NOPI Vacuum Manifold

Preliminary Report

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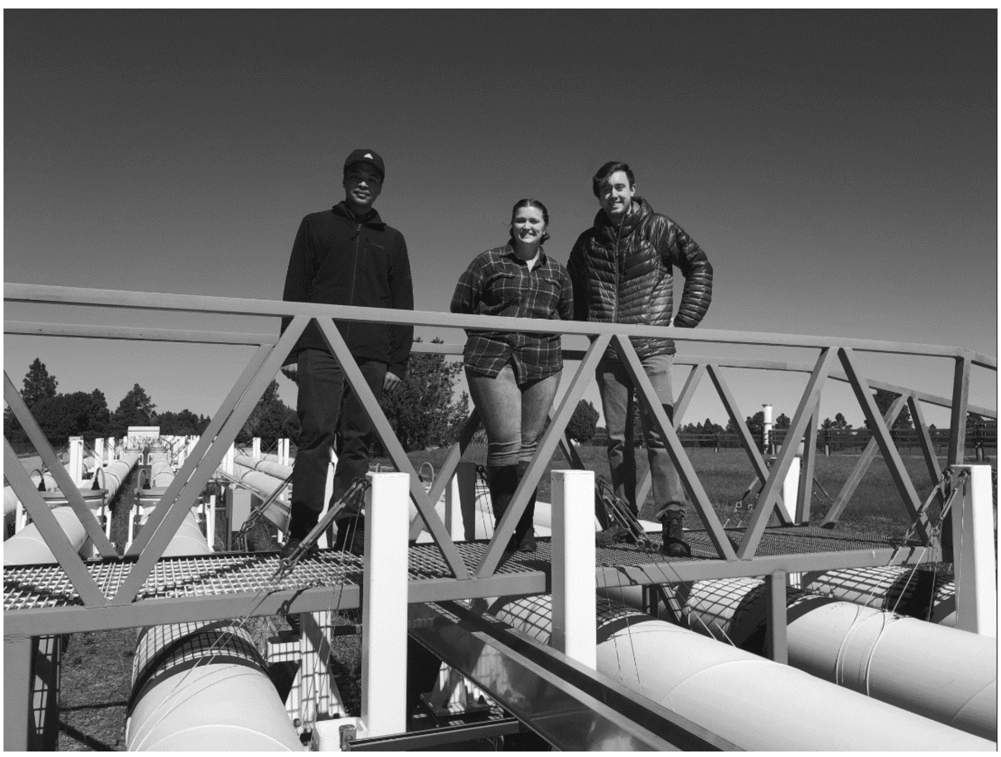

(Alex, Cydny, Wyatt)

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

The Navy Precision Optical Interferometer (NPOI) is the world's largest optical interferometric-based observatory. NPOI currently operates with a combination of up to six Siderostats (a flat mirror device used to collect and direct starlight) stations that are reconfigurable to produce unique and interesting sets of data. NPOI combines starlight collected by the six stations to synthesize a much larger telescope. This, in effect, makes NPOI the world's largest optical telescope. To minimize photon loss and atmospheric abortions which could contaminate datasets the entire array is held in a vacuum.

"Fast Delay Lines" (FDLs) are used to account for variation in light path length between Siderostat stations. The FDL system, like most of the NPOI, must maintain a vacuum for operation. To achieve vacuum, a manifold connecting and isolating each delay line to a greater vacuum system is in operation. The existing structure is old and failing. Should the current manifold fail the NPOI facility would shut down until a solution could be made. A system-wide shutdown would negatively affect the scientists working at NPOI, the night operations team, the military and civilian clients who utilize NPOI data, ongoing visiting programs who utilize NPOIs unique delay lines, and the engineering team responsible for system performance.

The Director of NPOI, Jim Clark, has personally undertaken the responsibility of sponsoring an NAU Capstone team. This team is tasked with designing, manufacturing, installing, and validating a new FDL vacuum manifold system before the current system experiences a catastrophic failure. This is a time-critical and costly endeavor that, when complete, will eliminate the FDL manifold as a point of extreme concern to all parties. This project will deliver a system that will be utilized 24/7 to help produce real scientific data and potentially lead to new scientific discoveries.

This report covers in detail the technical challenges, scope of the project, budget, time management, concept generation, concept evaluation, and preliminary technical analysis of the NPOI FDL Vacuum Manifold NAU Capstone Project.

1.2 Project Description

Following is the original project description provided by the sponsor [1]

> "An NAU capstone project would be charged with designing, analyzing, and possibly manufacturing a new vacuum manifold for the Fast Delay Lines. The new manifold would be separate from the vacuum snoots allowing for shorter down times when working at the front of the tanks. Additionally, the relocation of the vacuum manifold would eliminate forces on the snoots reducing potential for vacuum failure. The proposed manifold would be required to interface with the existing bulkhead plates, greatly reduce risk of vacuum failure, partition each of the six delay lines so an individual tank can be vented without disrupting operation of other delay lines, and reduce maintenance time when working on the FDL carts. Other considerations include location of the vacuum pump to reduce/eliminate vibrations that effect optics cart performance, and access to partitioning valves. Above and beyond features could include a data logging system for vacuum performance utilizing the existing sensor array. Currently, vacuum pressure is recorded by hand in a notebook. Development of a sensor package to research any correlation between vacuum performance with humidity and temperature changes in the room could be useful for continued engineering development. The scope of this project requires analysis of material properties, hydrostatic loading, cycle degradation prediction, cost optimization, and FEA evaluation to generate a fully engineered final product.

Construction, assembly, and installment of the proposed manifold could be included in the capstone requirements requiring students to learn manufacturing processes and evaluation of final system."

1.3 Original System

This section of the report covers the existing structure at NPOI and some of the unique challenges faced by the NAU Capstone team. This is not an in-depth engineering analysis of the current system, rather an overview of the main technical components to help the reader understand the scope of the Capstone project and the limitations of the current design.

1.3.1 Original System Structure

The existing FDL vacuum manifold is comprised of six isolation branches connected to a wall-mounted turbomolecular vacuum pump and an additional isolated branch connecting the manifold to the main array vacuum pumps for roughing from atmospheric pressure. Figure 1 depicts partial disassembly of the front end of FDL 5 and 6. The copper pipes featured in Figure 1 are the isolated branches of the current system. These pipes connect directly to the "snoot" of each FDL tank. The "snoots" in Figure 1 are covered by insulation material and hold delicate optical components.

Between the snoot and the isolated branch is a vacuum bellows which compensates for variation in manifold length and thermal expansion of the system. The bellows are not intended to provide axial support and often fail in shear and torsional loading conditions.

Isolation of each branch is achieved by manually operated vacuum valves. These valves are located near the top of the manifold and can be seen at the forefront of Figure 1. The current system requires operators to cross an elevated bridge over the FDL tanks and reach over to turn the valvevalve's knob.

Figure 1:Where Pipes Connect to "snoot" on Original Vacuum Manifold at NPOI

KF50 (also known as QF50) is the standard flange connection used in the current system. This flange style allows for quick connection and disassembly of the vacuum components and allows for industry-standard components to integrate with the system.

Figure 2 illustrates how the current manifold connects to the turbomolecular vacuum pump. The turbo is not visible in Figure 2 but is eclipsed by an electronically controlled solenoid valve (black component located under the backing pump). Suspended on a shelf is the backing pump which reduces the backpressure of the turbomolecular pump. A filtered "breather" valve is suspended on the right side of the manifold. This is used to bring the FDL tanks back up to atmospheric pressure. A copper pipe attached to the back wall can be seen in Figure 2. This pipe connects the FDL manifold to the larger main array pumps. Wires wrapped around the manifold connect high vacuum pressure sensors to control boxes that relay pressure data to an archived server and possess the authority to automatically shut down the turbomolecular pump and close isolate the manifold from the vacuum pump.

Figure 2: Connection of Vacuum Pipe to Vacuum Pump via Flange

1.3.2 Original System Operation

The original system utilizes a turbomolecular vacuum pump system, seen in Figure 2, always operating to maintain the desired vacuum pressure. The turbomolecular pump is capable of running at 120 thousand RPM, however, NPOI runs between 70 and 90 thousand RPM. When work on the FDL system is required vacuum valves, also seen in Figure 2, are used to isolate individual delay lines. Once isolated, atmospheric pressure can be introduced to the tanks requiring maintenance while maintaining a vacuum for the other operational FDLs. Once back to atmospheric levels, if work was needed to be done at the front of the FDL, the entire snoot assembly must be removed to access the front of the tank. What needs to be removed can be seen in Figure 1 where FDL 5 and 6 (closest tanks in photo) have their snoot assembly removed. This is a complex task as the snoots hold delicate optical components. Additionally, the snoots extend through the “inner room” wall and terminate close to table-mounted optics as seen in **Error! Reference source not found.**. Because of these added complexities removing the snoots increases the downtime of the FDLs especially when the longer snoots must be extracted as there are more obstacles to navigate. To remove a snoot the vacuum manifold must be partially disassembled as well.

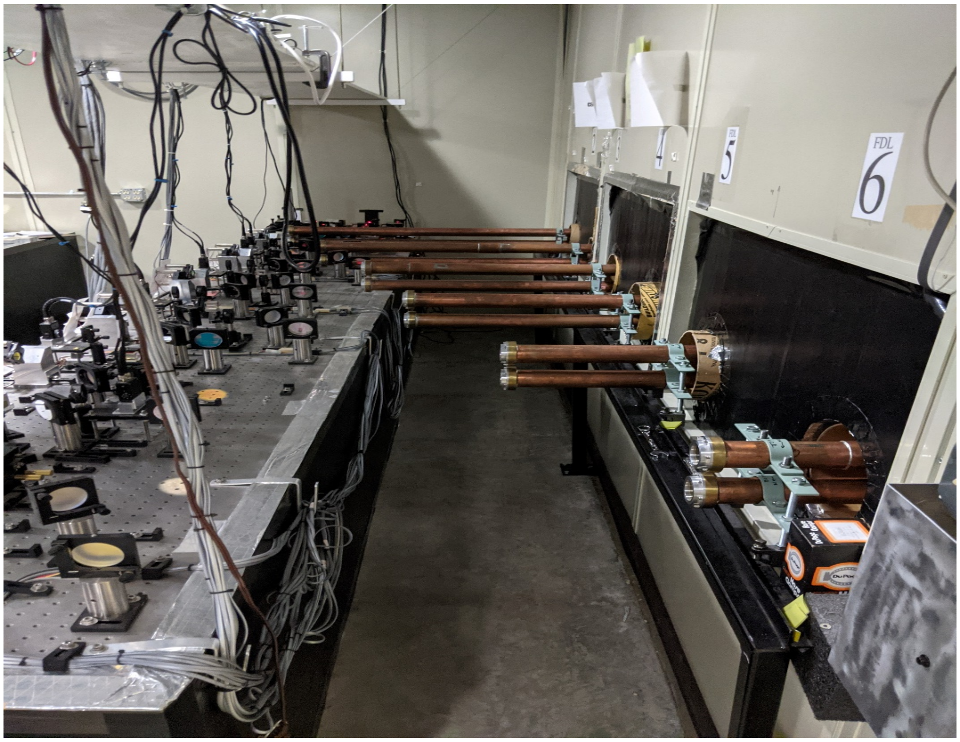

Figure 3: Image of the snoots that are in the optics lab

To isolate an individual tank an operator must climb onto a bridge suspended over the FDL tanks and then reach over and turn the valve open or closed. When pulling down from atmosphere or releasing vacuum the operator must control the flow of air by adjusting the valve open/closed position. This is critical as air currents can dislodge dust particles which can damage optical components. The adjustment of flow rate is also required to not overburden the vacuum pumps when operating at high pressures.

In normal operation, high vacuum pressure sensors relay data to an online server allowing operators to monitor the system. These sensors also control an emergency solenoid valve which closes when pressure is above the cutoff. This is to prevent the pumps from overworking in the event of a major vacuum leak. To obtain a vacuum a manual bypass must be initiated to ignore the safety protocol.

1.3.3 Original System Performance

The standard operating pressure for the FDL tanks is between 5 to 8 mTorr with a maximum operating pressure of 30 mTorr. The carts house several piezo actuators that operate at high voltage. At pressures less than atmosphere and above 30 mTorr the piezo are at elevated risk for electrical arch which could damage the actuators or other systems. The vacuum manifold is responsible for maintaining safe operating pressure to prevent piezo damage.

NPOI is a remote site that frequently experiences power outages. Many of the control systems are protected by a large battery backup. The Vacuum pumps are not protected during a power outage. When the power goes out it is important to maintain low vacuum pressure in the FDL system. The current manifold and FDL tanks can stay below 30 mTorr for approximately 5 days without a pump pulling a vacuum. The new system should meet or exceed this standard.

If maintenance at the front of the FDL system is required, the current vacuum manifold must be partially disassembled to allow for snoot removal. Disconnecting the vacuum manifold, removing the snoots, and lifting the front-end cap off the FDL tank takes about 1.5 hours. This process must be done in reverse with the addition of reinstalling the insulation material around the snoots when reassembly takes place consuming another 2 hours of labor. The connection between the snoot and the vacuum manifold requires the snoots to be oriented perfectly each time they are replaced, and the insulation material must be made to allow for an additional pipe connection. Regardless of any new manifold design, the snoots pose a hazard to remove. However, the current system includes the added complexity of vacuum manifold dismantlement.

1.3.4 Original System Deficiencies

Where the current system meets to fail customer requirements is with safety, ease of use, repairability, longevity. Both the problems with safety and longevity of the system can be traced to the bellows used to connect the snoot to the vacuum pipe. Because of the vacuum forces that are exerted on the pipe by the atmosphere, a moment is present that has been slowly twisting the pipe. Because of this the bellows are experiencing both a compressive and shear load which they are not designed to handle. This mismatch in load abilities is expected to cause the bellows to fail at some point soon. When this failure occurs, besides causing damages, it could injury anybody nearby as air rushes into the FDL. The problems that cause the current system to have low repairability and ease of use is with the fact that the vacuum manifold attaches to the snoot. Because of this design choice it makes the FDL hard to repair when anything goes wrong as the entire snoot assembly must be carefully removed before work can be started.

2 REQUIREMENTS

As mentioned in previous sections the current FDL manifold at NPOI fails to meet the requirements of our client. In this section both the customer requirements and the derived engineering requirements will be discussed in greater detail.

2.1 Customer Requirements (CRs)

The first and most important customer requirement is safety. The volume of evacuated space at NPOI represents an increased opportunity for catastrophic failure. Any sudden breach to the vacuum system could result in serious injury to nearby people and damage to the vacuum protected optics inside the system. Safety is taken seriously at NPOI. An example of system redundancy are the support cables holding the Long-Delay-Lines (LDLs) outside the FDL building. The design supports each end of pipe with two braded steel cables. One cable is rated to hold the weight of the pipe, yet a total of 4 cables are used to increase redundant safety at a low financial cost. The result is a minimum factor of safety of 4 supporting the LDL system. Our client emphasized there is no weight or size limitation to the new vacuum manifold allowing the Capstone team to primarily design for safety. This is the 1st requirement which weighs 50% in the overall decision making prosses.

The next requirement provided by the client is increased reliability and service life over the old system. The FDLs are a mission critical component to NPOI. If the carts are not held in vacuum, the system cannot be operated and no data collection can occur. The vacuum manifold is the component responsible for maintaining FDL vacuum and therefore is a critical component of the interferometer. By designing a new manifold, the team will increase the reliability over the current system, and by optimizing the materials used the team will provide a solution that will last the duration of the NPOI's mission lifetime. This is the 2nd requirement which weighs 12.5% in the overall decision making prosses.

Our client pointed out the necessity for regular system maintenance and instituted a requirement for maintenance accessibility. Presently, the vacuum manifold must be physical disconnected from the FDL tank when cart maintenance is required. This operation is time intensive, requires skilled personnel, and presents a risk to the overall system due to the number of components being disassembled. The new manifold must allow for cart access and decrease the disassembly of optical and vacuum components. This is the 3rd requirement which weighs 12.5% in the overall decision making prosses.

The fourth requirement is the that the team is to stay within the budget allocated to us by NPOI. This is desired because it challenges us to create something meaningful from limited resources and it also ensures that the materials used could be replaced without great cost to NPOI in the future if needed. This is the 4th requirement which also weighs 12.5% in the overall decision making prosses.

The fifth requirement is that the new manifold should be easy to use. This is desired because it would be a hassle for the client to have to retrain his employees in the operation of the system.

The last requirement is to allow for future project integration. The NPOI instrument is not only an operational observatory, but a testing ground for new and exciting types of experiments and technology. It is unknown what requirements future programs might have for the NPOI facility; therefore, it is necessary to provide integration and access points within our design. This fundamental feature of the new manifold is already being utilized by replacing the existing electrical passthrough to accommodate more electrical connectivity per the client's request. This is the 5th requirement which weighs 12.5% in the overall decision making prosses.

2.2 Engineering Requirements (ERs)

For each of the CR's previously listed at least one engineering requirement was made to correlate to it. For safety, the ER is factors of safety (FS). As mentioned before part of the vacuum pipes that NPOI support cables with FS of two and has two sets of the wires which would give it a total FS of four. Because the cost of materials increases with the FS used, the team decided that a FS of 2.5 ± .5 would be the target value to ensure safety and keep costs low.

The client budget expectation was matched together with manufacturing lead time and with project cost. For manufacturing lead time are goal was to have it be under four weeks plus or minus three days. In terms of project cost the goal was to have it be 10000$±4000$.

Both reliability and repairability were incorporated into a minimize downtime ER. The hope for this would be that the maintenance would be reduced to 2 ± 1 hours for a disassembly and reassembly of the manifold system.

The new vacume manifold must provide suffisent flow rate to evauate one FDL line over the course of one day. Constriction in the pipe, poor geometric design, and insufisent vacuum power could reduces the teams ability to deliver a system capable of meeting this design requirement. Analysis and validation of the completed system will be done to evaluate the systems performance and influence final design.

2.3 House of Quality (HoQ)

As previously mentioned in section 2.1, 2.2 we had a total of five customer requirements that had a total of five engineering requirements corresponding to them. In the house of quality, safety has a weight of nine, cost is three, ease of use is three, reliability is nine, repairability is nine, longevity is three, and future project integration is one. Using these weights and the relevance to each of the engineering requirements it was found that the three most important ER are the factor of safety, followed by project cost and finally minimize downtime. The two systems that were used to benchmark against the current system is the Laser Interferometer Gravitational-wave Observatory (LIGO) and the European Council for Nuclear Research (CERN) Large Hadron Collider. These two systems were used as benchmarks because they both utilize large vacuums to gather observation data. In this case, LIGO is a closer match to NPOI then CERN in the sense of what they do. The completed house of quality can be seen in appendix A.

3 DESIGN SPACE RESEARCH

This section includes the literature reviews done by each of the team members spanning multiple different topics from which material is the best to use in vacuum systems, how other facilities have made their vacuum systems, and to the safety protocols at various locations. In addition to the literature review, several other systems that operate in a similar fashion to NPOI were evaluated as benchmarks. The information was then used to create a black box model of the vacuum manifold as well as a functional decomposition and hierarchical chart.

3.1 Literature Review

3.1.1 Student 1 (Wyatt Clark)

A vacuum manifold can be characterized by the external and internal geometry, number of connections, materials utilized, and flow efficiency. To optimize the effectiveness and safety of any vacuum system engineers must balance the above-mentioned parameters starting with the geometric constrains of they system. Working with the client and though research the team has determined most vacuum system to be comprised of thin-walled pressure vessels. For the team to develop safe hardware information and equations from *Materials Selection in Mechanical Design* [2] can be used to evaluate the geometry of new vacuum hardware. For this Capstone project the team is tasked with integrating into an existing system which carries with it a history of standardization. The majority of vacuum components at NPOI utilize the standard KF vacuum connections. The KF connection type has been evaluated based on current system compatibility and with *KF (QF) HV Flange Technical Notes* [3] provided by the Kurt J. Lesker Company, a well-known and trusted manufacturer of vacuum hardware. The utilization of a quick flange was not specified by the client, therefore, additional research regarding different types of connection standers was performed. Another document provided by Kurt J. Lesker Company, *Flange System Overview* [4], was used to evaluate the advantages of various flange connection styles within industry. Flange research concluded for the specified operating range of the new vacuum manifold a KF flange style will be sufficient and compatible with existing NPOI vacuum systems.

The design of a new vacuum manifold requires the Capstone team to consider the existing pumping infrastructure. The current system is connected to a turbomolecular pump with accompany backing pump running 24/7 to maintain low vacuum pressure. Additionally, a combination large rotary-vane and roughing pump can be used to pull vacuum to reduce pressure from atmospheric down to the turbomolecular pumps operating range. To better understand the mechanics of the current system, and to help in development of a user guide for the new manifold research was conducted on turbomolecular vacuum pumps. Edwards is a well-known and trusted source for vacuum technologies. The Edwards document *Vacuum Equipment for Research and development* [5] covers the ideal operating range for turbomolecular pumps. The team learned it is important to protect the turbomolecular pump from "shock" and "blowback" when the turbine is up at speed. Because of this the team will now be installing an additional valve in front of the turbomolecular pump to better control the flow of high presser throughout the system.

A mandatory feature of the new design, stated by the client, is the ability to isolate individual FDL tanks to perform optical/mechanical maintenance of the carts. Integrated into the vacuum manifold must be some combination of valves to direct and control the flow of air out of the system. There are many types of vacuum rated valves each best suited to a specific applicant. The *Valves Technical Notes* [6] from the Kurt J. Lesker Company discusses the advantages and best use cases of each valve type. Gate valves are used for quick operation and maintain pipe continuity, i.e., a gate valve does not constrict flow or optical path when fully opened. A bellows sealed valve allows operators to control the flow of air though the valve. The manifold the Capstone team is developing does not required pipe continuity but will depend on the ability to regulate the introduction of high-pressure air though the system. Based on this research the team will use a bellows-based valve to isolate the individual tanks and integrate with the existing vacuum pump system.

3.1.2 Student 2 (Alex McClinton)

When we first talked with our client, he made it clear that due to the uncertainties in the positions of the FDL pipes as expansion from heat, that are design would have to include a bellows somewhere withing it. Because of this the first source was *Metal Expansion Joints and Metal Bellows* by MACOGA Engineered Expansion Joint [7]. This webpage provided by the company details the various types of expansion joints and metal bellows that can be manufactured by them and how to best utilize them. This will help our design project because it will allow us to design the manifold to have the bellows to account for the positional uncertainties while also allowing us to make sure that they are loaded correctly, that way they will not fail like the system we are meant to replace. When design our project it can also be helpful to looked into how other systems were designed. Thus, the second source is *Vacuum Technology of the LIGO Interferometers* by LIGO [8]. This covers the basics of how LIGO achieves its 10^{-9} torr vacuum which includes details on the various pumps they use to remove the air. In addition, they also detail the initial stages of building LIGO and how to make sure that there was minimal outgassing they heated the entire structure for three weeks. This source also goes into the challenges in maintaining this low pressure which includes how they measure for leaks. Another important step in design out vacuum system is choosing the right materials to build the vacuum pipes out of. For this information the third source of *Vacuum Physics and Technology* Chapter 8 by Y. Shapira and D. Lichtman [9] was used. This chapter in the book covers how various materials react to vacuum pressure. This includes properties like vapor pressure and outgassing. They then use these considerations to showcase the best materials for building vacuum pipes. Our team will most likely be reusing the pressure gauges that NPOI has but if it was decided that a new set was needed the information from "Gauge Selection Guide" by Kurt J. Lester company [10] would help. This source gives on overview of all the different pressure gauges that they offer which allows you to find one that suits your particular vacuum needs. The final source is about support beam design. Because if you have a design that extends over the FDL tanks some sort of support beam would have the be added to mitigate the torques and other forces acting of the manifold to make sure that the system does not have the potential for failure. In order to do this" Beam Design – Basic" by John F Mann of Structural Support [11] was sued. This source goes into detail on how to design horizontal beams that are meant to support a load.

3.1.3 Student 3 (Cydny Clark)

After the first client meeting and a tour of NPOI it was made very clear that a vital aspect of this project of this project is safety. One way to ensure safety in the function, observation, and maintenance of the within the lab facilities is the use of safety protocols and other safety training. The goal of this literature review is to look at the safety protocols and safety training implemented at the current system NPOI), the CERN Large Hadron Collider (CERN LHC), and the Laser Inferometer Gravitational- Wave Observatory (LIGO). The focus of the first two sources is safety training and the analysis of the safety plan in place at The CERN LHC. The first source is *Formal Methodology for Safety-Critical Systems Engineering at CERN* by F. Valentini[12], which describes that for the function and operation of the CERN LHC one major aspect of the safety plan is to use safety function modeling. From the modeling they can determine any places and aspect of the safety plan that might be lacking or under explained. The second source is *CERN Accelerating Science: Safety Training* by CERN, which is a course that informs and trains the entire CERN population on the potential health hazards, safety issues and risks they may encounter in the workplace, according to the Learning & Development and Safety policies of the Organization. Both sources demonstrate that in large lab systems, there is ample training, resources, and analysis to best prepare the people using, maintaining, and observing certain aspects of the Collider. Another source for a different system is *LIGO Caltech 40 Meter Laboratory Laser Safety Plan* by Alan Weinstein[13], which outlines the overall safety goal as well as the safety procedures for the use of the lab facilities. This is a document given to any person entering the lab and is to be signed off on, stating that each person understands the contents of the documents and the outlined safety precautions. As for the current system, there are two different documents that describe the system systems function and operation. *Vacuum System Overview and Operation* by NPOI [14] is a document that employees have access to which is a step-by-step instruction manual on how to use, work on and maintain the vacuum system. Another vial source is *Observer Troubleshooting- Vacuum* by NPOI [15] which is a document serves as a list of instructions of what to do and what not to do when working with the vacuum. There are also question and answer sections that describe how instruments should be functioning. In conclusion, it was determined that an additional aspect of this project is to incorporate a new and improved safety plan and protocol to the new system implemented by the team.

3.2 Functional Decomposition

3.2.1 Black Box Model

The first step to make concepts for this project was by first understanding what goes into our system. To do this a black box model was created that visualized the material, energy, and signal inputs into our vacuum manifold and the also the corresponding outputs. This helps to visualize the project by giving a broad overview of what are system is supposed to being doing and what inputs are required to make it work. The final black box model can be seen in Figure 4 below.

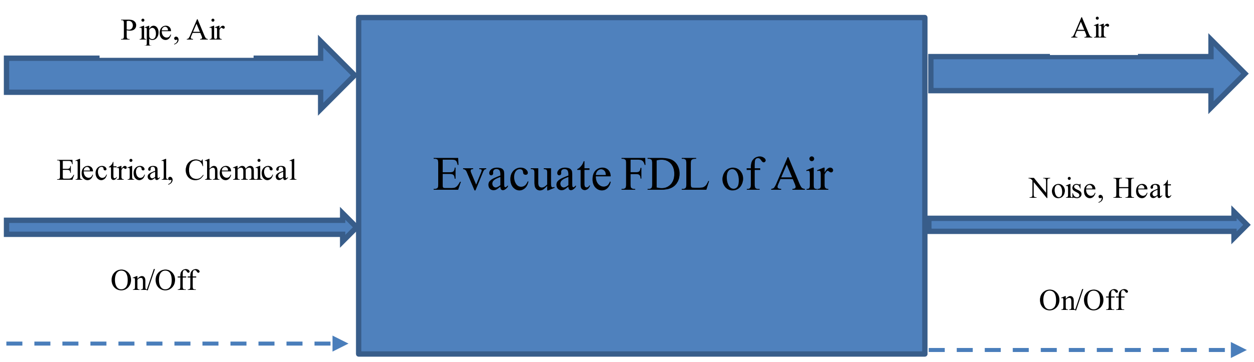

Figure 4: Black Box Model For Vacuum Manifold

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

The functional model helps the team by giving a more detailed view of how each of the systems inside of the vacuum manifold work and how the various parts work together. The decomposition uses the same three inputs from the black box model of material, energy and signal. The decomposition that was made for the vacuum manifold can be seen in Figure 5 below.

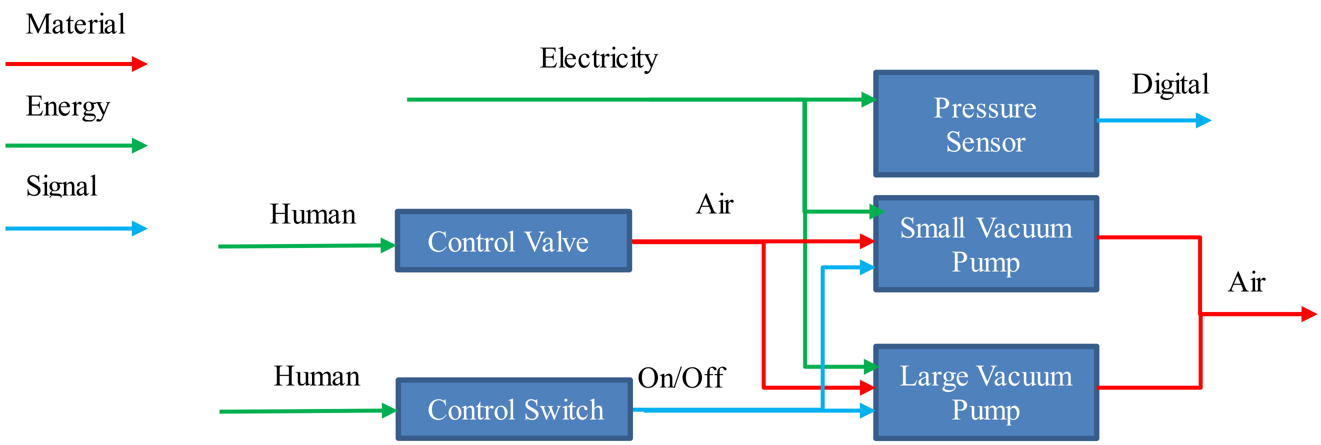

Figure 5: Function Decomposition for Vacuum Manifold

In addition to the functional decomposition, a hierarchical chart was created to show the breakdown of the vacuum manifold system to its lowest manageable parts. This was done in order to visualize the parts of the system and how they come together to achieve the end goal of a fully working vacuum manifold. The hierarchical chart can be seen in Figure 6

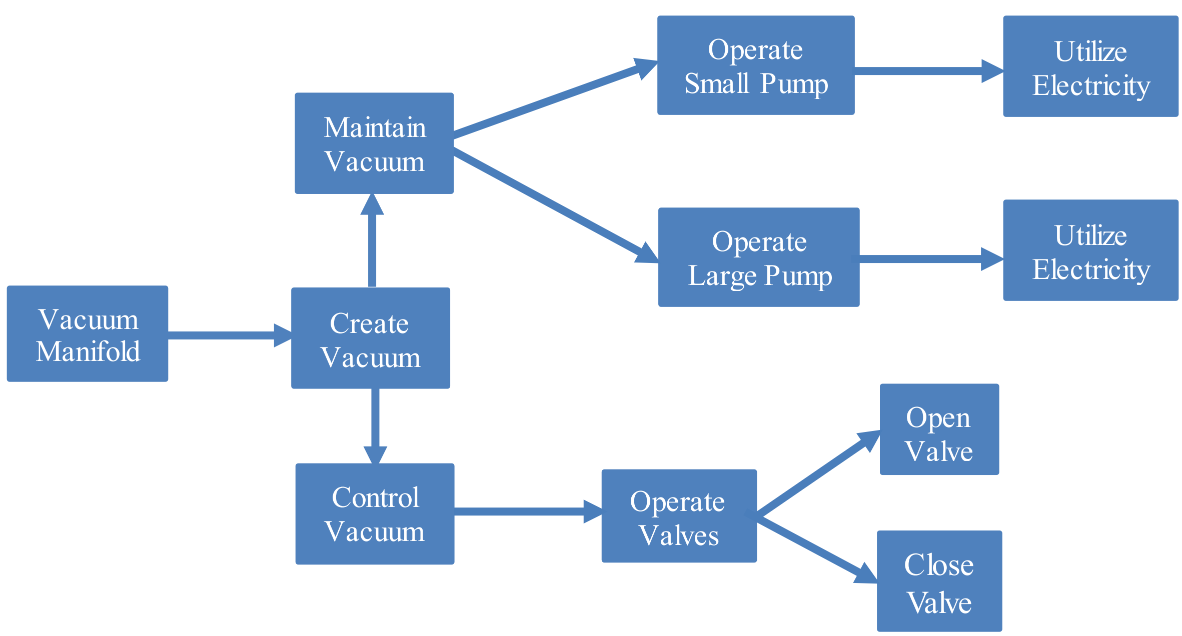

Figure 6: Hierarchical Chart of Vacuum Manifold

3.3 Benchmarking

3.3.1 System Level Benchmarking

3.3.1.1 Existing Design #1: Laser Interferometer Gravitational-Wave Observatory (LIGO) [16]

LIGO utilizes two 4km long arms to do its observations. These arms have a volume of $2*10^7$ L that is keep at a pressure of 10^{-9} torr. To achieve this pressure when the system was first built every piece of tubing was subjected to a rigorous cleaning process followed by a helium leak test. Once assembled the parts were heated to 160°C for three weeks to ensure there was not trapped gases inside the metal that would leak out. Once this process was completed, they could use a combination of turbopumps and ion pumps to remove the air from the tubes. The way this system relates to our requirements is because a great deal of safety was put into how to make their vacuum system to ensure there were no serious failures. For LIGO a failure in their vacuum system would be greater than one at NPOI because they have more special instrumentation, operate at a lower pressure, and have a large amount of volume that could suck people in if a hole were to open. They also designed this system to be reliable because it took millions of dollars to make and is expected to continue operations for a long time.

3.3.1.2 Existing Design #2: Vacuum Tower Telescope (VTT) [17], [18]

The VTT is designed to study the sun. Using two pivoting mirrors on the roof of the tower, they capture the sunlight [17]. To ensure the quality of the image the shaft that the light is directed into must be evacuated of air to reduce any image distortion from convention from the air as it gets heated by the concentrated rays of the sun. This chamber is 21 meters long and has a diameter of 1.80 meters and is evacuated to a vacuum of less than 0.5 millibar using two vacuum pumps in series [18]. A picture of the overall design of the VTT can be seen in Figure 7 below.

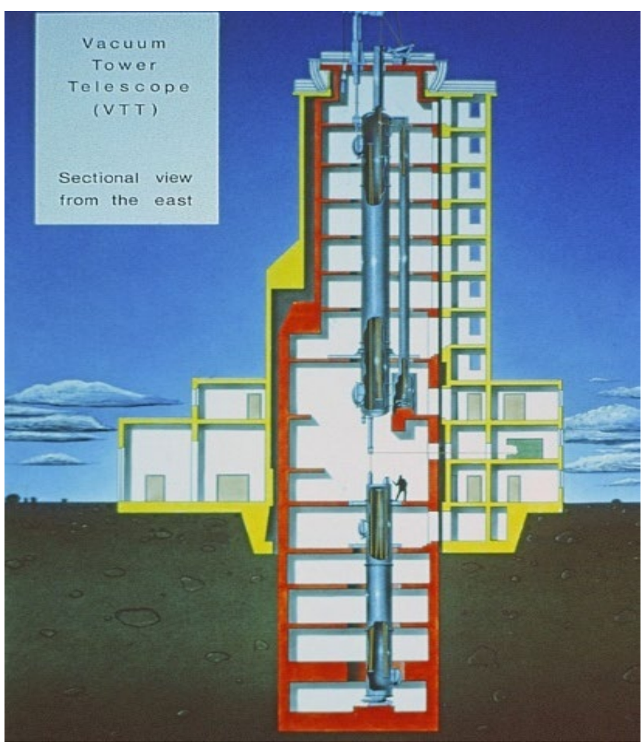

Figure 7: Layout of VTT [17]

3.3.1.3 *Existing Design #3: 1-meter Swedish solar telescope (SST)* [19]

The SST is very similar to the VTT in the previous section as they both have the objective of studying the sun. Just like the VTT to increase the image quality the SST uses a vacuum chamber when directing the sunlight. To achieve a vacuum pressure 0.2 mbar the vacuum pumps they utilize need to be keep on constantly [19]. When a larger pressure of 0.3 mbar is acceptable the system only requires that the pumps stay on for 2 × 20 minutes per day. With the glass mirror being part of the vacuum design, it was found through FEMA that the maximum load would be 4.0 MPa which is below the recommended design stress of 6.8 MPa for fused silica [19].Below in Figure 8 is a diagram of the SST.

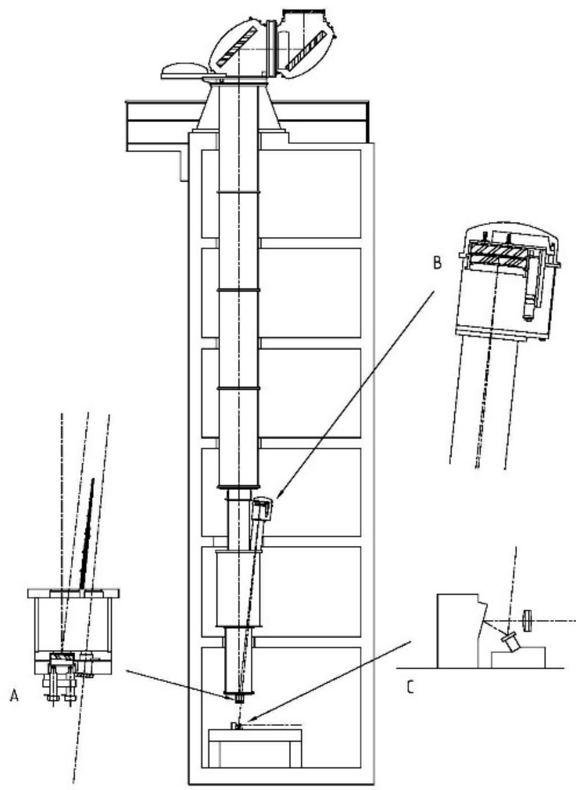

Figure 8: Layout of 1-meter SST [19]

3.3.2 Subsystem Level Benchmarking

The complexity of a vacuum manifold is often masked by the elegance of design. To create an efficient and reliable vacuum manifold special attention must be given to critical sub components. This section of the report outlines, in some detail, research conducted by the Capstone team regarding these critical components.

3.3.2.1 *Subsystem #1: Pressure Valve*

A key feature of the vacuum manifold is its ability to isolate sections of the vacuum system. During maintenance of one of the FDL carts not all FDL tanks need to lose vacuum pressure. Discrete isolation allows modularity for the overall system and reduces time/energy spent pulling large volumes of vacuum. Controlling the flow rate of air though the system prevents damage to electrical, mechanical, and optical systems. Therefore, it is necessary to include vacuum rated valves into the final manifold design.

3.3.2.1.1 Existing Design #1: Gate Valve

Gate vales, shown in Figure 9, are discreet vacuum rated valves that work in line with vacuum pipes. Their operation can be manual lever, manual turn knob, electrically actuated, or pneumatically actuated. Their construction typically consists of a rectangular body, in which is housed a sliding sealing surface. When the internal surface is moved inward it blocks through access of a vacuum system. When the seal is moved out, fluid is able to move freely. Gate valves are rated to hold 10^{-8} Torr [20].

Gate valves are used on some components at NPOI. The design of a Gate valve allows light to pass directly though an open valve which is why they are used to isolate the outer arms from the inner array at NPOI. Their construction limits their ability to control the rate of flow. Manufacturers warn not to leave some gate valves in the halfway position as this could damage the membrane.

For the Capstones vacuum manifold project, we do not require the fast actuation, clear passthrough, or compact design of a Gate valve. We do require the ability to adjust the flow rate of the vacuum system which the Gate valve dose not meet.

Figure 9: Gate Valve [20]

3.3.2.1.2 Existing Design #2: Angle Valve

Vacuum rated angle valves, shown in Figure 10, operate with a deformable diaphragm attached to screw mechanism much like a standard needle valve. The diaphragm can be made from rubber or metal depending on the application and is used as the sealing surface. These valves are rated to operate at 10^{-9} Torr [21]. Orientation of the valve is important as it can leak if more than 15 psi is applied as backpressure against the seal [6].

Angle valves are used in the current manifold system and the client offered to let the Capstone team utilize them. The diaphragm design is able to provide crude flow control reducing risk of damaging the internal optical components with a blast of air. The 90-degree geometry can be integrated into the manifold design reducing the need for an elbow.

These valves cannot be actuated electronically or pneumatically but require manual operation. This means the new manifold should also include some automated valve somewhere in the system to isolate leaks and prevent vacuum pumps from over working.

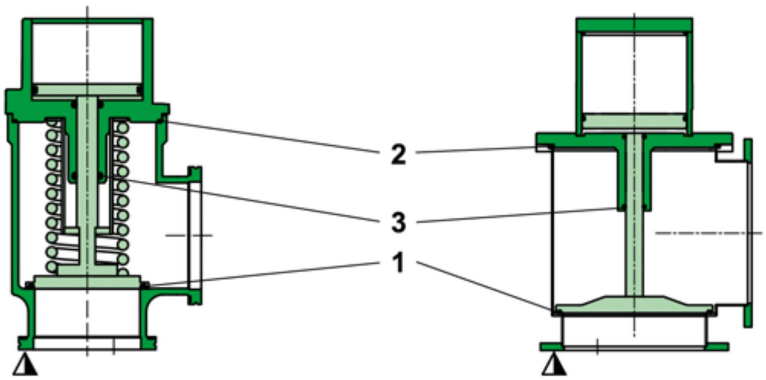

Figure 10: Angle Valve [21]

3.3.2.1.3 Existing Design #3: Butterfly Valve

The Butterfly valve or Soft Start Valve, shown in Figure 11, is a time-tested technology and common place in the automotive industry. This design consists of a circular plate contained within a circular housing. The external housing can be mated to the vacuum system. The internal plate can be rotated about the center of the housing. This actuation allows the disk to seal against the internal features of the housing or be rotated breaking the seal and allowing flow. Butterfly valves are able to control flow rate and can be automated to dynamically control the amount of flow. This design works in line with vacuum systems but does eclipse the center of the path. The flap is able to reduce the pipe cross section by 99% and will not operate in a backflow application [22].

This style of valve meets the requirements of the NPOI vacuum manifold but is a less conventional style valve for this application, presents technical integration challenges, and NPOI does not have a surplus of this type of valve which would require the Capstone team to purchase new valves.

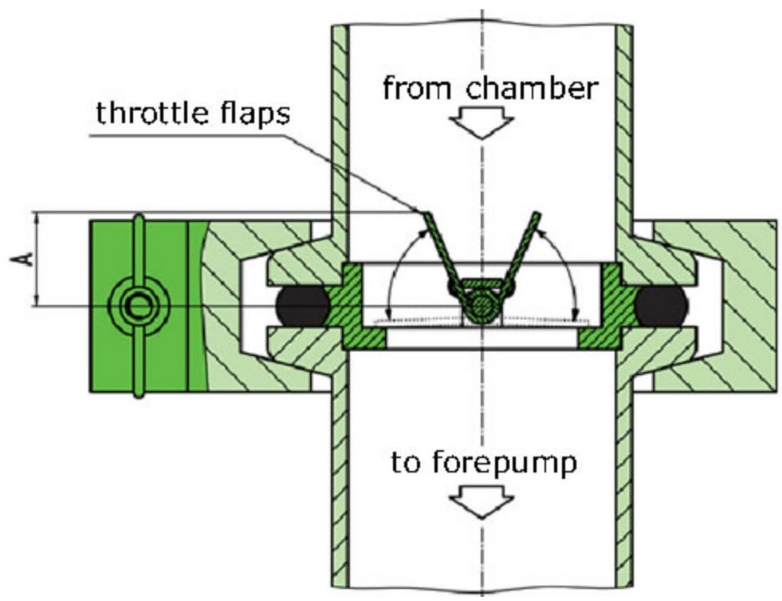

Figure 11: Butterfly Valve [22]

3.3.2.2 Subsystem #2: Flange

The flange fitting is a critical component to the vacuum manifold and exists at the forefront of the design space. There are many types of vacuum fittings to connect different types of vacuum hardware. Selection of the correct flange type is critical to the success of the vacuum manifold system. Below are several industry standard flange types and their functions.

3.3.2.2.1 Existing Design #1: ConFlat (CF) UHV Flange

The ConFlat flange design, shown in Figure 12, is typically used in applications that require infrequent disassembly. This style of flanged connection utilizes a circular bolt pattern to draw two unisex flanges together. Between the matting surfaces exists consumable soft metal gasket. Machined into the flange surface is a sharp knifelike feature. As the external bolts are tightened the flange cuts into the soft metal gasket creating a vacuum seal capable of holding 10^{-13} Torr [23]. The gasket is only used once and must be replaced before the flanges can be reassembled. Additionally, the bolt pattern limits the orientation of matting components reducing overall design flexibility.

This type of connection could be utilized by the Capstone team. This system allows for modularity and some adaptability of design. This flange style is capable of maintaining the vacuum pressure requirements of the FDL manifold. The vacuum manifold is not expected to be regularly dismantled and therefore the consumable nature of the seals is not an issue.

This type of connection is limited in the orientation of connecting components. Because this Capstone must integrate with an existing structure it is unknown what exact orientation is required for the final assembly largely due to differences in “As-Built” and technical drawings of the system. Additionally the majority of NPOI components utilize a different flange type. Introducing a new style of connection would increase the complexity of NPOI headwear.

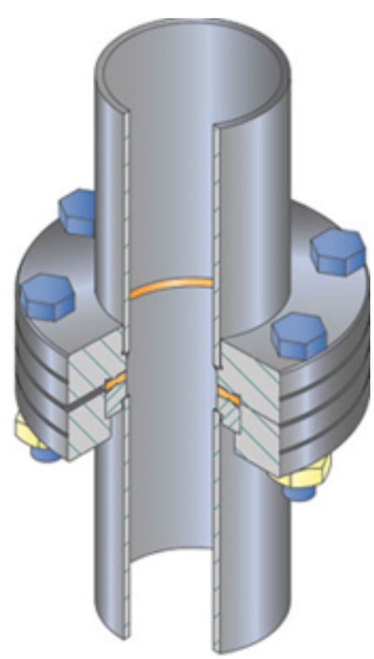

Figure 12: CF Flange [23]

3.3.2.2.2 Existing Design #2: Quick Flange

The Quick flange, shown in Figure 13, style of vacuum connection is popular within industry. Noted for its adaptability and versatility many systems including NPOI utilize this connection type. The flanges are unisex with a machined feature to suspend an O-ring between mating surfaces. The O-ring can be made of many different types of polymers depending on the application. A collaring clamp is placed over the angular external surfaces of the matting flanges. As the collar is tightened, typically by a wingnut, the flanges are pressed together and squeeze the suspended O-ring. The O-Ring limits the operational temprerature range from 0-180 degrees Celsius [3]. Additionally, the KF flange connection is rated at 10^{-8} Torr [3], which exceeds the specified vacuum pressure requirement.

As an industry standard this style of flange can be sourced from several different companies and integrated into existing or developing systems. A unique characteristic of this flange design is that it allows mating parts to be rotated before final clamping. This means the Capstone team can orient downstream components without major system modification. The O-Ring is not consumed when the seal is made allowing for quick disassembly and reassembly without additional components. Finally, much of the vacuum system at NPOI utilizes the KF50 style of connection. NPOI has a stock of spare KF50 components and adaptors that could be used by the Capstone team.

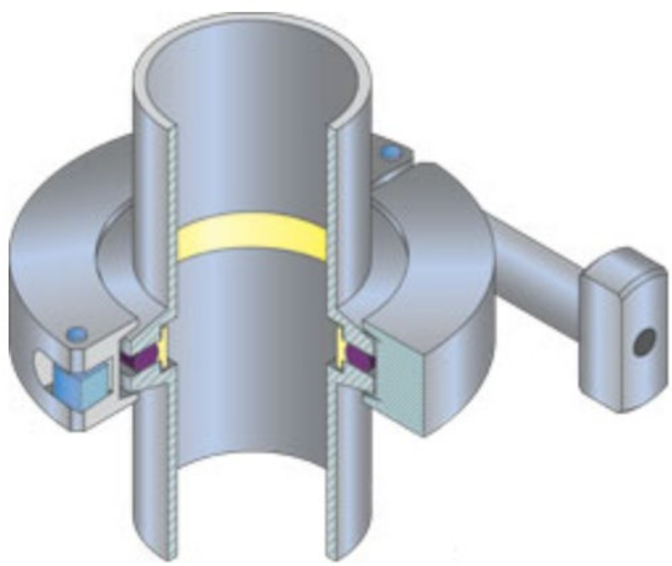

Figure 13: KF Flange [3]

3.3.2.2.3 Existing Design #3: Welding Components

For mature vacuum programs custom welded connections are utilized. These types of connections are permanent and costly. Engineers would only select this type of connection if they were dealing with small delicate systems, large permanent subsystems, or the environmental conditions that demand welded assemblies.

Welding eliminates the possibility of disassembly for complex systems, reduces points of failure in the overall system, reduces opportunity for leaking, increases structural rigidity of large components, and can be used to extend short pieces of vacuum manifold. Ultimately this is not an option for this Capstone as the cost of vacuum rated welding extends beyond the budget allowance. Welding components together reduces flexibility of design and requires precision dimensioning of the integration structure. Regardless of welding shortcomings, it is still the strongest and most reliable form of constructing a vacuum system.

3.3.2.3 Subsystem #3: Manifold Pipes

3.3.2.3.1 Existing Design #1: LIGO 4km Pipes [8]

The construction of the tubes was done 3.2 mm thick 304L Stainless Steel tubes. These tubes had external stiffeners attached to them to help prevent bucking. This steel was then cleaned and heat at 455°C for 36 hours to remove as much hydrogen from the steel as possible. Once the section was tested it was then butt-welded together in a travelling clean room. With the way it was designed it tubes are meant to never be vented. The way this relates to our project is that it gives us a sense of what material can be used to with stand large vacuum from LIGO and as such would work for our smaller vacuum as well. In addition, it also shows ways to lessen the outgassing from the pipes themselves allowing for longer periods of operation in the event that the vacuum pump fails.

3.3.2.3.2 Existing Design #2: CHARA Array Light Pipe Vacuum System [24]

The Center for High Angular Resolution Astronomy is an optical interferometer based roughly on the designs made from NPOI. The way that CHARA operates its vacuum system is that it utilizes PVC pipe, plastic pool valves, and a two-stage vacuum pump system. With the current setup the system can go down to a rough vacuum of 1 torr. The way this relates to our project is that by using PVC and plastic the cost of the manifold is greatly reduced. However, the downside to these materials is that the vacuum that PVC and plastic can hold is much less then what NPOI needs to operate.

3.3.2.3.3 Existing Design #3: Vacuum Pipe Material Selection [25]

Not only is the pipes geometry critical to the success of any vacuum manifold but the materials used to construct the vacuum pipe represents a major decision in any manifold project. Engineers must select materials based on the specific application. For example, situations with corrosive chemicals might require engineers to select ceramic rather than metal.

Atmospheric diffusion though the material is another major factor to consider when selecting vacuum pipe components. According to Normandale Community College a typical stainless steal has a diffusion rate of 6×10^{-9} Torr liter/sec/cm^2 where brass operates at 4×10^{-6} Torr liter/sec/cm^2.

The current manifold utilizes strain hardened copper pipe. Although less expensive than stainless steal, copper will leak up to atmospheric pressure faster than a stainless steal manifold. Additionally, ceramic manifold components are unnecessary as the environment does not pose elevated thread to material degradation.

4 CONCEPT GENERATION

This section of the report outlines the concept generation prosses, evaluation, and comparison techniques utilized by the team for the purposes of this Capstone course. Many of the concepts are derived from brainstorming, conversations with the client, industry standards, and bio-inspired design.

4.1 Full System Concepts

4.1.1 Full System Design #1: Back of Tank Extension With Support Bridge

This design adds an extension to the back of the FDL that has three different ports. One of these would be for the manifold piping, another for a pressure sensor and the last for any future projects on the FDL. The pipes that connect to the manifold would then be routed into each other and meet underneath a bridge that would have to be constructed. The bridge would be where the vacuum pump would be moved and where the manifold gets connected. The model created for this design can be seen in Figure 14, below.

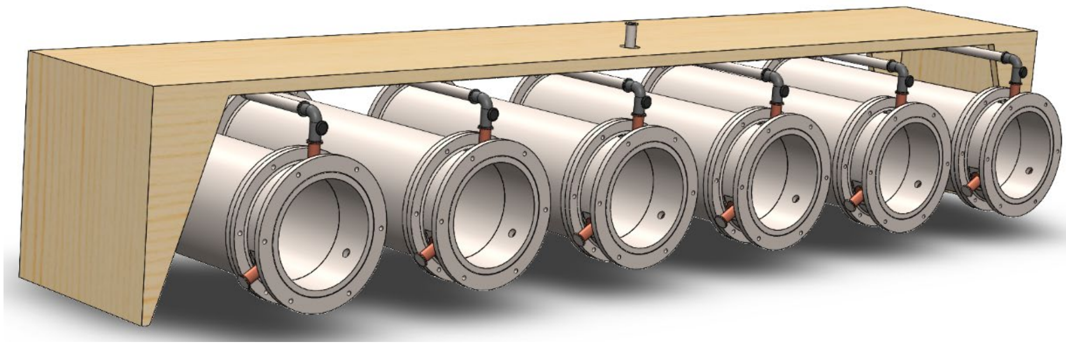

Figure 14: Solidworks Model Based on Design One.

The advantages of this are the reduced vibrations by connecting the bridge to isolated concrete slabs on either side of the FDLs. When conducting maintenance on the back of the pipe the bridge would also act as storage for the extension and end plates. This design also provides more feed through ports for sensors or other projects. Lastly because the vacuum pump is now on the bridge it also makes maintenance on it easier. The disadvantage is that the bridge would impede the motion of crane and a bridge capibable of holding the vacuum pump and plates must also be designed.

4.1.2 Full System Design #2: Front of Tank Ribbon Cable Interconnection With Long Pipes

This design would utilize the ribbon cable connection to the FDL. Coming out from the connection would have to be a cross of some sort that we would then have to add a standard ribbon cable connection to it. from this cross a pressure sensor can be added as well as any future project integration. One of the ports on the cross would connect to the manifold were the pipping would run along the ground. All of the pipes from the six FDLs will go over to one side where the pressure values will be. From the pressure values all the tubes can be connected into one and then routed to the vacuum pump. The Solidworks model created for this design can be seen in Figure 15, below.

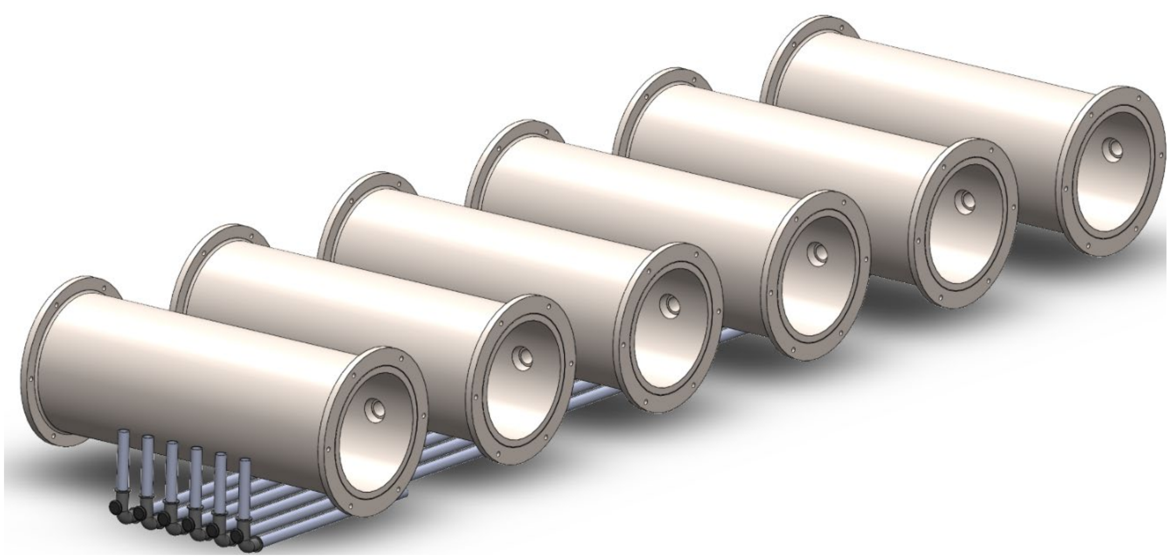

Figure 15: Solidworks Model Based on Design Two.

Some advantages for this connect is that the manifold pipes can be attached to ground for static stability to ensure that no torque twists the pipes like in the original design. With the valves all being on one side a bridge is no longer needed to operate valves for the different FDLs. Finally with this design it would replaces the poorly designed electrical feed through of the original design with a more conventional feed through. The disadvantages to this connect is that by using multiple long pipes the cost of the design increases rapidly. With it also having this many pipes it also takes up more space underneath the FDL which limits room for other devices that might get installed in the future.

4.1.3 Full System Design #3: Back of Tank Adapter Routed into SID lab

The design would be reusing the same adapter as first concept to connect the manifold to the FDL's. The vacuum pump would be moved into the SID-Lab on a rubber isolator with the vacuum pipes going through the wall to connect with the pump. The Solidworks model for this concept is shown in **Error! Reference source not found.** below.

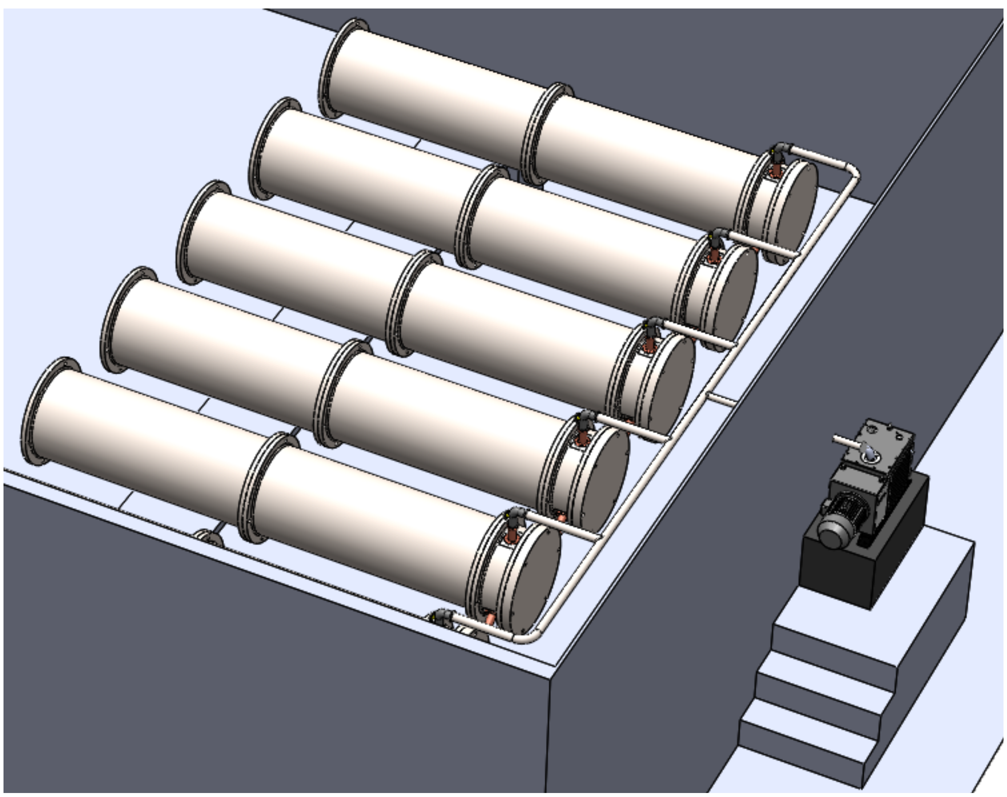

Figure 16: Solidworks Model Based on Design Three with Turbopump Model [26]

The advantage of this design is that it greatly reduces vibrations from the pump felt in the optics lab. This is because the pump is on a rubber isolator to dampen vibration as well as the fact that it is on the other side of the room from the optics lab allowing the vibrations to dissipate more. In addition to reducing vibration by moving the vacuum pump closer to the ground it allows for easier maintenance on the vacuum pump. The disadvantage to this design is that it would requires a sturdy support structure to make sure that any toques created by the manifold are contained to ensure the system does not fail in the same way again. The other downside to this design is that it requires building in two rooms which would take up more space than before.

4.2 Concept Variants

4.2.1 Manifold Geometry and Design Layout

The unique challenge of this Capstone is integration with an existing system. The most impactful factor to our design will be manifold geometry and location. The presented concept variations illustrate several combinations of manifold design and location. All are unique and serve as useful variations to guid final design generation.

4.2.1.1 Design #1: Apex Manifold

This design, featured in Figure 17, would involve having the manifold pipes from the FDL converge at an angle to each other to form a shape like a pyramid. This could either be oriented vertically or horizontally with extra supports.

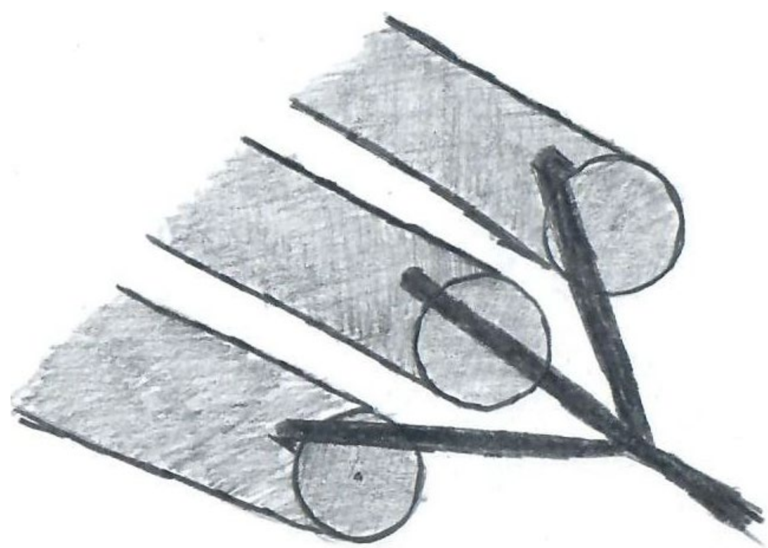

Figure 17: Apex Manifold

The disadvantages to this design is that orienting the pipes in such a way causes them to be longer in the end and as a result this idea would cost more to make. Additionally with the six different pipes coming together the part that joins them all together would have to custom made as no six way adapter in this orientation exists.

4.2.1.2 Design #2: Long Pipes to One Side Under FDL

This pipe concept, depicted in Figure 18, is the one used in concept two of section 4.1, where after the pipes connect to the FDL they go underneath them all to one side where the pressure valve would be.

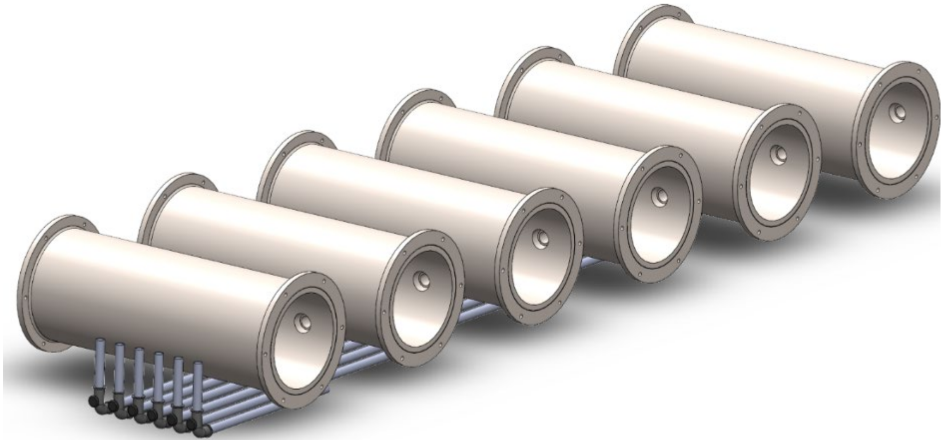

Figure 18: Concept Variant Long manifold pipes suspended under the FDL tanks to a bank of valves

This design has two majors pros to it. The first is that with the pipes being close to the ground they can be securely connected to remove any torques on the pipes. The second benefit is that with all the valves on one side the bridge over the FDL is no longer needed to reach certain valves. The biggest disadvantage to this design is that the cost is quite large due to the amount of piping that is needed to have all of the valves on one side.

4.2.1.3 Design #3: Long Pipes to One Side Over FDL

This design is based on the manifold from concept two in section 4.1 and design two from above. Unlike these concepts where the pipes are routed underneath the FDL in this design the pipes would go on top of the FDL and be secured with straps to the FDL's themselves. It would also have all of the pressure valves on one side for convenience like design two. This design is shown in Figure 19 below.

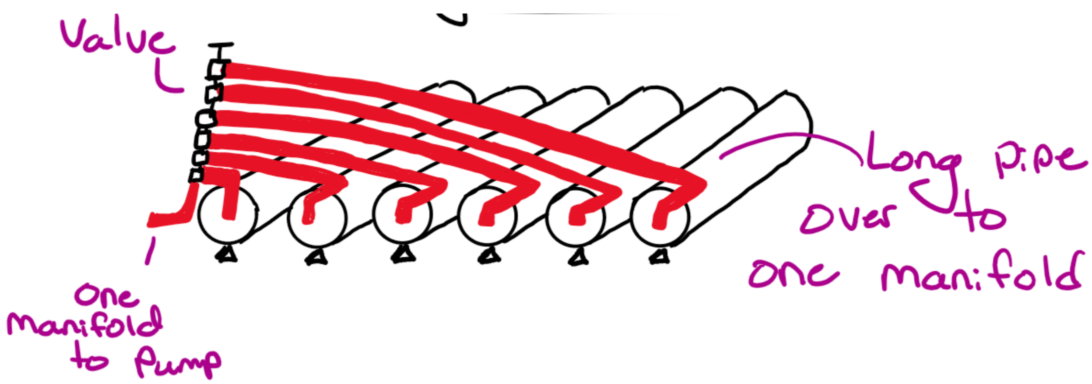

Figure 19: Long Pipes to One Side Over FDL

The advantage to this design is that by securing the manifold to the FDL tanks it ensures that there are no unbalanced forces acting on it because the FDL pipes themselves are securely fastened to the ground making them a great item to anchor onto. Additionally, with having all the pressure valves on one side of the FDLs it makes it easier to service them because no one would have to walk over the bridge to reach certain pressure valves. Just like the previous design with the design involving multiple long pipe sections the cost of this design is higher than others.

4.2.1.4 Design #4: Manifold in Front Pump in Back With long pipes

With this design, featured in Figure 20, the manifold would connect to the FDL at the front and then each tank would have a pipe that goes on top of the tank. At the back of the FDL is where the pressure valve for each tank would be located after which the pipes would converge and connect to the vacuum pump. The vacuum pump would be on a rubber isolator.

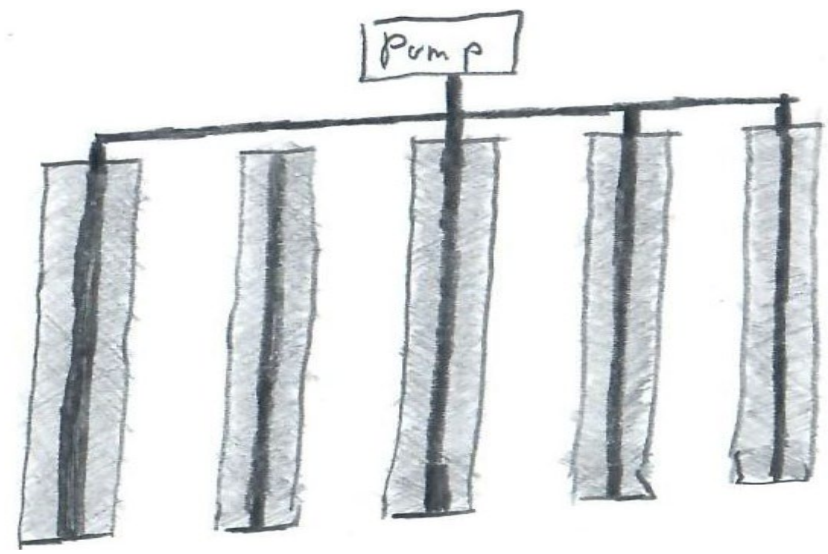

Figure 20: Manifold in Front Pump in Back With long pipes

The advantage to this design is that with the pipes going over the FDL they can easily be secured to them which would reduce any torques that the manifold would experience. By moving the vacuum pump to the back and placing it on a rubber isolator the vibrations that the optics lab feels would also be greatly reduced improving image quality for NPOI. An added benefit of the vacuum pump being on a rubber isolator is that it is closer to ground level and thus makes it easier to perform routine maintenance on the pump. The disadvantage to this design is the large amount of piping needed to do it because the stainless-steel pipe we hope to use is quite expensive already and having more would be a large part of our budget.

4.2.1.5 Design #5: Manifold in Front, Pump in Back, With Less pipes

This design, Figure 21, is very similar to design five with the difference being that all the pipes converge at the front of the FDL instead of the back.

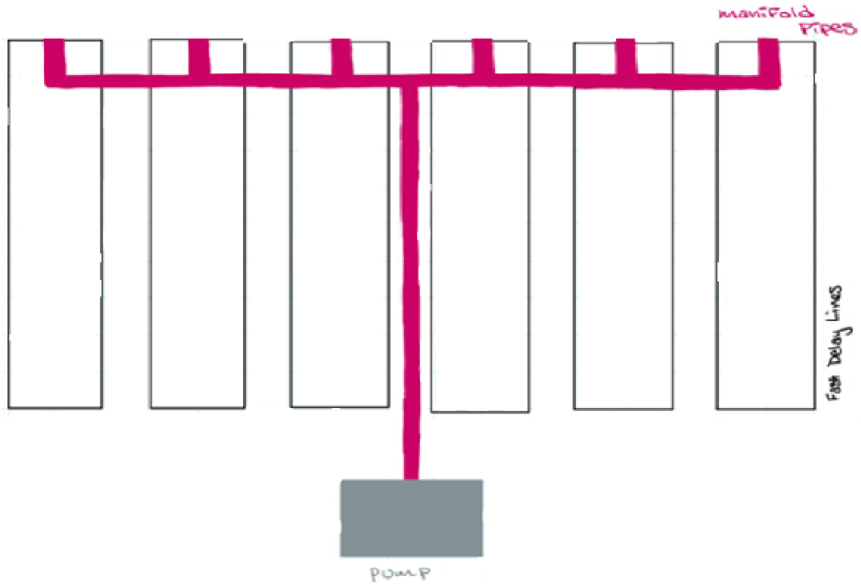

Figure 21: Manifold in Front Vacuum Pump In Back

Just like design four, with the vacuum pump being in the back on a rubber isolator the vibrations that it causes would be reduced and with it being on ground level the maintenance would also be easier on the pump. Compared to design four this design is also cheaper because it uses less tubing overall however, it is still expensive since a manifold pipe is required to cover the entire length of the FDL tanks which are approximately 16 meters long. Another problem this design has is that it still requires the current bridge to access the various pressure valves which would be at the front of the FDL tanks.

4.2.1.6 Design #6: Simple Front Plate

For this design,shown in Figure 22, we would remove the current connection of the vacuum manifold to the fast delay lines which is also connected to the snoots and cap the fast delay lines with a simple front plate. This plate would have an extending arm that connects the new vacuum manifold to the fast delay lines.

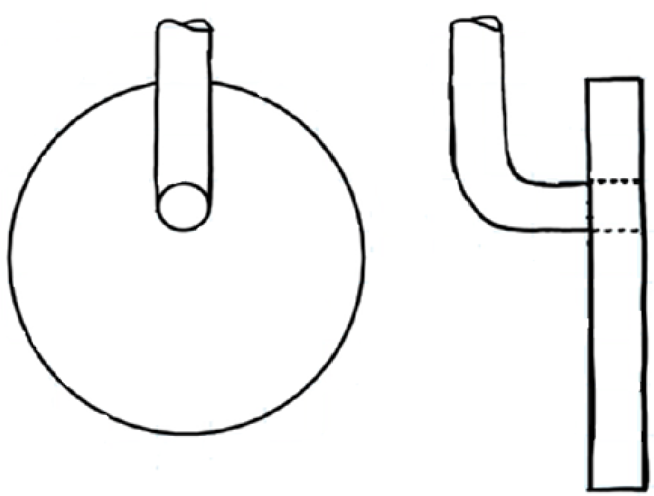

Figure 22: Simple Front plate

The benefit to this design is that it is rather simple to do. This design would also allow for easier access to remove the snoots without breaking down other aspects of the design, as well as the overall maintenance of the vacuum manifolds and the fast delay lines. The downside to this design is that it doesn't solve any other problems from our client or allow for extra projects in the future.

4.2.1.7 Design #7: Pumps for each FDL

For this design, Figure 23, each of the six FDL lines would be attached to their own vacuum pump. These vacuum pumps would attach to the back of the FDL and they would be placed on rubber isolators.

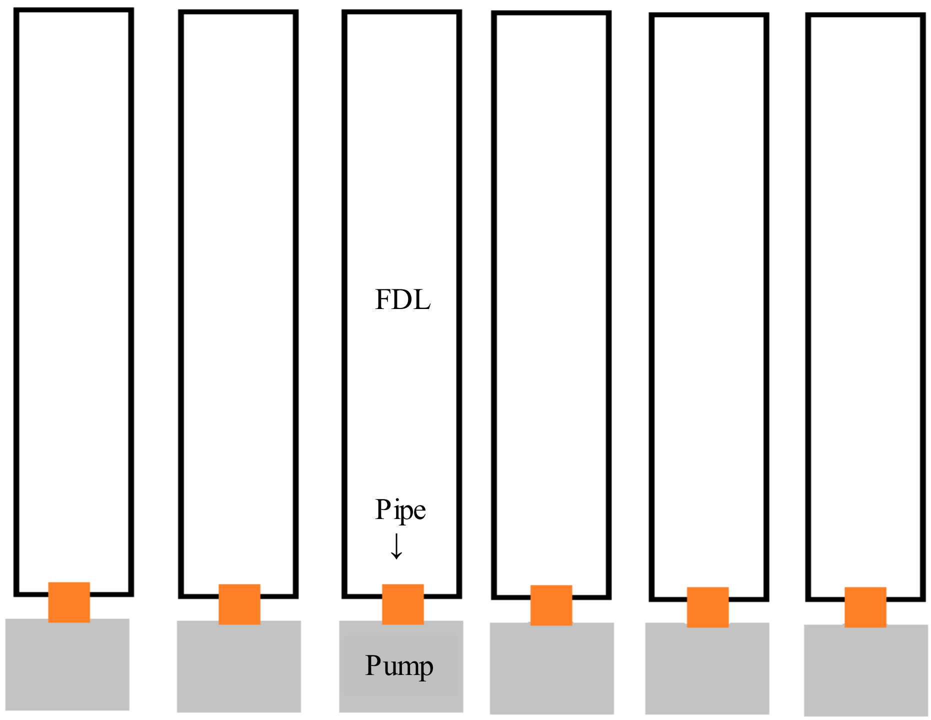

Figure 23: Pumps For Each FDL

The benefit of this design is that it requires very little piping to implement, it would have reduced vibrations in the optics lab by moving the vacuum pump away and having it be on rubber isolators. The drawback to this design is that it would be incredibly expensive to purchase five new vacuum pumps and there could be potential harmonic vibrations from all the vacuum pumps which could damage the foundation or be felt in the optics lab.

4.2.1.8 Design #7: Front With Support Bridge

This design is shown in Figure 24. This design would increase the rigidity of the entire vacuum manifold system. The vacuum pump could be located on the bridge rather than the lab wall making regular maintenance easier. When work at the front of the tank occurs, the front plates could be set on the bridge rather than moving them with the crane off to the side of the building. The bridge would need to span over the center isolated concrete pad to minimize the introduction of mechanical vibration to the inner room. Because the bridge would become part of the support structure for the vacuum system the bridge would become stationary. Currently the bridge at NPOI is not anchored and can be moved to assist with other projects or to free up space. This concept would require the bridge to remain stationary.

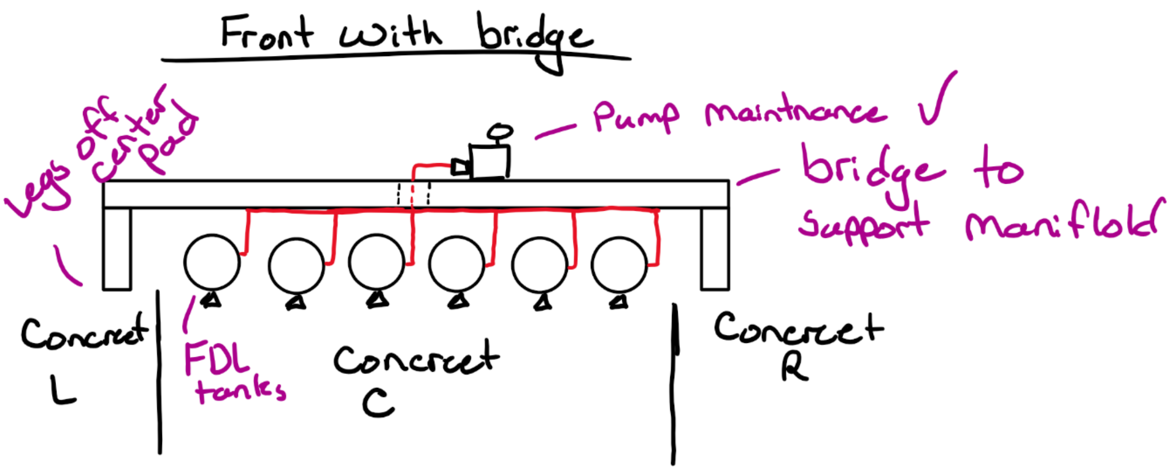

Figure 24: Concept Variant Front with support bridge

4.2.1.9 Design #7: Giant Lung

Error! Reference source not found. Figure 25 depicts a bioinspired design replacing the vacuum pump system with a synthetic lung. The size of this design makes it impractical for use in this FDL manifold system, however the concept is valid and could be looked into for other projects.

The principal is simple, once connected and sealed the lung would enlarge creating more volume. A check valve could close, the captured air released to atmosphere, and the cycle could repeat. The cadence of operation could greatly reduce the introduction of vibration to the inner room and this system does not require integration with existing pumping heaters.

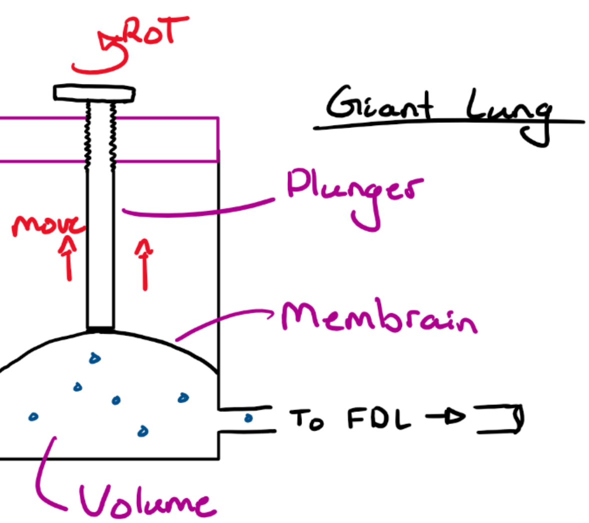

Figure 25: Concept Variant Giant Lung

5 DESIGNS SELECTED – First Semester

This section contains the process that was used by the team to decide on the top two designs from the previous sections. In addition, this section also contains the rationale used to justify the two designs that are chosen.

5.1 Technical Selection Criteria

To choose between the various designs that the team created in section 4, first a Pugh chart was used. The customer requirements were used to evaluate the designs because the client needs are of great importance and if a design fails to meet those CR's there is no point in evaluating them in reference to the engineering requirements. The CR's that were used to evaluate the different concepts were safety, cost, reliability, ease of use, and future project integration. The first four listed CR's were chosen as those were some of the most important to our client and as such need to be represent well by our concepts. Future project integration was also used as a criterion because the client seemed to enjoy the idea of being able to add items to the FDL if possible and as such we would like to fulfill that wish as well.

The winning designs from the Pugh chart would then go into a decision matrix where they would be evaluated based on engineering requirements from the HoQ. The ER's that were used to score the designs are material cost, manufacturing cost, reliability, and minimize downtime, with weights of 15%, 25%, 50%, 10% respectfully. This ER's were chosen as they represent some of the more important CR's that they were derived from. The weighting was chosen such that 40% would be with the two cost ER's because we cannot go over budget with our design and as such it is very important to consider. Reliability was weight at 50% because it relates to the client's desire to have a system that works for a long time without failure that way he does not have to deal with the problems he had before our team was created. Minimize downtime was only given 10% because the team decided it was more important for the system to work properly for a long period of time and to have the project be completed on budget.

5.2 Rationale for Design Selection

Using the five customer requirements mentioned in section 5.1 the Pugh chart for the 10 concepts discussed in section 4 was made. The completed Pugh chart can be seen in table 1 below. The concepts goes in order of how they were presented in sections 4.1, 4.2.

Table 1: Pugh Chart

Criteria \ Concept	1	2	3	4	5	6	7	8	9	10
Safety	+	S	S	S	DATUM	S	S	S	S	-
Cost	-	-	+	+		S	-	-	-	-
Reliability	+	S	+	-		S	S	S	-	-
Ease Of Use	+	+	+	S		S	S	S	S	-
Future Project Integration	+	+	+	-		S	S	S	+	-
∑+	4	3	4	1		0	0	0	1	0
∑-	1	1	0	2		0	1	1	2	5
∑S	0	1	1	2		5	4	4	2	0
Total	3	2	4	-1		0	-1	-1	-1	-5

From the Pugh Chart the three winning designs were concepts 1-3. Because the cost on the Ribbon Cable interconnect was the one weakness it had in the Pugh chart it was decided that a better option would be to have the lines connect as one in a similar way to concepts 1,3. These connects then went into our decision matrix using the previously mentioned engineering requirements. The complete decision matrix can be seen in table 2 below. For the two cost criterion, lower numbers indicate that the design would cost more.

Table 2: Decision Matrix

		RAW	WEIGHTED	RAW	WEIGHTED	RAW	WEIGHTED
Criterion	Weight	Back Extension with Bridge		Ribbon Cable Interconnect		Back Extension to Sid-Lab	
Material Cost	15%	4	0.6	8	1.2	6	0.9
Manufacturing Cost	25%	3	0.75	5	1.25	7	1.75
Reliability	50%	8	4	7	3.5	8	4
Minimize Downtime	10%	9	0.9	7	0.7	8	0.8
Totals		24	6.25	29	7.65	27	7.45
Relative Rank		3		1		2	

A breakdown of the material cost analysis for the designs in the decision matrix can be seen in Appendix B. From these calculations it was found that design 1 would be the most expensive to build and that design 2 would be the cheapest with design 3 being roughly in the middle. Because of this distribution, they got their respective scores in material cost.

For the first design only the bridge needs to be fabricated, everything else is standard parts that can quickly be assembled. Assuming time to assemble the bridge would be around 10 hours. At minimum wage that's a cost of $150. For the second design the custom interconnect needs to be fabricated, everything else is standard parts. Assuming the time it would take to mill the piece is about 7 hours. At minimum wage that's a cost of $105. For the third design, the hole going into the SID room and the rubber isolator pad need to be constructed, everything else is standard. This process should only take about 4 hours. At minimum wage that $60. From these calculations it can be seen why designs 1-3 got the scores of 3,5,7 respectfully in the decision matrix for manufacturing cost.

Reliability of each of the designs was based on how easy it would be to maintain the vacuum pump and other parts on the vacuum manifold itself like pressure sensors, valves, cables, etc. For the back extension the reliability was rated an eight because with the vacuum pump being moved onto the bridge it would make it easier to maintain instead of its current location on a shelf. It would be hard to quantify the amount of time saved by not having to use a ladder, but it would streamline the process improving efficiency and reliability. For the vacuum interconnected it was rated a 7 because by changing the design of the cable interconnect to something more standard it makes it much easier to maintain the electrical side of the FDL if something were to break on a cable and it would need to be replaced. For the back of the side lab design, it got an eight for the same reason that the first design got an eight.

For minimize downtime it was based on how fast it would be to remove the manifold and its respective plate from the FDL. For the first design the reason minimize downtime got a nine is that when the plate needs to be removed the crane that is used to do it is stored in the back and as such people will not need to wait the 2 minutes to move the crane to the front of the FDL's. Also, with the addition of the bridge the plates can be placed onto it for storage just like in the current design. Finally with the manifold no longer being attached to the snoots the process in general is much quicker. These reasons are why the first design got a nine. For the second design removing the plate would still be quicker than the original design because they are no longer connected to the snoots. Unlike in the back the optics tube would still have to be taken out to remove the front plate which is why it only scored a seven. The last design should be able to use the crane in the back of the FDL room as well like in design 1. However, because this design does not have its own bridge the original bridge would have to be moved over to store the plates or an extra table that can handle the weight of the plates would need to be used. Because of this reason design three only got an eight and not a nine like design one.

With all of these calculations driving our decision matrix, the top two designs are the ribbon cable interconnect (concept 2 from section 4.1) and back of tank adapter routed into the SID lab (concept 3 from section 4.1). With this information these concepts were then shown to our client. From the top two choices, the ribbon cable interconnect was the preferred design because the team is both solving the original vacuum manifold problem as well as helping the client with problems that he has been experience with the ribbon cable pass through. However, the client also showed interest in the SID-lab concept because it would have greatly reduced vibrations from the vacuum pump in the optics lab which would have also solved another problem that the client has.

5.3 Leading Design CAD Model

Based on the top two designs the team is able to create a 3D CAD model of a working prototype. To generate the leading CAD design the team took Engineering schematics of the existing NPOI FDL system and dimensionally accurate CAD components provided by Kurt J. Lesker Compony [21, 27-29]. Using Solidworks the team generated a dimensionally accurate (according to provided FDL schematics) CAD model to share with the client and perform analysis on.

This design utilizes the FDL electrical feedthrough located near the front of the FDL tanks. The existing feedthrough screws into a welded shoulder creating a vacuum seal. By utilizing the feed through the team moves the manifold out of the way of other critical operations, improves upon the existing custom electrical components and replaces them with industry standard equipment, and by utilizing industry standard components the new manifold can be integrated with other vacuum systems at NPOI. An isometric view of the model is seen in Figure 26.

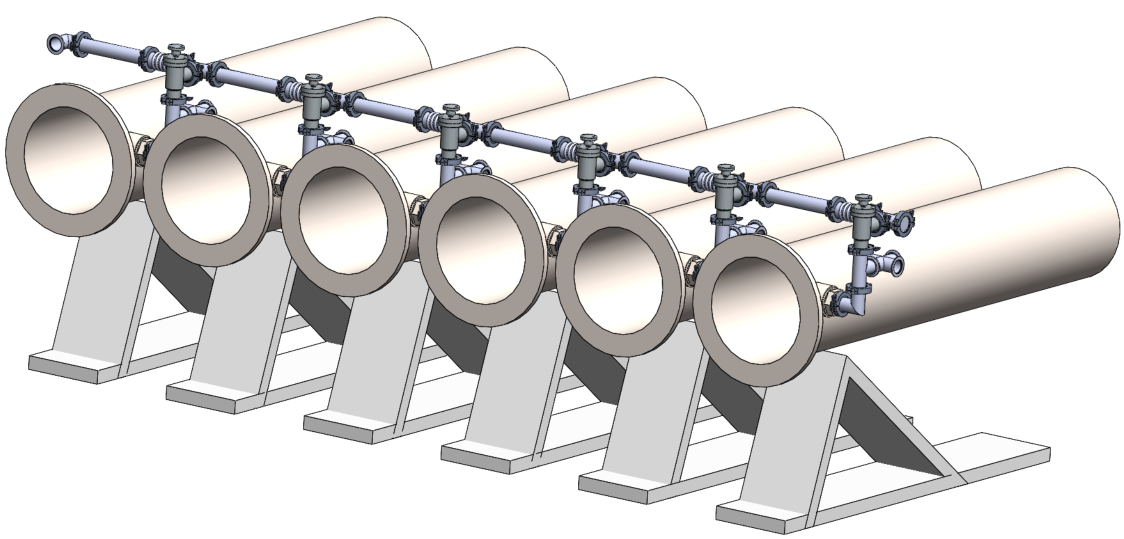

Figure 26: Isometric View Leading CAD

Figure 27 shows the front on view of the leading CAD model. This image illustrates the compact design of the new vacuum manifold and highlights some potential challenges in the assembly of the new manifold. The distance between the existing tank structures require the use of a 90 degree miter elbow fitting. The KF50 flange connection allows the team to assemble to structure despite the tight geometry. Additionally, the KF50 flange allows the team to rotate each vertical section of the manifold to align with the top portion where other flange types would limit this ability.

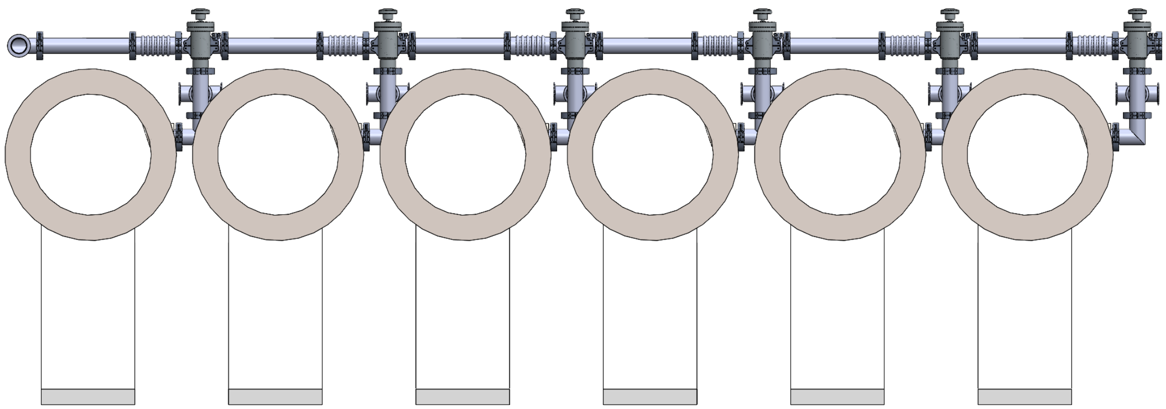

Figure 27: Front View Leading CAD

Figure 28 gives a close up perspective of the FDL 6 manifold connection. The top section of the manifold leads to the vacuum pump. A 90 degree valve is installed such that an isolated connection can be made to the individual tanks. Sine the team is consuming the existing electrical feed through, the new manifold must provide electrical pass through for new electrical cables. A cross, located under the valve cut off will be used as the new electrical feedthrough as well as a mounting point for the vacuum pressure sensor.

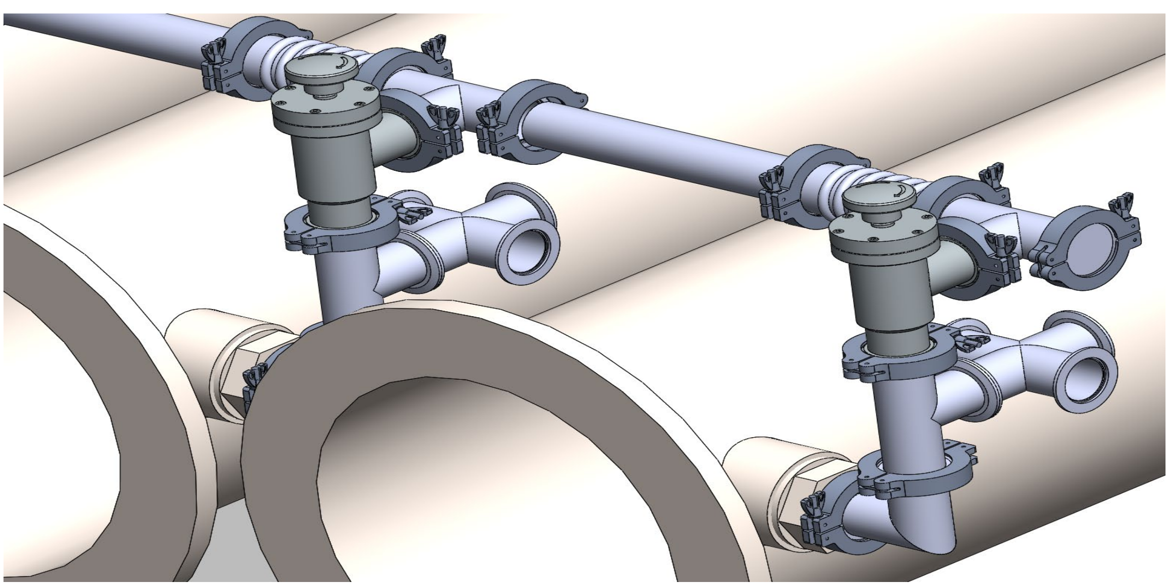

Figure 28: Isometric Close Look Leading CAD

Figure 29 shows the implementation of a bellows to compensate for pipe misalignment, differences in the as bult system, thermal expansion, and works to impede the transfer of vibration. The decision to mount the bellows as part of the upper manifold assembly increases the static stability over the existing design. This cross sectional view allows the reader to see the custom connection point between the existing FDL tank and the new manifold. A custom component will be manufactured such that it will thread into the FDL tank shoulder and convert to a KF50 flanged connection.

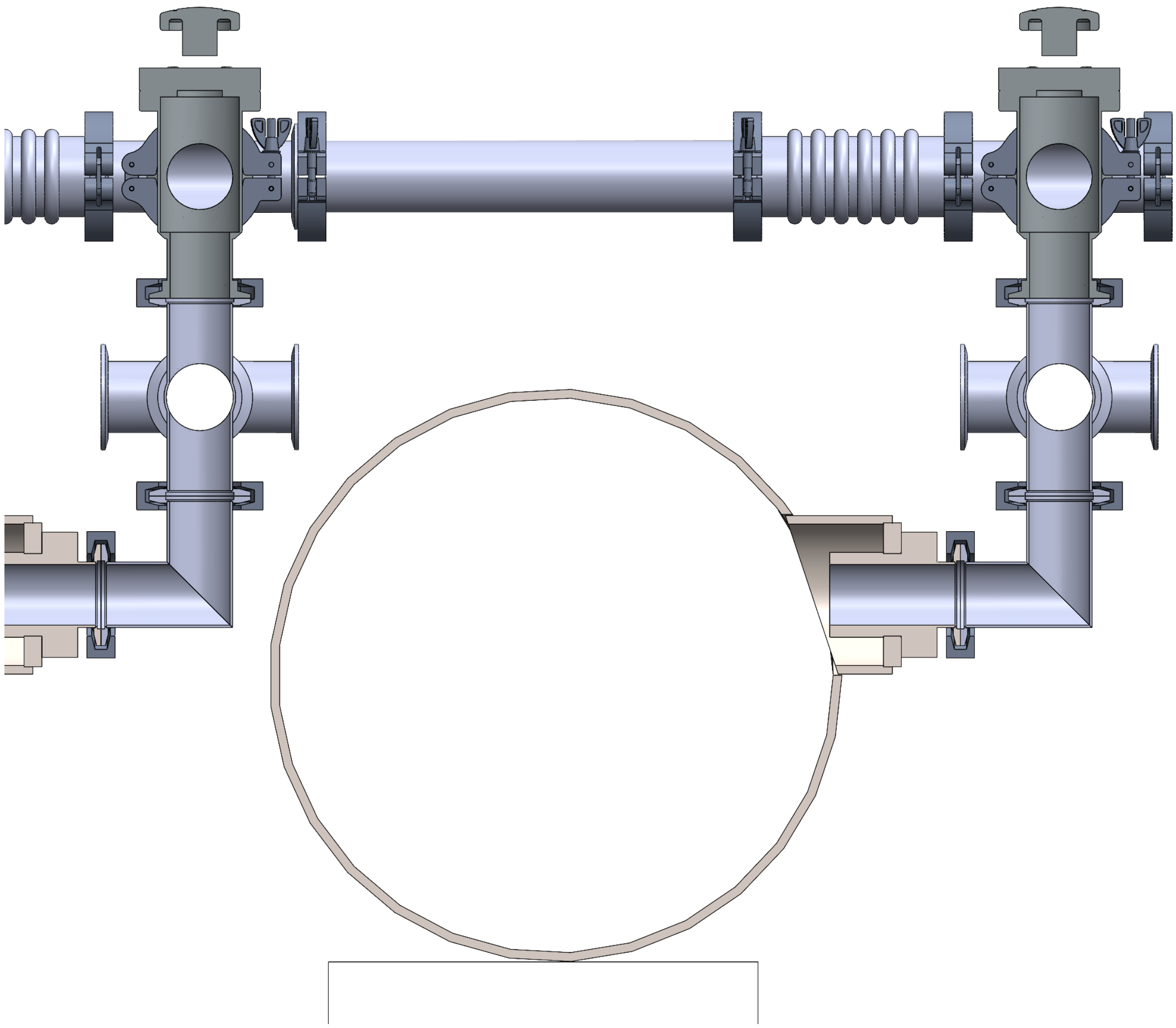

Figure 29: Cross section Front View Leading CAD

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7 APPENDICES

7.1 *Appendix A: House of Quality*

House Of Quality		*	↓	↓	*	*	↑	↑	Improvement Direction				
Design Requirements / Customer Requirements	Importance	Factors of Saftey	Manufactureing Lead Time	Project Cost	Smaller Pump Flow Rate	Main Pump Flow Rate	Minimize downtime	Youngs Modulus	Customer Competitive Assessment: 1 Worst	2	3	4	5 Best
Safty	9	9	1	9					A				BC
Cost	3	9	9	9			1		B	C	A		
Ease of use	3			1	1	9	3			BC	A		
Relyability	9	9		3			3	3		A		BC	
Repairability	9	1	1	3			9	1		A	BC		
Longjevity	3	9	1	3	1			3		A	BC		
Furture project intagration	1		1	3		1	1			ABC			
Technical Importance: Absolute		147	34	102	10	81	84	33					
Technical Importance: Relative		35%	8%	27%	1%	4%	19%	7%					
Target Value		2.5	4	10000	2.1	350	4	190					
Units		N/A	Weeks	US$	Torr/min	m^3/Hr	Hr	GPa					
Design Competitive Assessment	Worst: 1						A						
	2		A	C									
	3		BC	AB			BC	A					
	4	A			A	ABC		BC					
	Best: 5	BC			BC								

Key	
Current Sy	A
CERN	B
LIGO	C

7.2 Appendix B: Back of Envelope Material Cost Analysis for Designs in Decision matrix

Back Extension with Bridge:

Bridge

Top of Bridge.

Dimensions of Top are 12′ (length of FDL) by 1.5′ (width of pump + space for person). A total of nine 2″ x 12″ x 12′ boards would be needed. Cost for one plank is $28.12 [30]. Total cost for top of bridge is $253.08

Railing for bridge

Height of rail is 36″ (IRC standard [31]). Three pieces of wood needed to hold up rail for one side. One long horizontal piece also needed for one side of rail. Cost for one vertical 2″ x 2″x 3′ part is 2.82 [30]. Cost for one horizontal 2″ x 12″ x 12′ horizontal part is 28.12 [30]. Total cost for railing is $73.16

Steps for bridge

Assuming steps are just a vertical wall to simplify calculations. Are 1.5′ x .5′ x 4′ (top of FDL is 3′ from ground and want bridge to be 1′ above FDL). Total of nine 2″ x 4″ x 4′ needed for one side. Cost for one 2″ x 4″ x 4′ is $4.68 [33]. Total cost for stairs is $84.24

Stain

2 gallons stain. Cost for one gallon is $41.98 [34]. Total cost for stain is $83.96

Manifold

Length of pipe needed

12′ (FDL length) + 6*1′ (length above FDL). Cost of 12.6″ long 2″ diameter Stainless Steel tube is $89 [35]. Total Cost of piping is $1620

Elbow Pipes

6 (One for every FDL) + 2 (ends of manifold) +1 (last turn to vacuum pump). Cost of one elbow is $96 [29]. Total Cost for elbows $864

Tee sections

4*1 (for 4 interior FDL pipes) + 1 (connection to final vacuum line that runs to pump) Cost of one Tee is $146 [36]. Total cost for tees is $730

Bellows needed

6*1 (one for each FDL). Cost of one bellows is $123 [37]. Total cost for bellows is $738

Pressure Valves

6*1 (one for each FDL). Cost per valve is 0 as they will be reused

Total Material Cost is 253.08+73.16+84.24+1530+864+730+738

= <u>$4446.44</u>

Ribbon Cable Interconnect

Manifold

Ribbon Cable Connection

Needs to be built by the team. Size of steel is .25in .5in 1ft. Cost for one 1/4" x 1/2" x 1' CF-1018 Steel Flat Bar is $8.93 [38]. Total cost for connection is $8.93

Pipe Cost.

12′ (FDL length) + 6*1′ (length above FDL). Cost of 12.6″ long 2″ diameter stainless steel tube is $89[35]]. Total Cost of piping is $1620

Elbow Pipes

6*1 (one for every FDL) + 1 (for the end furthest away from pump). Cost of one elbow is $96 [29]. Total Cost for elbows is $672

Tee sections

5*1 (one fore each FDL expect last one). Cost of one Tee is $146 [36]. Total cost for tees is $730

Bellows needed

6*1 (one for each FDL). Cost of one bellows is $123 Total cost for bellows is $738

Pressure Valves

6*1 (one for each FDL). Cost per valve is 0 as they will be reused

Total Material Cost is 8.93+1620+672+730+738

= <u>$3408.93</u>

Back Extension to Sid-Lab

Manifold

Pipe Cost.

12′ (FDL length) + 6*1′ (length above FDL). Cost of 12.6″ long 2″ diameter stainless steel tube is $89 [35]. Total Cost of piping is $1620

Elbow Pipes

6*1 (one for every FDL) + 2*1 (extra one for each end) Cost of one elbow is $96 [29]. Total Cost for elbows is $768

Tee sections

4*1 (for 4 interior FDL pipes) + 1 (connection to final vacuum line that runs to pump) Cost of one Tee is $146 [36]. Total cost for tees is $730

Bellows needed

6*1 (one for each FDL). Cost of one bellows is $123 [37]. Total cost for bellows is $738

Pressure Valves

6*1 (one for each FDL). Cost per valve is 0 as they will be reused

Total Material Cost is 1620+672+730+738

= <u>$3856</u>