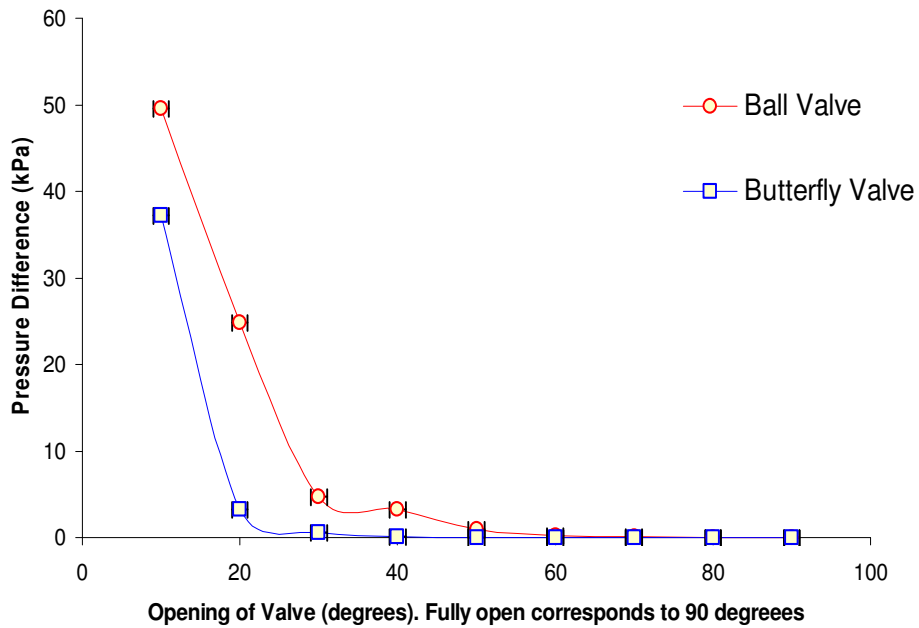
We were able to complete one round of testing before we had a seal malfunction. Figure 24 shows the pressure difference of the valve with respect to opening. The initial motion did have a linear portion, but the pressure difference dropped off quickly for both of the plates. The slotted plate has the greater potential to achieve this linearity, since the flow area is very small until the valve is halfway open. At this time, the pressure difference drops to near zero.

**Figure 24. Lab data of sliding plate valve does not show a distinct linearity. Error bars are too small to be seen.**



As a comparison, we also tested a ball valve and a butterfly valve. These two valves had a much sharper drop off when initially opened.

**Figure 25. Lab data of ball and butterfly valves does not show a distinct linearity. Error bars are too small to be seen**



We had several problems during testing. The main problem was the leakage of the sliding plate valve when fully closed. As seen in the figures above, the commercially manufactured

ball and butterfly valve recorded pressure differences of up to 50 kPa; however, our valve only reached about 6-7 kPa, signifying a large leakage. The future improvements section details this, as well provides a solution. The leakage is also due in part to the clearances at lower temperatures. The valve was designed to operate at a max temperature of 500° C, therefore the clearances were designed using a thermal strain of  $8.3 \times 10^{-3}$ . We believe that if we were able to test at the working temperature, before the recommended changes, the leakage would be greatly reduced.

We could not achieve the high speed produce by the combustion process of the HCCI engine. Our max speed during testing was 5 m/s, much lower than the estimated speed of 103 m/s. We determined that the only way to accurately test the valve would be to install it in the exhaust of a test engine, which was not possible. The EPA did not allow us to use their lab, and an attempt to use an engine in the University's Auto Lab was not allowed, due to safety reasons.

## 11. ENGINEERING RECOMMENDATIONS

We found during the testing procedure that the valve had excessive leakage. This is due mainly to the manufacturing procedure used. To remedy this problem, more precise machining is needed. The slot in the middle of the valve needs to be finished first on a surface grinder, to remove variations in the clearance between the valve plate and housing. The next step to ensure better sealing would be to lap the parts together. In general, lapping is performed by placing a fine abrasive between the housing and the moving surface of the valve plate. This technique matches the surface mating of the parts very closely, providing a much better seal.

Although we believe that the simple process of using very precise machining techniques would work, a graphite seal could also be used in the housing, mounted along the plate slides, to reduce leakage. Graphite seals come in several different styles, and we would use a thin, woven seal along the slides.

Another improvement is using a linear bearing rated at a higher temperature. Graphalloy of New York provided us with a quote of a graphite bearing that would perform quite well. The specifications for these bearings can be found in Appendix E.

The final design change has to do with the seal. During testing, the seal did not hold up, and eventually was torn. To improve this, a tighter fit between the seal and the end plate would be needed, and a more precise alignment of the plate shaft and housing seal.

## 12. CONCLUSIONS

We set out with two main goals for the turbocharger bypass valve. The first was to minimize leakage across the valve when closed while maximizing flow when fully open. The second was to linearize the pressure drop across the valve versus the motion of the actuated valve. We ran into several issues trying to meet these goals. Our final design showed promise in approaching the linear relationship and the minimized pressure loss, but our prototype had considerable leakage. Several problems lead to the poor performance of our valve. We built the valve with tolerances based on a 500°C operating temperature. We

tested the valve at 25°C and noted considerable leakage throughout the valve. Our valve showed some improvements over the past design. During our test, we measured just trace pressure losses in the fully open valve, likely because of the larger opening we designed. The more difficult task was approaching the linear relationship. During our testing, we noticed a quasi-linear relationship during the initial motion of the valve, however still not remaining linear throughout the motion. Another problem we ran into was our testing setup. We were using shop air to test the valve, and the valve had considerable leakage. This restricted our testing from getting anywhere near the operating pressure of 250 kPa. Based on the data we collected on our valve, we can see that, with improvements, this valve is an improvement over the past design. This valve will not likely fulfill both goals, but with better sealing, this valve will improve the transition between turbochargers. With these operating conditions, it is difficult to estimate exactly how any valve will perform in the system. The design we tested did not meet every specification, but with future design and testing, could possibly meet both the goals.

### 13. ACKNOWLEDGEMENTS

We would like to thank our sponsor, Dr. Andrew Moskalik of the EPA for his help and support. Thank you to professors Katsuo Kurabayashi, Kazuhiro Saitou and Mohammed Shalaby for all their help. Also thanks to Bob Coury, Marv Cressey, and Steve Emmanuel for all their help in the manufacturing of the valve and the testing equipment. Thank you to Tom Bress and Todd Wilber for their help in the testing, as well as supplying us with testing equipment. Finally, thank you to Dong Hyun Lee for all of his help with the computational fluid dynamic analysis.

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<<http://www.danahermotion.com>>



## 15. TEAM MEMBER BIOS



### **Hyuk Jin Chung**

Hyuk Jin Chung was born and raised in Seoul, Korea. He prefers to be called Jin. Since he was young, his interest was math and physics. After he graduated high school in Korea, he came to USA to study mechanical engineering. His interest in mechanical engineering is control systems. He is planning to serve in the Korean military after graduating because it is mandatory for all Korean males. He wants to come back to USA after serving and go to graduate school. He likes to travel to new places and play tennis and golf. His current interest is finding the best place to travel during spring break and finding an internship for summer.



### **Jason France**

Jason France grew up in Dexter, Michigan, and graduated from Dexter High School in 2003. Jason's biggest interest in mechanical engineering is design, specifically engine component design. After graduating from U of M, he intends to attend graduate school here at Michigan, or possibly at UCLA. After getting a job in the engineering field, Jason plans to return to school for a Masters of Business Administration. He loves being outdoors and enjoys a wide array of sports.



### **Andrew Swanson**

Andrew Swanson was born in Ann Arbor, Michigan and has lived his entire life in Hamburg, Michigan. He graduated from Pinckney High School in 2001, and attended classes at Washtenaw Community College before applying to the College of Engineering at the University of Michigan. His major interest in mechanical engineering is the versatility of the field, as well as the application to automotive systems. He has a strong background in automotive technology and repair, and plans to work in the automotive field, in product development or testing after graduation.



### **Michael Yu**

Michael, or Mike, was born and raised in Ann Arbor, MI. He graduated from Huron High School in 2003 and went on to attend the University of Michigan College of Engineering. Mike plans to graduate with a B.S. in Mechanical Engineering in December 2007. After graduating, he intends to continue working on his business (non-profit and ticketing network) then eventually going back to school for an M.B.A. He enjoys playing basketball and golf.

## 16. APPENDICES

### Appendix A: Figures

**Figure A.1: Gantt chart of necessary task and key dates.**

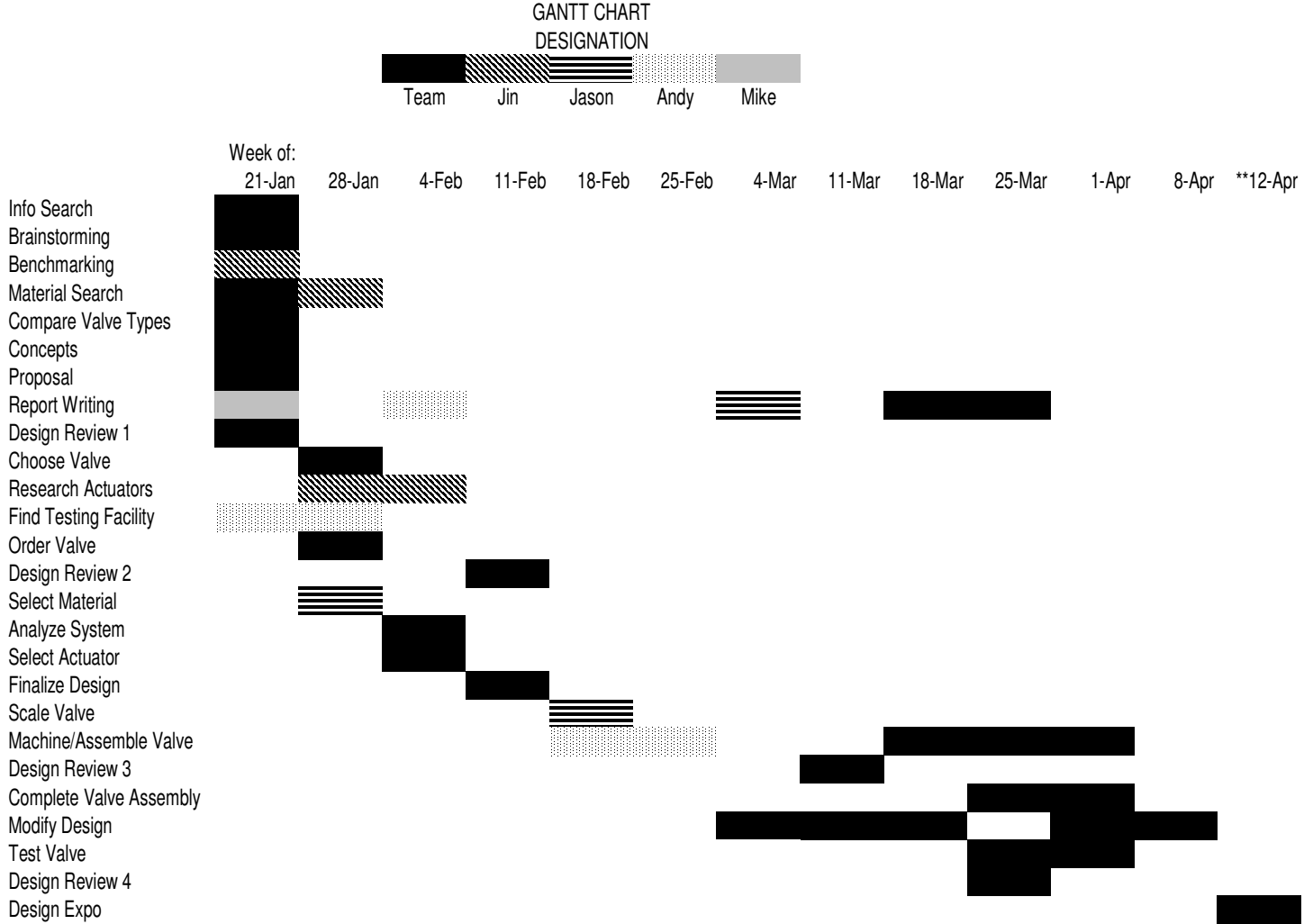
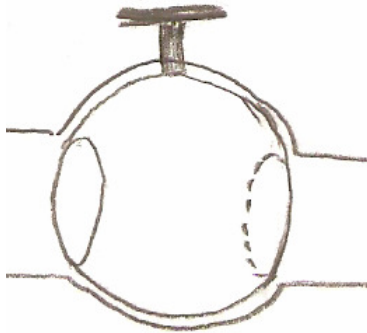
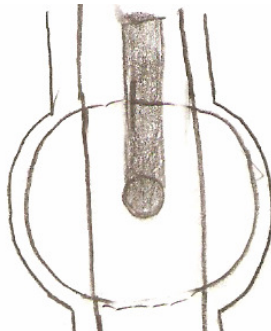




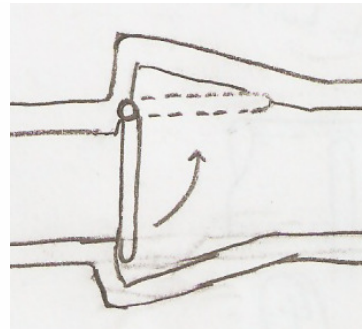
Figure A.3: Possible concepts: selected concepts marked in brackets [ ].



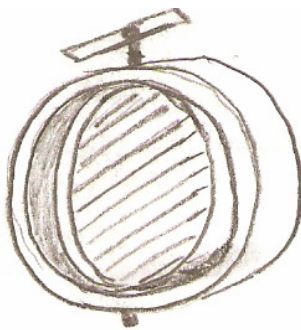
A.3.1 [1] Ball Valve (Side)



A.3.2 Ball Valve (Top)



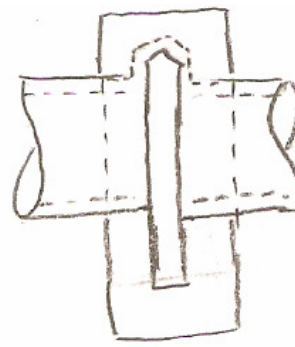
A.3.3 [2] Gate Valve



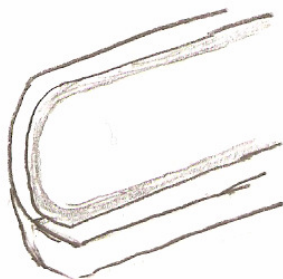
A.3.4 [3] Butterfly Valve



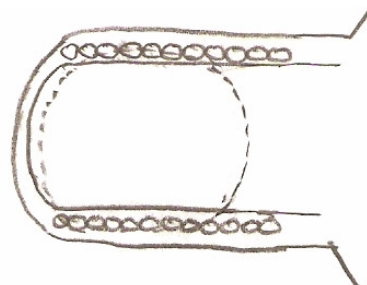
A.3.5 [4] Sliding Plate Valve



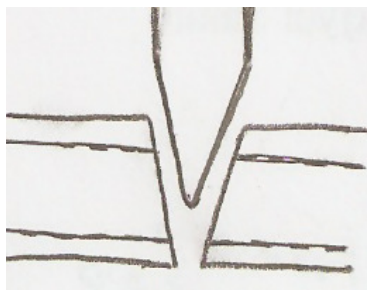
A.3.6 Sliding Plate Valve



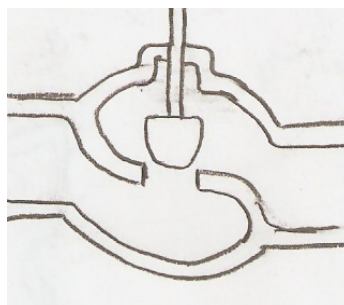
A.3.7 Knife Edge Sliding Plate



A.3.8 Sliding Plate on Bearings



A.3.9 [5] Wedge Gate Valve



A.3.10 Globe Valve



A.3.11 "Portal" Valve

**Figure A.4: Morphological chart showing necessary functions and concepts**

Function	Concepts				
Fully Close	Plastic/rubber seals	Tight metal fittings			
Fully Open	Increased area	No blockage			
Withstand high temp.	Cooling system	Proper metal	Insulation		
Withstand high press.	Thicker parts	Stronger parts	Framing		
Electric actuator	Vacuum part	Battery	Onboard computer		
Opens smoothly	Bearings	Knife edge	Modulating actuator	Preset actuator	Lubricant

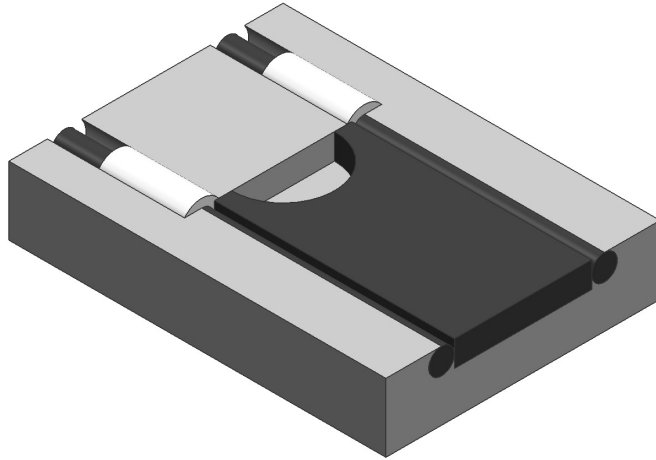
**Figure A.5: Pugh chart showing selected concepts and their functions**

Customer Requirements	Concept	1	2	3	4	5
	Weight (1-10)					
Minimize Leakage	10	0	1	0	1	1
Minimize pressure drop (maximize area)	10	1	1	-1	1	1
Press. drop varies linearly vs. valve motion	6	1	-1	0	1	-1
Functions at high temp. and press.	10	1	1	1	1	1
Cost	3	1	0	-1	0	0
Compatibility	4	0	0	0	0	0
Ease of Installation	2	1	0	1	1	0
Easy to Maintain	4	-1	-1	0	0	-1
Durability	4	0	1	0	0	1
Feasibility	3	1	-1	1	1	-1
	Weighted	30	21	1	41	21
	Rank	2	3	5	1	3

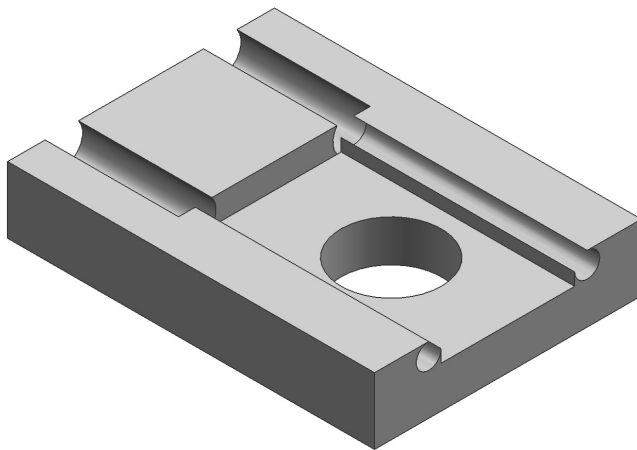
Key	
1	Positive
0	Neutral
-1	Negative

**Figure A.5: CAD models of the complete prototype**

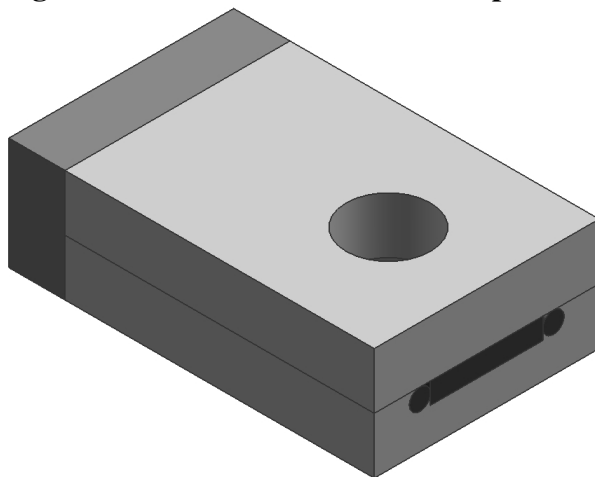
**Figure A.5.1: Isometric view of valve plate in housing half**



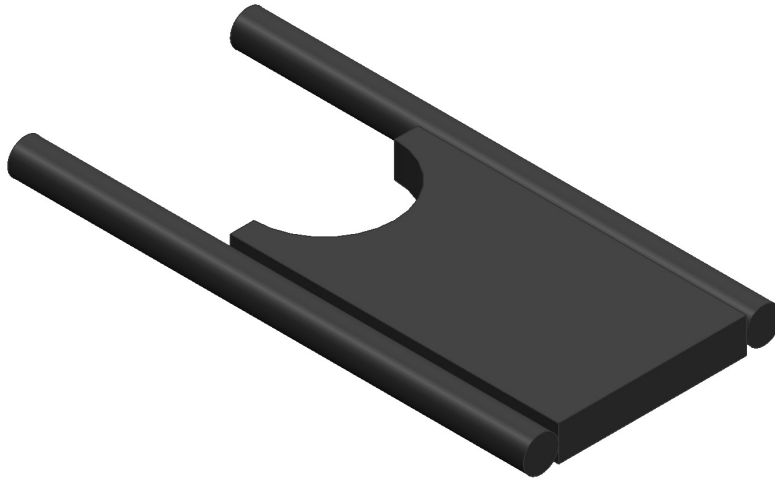
**Figure A.5.2: Isometric view of housing**



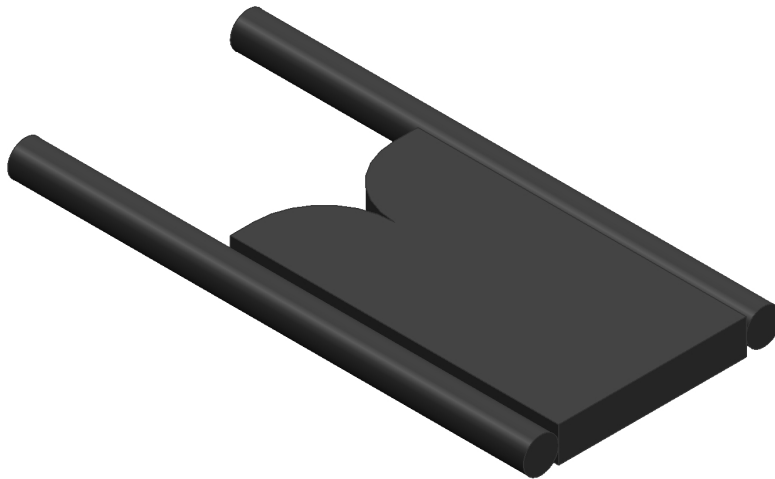
**Figure A.5.3: Isometric view of complete assembly**



**Figure A.5.4: Isometric view of circular plate**



**Figure A.5.5: Isometric view of concentric circle plate**



**Figure A.5.6 Side view of housing half with valve plate and bearings**

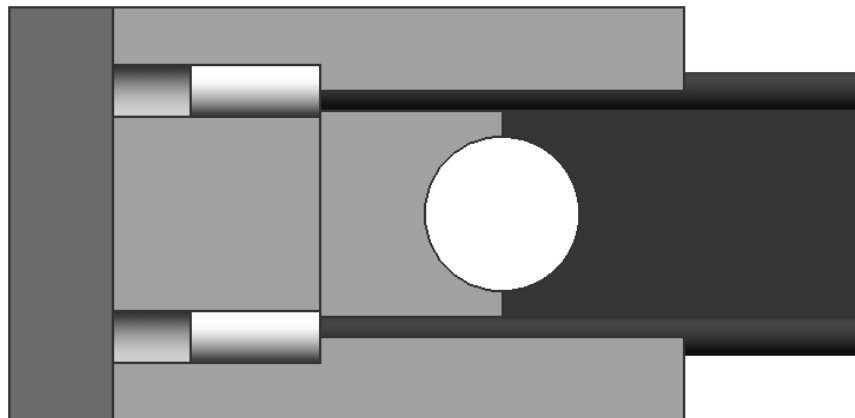




Figure A.6: Engineering drawings of complete prototype

Figure A.6.1: Valve housing

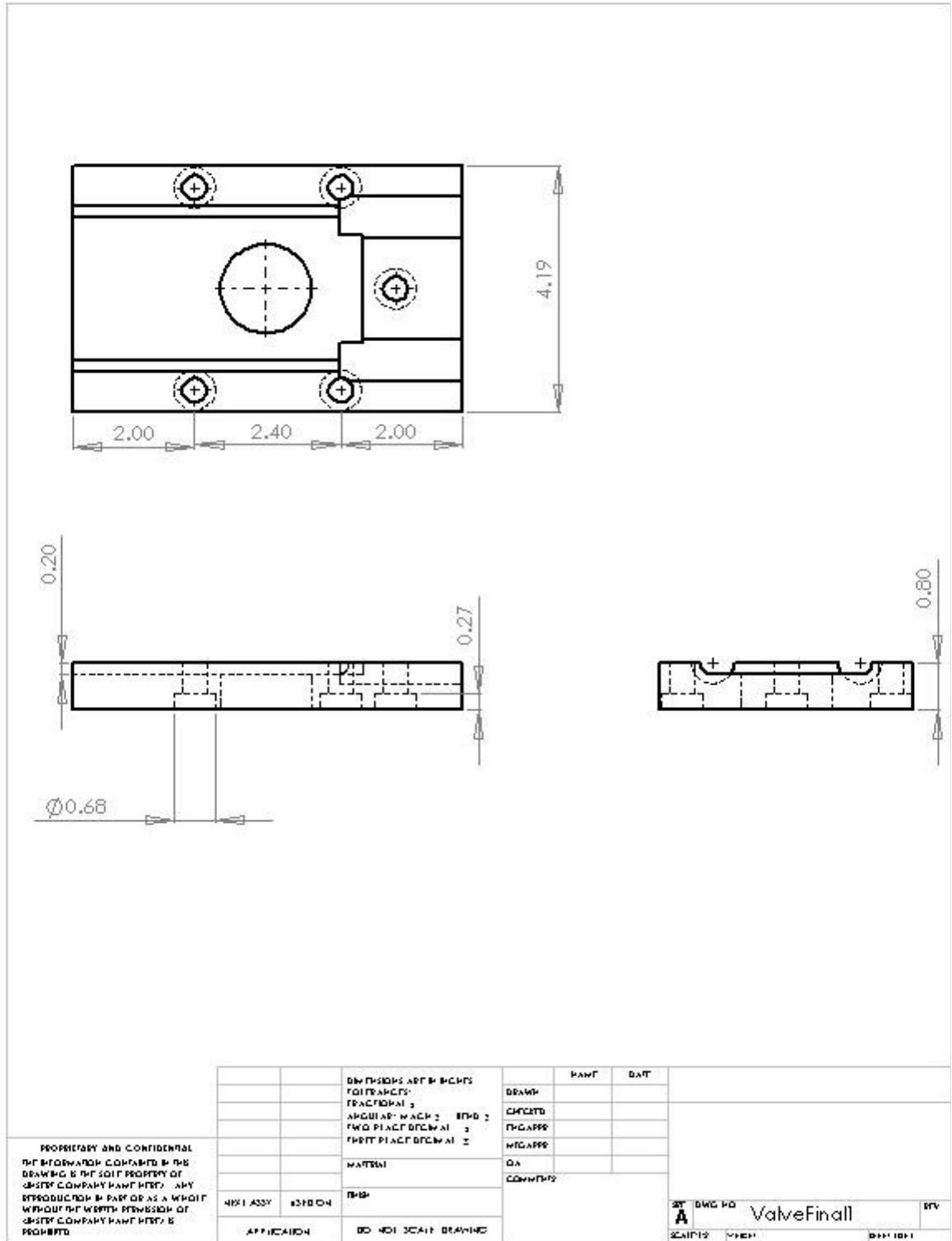




Figure A.6.2: End plate

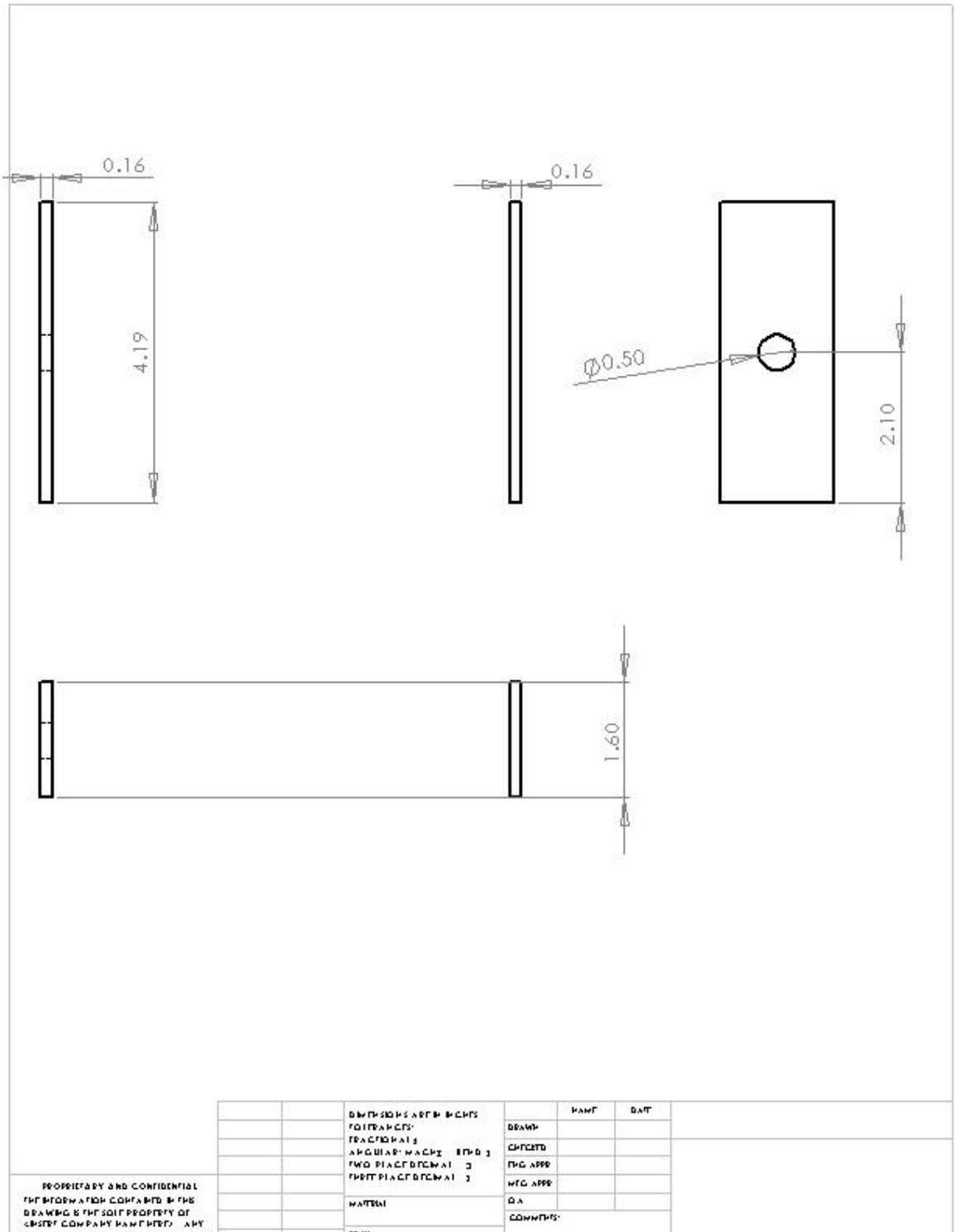
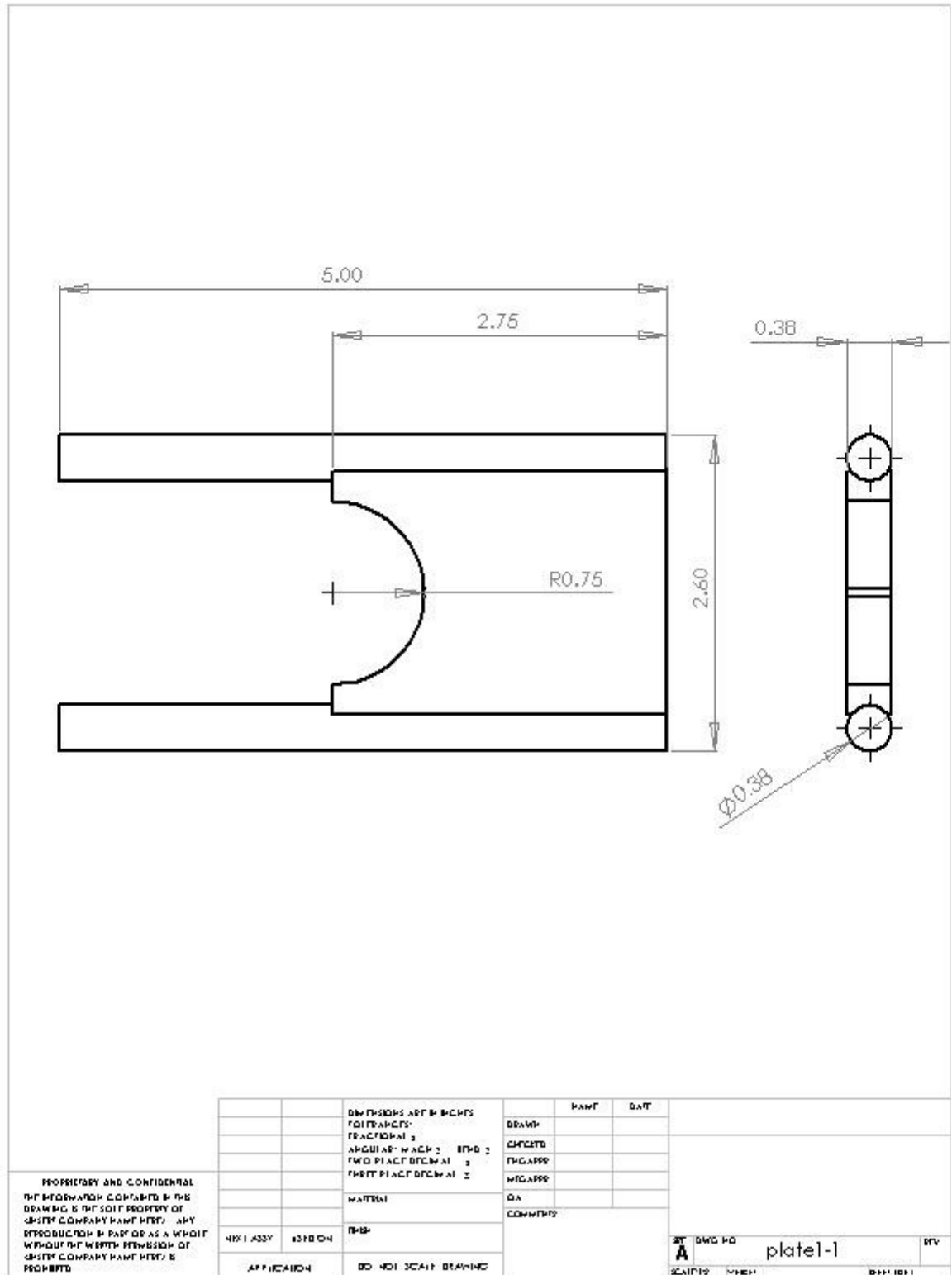


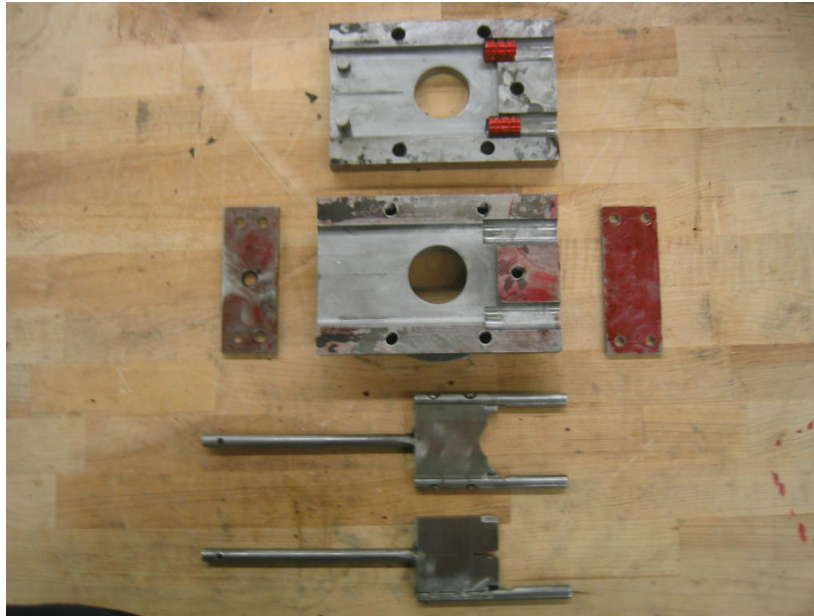
Figure A.6.3: First valve plate





**Figure A.7: Prototype photographs**

**Figure A.7.1: Photograph of valve components**



**Figure A.7.2: Photograph of assembled valve partly opened**



## Appendix B: Manufacturing Procedure

### Housing Assembly

1. Cut two 4.25 in. by 6.5 in pieces of steel from 0.75 in. stock.
2. Using a mill and proper tooling, face and square both pieces to within .01 in.
3. ON the front face, drill five 0.391 in. holes, as shown in figure XXXX, and countersink the holes at a diameter of 0.6875 in, to a depth of 0.25 in.
4. On the rear face, drill five holes using an R sized drill. Tap the holes using an M10 X 1.5 mm tap.
5. Bolt the two faces together, and re-square complete housing assembly.
6. Place the housing assembly in a lathe using a four jaw chuck, using the center of the 1.5 in. hole as the chuck center.
7. Drill the hole in steps, to a diameter of 1 in. Then, using a boring 0.625 in. hole at LH face of housing assembly
8. Unbolt assembly, and mill center plate slot to a depth of .1875 in, staying within the previously drilled holes.

### Valve Plate

1. Cut a 2 in. by 2.75 in. piece from a 0.375 in. thick steel plate.
2. Square the piece, removing as little material as possible
3. Cut valve shape into LH face of the plate; The slotted plate uses a band saw, the circular plate uses a 1 in. drill
4. Cut two 4 in. pieces of 0.375 in. diameter steel rod
5. Remove 0.075 in. from the steel rod, from half of the length.
6. Weld the steel rods to the top and bottom of the plate using a MIG wire welder.

### End plates

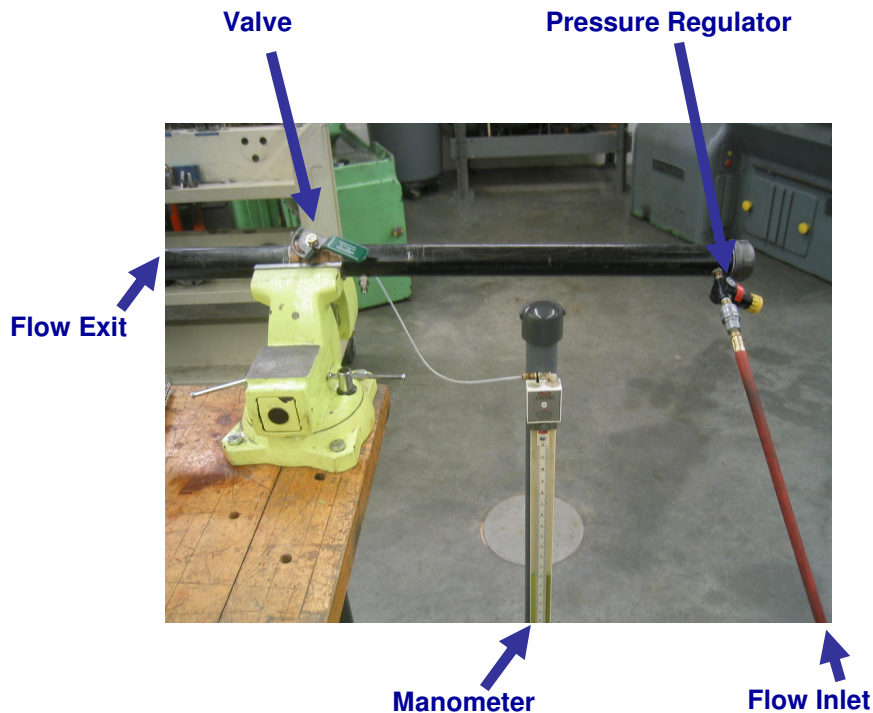
1. Cut two 1.6 in. by 4.25 in. pieces of .125 in. thick steel plate.
2. Square both pieces within 0.01 in. of each other.
3. Drill four 0.25 in. holes in each end plate, as seen in figure
4. For the RH plate only, drill a 0.484 in. hole in the center, and ream to a diameter of 0.5 in.

## Appendix C: Testing Procedure

The following procedure is valid for the three valves tested. The only difference in the testing is how the piping was attached to the valve. For the ball and butterfly valve, the pipe was threaded into the valve. For the sliding plate valve, the pipe was bolted to the valve using a flange. For reference to the laboratory setup, see figures C.1-2.

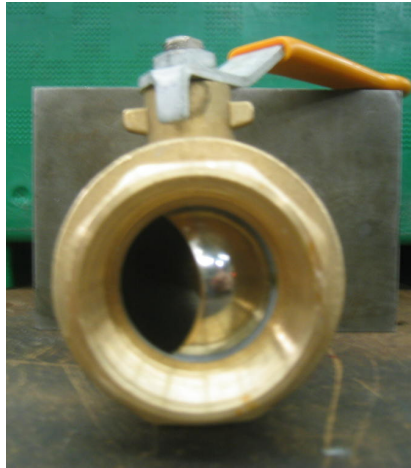
Attach a pressure regulator to the inlet pipe, followed by the pressure gauge and water manometer. Starting with the valve completely shut, adjust the pressure regulator until the full pressure is flowing into the pipe. Observe any leakage past the valve. Record the pressure at the inlet pipe and outlet pipe. For the ball and butterfly valve, slowly open the valve 10 degrees, and record the data. Continue in 10 degree increments until the valve is fully open. For the sliding plate valve, move the plate open .125 in, and record the data. Continue moving in .125 in. increments until the valve is fully open.

**Figure C.1: Testing setup**





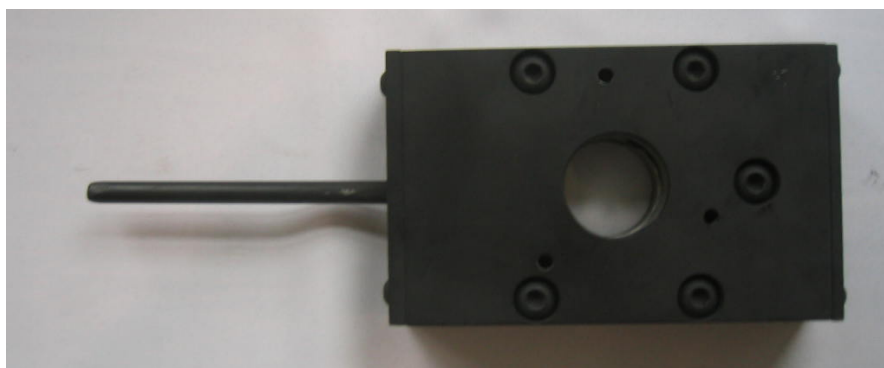
**Figure C.2: Valves used in testing**



**Ball Valve**



**Butterfly valve**



**Prototype valve**

Appendix D: Results for computational fluid dynamics using Fluent

Figure D.1: Pressure Distribution

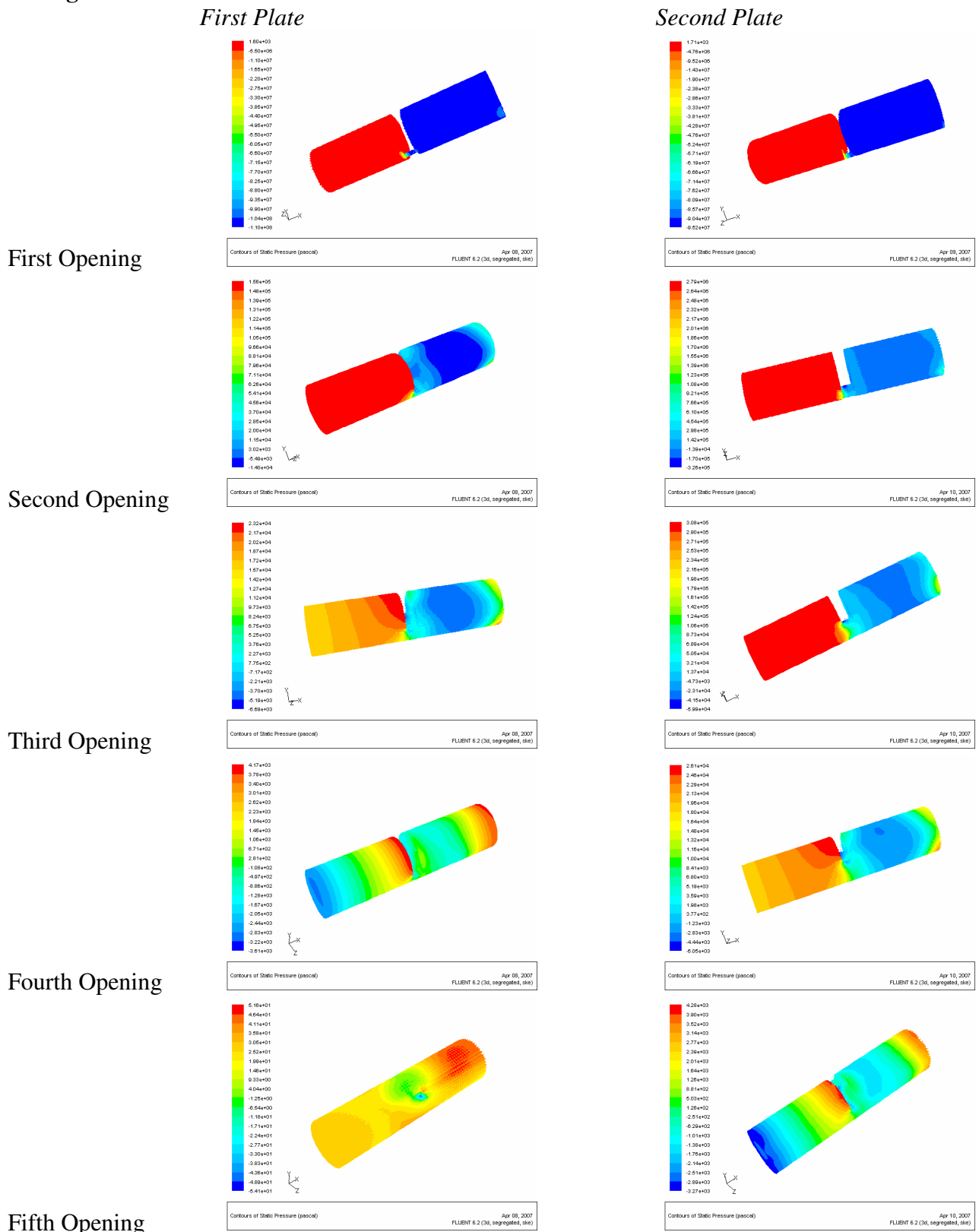


Figure D.2: Velocity Distribution

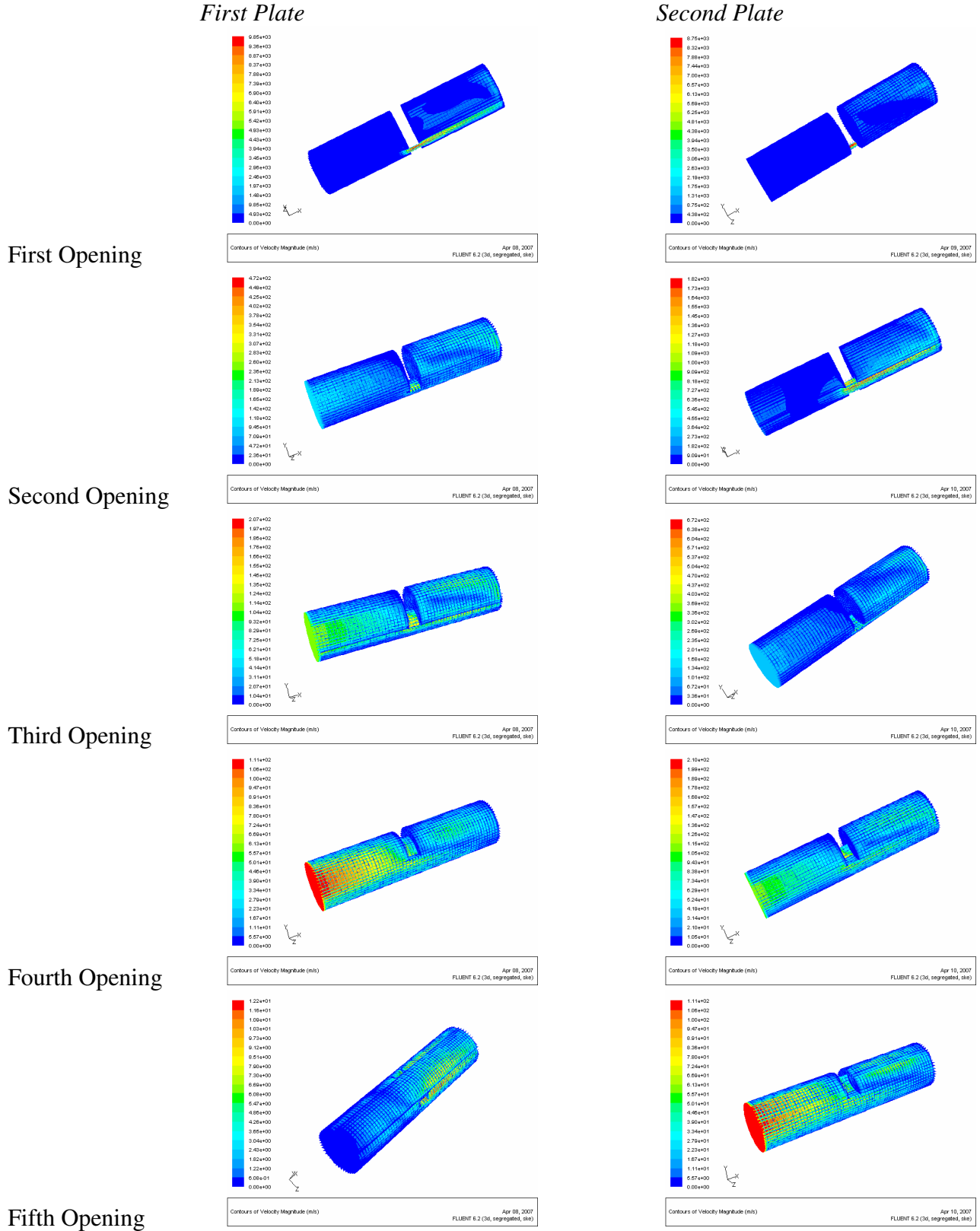
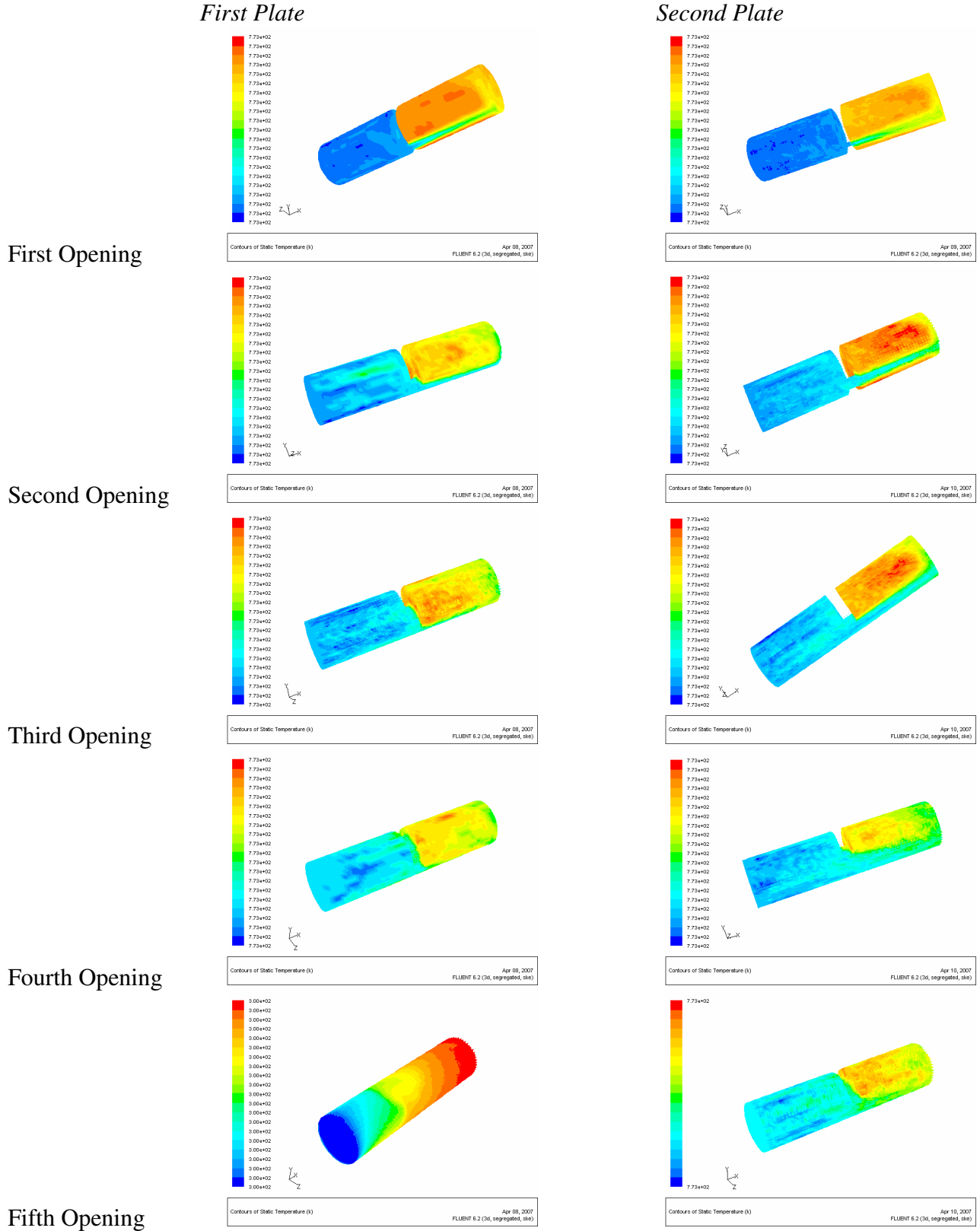


Figure D.3: Temperature Distribution



Appendix E: Specifications and quote for graphite bearings

Graphite Metallizing Corporation



MANUFACTURERS OF GRAPHALLOY® PRODUCTS



FAX: 914-968-8468
TELEPHONE: 914-968-8400
WWW.GRAPHALLOY.COM

1050 NEPPERHAN AVENUE

YONKERS, NY 10703 U.S.A.

March 19, 2007

phone
fax

Mr. Andy Swanson
UNIVERSITY OF MICHIGAN
11110 HALL
WHITMORE LAKE, MI 48189

Re: Your RFQ 3/12/07
Our Quotation No: 119417-0

Dear Mr. Swanson:

Thank you for your inquiry. We quote as follows:

EQUIPMENT: EXHAUST VALVE TEMPERATURE: 500 DEG C
ENVIRONMENT: ENGINE EXHAUST

ITEM 1 HOUSING ID: 0.625 INCH
SHAFT OD: 0.375 INCH

Table with 2 columns: Description and Price. Includes items S125735-1, GRADE GM GDG-2 GRAPHALLOY BUSHING, and various dimensions (0.632, 0.385, 0.505, etc.) with quantities and unit prices.

CHAMFER OD AND ID ENDS .015 X 45 DEGREES

Shipment - 5 Weeks after receipt of order.
Terms - Net 30 days, FOB Yonkers, New York, subject to approval
Price - Firm for 30 days, U.S. Funds

Very truly yours,
Graphite Metallizing Corporation

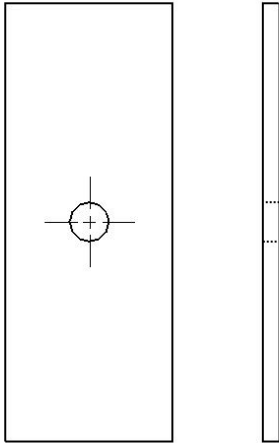
KBK/AA
cc: James Cox
Sales Representative
219-947-2290

Ken B. Krieger
Sales Engineer

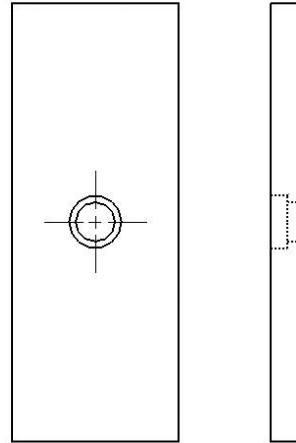
Handwritten signature of Ken B. Krieger

**Appendix F: Engineering Changes Notice**

**Was:**



**Is:**



In order to hold the seal more securely, a thicker end plate with a lip to hold the seal in place will be used