Honeywell Reference Pressure Regulator

Final Design Proposal

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DISCLAIMER

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EXECUTIVE SUMMARY

Honeywell International, Inc. as a company works within four different business units: Aerospace, Home and Building Technologies, Safety Productivity Solutions, and Materials and Technologies. The company generates both commercial and consumer products, as well as engineering services and aerospace systems. The reference pressure regulator, which falls within the Engines and Systems department of the Aerospace sector of business, is a system that provides several functions; most commonly, the reference pressure regulator established a standard pressure that is used as a reference point for other function controls with an aircraft.

Honeywell International, Inc. has tasked the Honeywell Pressure Regulator team with redesigning their current pressure regulator system in order to minimize hysteresis and to make the system more resistant to contamination. Per the client's specifications, the chosen pressure regulator design must accomplish the following functions: 1) a complete shut off of the system, 2) area modulation (lots of stroke with small area change), and 3) flow diversion (redirecting the flow through different passages).

The purpose of this report is to discuss the Honeywell Pressure Regulator team's progress thus far. The project as a whole is meant to be treated as a trade study; the client has specified that the team first needed to become familiar with Honeywell's current regulator design. Following the understanding of the current design, the team was tasked with comparing and contrasting current designs with other designs on the market, as well as other existing design considerations. Ultimately, the purpose of the project is to provide Honeywell with a redesigned reference regulator, as well as a proof of concept, that minimizes hysteresis throughout the system, is able to operate at high pressures and temperatures, and that is minimally susceptible to contamination.

The majority of the Fall 2017 semester was spent understanding the scope of the pressure regulator system while simultaneously brainstorming ways to address the issues with the current design. The team generated many designs in order to address these issues; ten of those designs are discussed below. Each concepts was generated keeping the issues of the original design in mind and how those issues could be improved upon. In order to reduce the number of concepts generated the team had to use concept evaluation techniques. These techniques included a Pugh chart and a decision matrix. Both of these methods compare the designs against each other and their ability to satisfy the engineering requirements.

After performing concept evaluation it was decided that two of the designs will be further pursued and analyzed. The concepts were not cut to one because the client is interested in seeing more options expanded upon. The two designs chosen to be further looked into include the turbo-expander and the eyelash bellow design. The turbo-expander uses a turbine and induction generator to control the shaft speed and therefore outlet pressure of the system. The eyelash bellow design uses bellows to actuate the area reduction with a mechanical pressure balance system. These two designs have potential to perform better than the original Honeywell pressure regulator design.

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1 BACKGROUND

1.1 Introduction

The Honeywell Pressure Regulator Team is assisting in the development of a different type of reference air pressure regulator for use on commercial airliners. Most of the controls and actuators on commercial airliners are pneumatically controlled. For pneumatics to function, they need to reference a specific amount of pressure. This is achieved through the use of a reference pressure regulator. The reference pressure regulator takes in different levels of inlet pressure and outputs at a constant pressure level.

Honeywell has been building upon a legacy reference pressure regulator design for the last 60 years. They have slowly worked out inefficiencies and design flaws in this design. However, their current design has inherent flaws which limit its overall performance. The job of the Pressure Regulator team is to establish a new solution to the reference pressure regulator.

Improving the regulator design would increase the accuracy of pneumatic controls on the aircraft, which could increase economy of the system and safety to the passengers. The economy would also be increased through the improved durability and longevity of the system leading to less replacement parts and maintenance. There are about 15 reference pressure regulators on B737, one of the most common commercial airliners in the world. For a large company such as Honeywell, with products produced on a large scale, the small decrease in maintenance or production cost can benefit the companies' profits greatly.

1.2 Project Description

The Pressure Regulator team was introduced to the project through the following project description provided by the sponsor, Honeywell.

> "In Tempe Arizona Honeywell produces a line of Pneumatic Controls for use in aircraft. These controls take the form of valves that are used for controlling the temperature, pressure, and flow of pressurized air that is extracted either from the aircraft's main propulsion engines, or from a smaller auxiliary power unit (APU). These valves run from small 3/8ths-inch line sizes up to 10 inches in diameter, an carry pressures from just above atmospheric to 600 psig, with temperatures running from -40F to 1300F. The extracted air is cooled and the pressure regulated, and is provided to various "user" systems including wig anti-ice and cabin pressurization and environmental control. Many of the world's aircraft use valves produced by Honeywell, and most aircraft have dozens of these valves. Virtually every valve has a small on-board pressure regulator that serves some controlling function. The purpose of this project is to evolve and improve these pressure regulators.
>
> The pressure regulators in question provide several functions. Some simply limit the pressure in the valve actuator for structural reasons, while others produce a pressure that is used as a reference for control (where other pressures are compared to that reference for the purpose of controlling some function). While it is not quite correct to refer to all of them as reference pressure regulators because they don't all provide that function, it is common to do so, and since the design does not differ, we'll follow that habit."

1.3 Original System

The following sections describe the original pressure regulator system as designed by Honeywell.

1.3.1 Original System Structure

As previously stated, this project is the redesign of Honeywell's existing reference pressure regulator in use today on many aircrafts. Figure 1 shows the existing design currently in use by Honeywell. The reference pressure regulator works through what is called a pressure balance. The inlet is located at the bottom of the device where the poppet is. The poppet is a small conical closure element that is attached to a guide rod which is attached to the calibration spring. The airflow passes through the inlet, around the poppet, lowering the pressure as it passes through the narrowed passageway. This passage around the poppet effectively acts as a nozzle to increase the velocity of the flow and reduce the pressure. Figure 2 shows the basic pressure regulator design, which is very similar to Honeywell's design.

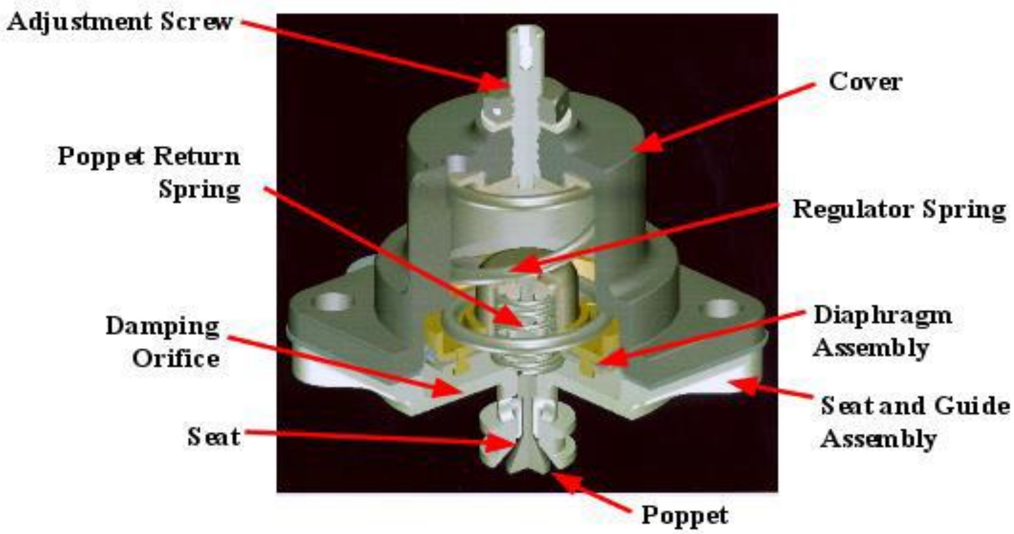

Figure 1: Honeywell Reference Pressure Regulator [1]

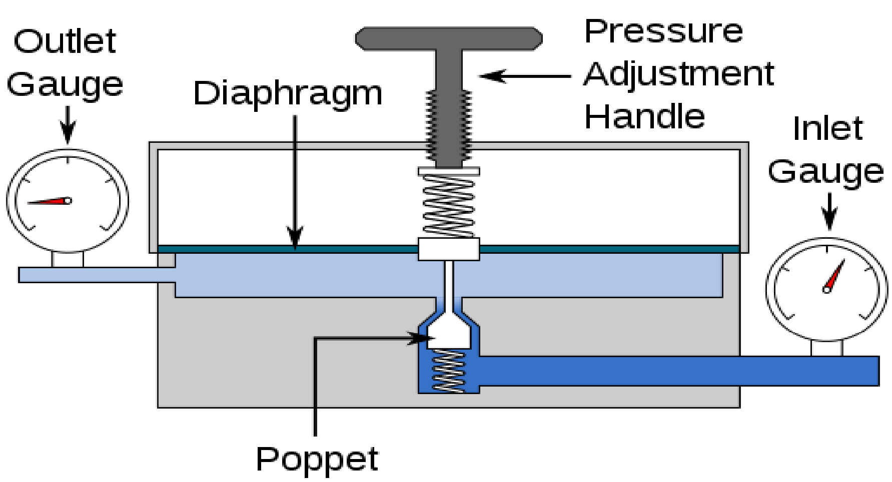

Figure 2: Basic pressure regulator design [2]

1.3.2 Original System Operation

The size of the passage around the poppet is constantly changing, depending on the poppets distance from the seat. If the inlet pressure is increased, the pressure force on the diaphragm will press down on the poppet, guide rod, and calibration spring assembly to close the inlet, in turn reducing the outlet pressure. Vice versa, if the inlet pressure reduces, the calibration spring will overcome the pressure force, allowing the poppet to retreat from the seat, opening the inlet and increasing the outlet pressure. This can be thought of otherwise as the greater the inlet size the smaller the difference between the outlet and inlet pressures. Therefore, the inlet size and pressure difference are inversely proportional.

1.3.3 Original System Performance

Since the team does not have experimental data from Honeywell, the basic performance of gas pressure regulators will be evaluated instead. Figure 3 shows the outlet pressure of a pressure regulator as a function of air flow. The plot displays how a pressure regulator works under a different air flow. Note that air flow and inlet pressure are not the same; although they have dependencies, they are not directly dependent. As shown, the outlet pressure of a regulator drops with an increasing air flow, this phenomenon is called "Droop". This is a common difficulty with all pressure regulators is a difficulty the team will work to solve with the redesign. [3]

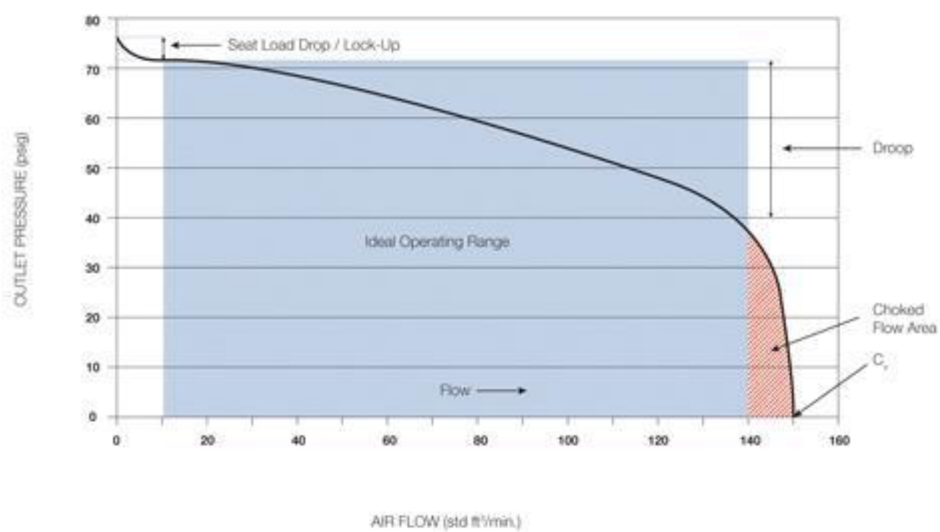

Figure 3: Pressure regulator flow curve [3]

If a pressure regulator were to work ideally, the curve would stay horizontal throughout a changing flow rate. To flatten out the curve, inlet pressure can be increased, which will help decrease droop, shown in Figure 4. Increasing the inlet pressure also increases the capability of the regulator itself in terms of flow rate. Towards the end of the curve the slope becomes exponentially more negative as the flow becomes choked and the outlet pressure equalizes with the inlet pressures. [3]

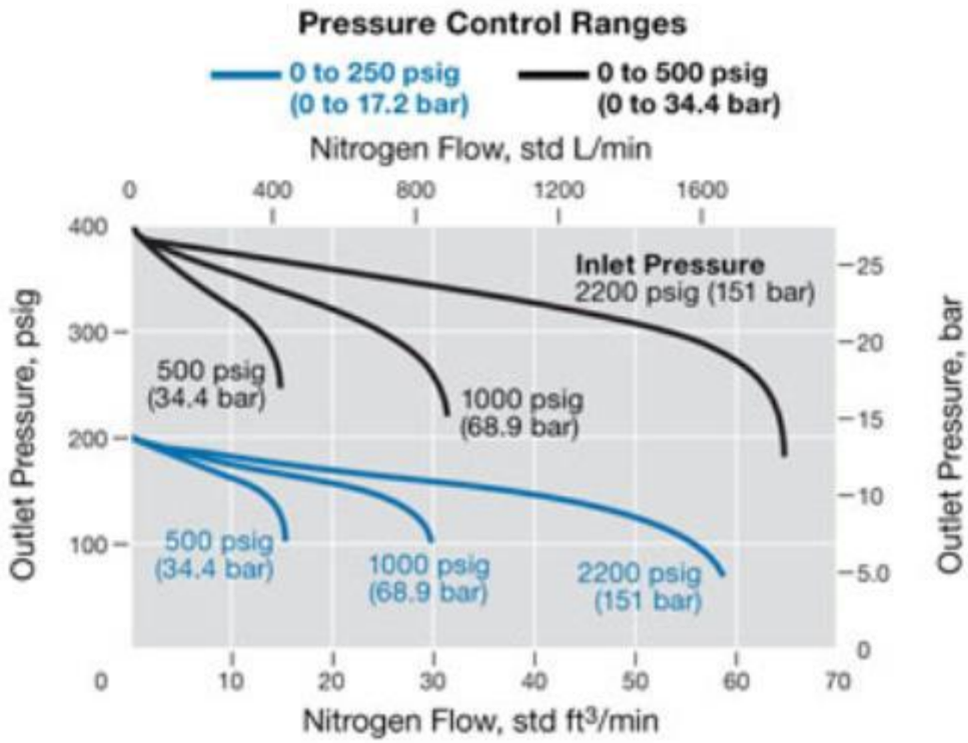

Figure 4: Nitrogen flow curves of multiple inlet pressures [3]

1.3.4 Original System Deficiencies

One issue brought to attention by the Honeywell Contact is the hysteresis the system shows as the inlet pressure and flow rate change, shown in Figure 5. The hysteresis reduces the accuracy of the system as well as its consistency. For instance, the regulator might output a different pressure at the same inlet pressure depending on the immediate history of the inlet pressure. This can lead to miscalculated actuation in the pneumatic controls on the aircraft. The team will work towards reducing the hysteresis loop area as much as possible to increase consistency of the system [3].

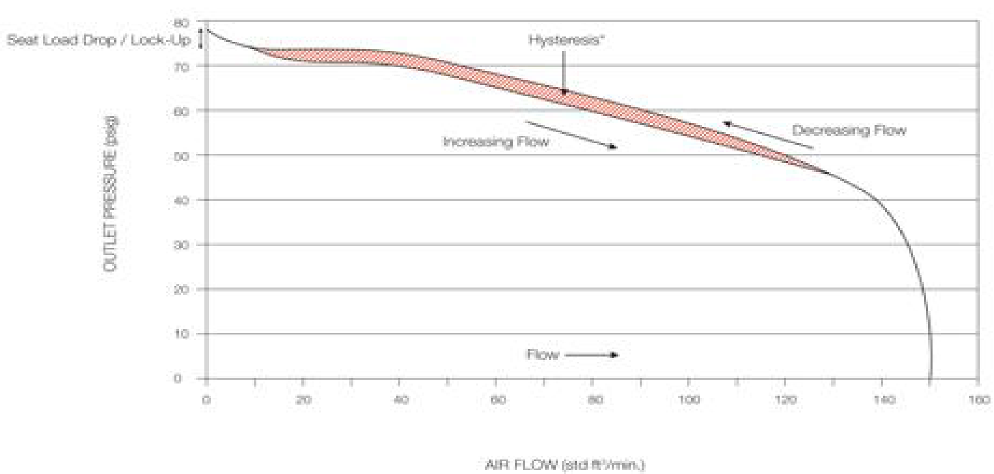

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Figure 5: Hysteresis loop from varying flow rate [3]

Hysteresis is caused by friction in the system, which in the case of the Honeywell design, mostly occurs along the guide rod. As shown in Figure 6, the guide rod (gray) is in contact with its housing (orange) the entire time it is moving to adjust outlet pressure. This could be reduced by minimizing the area of contact or by inserting a linear bearing to ease the sliding action. These options could however increase the leakage, which was another issue brought to attention by Honeywell [1].

The poppet design is one of the best designs to reduce leakage, however it still occurs. Leakage can occur when the closure element is forced against one side and seats/rubs against the seat. This leads to wear and dents on the closure element which causes instability in the system. Originally Honeywell used a ball as a closure element, but leakage was a large problem which was improved using the poppet design. [4]

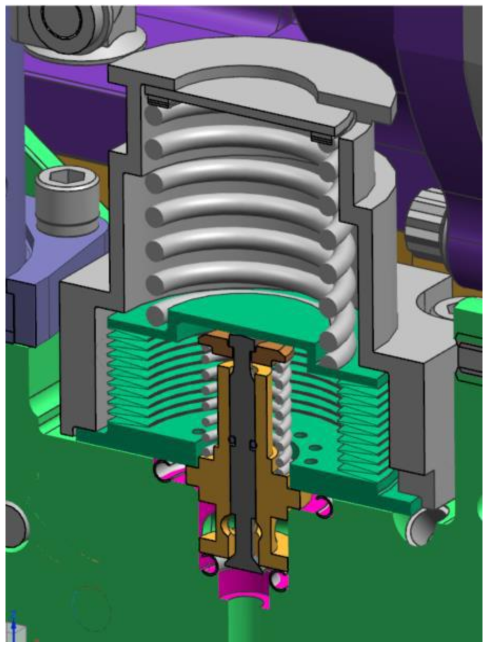


Figure 6: Honeywell reference pressure regulator design [5]

2 REQUIREMENTS

Customer requirements (CRs) and engineering requirements (ERs) were generated from the project description, provided by Honeywell. Customer requirements encompass the scope of the project, and highlight what the final product should accomplish. To ensure that CRs are met, ERs are specified as quantifiable goals. A target and tolerance is assigned to each ER to ensure that all goals are met..

2.1 Customer Requirements (CRs)

The following CRs were generated from the project description provided by Honeywell, as well as through conversations with Honeywell representatives. The customer requirements were evaluated for their significance on the final design. Each customer requirement was given a weight out of five.

- Reliability (5.0) & Safety (5.0)

  The final product's intended use is to regulate pressure within an aircraft; because of this, the final design must be reliable and safe. The device needs to be able to regulate pressures consistently, without any concern for failure. Reliability and safety have been designated weights of five, and have been deemed to be the most important design considerations.

- Durability (4.7) & Maintenance (3.0)
  One of the concerns identified by the client was that current pressure regulator designs are not as durable as they would like them to be. Designing for durability and easy maintenance minimizes the frequency of complete replacement.
- Effectiveness (4.5) & Accuracy (4.5)
  Because the redesigned pressure regulator is intended for use in an aircraft, it is essential that the product performs accurately and effectively. The team will be focusing on redesigning the pressure regulator so that pressure is regulated just as well, if not better, than the client's current design.
- Production Time (2.5)
  Production time is the lowest consideration for the redesign of the preference pressure regulator. While it is important to keep in mind how long the product will take to manufacture, it is not one of the main design considerations that the client has asked the team to focus on.

2.2 Engineering Requirements (ERs)

The table below illustrates the engineering requirements, the target values to achieve, and the tolerances in which the target values are allowed to be between. The engineering requirements are based off of the customer requirements; the ERs provide quantifiable values to each customer requirement in order to ensure that goals are met, and that the client requirements are achieved.

Table 1: Engineering requirements overview

Requirement	**Units**	**Target**	**Tolerance**	**Range**
Volume	in^3	.0012	±.001	0.0001-0.0023
Pressure	psi	600	±25	575-625
Strength of Material	MPa	250	±25	225-275
Weight	lb	1	±0.5	0.5-1.5
Friction	N	1	±0.5	0.5-1.5
Cost	$	200	±50	150-250
Part Count	#	6	±3	3-9

Accuracy	psi	1	±0.5	0.5-1.5
System Instability	%	1	±1%	N/A
Leakage	cfm	1	±1%	N/A

2.3 Testing Procedures (TPs)

In order to verify if the design satisfies the engineering requirements the team must create a procedure to verify each one. A general operating procedure can be implemented that will ensure each requirement will be satisfied during the testing of the prototype. These tests must be set up in the layout below in Figure 7. The equipment for this testing; thermocouples, digital pressure gauges, a compressor, and a hot wire anemometer are all located in the thermo-fluids lab. Other to be decided tubing and joints will also be required. Each engineering requirement will be evaluated in the series of steps listed below.

2.3.1 Pressure

1. Mount regulator to outlet of compressor
2. Turn on compressor
3. Fully open valve
4. Read the inlet pressure to verify the inlet pressure is maximized
5. Monitor if outlet pressure is maintained at maximum inlet pressure
6. If outlet pressure does not vary outside of tolerance the requirement is satisfied

2.3.2 Temperature

1. Mount regulator to outlet of compressor
2. Turn on compressor
3. Fully open valve
4. Monitor values of all thermocouples
5. Monitor if outlet pressure is maintained at all various temperatures
6. If outlet pressure does not vary outside of tolerance, the requirement is satisfied

2.3.3 Accuracy

1. Mount regulator to outlet of compressor
2. Turn on compressor
3. Open valve until inlet pressure equals desired outlet pressure
4. Record inlet and outlet pressure
5. Open valve an increment further
6. Repeat steps 4 and 5 until valve is fully open
7. If outlet pressure does not vary outside of tolerance the requirement is satisfied

2.3.4 System Instability

1. Mount regulator to outlet of compressor

2. Turn on compressor
3. Begin digital recording of inlet and outlet pressure
4. Gradually open valve until fully open
5. Gradually close valve until inlet is desired outlet pressure
6. Repeat steps 4 and 5 five times
7. If outlet pressure does not vary outside of tolerance the requirement is satisfied

2.3.5 Leakage

1. Mount regulator to outlet of compressor
2. Turn on compressor
3. Open valve until inlet pressure equals desired outlet pressure
4. Fully close regulator
5. Record velocity of outlet flow
6. Multiply velocity by the area of the outlet and record flow rate
7. Slightly open valve
8. Repeat steps 5 through 7 until valve is fully open
9. If leakage does not exceed tolerance the requirement is satisfied

2.3.6 Friction

1. Mount regulator to outlet of compressor
2. Turn on compressor
3. Begin digital recording of inlet and outlet pressure
4. Gradually open valve until fully open
5. Gradually close valve until inlet is equal to desired outlet pressure
6. Repeat steps 4 and 5 five times
7. If outlet pressure hysteresis loop is minimized the requirement is satisfied

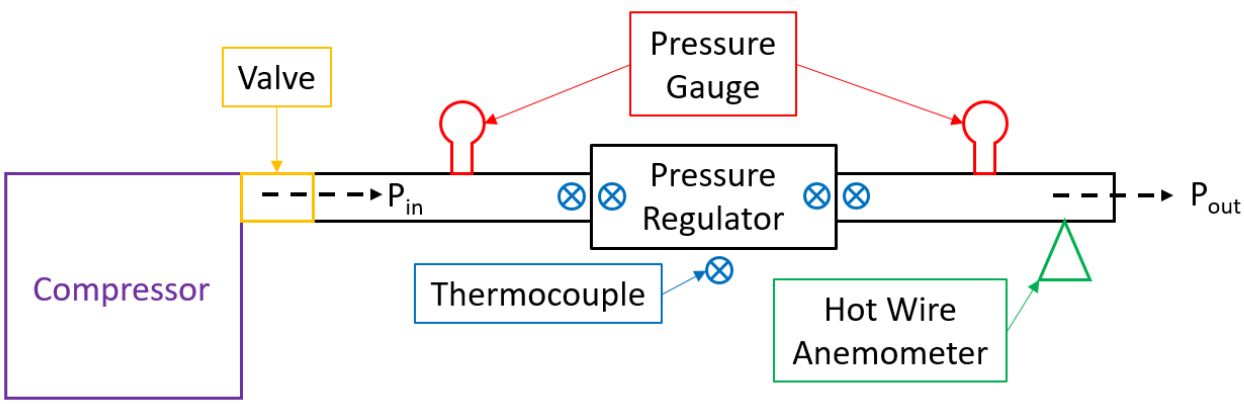


Figure 7: Testing layout

2.4 House of Quality (HoQ)

The House of Quality is used to relate customer and engineering requirements. Each customer requirement and engineering requirement's relationship is assigned a value of either one, three, or nine—one being a low correlation, and nine being a high correlation. Using the House of Quality allowed for identification of which engineering requirements were most important to design for in order to satisfy customer needs. Target values and tolerances for each engineering requirement is also highlighted in the House of Quality. These target values and tolerances are currently tentative, and will be finalized in the coming weeks as research and discussions with Honeywell continue. See Appendix A for the House of Quality spreadsheet.

3 EXISTING DESIGNS

3.1 Design Research

To perform research for different designs the team used many different forms of media searches. The first search method was the compendix and other scholarly articles searches through NAU Cline library. Through this research the team found that the options for pressure regulator designs are very limited. Due to this limitation, benchmarking becomes very difficult, as most data is for different inlet pressures and gases rather than different designs. Therefore, most of the data for the systems and subsystems listed below were taken directly from information given to the team by Honeywell.

3.2 System Level

Most pressure regulators use a similar design but are simply scaled to the needs of the application. Most pressure regulators used are of the same design using a calibration spring, sensing area (diaphragm), closure element, and a guide. This is scaled when the pressure entering the system is either very large or fluctuates with high amplitudes and frequencies. They are scaled by adding more chambers and springs in order to reduce the amount of pressure on each spring and forcing the outlet pressure to be a function of the deformation of more than just one spring. These designs are outlined in the following sections.

3.2.1 Existing Design #1: Single Stage Regulator

Single stage regulators (Figure 2) are a good choice for applications where the supply pressure will be relatively consistent over time, such as when the source is coming from a compressor. A single stage regulator is the current design that Honeywell has implemented into their pressure regulation system. High pressure gas is supplied from the inlet valve into the regulator. Gases proceed into the body of the regulator, the body is controlled by the valve, generally a poppet valve. When inlet pressure increases the diaphragm, connected to the inlet valve, closes and prevents any more gas from entering the regulator. The outlet side is equipped with a pressure gauge. When gas is drawn from the outlet side the pressure of the outlet side drops. The diaphragm springs back open and allows more gas into the outlet area because of the force balance between the gas and spring. Therefore, the pressure depends on the spring force and spring force can be adjusted by adjusting a calibrating handle or knob. [6]

The single stage regulator reduces pressure only in one step to produce pressure within a specific range. The corresponding regulator will show noticeable changes in the outlet pressure when the cylinder pressure is lowered. Therefore, single stage regulators are best suited for applications where constant outlet pressure is not important, where an operator can monitor and readjust the pressure, or where the inlet pressure is stable. [6]

3.2.2 Existing Design #2: Two Stage Regulator

If supply pressure fluctuation is large or decays with time, a two-stage regulator may be better suited for the design. Two-stage pressure regulators are basically two one stage regulators in series. This allows regulators to reduce supply pressure in two smaller steps. In a two-stage design, drooping characteristics of each stage are eliminated. Two stage regulators are designed for stability, even if the inlet pressure or flow rate change significantly the system will provide a stable outlet pressure. [7]

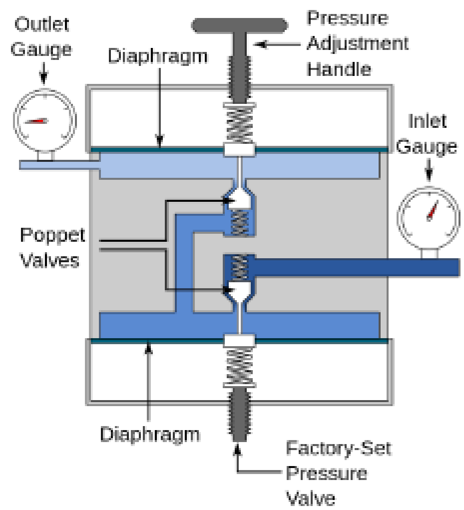


Figure 8: Two stage pressure regulator [2]

Two-stage regulator is two single-stage regulators; its operation is based on two stages gradually reducing pressure. The first stage of the two-stage regulator reduces pressure to an intermediate stage. The intermediate stage then goes through a second pressure regulator to reduce the gas pressure to its final outlet pressure. The two-stage regulator has two safety valves, one for each stage, so that the pressure regulator will not fail catastrophically if inlet pressure is too big. Two stage regulators are more robust in the face of varying inlet pressures. Single stage regulators will require operator observation and input if the inlet pressure varies largely but two-stage regulators are able to handle significant changes in inlet pressure without adjustment. [7]

A two-stage regulator has the same function as a single stage regulator; however, when the cylinder pressure drops, the transmission pressure remains constant. The accuracy of the pressure control is improved because the pressure reduction is performed in two steps. For applications requiring constant outlet pressure in the service life of a gas cylinder, a two-stage voltage stabilizer is recommended. *[7]*

3.2.3 Existing Design #3: Three Stage Regulator

Three-stage pressure regulators provide stability similar to the two-stage regulator outlet pressure, but with significantly higher maximum inlet pressure. Although supply pressures might change drastically, three stage regulators are able to maintain low, stable output pressures. Applications of three-stage regulators are generally higher end lab equipment where accuracy is highly important or portable devices where inlet pressure varies largely. Examples include portable analytical equipment, hydrogen fuel cells, drones, stored high pressure gas cylinders, and medical equipment. [8]

3.2.4 Existing Design #3: Three Stage Regulator

Scuba pressure regulators operate in a similar way to general pressure regulators with only a few exceptions. The scuba pressure regulator has two stages. The first stage regulator (Figure 9) attaches to the tank and allows pressure into an air hose. The second stage regulator (Figure 8) is on the end of the air hose. A user breathes in on the first stage regulator which triggers both the first and second stage regulators in series. Using pressure regulators in series for large pressure reductions is common and not unique to scuba regulators. [4]

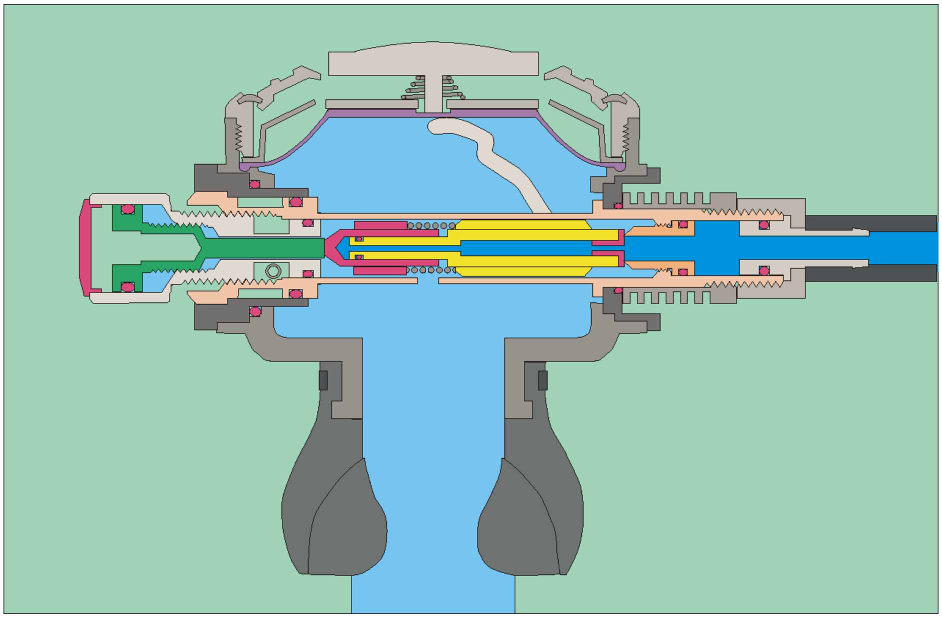


Figure 9: Scuba tank regulator [4]

The primary difference between a scuba air regulator and other commonly used air regulators is that two liquids are used in the process. Scuba regulators are submerged while in use and use the ambient water pressure to push on the diaphragm and keep the valve closed while the user is not breathing in. Average pressure regulators usually have an atmospheric pressure on the outside of the diaphragm and place force on the diaphragm with a spring, bellows, or some other mechanical device. [4]

The other primary difference between scuba pressure regulators and common regulators is the means of actuation in the second stage regulator. As seen in Figure 8, the diaphragm pushes on the lever which translates the motion of the diaphragm ninety degrees to the poppet valve. This lever action is unique to scuba regulators. Because two separate fluids are used on either side of the pressure regulator, a soft rubber material is utilized for the diaphragm. Using soft rubbers for a diaphragm is not unique to scuba regulators. [9]

Unfortunately, many of the qualities that make scuba regulators unique are impractical to use in the design of an airplane pressure regulator. The pressure regulator will likely not be surrounded by water so using a different fluid to press on a diaphragm is not logical. The lever actuation of the poppet in the second stage regulator is also likely not useful in this design. The lever actuation complicates the pressure regulator mechanically and would likely detract from the regulators reliability. A soft rubber diagram is also not practical to use in this pressure regulator because it will likely see temperature extremes which will affect a soft rubber material. [9]

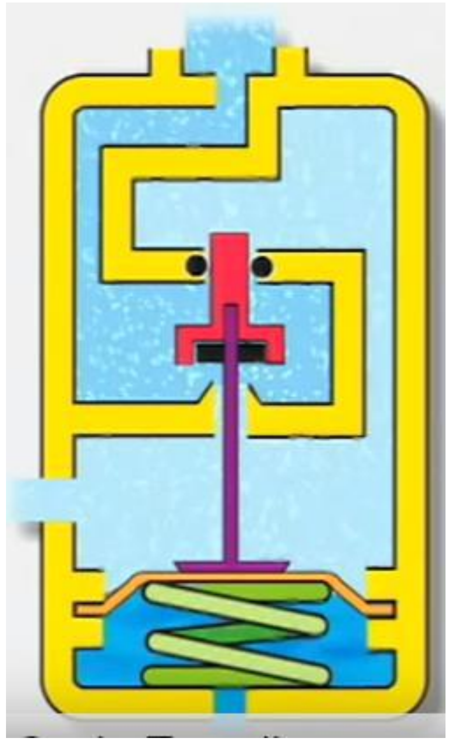


Figure 10: Scuba tank regulator [9]

3.3 Functional Decomposition

An initial step in beginning the design process is understanding the underlying concept of the component we are engineering. For this project, it is a pressure regulator. There are many factors that go into the design of the pressure regulator. While there are improvements that could be made throughout the entire design, our client would like the team to focus on the closure element of the pressure regulator. Because of this reason, the team will not be focusing on what material the casing of the regulator is made of. We will more be focused on the mechanical operation and reducing the friction and wear inside of the regulator. While the mechanical operation of the regulator is complicated, it can be reduced into simple input and outputs. The system can be broken down into steps, starting with air entering the regulator, and then exiting the regulator at the desired pressure.

3.3.1 Black Box Model

The Black Box model below (Figure 10) shows the energy and materials entering and leaving the system, which helps to visualize the function of the component. To the left of the box are the inputs. The top thick line details the material going in and out of the pressure regulator. For a pressure regulator, only air is going in; however, air is at high pressure going in and low pressure coming out. The second line depicts the energy going in and leaving the system. Entering the system is air which contains pressure and kinetic energy. This energy leaves with different values as well as heat lost through friction. The last dashed line shows the signals in the system. Since a pressure regulator operates autonomously, there is no need for a signal in or out of the system.

Figure 11: Black box model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

To fully be able to visualize what is happening inside the pressure regulator the team has created a function model. By focusing on what is happening inside of the pressure regulator instead of the physical mechanics of how it is happening the team simplified the process into a step-by-step functional model. The functional model diagram can be seen below in Figure 11. The functional model shows the basic mechanics of the air as the pressure is reduced. The pressure regulator is a balancing device so the functional model is circular. A hand is imported to calibrate the pressure regulator to a desired outlet pressure. Both high pressure air and the calibration spring press on the diaphragm. The diaphragm is connected to the closure valve which reduces the air pressure through friction loss. The functional model then exports reduced pressure air.

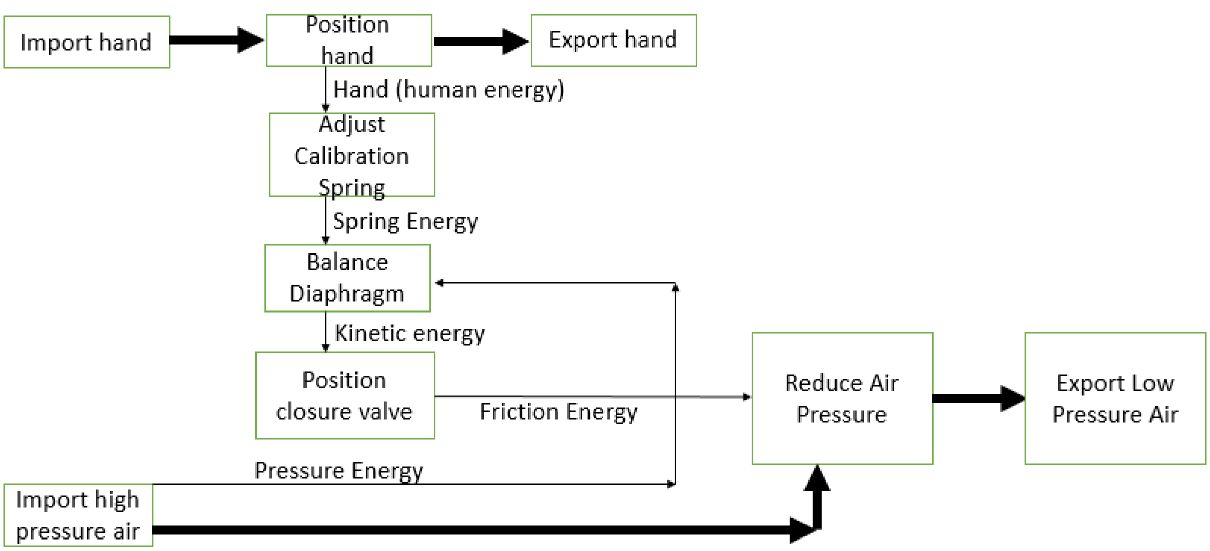


Figure 12: Process flow diagram

3.4 Subsystem Level

There are many variations of pressure regulators currently on the market; however, despite there being many different providers of pressure regulators, most are comprised of the same elements. Throughout the benchmarking process, there was little variation in design elements. Three elements were analyzed in order to better understand current designs, and to begin to think about elements that could be redesigned: the diaphragm, calibration spring assembly, and closure elements.

3.4.1 Subsystem #1: Diaphragm

The diaphragm serves a large role in regulating outlet pressure in most pressure regulators. When a pressure regulator is functioning properly, the area beneath the diaphragm will have air at the outlet pressure. The calibration spring pushes on the diaphragm and balances the force of the outlet pressure. If the pressure below the diaphragm rises, the air will push on the diaphragm compressing the calibration spring. This will cause the poppet to sink into its seat and restrict the flow of air into the area below the diaphragm, effectively lowering the pressure below the diaphragm. If the outlet pressure becomes too low, the diaphragm will have less pressure holding it in place and the calibration spring will extend. This allows the poppet to rise off of its seat and airflow through the valve increases, increasing the outlet pressure. Diaphragm material, size, and the nature of the calibration spring that presses on the diaphragm all have a large effect on the possible uses of a pressure regulator.

3.4.1.1 Existing Design #1: Hard Diaphragm vs. Soft Diaphragm

Hard Diaphragms and Soft Diaphragms both have several advantages and disadvantages depending on the application they are in. Hard diaphragms are much more resistant to temperature changes. Soft diaphragms are usually made from rubber and have a limited temperature range they can operate in.

Soft diaphragms naturally damp the oscillation of the diaphragm and lead to a system that reaches stability quickly. Hard diaphragms rely on other means to damp the motion of the diaphragm. Systems with hard diaphragms can be just as stable as systems with soft diaphragms but they will be more mechanically complex. [10] Soft diaphragms naturally damp the oscillation of the diaphragm and lead to a system that reaches stability quickly. Hard diaphragms rely on other means to damp the motion of the diaphragm. Systems with hard diaphragms can be just as stable as systems with soft diaphragms but they will be more mechanically complex. [10]

3.4.1.2 Existing Design #2: Large Area vs. Small Area Diaphragms

The disadvantage of a large diaphragm area is that it results in a large pressure regulator. The reference pressure regulator assigned to our team has a size constraint depending on the specific application of the regulator. As per conversations with Honeywell engineers, the advantage of large diaphragms is that it results in a more accurate pressure regulator (the variable that affects accuracy is the ratio between the surface area of the poppet and the surface area of the diaphragm, but when all other variables are held constant it becomes the area of the diaphragm). Determining a diaphragm size will require balancing the size restraints of the pressure regulator with the accuracy requirements. Therefore, the ideal size of a diaphragm is dependent on the specific application of the pressure regulator it is a part of.

3.4.1.3 Existing Design #3: High Spring Coefficient vs. Low Spring Coefficient

High spring coefficients result in an accurate system that has low hysteretic effects. High spring coefficients also require either large airflows or outlet pressures to provide the force to balance the 18 diaphragm or a highly tuned system that has little variation in inlet pressure. If inlet pressure were to drop significantly in a system with a high spring coefficient then the valve might close completely.
Low spring coefficients offer less accuracy and a much higher response time between inlet pressure changes and changes in closure position. However, low spring coefficients offer a much higher range of allowable inlet pressures. [10]

3.4.2 Subsystem #2: Closure Elements

The closure element in the pressure regulator is where most of the reliability and accuracy falls. This element is often under a differential pressure which can affect the system and must be accounted for. An ideal closure element would not move in only one direction, would not wear, and would not be susceptible to pressure. Unfortunately, the closure element must account for all of these factors, therefore they must be researched.

3.4.2.1 Existing Design #1: Gate Valve

A gate valve, shown in Figure 13, is another possible option to replace the poppet as a closure element. The gate valve opens and closes vertically to decrease pressure and increase flow velocity. The gate valves motion is similar to the poppet however it acts perpendicular to the flow rather than parallel. This can cause issues because the valve can bend under large pressure and wear unevenly against one side. However, this can improve upon the poppet because the pressure is not directly acting on the closure element, leaving the output pressure to be decided only by the pressure on the diaphragm.

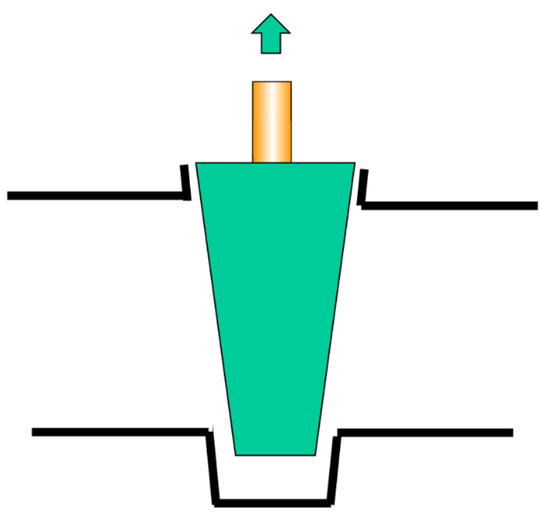


Figure 13: Gate valve [5]

3.4.2.2 Existing Design #2: Shear Block Valve

The shear block valve shown in Figure 14 also can work as a closure element by sliding perpendicular to the flow to open and close the inlet(s). This subsystem improves upon the poppet by not wearing unevenly and always sliding against the same edge. The pressure acting on the shear block also does not affect the inlet size until friction comes into play. The friction on the block is the largest issue with the shear blocks. Under a large pressure, the blocks will not slide perfectly, leading to friction and an even worse hysteresis than the original poppet design. Due to this, the design cannot be considered unless the friction can be solved.

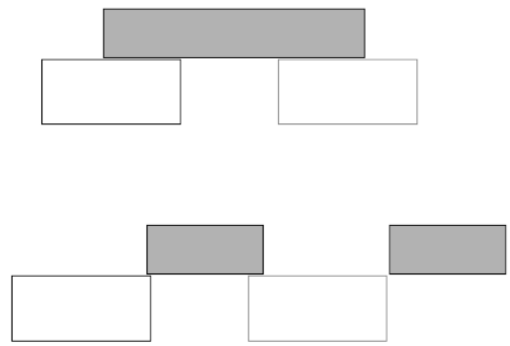


Figure 14: Shear block valve [5]

3.4.2.3 Existing Design #3: Pinch Valve

The pinch valve shown in Figure 15 can regulate flow by changing inlet area through changing the pipes cross-sectional area. In order for this to work, the pipe needs to be flexible enough to open and close many times easily enough to not fall victim to hysteresis or fatigue. The challenges of using this in Honeywell's pressure regulator design is the system is under very high pressures where strength is necessary for structural integrity. If there is a material that can handle the high pressures of the environment, this system would be effective because the pressure through the system would not act on the closure element at all.

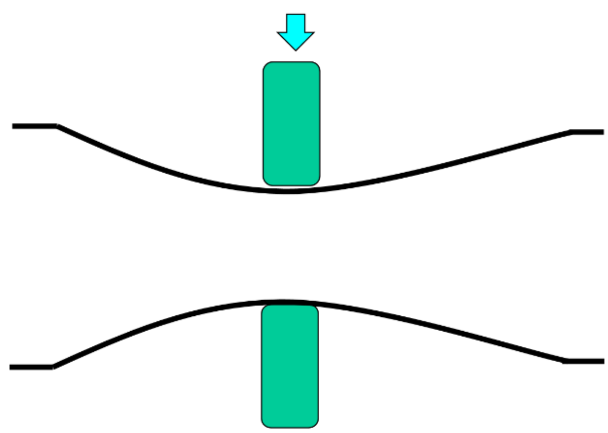


Figure 15: Pinch valve [5]

3.4.2.4 Existing Design #4: Floating Ball Valve

A type of closure element that can be taken into consideration is a ball valve, shown Figure 16. It should be noted that Honeywell has implemented a ball valve closure previously, and found that it did not perform as well as intended. A floating ball valve is comprised of two main mechanical parts: a spherical ball, and a cylindrical hole drilled through it. When the cylindrical hole (which acts as a valve) is aligned with the hole, the valve is considered open and allows airflow through the system; when the flow duct is at a right angle to the flow, the valve is closed. Ball valves are typically used in smaller pressure regulators, as weight of the ball increases significantly with size. The seals of the ball valves are typically made out of Teflon, which are limited to low temperatures; aircraft valves usually exceed the allowable temperatures, making a ball valve ineffective.

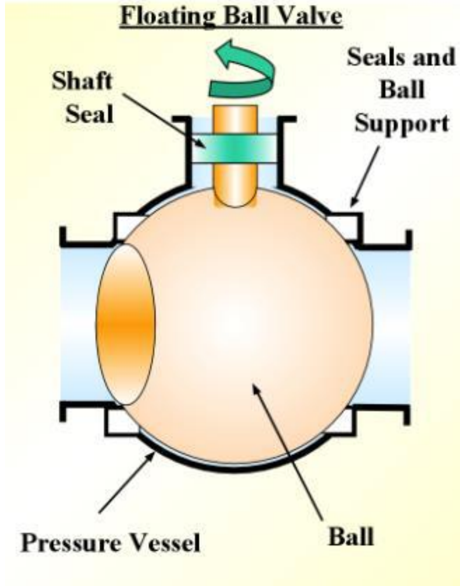


Figure 16: Floating ball valve [5]

3.4.2.5 Existing Design #5: Right Angle Poppet

Right-angle poppets house three main parts: an actuator, a shaft, and a pressure vessel. The shaft houses a circular disk, which is used to control the flow of air. When the actuator is aligned with the poppet, the air flows in through the side and out of the bottom of the valve. Though technically valves, right angle poppets can be used as pressure regulators when the inlet pressure is balanced. However, the use of right angle poppets increase friction, and is susceptible to seal failure. Right angle poppets also dramatically increase the weight in larger pressure regulators, and are recommended for use in smaller line sizes only.

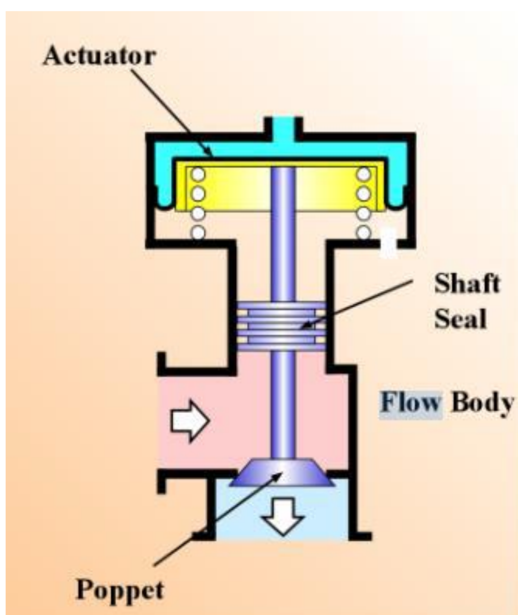


Figure 17: Right angle poppet [5]

3.4.2.6 Existing Design #6: Sealing Butterfly Valve

A sealing butterfly valve utilizes a disk and shaft assembly; when the shaft rotates, the disk becomes parallel to the flow opening the valve. As the shaft continues to rotate, the disk closes the valve as it becomes perpendicular to the flow. The key element that makes the sealing butterfly useful is that the shaft is angled, which allows the disk to make an unbroken seal. To properly position the shaft, piston rings are used; the orientation of the piston rings, help by a clip, is crucial in order for the butterfly valve to work correctly. The main issues with using a butterfly valve are that it does not seal properly, and that there is a too large of a pressure drop at in smaller butterfly valve sizes.

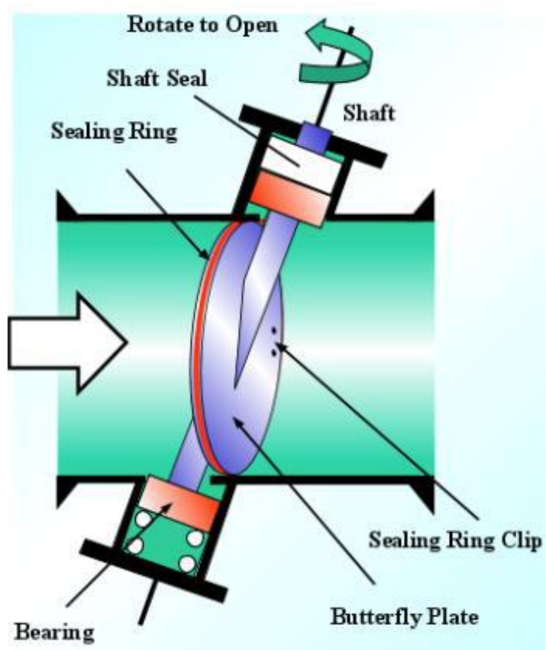


Figure 18: Sealing Butterfly Valve [5]

4 DESIGNS CONSIDERED

Using the information gathered through research and client discussions, the design team has compiled various design concepts that could possibly solve the design problem. Below are ten possible re-designs for the reference pressure regulator systems, with sketches as well as a comparison of the plausibility of each design in relation to the specified customer requirements.

4.1 Design #1: Poppet on Digitally Actuated Arm

Figure 18 shows the design for a poppet on a digitally actuated arm. A microcontroller, such as an Arduino, takes in data from an attached digital pressure sensor and controls the position of a poppet valve with a servo motor. The pressure sensor reads the outlet pressure and adjusts the poppet position to maintain a steady outlet pressure. A drawback of this proposed design is getting an electronic system to operate at the maximum operating temperature specified by the client. Similarly, the size does not easily scale in order to accommodate the design. This design meets the client specifications in that it reduces actuation exposure to contaminants, and the poppet closure minimizes leakage.

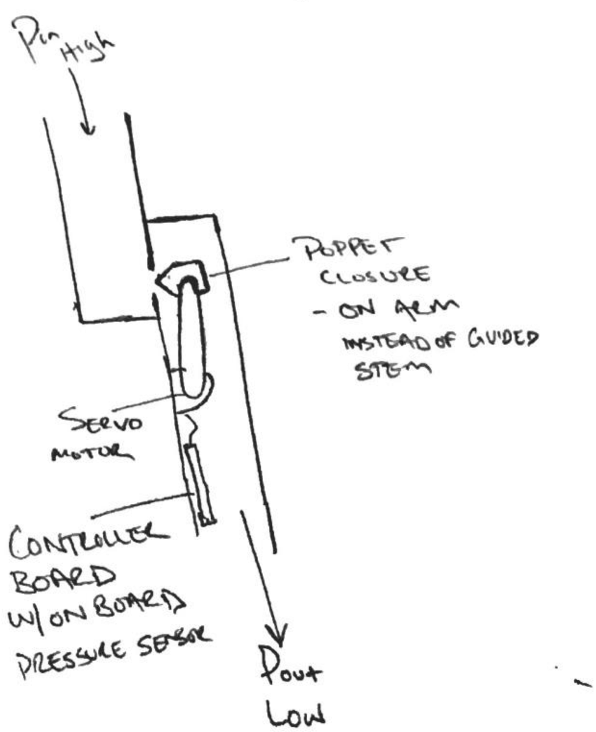


Figure 19: Poppet on digitally actuated arm concept sketch

4.2 Design #2: Magnetic Lever Regulator

This regulator design operates using a series of magnets. As the pressure increases in the outlet section, it will push a spring upwards. Attached to the end of the spring is a magnet. A magnet is also attached on the end a lever. As the spring gets pushed upward from the pressure force, it will cause the magnets to rise. As one end of the lever rises, it will move the other end downwards. As this section moves downward, it will move a plate down into the inlet section of the flow. When the plate moves down into the flow it will reduce the cross-sectional area of the inlet, achieving the needed pressure drop. The most significant issue with this design is the amount of friction. There is friction between the magnet and the walls, as well as friction in the hinges of lever arm. A major design requirement is to reduce the amount of friction within the regulator, and this design would cause more friction than the current design.

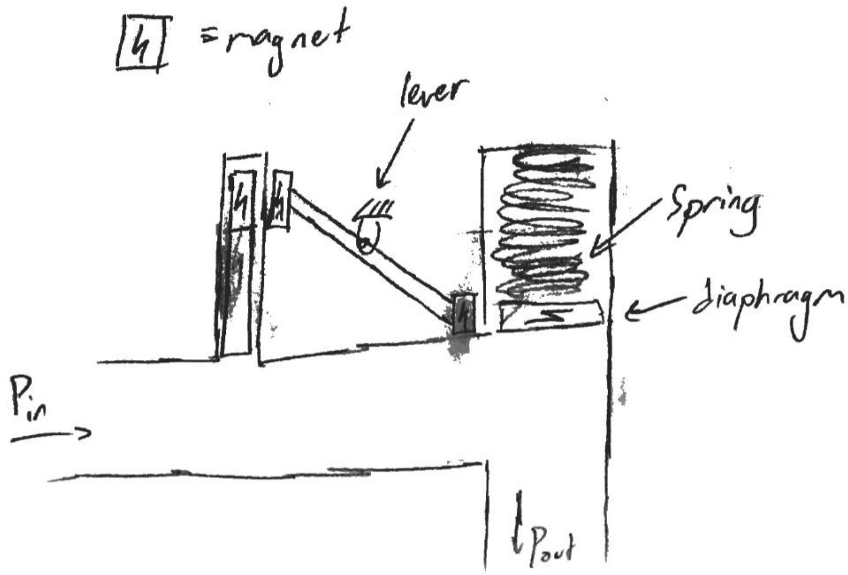


Figure 20: Magnetic Level Regulator concept sketch

4.3 Design #3: Turbo-expander

The turbo-expander design consists of a set of turbine-like blades mounted onto a rotating shaft which has one end suspended in an induction generator. As the fluid flows through the blades, the shaft will spin and the pressure of the air will be lowered proportionally to the shaft's rotational velocity. The outlet pressure will be read and sent to a controller which will read the pressure and then apply a load onto the induction generator using the power supplied. Electric speed control can be used to lower and increase this load to drag the shaft and decrease or increase the speed of the shaft and blades. This will accordingly lower or increase the outlet pressure, allowing for control and stabilization of the outlet pressure. This design works well because it can react very quickly and accurately because the mode of actuation is digital and magnetic. However, the faults of this design lie within cost and durability. The small precision parts are liable to be expensive to manufacture.

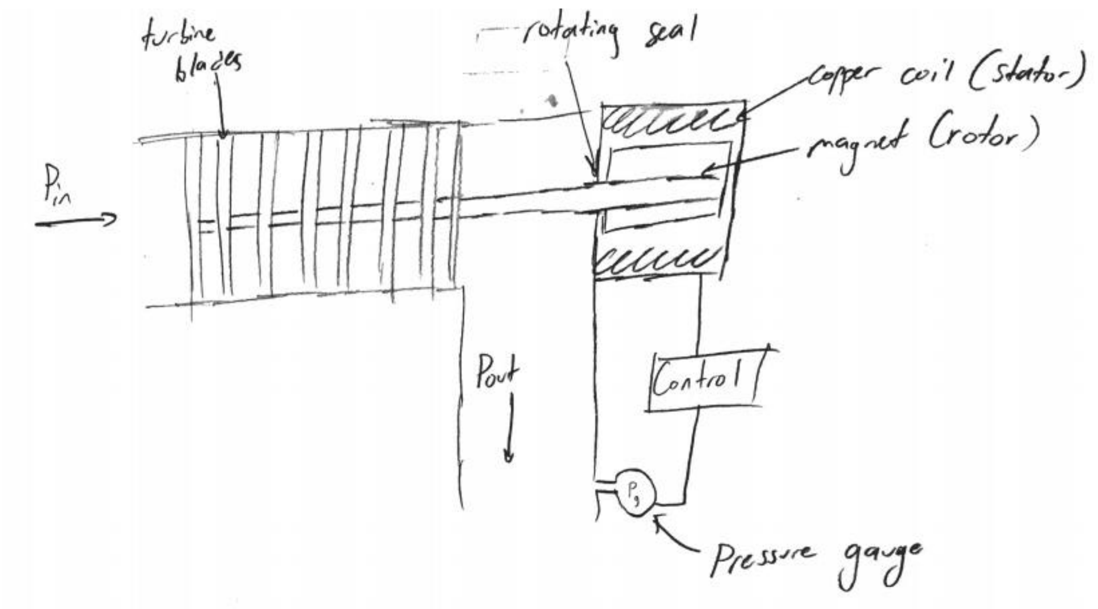


Figure 21: Turbo-expander concept design

4.4 Design #4: Deflection Pinch Valve

This regulator design operates on the basic principle of a pinch valve. As the cross-sectional area of the flow is restricted, the change in area will cause a pressure drop. In this design, the outlet pressure increase causes the bent area in section one of the figure to deflect and straighten. As the area straightens, the stiff link pinches the inlet area. The straightening of the bend achieves the desired pressure drop. Though this design is good in theory, it is difficult to find a material that can operate at the required high temperature. There are few materials that can operate without melting and compromising the operation of the regulator. This design will also be difficult to calibrate and operate at high precision.

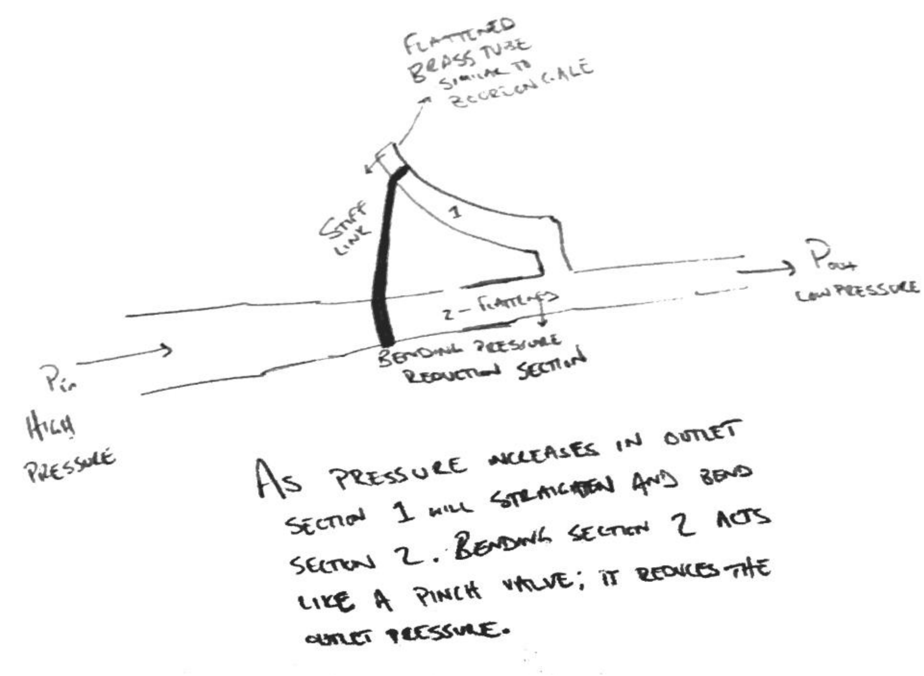


Figure 22: Pinch valve concept sketch

4.5 Design #5: Propelling Nozzle

The propelling nozzle design is based on the concept of a variable area nozzle. As the input pressure in the system changes, the nozzle will adjust the outlet cross-sectional area to achieve the needed pressure drop. This nozzle contains plates that slide over each other. When the plates move further apart, the cross-sectional area of the outlet becomes smaller. To be able to actuate the nozzle movement, a set of electric motors will pull a ring back, pulling the nozzle back, causing the plates to move closer or further apart. A pressure sensor will be located in the outlet section of the device. The outlet pressure is the parameter the motors will read to adjust the nozzle area. A setback to this design is the size of the nozzle. This design involves intricate parts, which will be hard to manufacture at the scale of the design parameters. This design also involves electronics, which are acceptable to the client, but would be difficult to integrate into the environment in which the regulator operates.

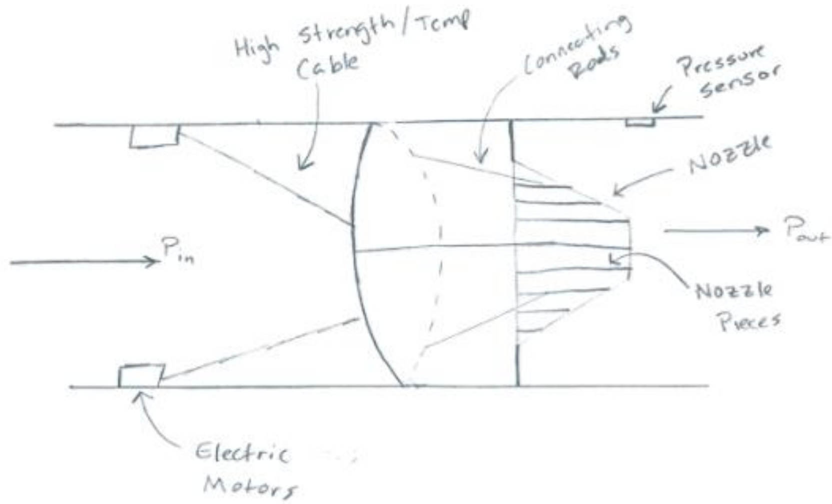


Figure 23: Propelling Nozzle Design Sketch

4.6 Design #6: Single Bellow Regulator

The single bellow design incorporates the concept of metal bellows from the current Honeywell design. A metal bellow is a series of sheet metal plates that are welding together and act as a spring. Welded onto the bellows are small "eyelashes." These eyelashes are what reduce the cross-sectional area within the regulator. A small servo motor will detect the outlet pressure and move the bellow back and forth to maintain a constant outlet pressure depending on a changing inlet pressure. As the bellow moves together the eyelashes get closer together and constrict the flow area. A drawback to this design is the way in which the regulator can be mounted. If the regulator is hard-mounted to a surface, it will not allow the bellow to move freely.

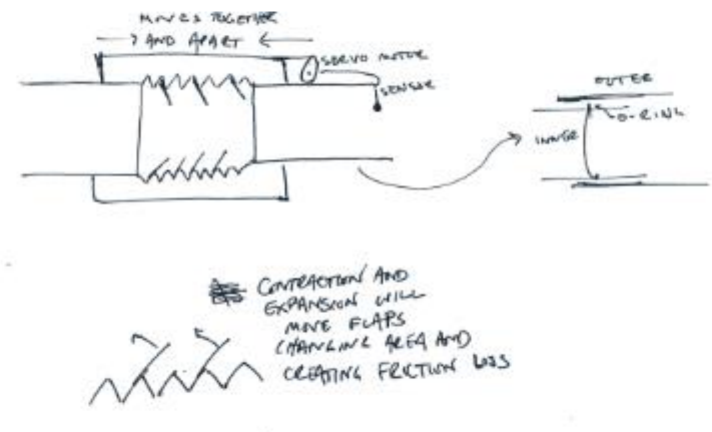


Figure 24: Single bellow regulator concept sketch

4.7 Design #7: Eyelash Bellow Regulator

This design utilizes the “eyelash” bellows from Design 6. Instead of using a pressure sensor and microcontroller to control the expansion and contraction of the bellows, this system is controlled via the diaphragm and spring used in the current design. This design also incorporates a second bellows upstream of the eyelash bellows to allow motion of the eyelash bellows.

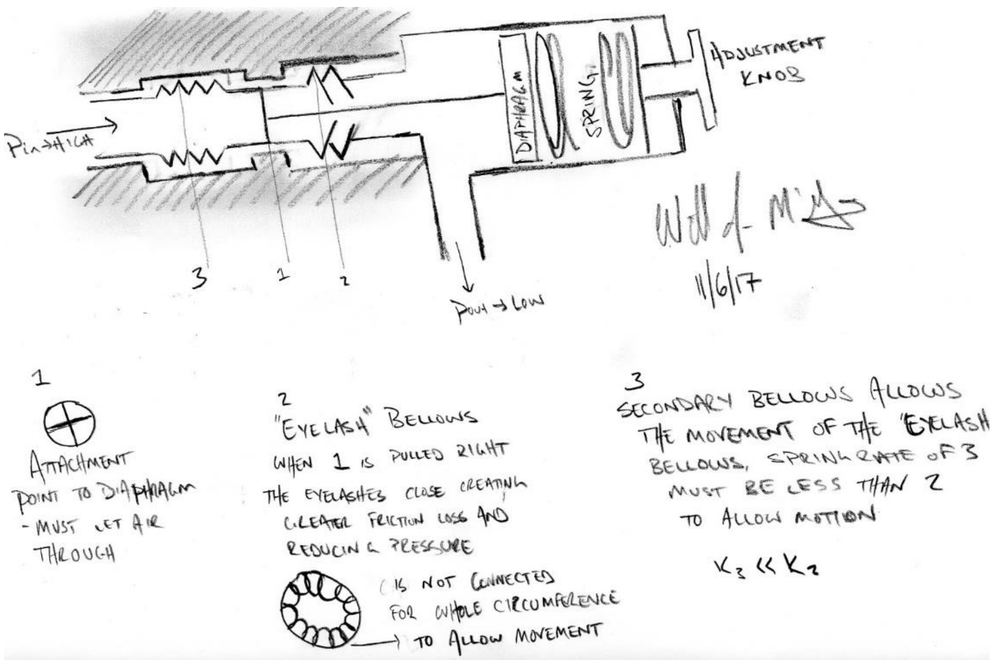


Figure 25: Eyelash Bellow Regulator concept sketch

4.8 Design #8: Lever Regulator

This design operates off a sensing diaphragm and a lever. When the pressure in the outlet region increases, the diaphragm lowers and the spring compresses. As the diaphragm lowers, one side of the lever arm is pushed down. As one side of the lever lowers, the opposite side raises. This causes the plate angle to increase and the inlet cross-sectional area to decrease. The main drawback to this design in the friction in the hinges. With many moving parts there are many places for contamination to become a noticeable factor. This design would also be difficult to calibrate, and would operate on a single spring rate. This would decrease the pressure range of the pressure regulator.

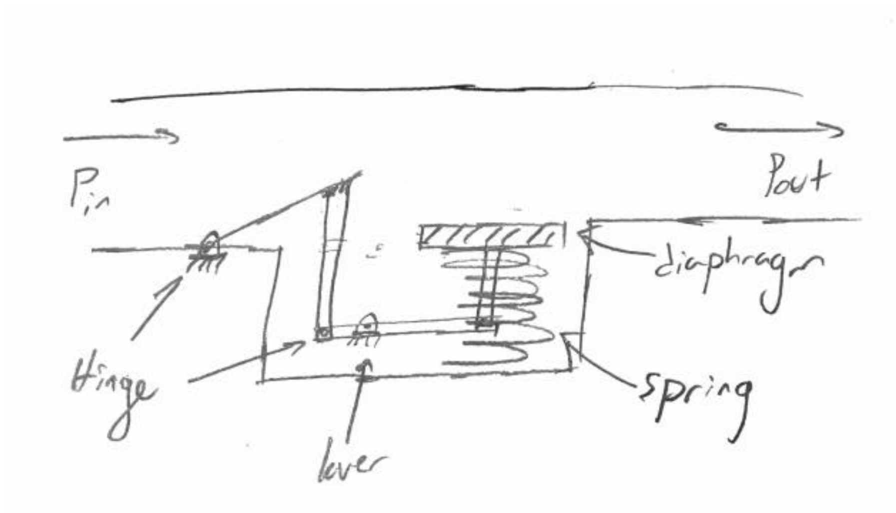


Figure 26: Level regulator concept sketch

4.9 Design #9: Rack and Pinion

This idea was inspired by a fan's operation. The fan blades of the valve move clockwise or counterclockwise to open or close the cross-sectional area. The rack and pinion control the gear that make the fan blades move. A spring on the side of the pinion allows the pinion to move in response to the change in pressure. When the area becomes small, the air flow rate decreases. As the air flow moves through the length of the system, the pressure decreases from inlet to pressure, ultimately resulting in a low pressure at the outlet. This system is operates mechanically, eliminating the need for electrical equipment in the system. The system should also be cheap and easy to prototype. This system would result in higher leakage, however, ultimately making the system less accurate.

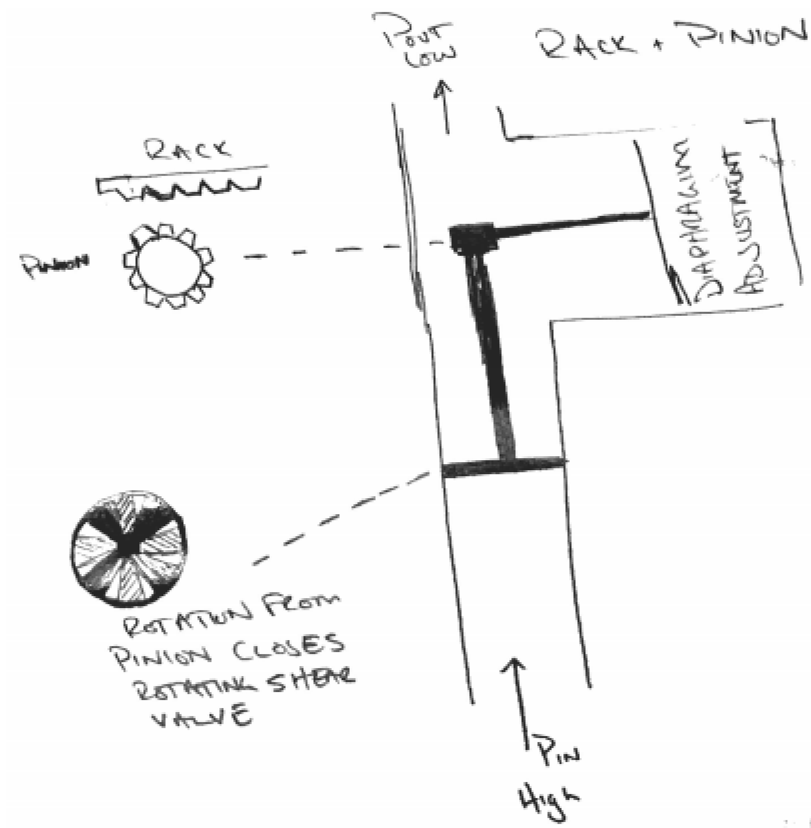


Figure 27: Rack and pinion concept sketch

4.10 Design #10: Iris Orifice Plate Regulator

The iris regulator design concept operates on the concept of an orifice plate. As the flow moves through a smaller cross-sectional area it will cause a pressure drop. The orifice plate in this design is an iris plate. As the pieces of the iris move about an axis, the center hole will increase or decrease in diameter. To actuate this movement, a connecting rod will be attached to a servo motor which will take readings from a pressure sensor on the outlet portion of the pressure regulator. A setback to this design is the friction between the plates of the iris. A key design requirement is reducing the contamination of the regulator. This design would allow contamination to accumulate between the different iris plates and increase the hysteresis of the pressure regulator.

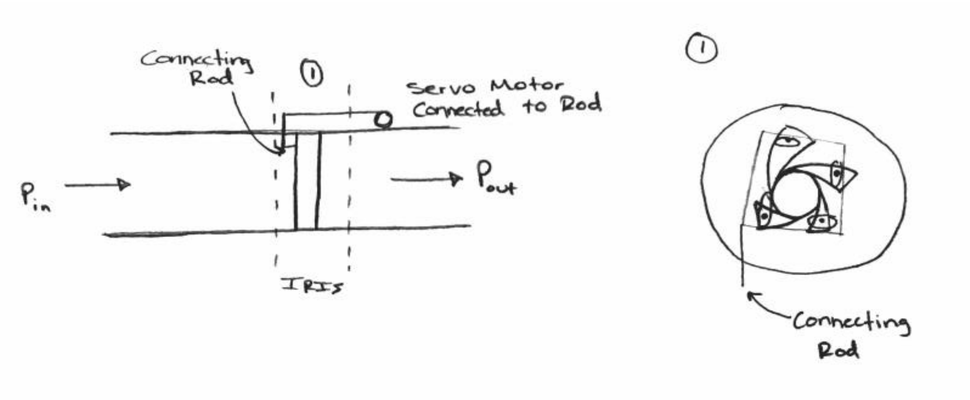


Figure 28: Iris Orifice Plate concept sketch

5 DESIGN SELECTED – First Semester

5.1 Rationale for Design Selection

The design selection process was narrowed down from ten concepts, to two possible designs. The client has specified that our team would benefit from working on multiple designs simultaneously. This would allow the team to conduct further research and analysis for both designs. The designs that were eliminated through the selection process did not meet the engineering requirements for the design. The main engineering requirements for the selection process were to decrease friction and contamination within the regulator while achieving a high accuracy while regulating pressure. Designs that were eliminated posed too much friction caused by moving parts that were exposed to the flow of air. Pollution and particulate matter in the air causes gunk within the part that resists frictionless motion in moving parts. Another reason for eliminating designs was the scalability of moving parts into the required size for the pressure regulator. With the team's current manufacturing capabilities, it is not possible to create a regulator on the size scale of the current design. For this reason, the prototyping process will consist of building a scaled-up version of the final product. The designs that were eliminated would be difficult to scale down after proving the functionality of pressure regulation. The two remaining concepts meet the engineering and customer requirements, however after the prototyping and testing phase of the design process, the team can assess the design the performs more effectively.

5.1.1 Pugh Chart

To assist in the design selection process, the team utilized a Pugh chart. Honeywell's current design was used as the datum. The datum helps to provide a baseline to compare possible concepts against. From the Pugh chart, the top three designs were selected. The eyelash bellow design was a second iteration of the bellow design, therefore narrowing it down to the top two concepts. Please see Appendix B for the finalized Pugh Chart.

5.1.2 Decision Matrix

To verify the results from the Pugh chart, the team completed a decision matrix. Using the engineering requirements, each concepts was rated on a 1-5 scale. The decision matrix shows that the same three concepts improve the current design. Through the two selection processes, the team is left with two possible design concepts. Please see Appendix C for the finalized decision matrix.

5.2 Design Description

5.2.1 Turbo-Expander

The first design selected is the turbo-expander (Figure 29). The turbo-expander works off the relationship shown below.

$$T\omega = \Delta PQ$$

where T = torque
ω = angular velocity
ΔP = change in pressure
Q = flow rate

A digital pressure sensor will monitor the outlet pressure of the turbo expander and a micro controller will adjust the torque placed on the shaft to regulate the pressure. This design addresses the need to reduce contamination in moving parts. The contamination will only affect the roughness of the blades. The blades can be selected to work with high roughness. The seat of the shaft is out of the airflow of the pressure regulator and will not be affected by contamination in the airstream.

The seat of the shaft is the rotor in the induction motor and had magnets mounted onto it. This rotor is housed inside of the stator of an induction generator. As air flows through the turbine the rotor will spin and generate a current inside of the stator, this current can be regulated therefore regulating the speed of the shaft. The outlet pressure is directly proportional to the speed of the shaft therefore by regulating the current in the stator the outlet pressure can be controlled.

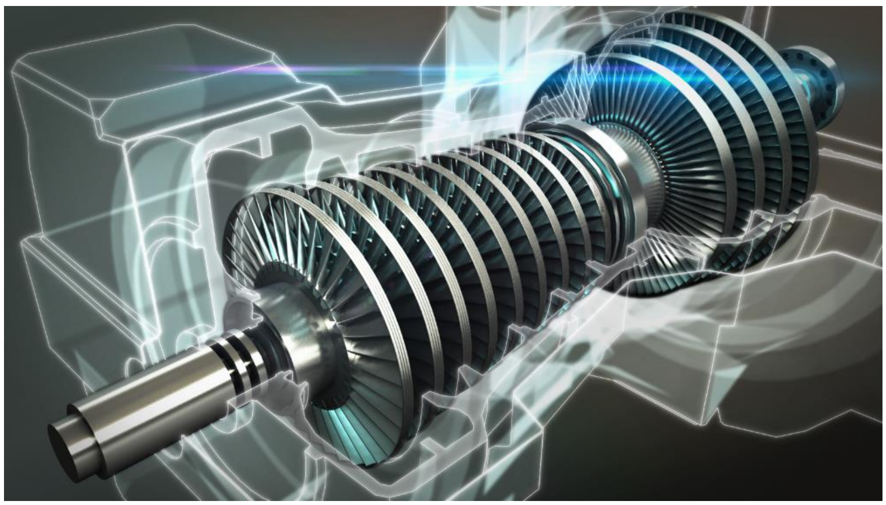


Figure 29: Turbine-expander concept [11]

The inclusion of a digital pressure sensor and a microcontroller in the design produce quick and accurate actuation. Since the outlet pressure is controlled by electronic actuation, the response time will be much faster than a mechanical pressure balance leading to less outlet pressure variance and therefore hysteresis. Also, since the reading is recorded digitally the accuracy of the outlet pressure can be greatly increases depending on the type of pressure sensors used in the design.

However by adding electronic parts to the system the modes of failure are increased drastically. Electronics cannot survive the same type of environments that a simple mechanical system can. The high temperatures can melt the plastics used in the printed circuit board (PCB) as well as affect accuracy and timing of the functions. Secondly, the microscopic soldered connections are susceptible to vibrations and prone to failure. Lastly, the cost of the system will also be greatly increased. The original design includes simple cheap mechanical parts however this design will need an expensive sensor, small precision parts for the turbine, a controlling system, and copper wire to generator a current. These parts can most likely be simplified in some way to reduce cost however the system will still be more costly than the original.

5.2.2 Eyelash Bellows

The second design selected is design number seven, the mechanically activated eyelash bellows. This design removes the moving parts from the airstream so that pollution or contamination will not cause increased friction. Compared to the existing design, which uses an internally guided poppet stem, the bellows are guided from the outside which removes friction surfaces from the airstream. The purpose of the second bellows is to create a complete seal on the part while still allowing motion.

This design involves a novel approach to pressure regulation; the team has sent it to NAU innovations to see if there is any intellectual property attached to it. Because of the originality of the design, there is no information available about the advantages or disadvantages of it. While this disallows benchmarking by comparing it to existing designs, it is a new technology that can be created and tested. The team is excited to begin the prototyping and benchmarking process for this design, beginning with a proof of concept.

Figure 30 is a preliminary CAD drawing of the eyelash regulator. It shows how the eyelashes would look in three dimensions and how the two sections of bellows are guided by outside supports.

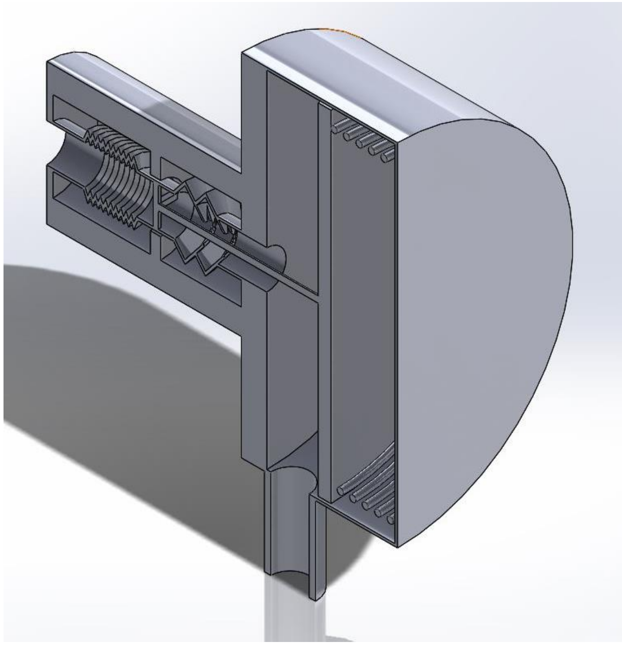


Figure 30: Isometric view of eyelash bellows concept design

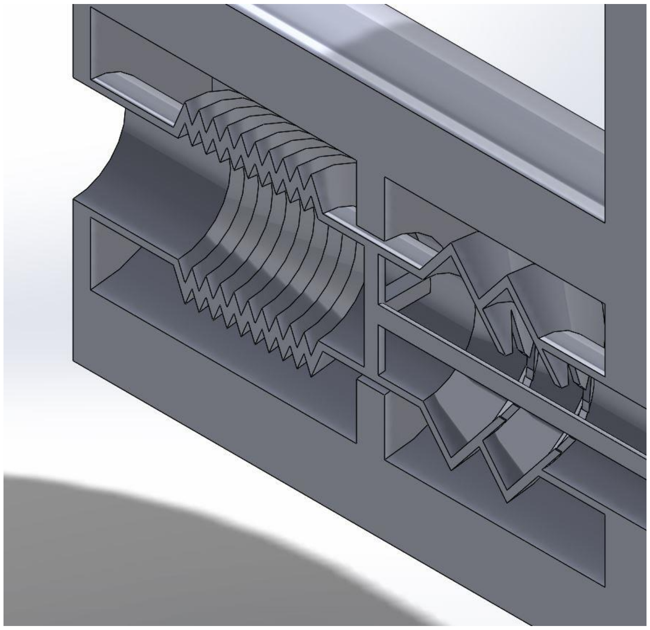


Figure 31: Isometric view of eyelash bellows system

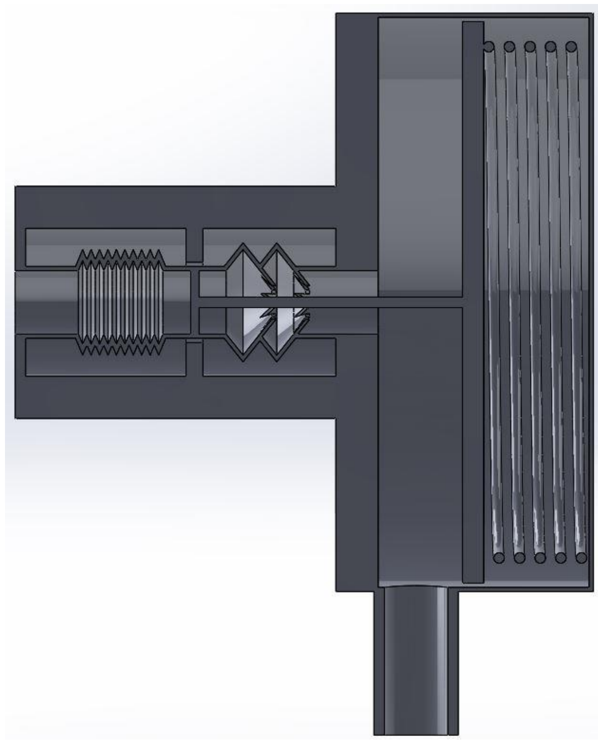


Figure 32: Side view of metal bellows concept design

5.3 Schedule

The schedule, found in Appendix D, outlines all proposed due dates through the end of the Spring 2018 semester. All dates are tentative and subject to change pending client approval. Similarly, as the team comes to finalize a proposed design, more tasks will be generated and assigned to team members as needed. The schedule provided is basic compilation of deadlines.

6 References

[1] Honeywell International, Inc., *Reference Pressure Regulator - Technical Exchange,* Tempe: Honeywell International, Inc. , 2008.

[2] "Pressure Regulator," Wikipedia, 5 September 2017. [Online]. Available: https://en.wikipedia.org/wiki/Pressure_regulator#/media/File:Single-stage-regulator.. [Accessed 6 October 2017].

[3] B. Menz, "Pressure Regulator Selection Strategy | Flow Control Network," Flow Control Network, [Online]. Available: https://www.flowcontrolnetwork.com/pressure-regulator-selection-strategy/. [Accessed 3 October 2017].

[4] S. Traveller, "How it works - Scuba Dive Regulators Balanced Diaphragm," YouTube, 31 January 2010. [Online]. Available: https://www.youtube.com/watch?v=VJeSifGgeiA. [Accessed 2017 October 2017].

[5] Honeywell International, Inc., "Closure Elements - Technical Exchange," Tempe, 2010.

[6] "Single-Stage versus Two-Stage Regulators," Air Liquide Australia, 2017. [Online]. Available: https://industry.airliquide.com.au/single-stage-versus-two-stage-regulators. [Accessed 4 October 2017].

[7] Sherex Industries, Ltd. , "Two Stage Pressure Regulator," 1998. [Online]. [Accessed 9 November 2017].

[8] "Understanding the Three-Stage Regulators," Sailnet Community, 2017. [Online]. Available: http://www.sailnet.com/forums/miscellaneous/22175-understanding-three-stage-regulator.html. [Accessed 07 October 2017].

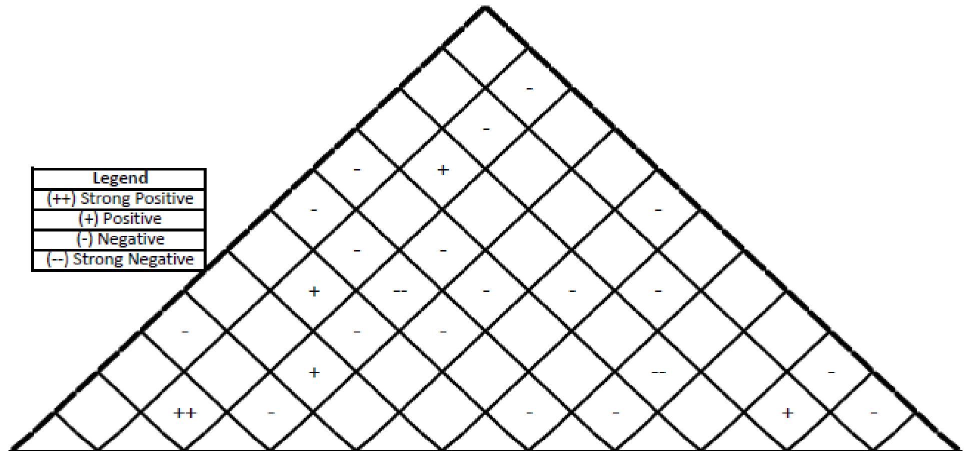
[9] Wikimedia Commons, "Scuba regulator 2nd stage animation gif," 31 December 2006. [Online]. [Accessed 02 October 2017].

[10] M. Ramzan and A. Maqsood, "Dynamic Modeling and Analysis of a High Pressure Regulator," *Mathematical Problems in Engineering,* p. 8, 2016.

[11] "Turbine in Bangalore|Manufacturers|Dealers|Suppliers|Search Pointer," Searchpointer.com, 2017. [Online]. Available: http://www.searchpointer.com/bangalore/turbine-in-bangalore-sp437cat14c1/. [Accessed 7 November 2017].

7 APPENDICES

7.1 Appendix A: House of Quality



		Technical Correlation										
Improvement Direction		↓	↑	↑	↓	↓	↑	↓	↓	↑	↓	↓
		Engineering Characteristics										
	Importance Weight Factor	Volume	Pressure Range	Strength of Material	Weight	Friction	Temperature Range	Cost	Part Count	Accuracy	System Instability	Leakage
Customer Requirements		in^3	psi	psi	lbs	N	F	$	#	psi	%	cfm
Reliability	5.0		9	9		9	9			9	9	3
Durability	4.7			9		9	3			3	3	9
Effectiveness	4.5		9							9	9	9
Maintenance	3.0	3		9	3			3	3			3
Production Time	2.5	3		3	1			3	9			3
Affordability	3.5	3	9	9			3	9	3	9	9	
Safety	5.0	3	3	3	3		9					3
Accuracy	4.5		9			9	1	9		9	9	3
Raw Score	1242.1	42.00	172.50	168.30	26.50	127.80	88.50	88.50	42.00	171.60	171.60	142.80
Relative Weight %		3.4%	13.9%	13.5%	2.1%	10.3%	7.1%	7.1%	3.4%	13.8%	13.8%	11.5%
Absolute Technical Important (ATI)		42.00	172.50	168.30	26.50	127.80	88.50	88.50	42.00	171.60	171.60	142.80
Relative Technical Importance (RTI)		9	1	4	11	6	7	8	10	2	3	5

7.2 Appendix B: Pugh Chart

	DATUM	1	2	3	4	5	6	7	8	9	10
	Honeywell Current Concept	Digitally Actuated Arm	Magnetic Lever	Turboexpander	Deflection Pinch Valve	Propelling Nozzle	Single Bellow	Eyelash Bellow	Lever Regulator	Rack and Pinion Regulator	Iris Orifice Plate
Volume	0	0	0	0	0	0	1	1	-1	0	0
Pressure Range	0	-1	-1	1	-1	0	0	1	-1	0	-1
Material Strength	0	0	0	1	-1	-1	1	1	-1	1	1
Weight	0	1	-1	0	1	0	1	1	0	-1	-1
Friction	0	1	-1	1	1	-1	1	1	-1	1	-1
Temperature Range	0	0	0	1	-1	0	1	1	0	0	0
Cost	0	-1	0	1	1	-1	1	1	1	-1	-1
Part Count	0	1	-1	1	1	-1	1	1	-1	0	-1
Accuracy	0	-1	-1	1	-1	1	1	1	-1	-1	0
System Instability	0	-1	-1	1	-1	0	-1	1	-1	-1	-1
Leakage	0	-1	-1	-1	-1	-1	0	1	-1	-1	-1
Σ+	+0	+3	+0	+8	+4	+1	+8	+11	+1	+2	+1
Σ-	-0	-5	-7	-1	-6	-5	-1	-0	-8	-5	-7
Σ	0	-2	-7	7	-2	-4	7	11	-7	-3	-6

7.3 Appendix C: Decision Matrix

Decision Matrix (1-5 Scale) / **Engineering Requirement**	Digitally Actuated Arm	Magnetic Lever Regulator	Turbo Expander	Deflection Pinch Valve	Propelling Nozzle	Single Bellow Regulator	Eyelash Bellow Regulator	Lever Regulator	Rack & Pinion Regulator	Iris Orifice Plate
Volume	2	2	4	2	3	3	4	3	3	3
Pressure Range	2	2	4	2	3	3	4	1	3	3
Material Strength	2	2	3	1	3	3	4	1	3	3
Weight	1	1	2	3	2	3	3	1	2	2
Friction	1	1	5	4	2	3	4	1	1	1
Temperature Range	3	3	4	1	3	4	4	3	3	3
Cost	2	2	3	2	1	3	3	2	2	2
Part Count	2	1	3	3	1	4	3	2	3	1
Accuracy	2	2	4	2	3	4	4	2	3	2
System Instability	2	2	4	2	3	4	4	2	2	2
Leakage	2	2	2	3	2	4	4	1	2	2
Total	21	20	38	25	26	38	41	19	27	24

7.4 Appendix D: Schedule

Client Meetings	**09/26/17**	**05/08/18**
Staff Meeting	09/12/17	05/08/18
Preliminary Report & Presentation	**09/29/17**	**10/06/17**
Individual Analysis I	**10/06/17**	**10/20/17**
Team Memo	10/06/17	10/13/17
Myla Azofeifa - Pinch Valves	10/13/17	10/20/17
Jordan Loos - Variable Area Nozzles	10/13/17	10/20/17
Yi Tong Zhang - Metal Bellows	10/13/17	10/20/17
William McGinn - Force Balance	10/13/17	10/20/17
Alex Rustaey - Turbo-Expanders	10/13/17	10/20/17
Final Design Proposal	11/03/17	11/10/17
Final Design Presentation	11/07/17	11/07/17
Final Design Proposal	11/03/17	11/10/17
Final CAD Package and BOM	**11/10/17**	**12/08/17**
Final Prototypes Summary	**11/10/17**	**12/08/17**
Final Design Proposal Revision	**11/17/17**	**12/11/17**
Individual Analysis II	11/10/17	12/01/17
Team Memo	11/10/17	11/17/17
Myla Azofeifa	11/17/17	12/01/17
Jordan Loos	11/17/17	12/01/17
William McGinn	11/17/17	12/01/17
Alex Rustaey	11/17/17	12/01/17
YiTong Zhang	11/17/17	12/01/17
Peer Evaluations	**10/13/17**	**05/11/18**
Peer Eval 1	10/13/17	10/13/17
Peer Eval 2	11/17/17	11/17/17
Peer Eval 3	12/13/17	12/13/17
Peer Eval 4	02/16/18	02/16/18
Peer Eval 5	03/16/18	03/16/18
Peer Eval 6	05/11/18	05/11/18
Individual Post Mortum	**01/12/18**	**01/19/18**
Myla Azofeifa -	01/12/18	01/19/18
Jordan Loos -	01/12/18	01/19/18
William McGinn -	01/12/18	01/19/18
Alex Rustaey -	01/12/18	01/19/18
YiTong Zhang -	01/12/18	01/19/18
Individual Analysis III	**02/16/18**	**03/02/18**
Team Memo	02/16/18	02/23/18

Myla Azofeifa	02/16/18	03/02/18
Jordan Loos	02/16/18	03/02/18
William McGinn	02/16/18	03/02/18
Alex Rustaey	02/16/18	03/02/18
YiTong Zhang	02/16/18	03/02/18
Hardware Review	**02/02/18**	**03/09/18**
Hardware Review 1	02/02/18	02/09/18
Hardware Review 2	03/02/18	03/09/18
Midpoint Report and Presentation	**03/02/18**	**03/16/18**
Midpoint Presentation	03/02/18	03/13/18
Midpoint Report	03/02/18	03/16/18
Spring Break	**03/19/18**	**03/23/18**
Final Product Testing	**03/13/18**	**04/13/18**
Begin Testing	03/13/18	03/13/18
Testing	03/14/18	04/12/18
Testing Due	04/13/18	04/13/18
UGRADS	**03/26/18**	**04/27/18**
Poster - Draft	03/26/18	04/06/18
Operation & Assembly Manual - Draft	03/26/18	04/06/18
Poster - Final	04/06/18	04/27/18
Operation & Assembly Manual - Final	04/06/18	04/27/18
Undergraduate Symposium	04/27/18	04/27/18
Final Report and CAD Package	**04/13/18**	**04/27/18**
Final Report	04/13/18	04/27/18
CAD Package	04/13/18	04/27/18
GRADUATION	05/11/18	05/11/18