NOPI Vacuum Manifold

Final Report

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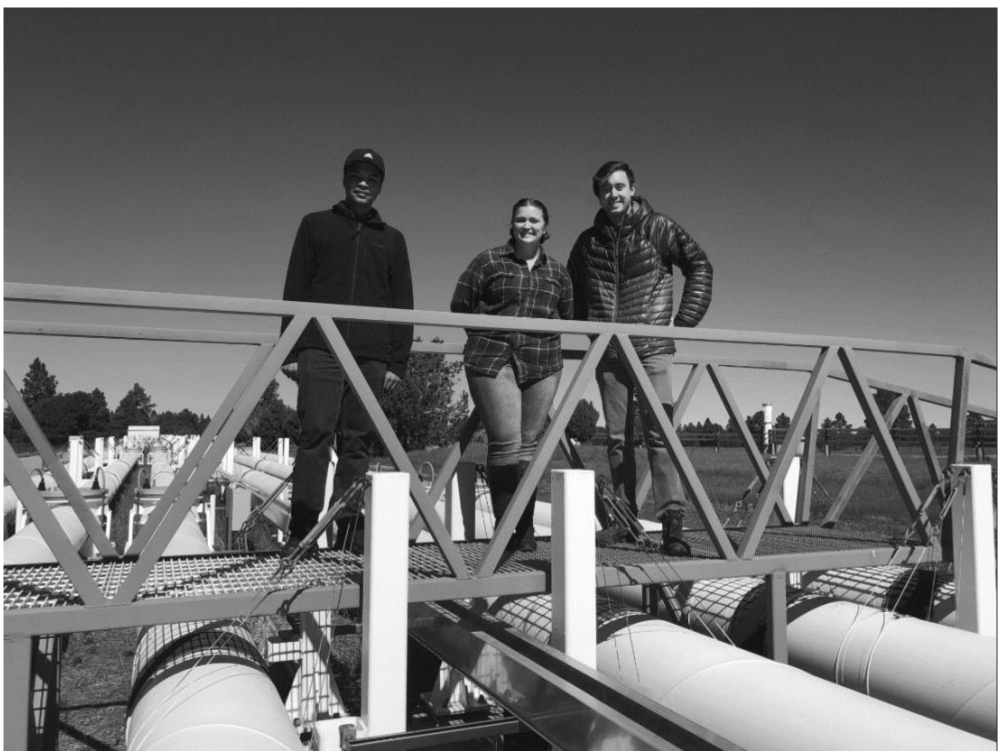

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DISCLAIMER

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EXECUTIVE SUMMARY

The Navy Precision Optical Interferometer (NPOI) Capstone team was created due to concerns over the projected service life of the previous Fast Delay Line (FDL) vacuum manifold system. The expected failure point of the original manifold was the vertically positioned bellows which were subjected to loading conditions beyond what they were originally designed to withstand. These loads were expected to eventually lead to a tear in the thin walls of the bellows which would have caused air to disperse into the FDL tank potentially leading to the destruction of the optical equipment inside. Due to this looming threat the purpose of the team was to redesign, implement, and test a new vacuum manifold for the FDL's at NPOI. The parameters that the team had to follow as requested by the client is that the new manifold would be safe, reliable, repairable, built within budget, be easy to use (i.e., no need for new employee training), and allow for future project integration. In addition, part of the design requirement was to move where the manifold connected to the FDL tanks such that they would no longer attach to the "snoot" of optics pipe. These expectations from our client were used to define the engineering characteristics that are design would follow. These engineering requirements were used when initially choosing the design of the manifold from the concepts that were generated. The final design that resulted after concept evaluation and multiple design iterations was that the manifold connected to the FDL tanks via the ribbon cable interconnect. To do this a custom interface was designed, after several iterations, by the team to connect the standardized parts of the rest of the manifold to the custom ribbon cable. From this connection point of the interface two different sections combined to make the resulting manifold segment. The first segment is where the electrical connections were put onto the manifold. This involved using a cross shaped pipe with electrical military shell connectors on either side to allow for the interface of electrical components. As part of this system, extensions were added to where they would be attached to allow for room inside the cross pipe to house both sets of cables. Next to this cross pipe there was a small valve that connected to the pressure sensor used for that specific FDL tank. The other part of the manifold involved the larger isolation valve as well as the piping that connected each of the manifold segments together. In this section, bellow pipes were used to account for the spatial variations between each of the FDL tanks. The final piece of the manifold involved the piping that would connect the manifold to the vacuum pump array at NPOI. This was done by cutting a piece of steel tubing to size and then connecting it to a pipe of the same diameter that had a vacuum rated quick flange at one end of it. Combing these two pipe sections was accomplished by using a neoprene hose to cover the spot where the pipes touched and then clamping the neoprene hose with four worm drive clamps to ensure a vacuum seal. After installing this system multiple tests where run to validate our design. This included ensuring that new ribbon cables were all continuous and where able to move the FDL carts as specified, testing the vacuum capabilities of manifold, and determining the time needed to preform basic maintenance. The manifold passed each of these tests and in some cases even exceeded expectations. The manifold achieved a vacuum that is 10 times better than the previous record and was able to hold an operational vacuum for seven days without the help from the vacuum pumps beating the previous record by two days.

ACKNOWLEDGEMENTS

Thank you Khristian Jones for the aide in the construction and testing of electrical components within the vacuum manifold system.

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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.

The "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 previous structure was outdated and failing. If it were to 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.

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."

2 REQUIREMENTS

This section of the report outlines the requirements that our design must meet based on the given customer requirements (CR). This is done by creating engineering requirements (ER) to match to the CRs and by utilizing a House of Quality to rank these ERs in order of importance relative to the CRs. Additionally, the function of the manifold was discretized to showcase the many subsystems that are needed for the manifold to function correctly. Finally, the codes and standards that our manifold should abide by are also addressed.

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 braided 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 process.

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 process.

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 process.

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 process.

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 process.

2.2 Engineering Requirements (ERs)

To account for our client's desire for safety in our system, it was decided that all applicable aspects of our system would need to have a factor of safety (FS) of 2.5 ± .5. This includes the loading capabilities of our system as well as the vacuum rating of the parts that were going to be purchased from third party vendor's. Although this is smaller than that of other systems at NPOI it was deemed acceptable by the client due to the limited budget for the project.

Regarding the budget expectation, the team accounted for this by tracking the total project cost. The plan was that the manifold would cost $10000 ± $4000 with most items being off the shelf to reduce costs.

Both reliability and repairability were accounted for by minimizing the downtime of the manifold. The goal was to have the regular maintenance of the manifold be 2 ± 1 hour for a disassembly and reassembly of the system.

For the manifold to be reliably it would also be expected to maintain vacuum if the vacuum pump arrays shutdown. Our expectation was that the leak rate of our vacuum manifold would be such that it could keep an operational vacuum for 5 ± 1 day without pump assistance. This would ensure that our manifold would have at least the same capability as the previous system.

2.3 Functional Decomposition

2.3.1 Black Box Model

To understand what goes into our system, 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 1 below. Since the beginning of the project more valves were added and as such the final black box model includes an Open/Closed signal now.

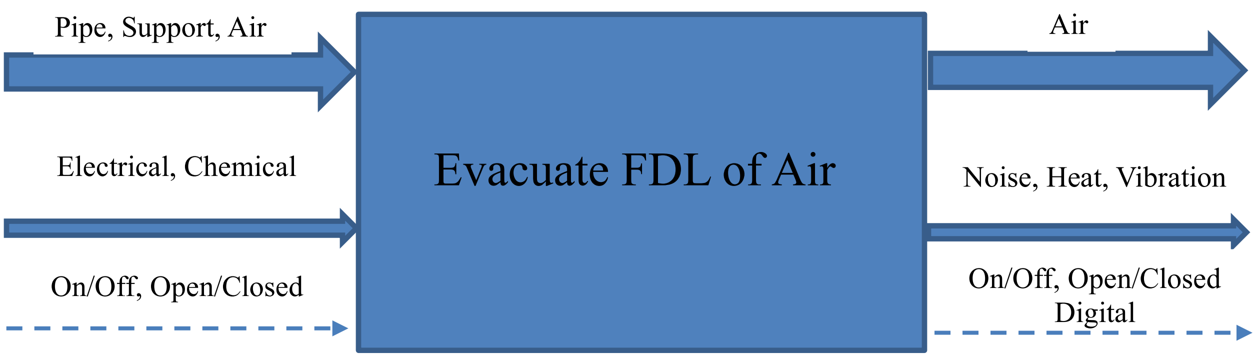

Figure 1: Black Box Model for Vacuum Manifold

2.3.2 Functional Decomposition

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 below. A change that has occurred was the addition of a control valve for the pressure sensor. This was done in accordance with a request of the client to have each pressure sensor be able to be removed from the FDL tanks without compromising the vacuum. An additional change to the decomposition was the addition of the FDL carts because are design takes an active role in electrical communication within the FDL tanks.

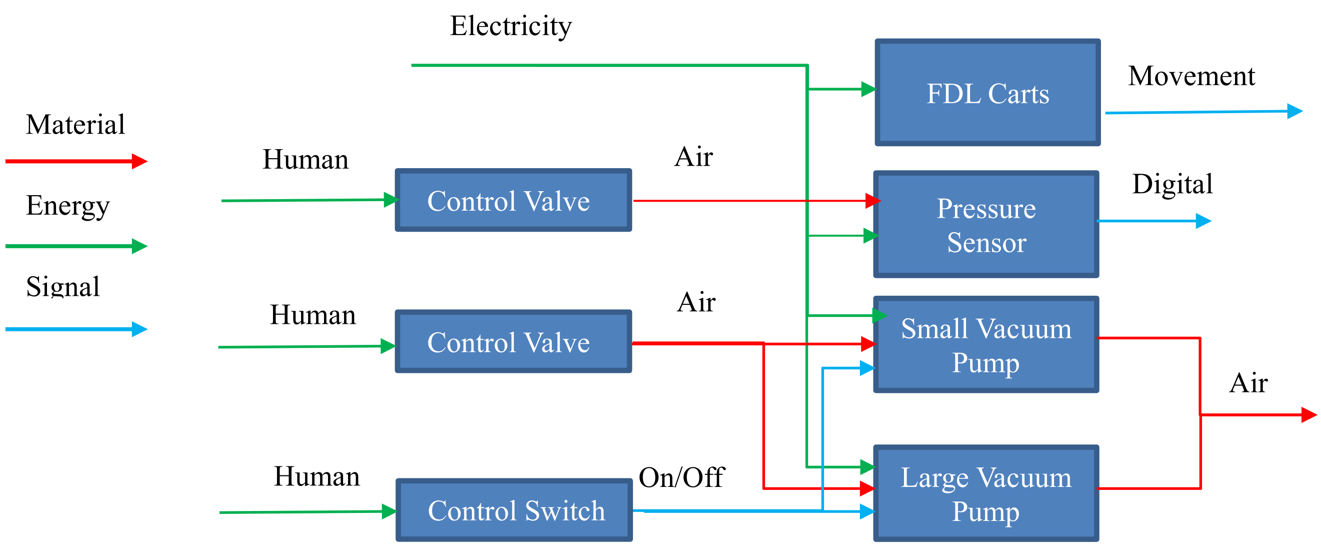

Figure 2: Function Decomposition for Vacuum Manifold

2.3.3 Hierarchical Task Analysis

A hierarchical chart was created to show the breakdown of the vacuum manifold system to its lowest manageable parts. This was done 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 3. Because our final design utilized the electrical cable passthrough the operation of the FDL carts was added.

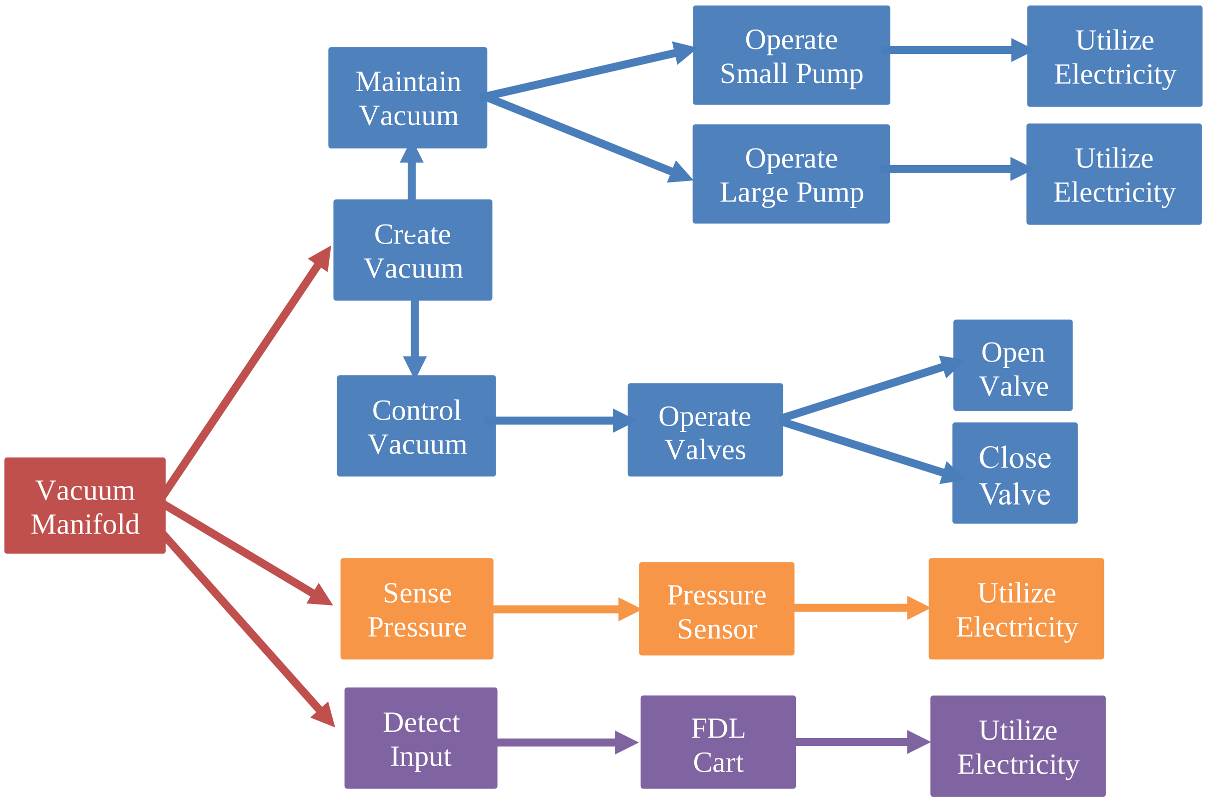

Figure 3: Hierarchical Chart of Vacuum Manifold

2.4 House of Quality (HoQ)

As mentioned previously there were a total of seven CR's and four ER's. To evaluate which engineering requirement had the highest technical importance to this project regarding satisfying the customer requirements, a house of quality (HoQ) was used to compare them. For each CR there was a weight assigned to them based on their importance to our client. The final weights were that safety had a 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 factors of safety, followed by project cost and finally minimize downtime.

The three systems that were used to benchmark against the previous manifold system are the Laser Interferometer Gravitational-wave Observatory (LIGO), the Vacuum Tower Telescope (VTT), and the 1-meter Swedish solar telescope (SST). These three systems were used as benchmarks because they utilize vacuums systems to gather observation data. Technically none of these comparisons are a perfect match to NPOI, however they offer decent compressions on how other vacuum systems operate in the world. The completed house of quality can be seen in appendix A.

2.5 Standards, Codes, and Regulations

As engineering students it's important that our design holds to accepted standards in industry. The standards that directly apply to our project our shown in Table 1.

Table 1: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it Applies to Project**
ISO 19685:2017	Specifications, calibration, and measurement uncertainties for Pirani gauges	The pressure gage used on the six FDL tanks are a Pirani gage. It is important they are calibrated correctly to provide accurate data for NPOI.
ISO 2861:2020	Dimensions of clamped-type quick-release couplings	Clamps are used throughout the manifold to attach adjoining pieces.
ASME Y14.5 - 2018	Dimensioning and Tolerance	Drawing sheets may be looked at in the future if one of the custom-built parts fails.
ASME P-15.7	Code of Ethics Engineers	It's a policy all engineers should follow in ever project.

Because the data boxes that are used to record the pressure from the gages are calibrated to the old sensors, each Pirani pressure gage that the team has, will have to be recalibrated with the boxes to ensure the correct data is being collected. In order to do this correctly the team will have to follow ISO 19685:2017 as these details how to properly calibrate the gages we have. Failure to properly calibrate the gauges can lead to the emergency shutoff system of NPOI prematurely activating or causing lost observational time due to incorrect readings above operational values.

ISO 2861:2020 is another important guideline to follow because every standard section of pipe that is used in our manifold needs to be clamped with a quick-release style of coupling. Although are team will not be making the clamps, it is important that we verify that the clamps that we order fall within the standards set to ensure that they work properly. Proper verification of the clamps ensures that the joints of the manifold are not able to have large leaks allowing for longer operation without vacuum pumps on as well as ensuring that the vacuum pumps can be run at lower RPMs during normal operation.

Because our manifold utilizes several custom parts in its design, their dimension and tolerances needed to be documented. For this reason, ASME Y14.5 – 2018 is used to ensure that each part follows the established guidelines allowing for the recreation of these parts in the future should they ever need to be replaced.

The final code that our team must follow is ASME P-15.7. This is the general engineering code of ethics that should always be used (in some variation depending on the organization) when working on a project. This applies to us too because are project can have real consequences if we fail to follow these practices.

3 DESIGN SPACE RESEARCH

3.1 Literature Review

Three areas of importance were investigated by the team when researching for our vacuum manifold. This included material/pipe selection, safety, and vacuum operation. Because of the limited budget the team was operating with, the material that was chosen would have to be resilient to various forces while at the same time being suitable for vacuum applications. To choose the correct material, chapter 8 of the book *Vacuum Physics and Technology* [2] by Y. Shapira and D. Lichtman was used. This book went into detail about the various materials that can be used in vacuum system and the inherent flaws that each material has. To better understand how to effectively use bellows and ensure their proper loading *Metal Expansion Joints and Metal Bellows* [3] by MACOGA Engineered Expansion Joint was used as reference. To determine the most effective vacuum flange to use for our system an outline by Kurt J. Lesker Company called *Flange System Overview* [4], was used. Additionally *Valves Technical Notes* [5] from Kurt J. Lesker Company was also used to determine the appropriate isolation valve to use on the FDL tanks. As safety is an important customer requirement *Formal Methodology for Safety-Critical Systems Engineering at CERN* by F. Valentini [6], *CERN Accelerating Science: Safety Training* [6], and *LIGO Caltech 40 Meter Laboratory Laser Safety Plan* by Alan Weinstein [7] were used for safety information on more powerful vacuum systems.

3.2 Benchmarking

3.2.1 System Level Benchmarking

3.2.1.1 Existing Design #1: Laser Interferometer Gravitational-Wave Observatory (LIGO)

The two LIGO locations utilize two 4km arms to do observations as shown in Figure 4. These arms have a volume of $2*10^7$ L that is keep at a 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 no trapped gases inside the metal that would leak out. Once this process was completed, they could use a combination of turbo-pumps and ion pumps to remove the air from the tubes [8]. 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 larger 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 into the foreseeable future.

Figure 4: The Two LIGO Locations [9]

3.2.1.2 Existing Design #2: Vacuum Tower Telescope (VTT)

The VTT is designed to study the sun. Using two pivoting mirrors on the roof of the tower, they capture the sunlight [10]. 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 [11]. A picture of the overall design of the VTT can be seen in Figure 5 below.

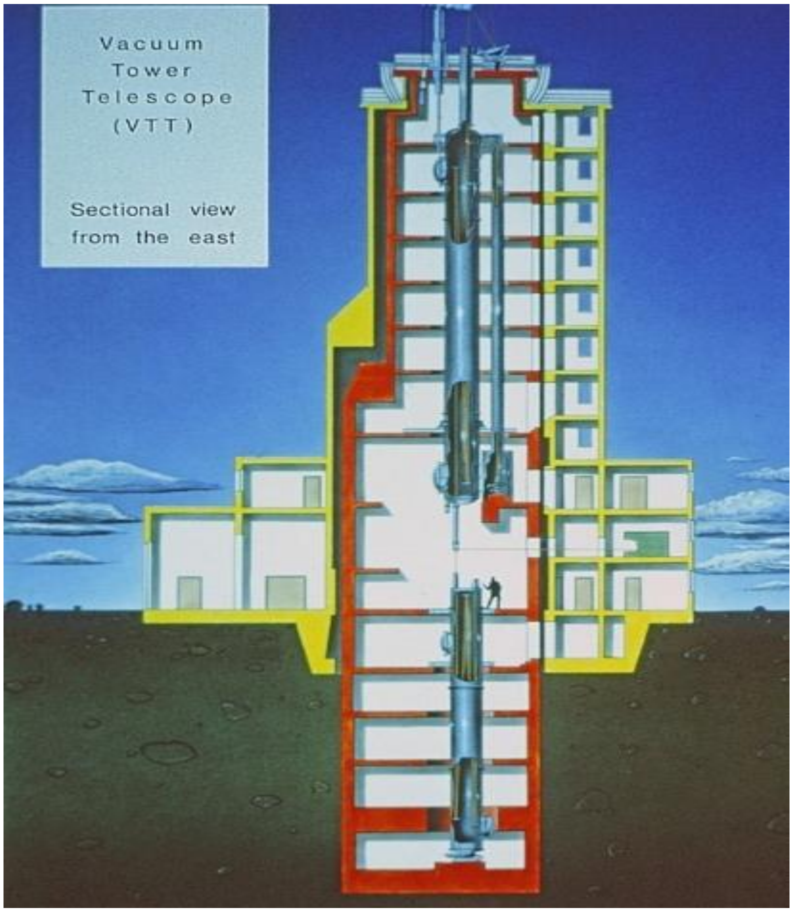

Figure 5: Layout of VTT [10]

3.2.1.3 Existing Design #3: 1-meter Swedish solar telescope (SST)

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 [12]. 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. Below in Figure 6 is a diagram of the SST.

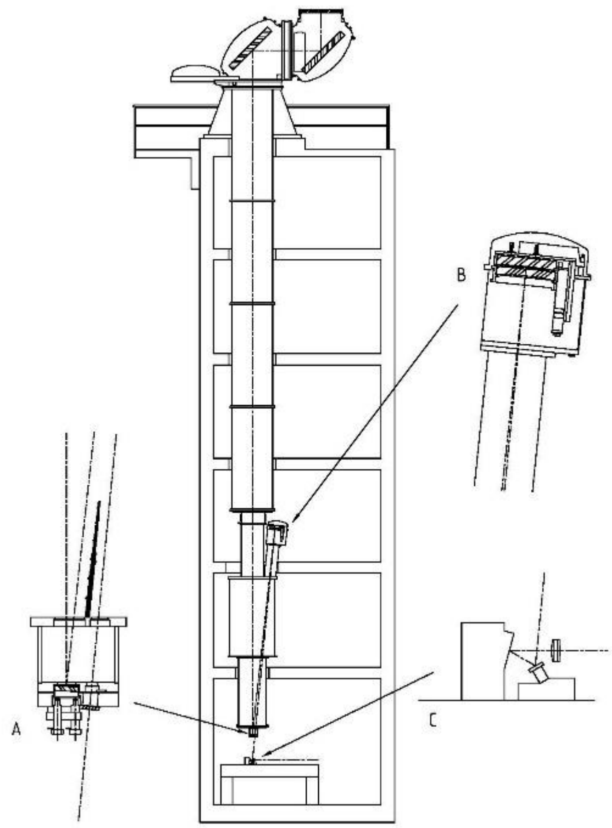

Figure 6: Layout of 1-meter SST [12]

3.2.2 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 subcomponents. This section of the report outlines research conducted by the capstone team regarding these critical components.

3.2.2.1 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.

3.2.2.1.1 Existing Design #1: Gate Valve

Gate vales, shown in **Error! Reference source not found.**, 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 access to the rest of the vacuum system. When the seal is moved out, fluid can move freely. Gate valves are rated to hold 10^{-8} Torr [13].

Gate valves are used on some components at NPOI. The design of a Gate valve allows light to pass directly through 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. 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 which the Gate valve cannot do.

Figure 7: Gate Valve [13]

3.2.2.1.2 Existing Design #2: Angle Valve

Vacuum rated angle valves, shown in 18, 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 and orientation of the valve is important as it can leak if more than 15 psi is applied as backpressure against the seal [14].

Angle valves are used in the current manifold system and the client offered to let the Capstone team utilize them. The diaphragm design can 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.

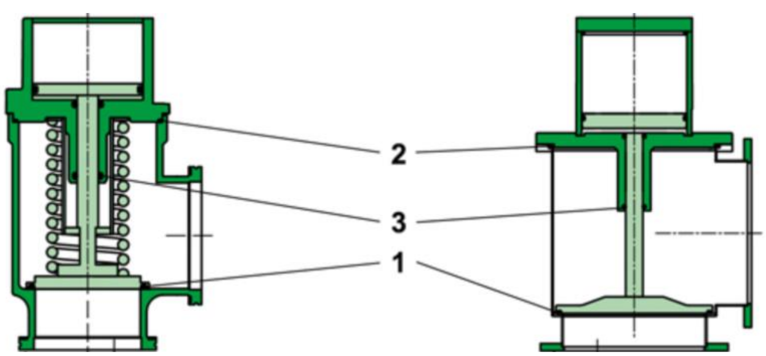

Figure 81: Angle Valve

3.2.2.1.3 Existing Design #3: Butterfly Valve

The Butterfly valve or Soft Start Valve, shown in 2, is commonplace 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 can 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 can reduce the pipe cross section by 99% and will not operate in a backflow application [15].

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.

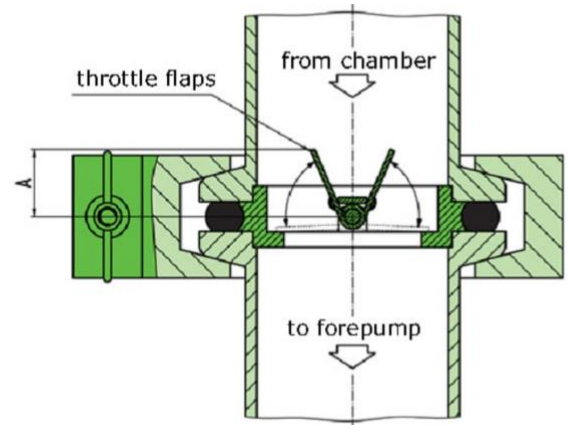

Figure 2: Butterfly Valve [15]

3.2.2.2 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.

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

The ConFlat flange design, shown in **Error! Reference source not found.**10, 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 [16]. 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. However, the majority of NPOI components utilize a different flange type. Introducing a new style of connection would increase the complexity of NPOI headwear.

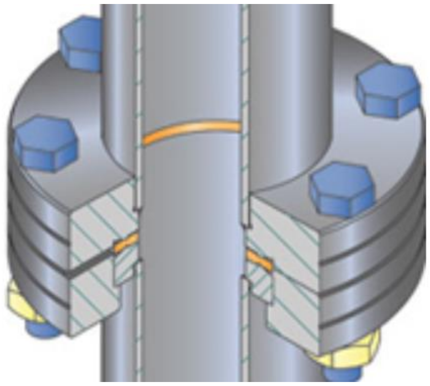

Figure 10: CF Flange [16]

3.2.2.2.2 Existing Design #2: Quick Flange

The Quick flange, shown in Figure 11, is a style of vacuum connection 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 wing-nut, the flanges are pressed together and squeeze the suspended O-ring. The O-Ring limits the operational temperature range from 0-180 degrees Celsius [17]. Additionally, the KF flange connection is rated at 10^{-8} Torr [17], 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.

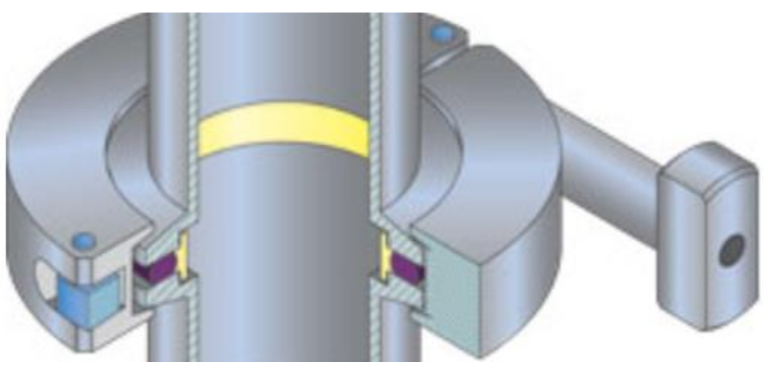

Figure 11: KF Flange [17]

3.2.2.2.3 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.

3.2.2.3 Subsystem #3: Manifold Pipes

3.2.2.3.1 **Existing Design #1: LIGO 4km Pipes**

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 traveling clean room. With the way it was designed it tubes are meant to never be vented [18]. 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.

3.2.2.3.2 Existing Design #2: The Center for High Angular Resolution Astronomy (CHARA) Array Light Pipe Vacuum System

CHARA is an optical interferometer based roughly on the designs made from NPOI that operates its vacuum system with 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 [19]. 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.

4 CONCEPT GENERATION

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.

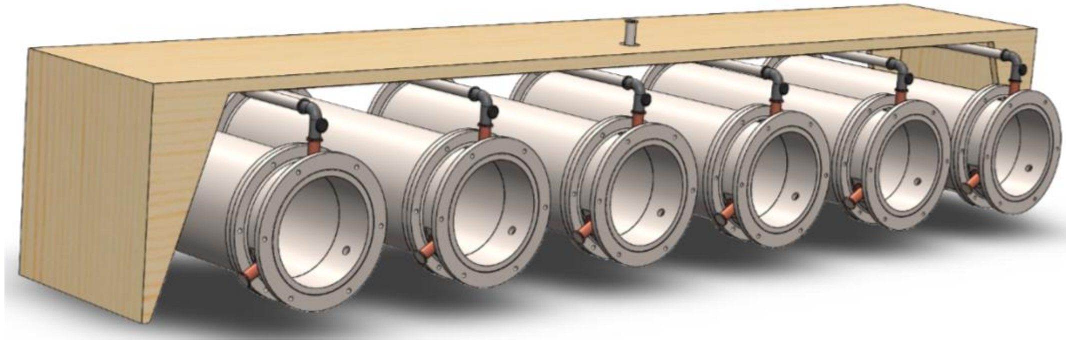

Figure 33: Solidworks Model Based on Design One.

The advantages of this design are reduced vibrations by connecting the bridge to isolated concrete slabs on either side of the FDLs, storage for the extension and end plates when doing maintenance and an extra port for future projects. Additionally, 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 capable 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 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 model created for this design can be seen in 414, below.

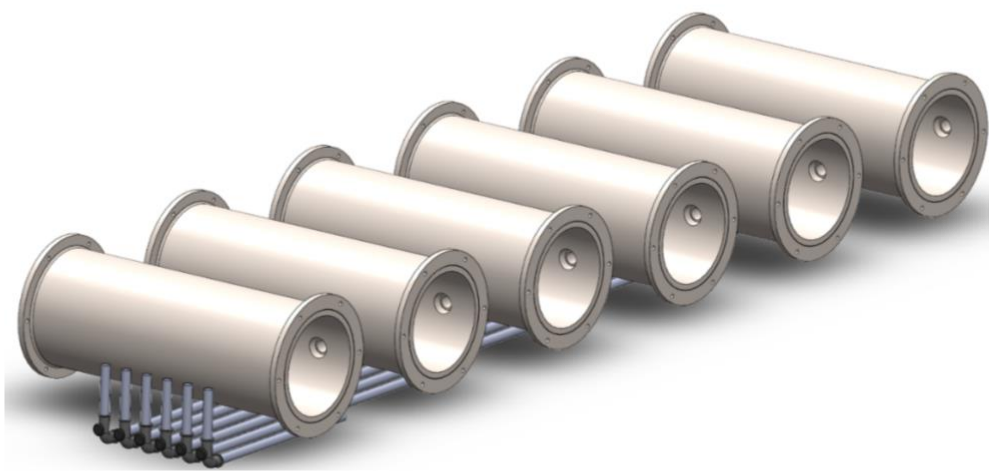

Figure 44: Solidworks Model Based on Design Two.

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 disadvantage to this concept 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. Finally the length of the pipes will cause the FDL tanks furthest away from the vacuum pump to generate their vacuum slower due to the greater distance that any air particles will have to travel to be removed from the system.

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

The design would be reusing the same adapter as the 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 model for this concept is shown in Figure 15 below.

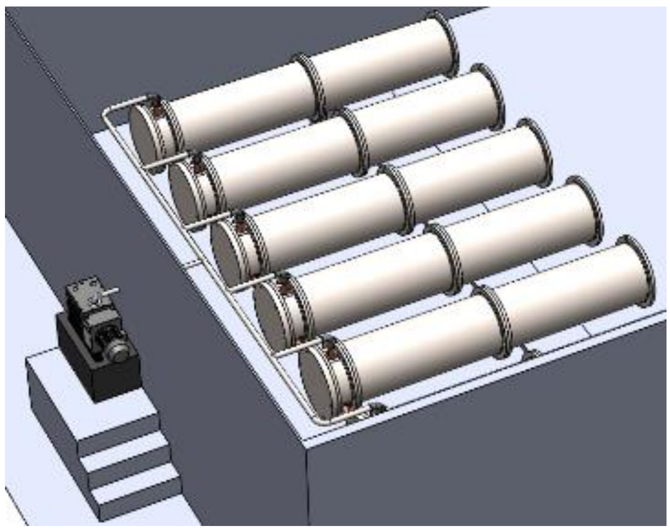

Figure 55: Solidworks Model Based on Design Three with Turbo-pump Model [20]

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 Small Scale 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 guide final design generation.

4.2.1.1 Design #1: Apex Manifold

This design, featured in **Error! Reference source not found.**6, 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.

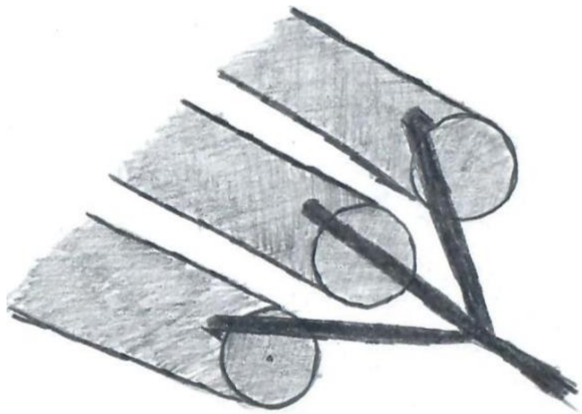

Figure 16: Apex Manifold

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 a 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 17, 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.

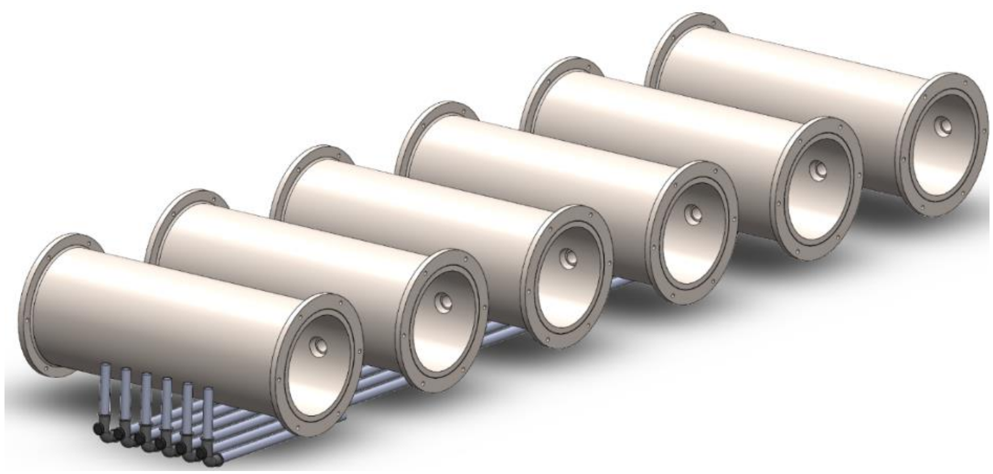

Figure 176: Concept Variant Long manifold pipes suspended under the FDL tanks to a bank of valves

This design has two advantages 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 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 design two above. Unlike that concept 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 the pressure valves on one side for convenience like design two. This design is shown in Figure 78 below.

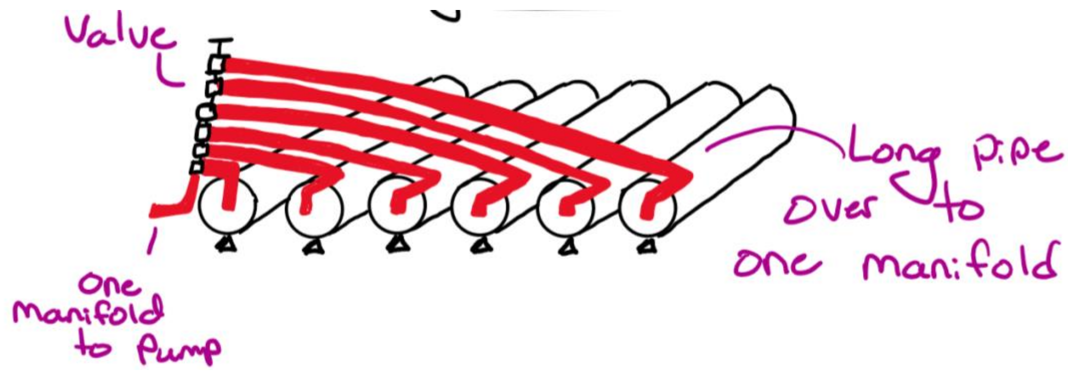

Figure 78: Long Pipes to One Side Over FDL

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 19, 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.

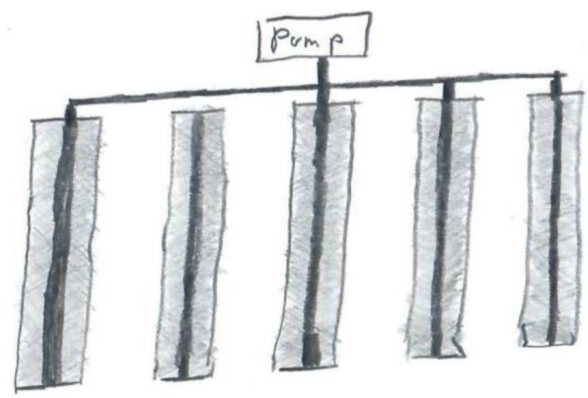

Figure 8: Manifold in Front Pump in Back With long pipes

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 with the vacuum pump being lower to the ground it makes it easier to perform routine maintenance on it. The disadvantage to this design is the large amount of piping needed and the cost associated with that.

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

This design, **Error! Reference source not found.**20, 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.

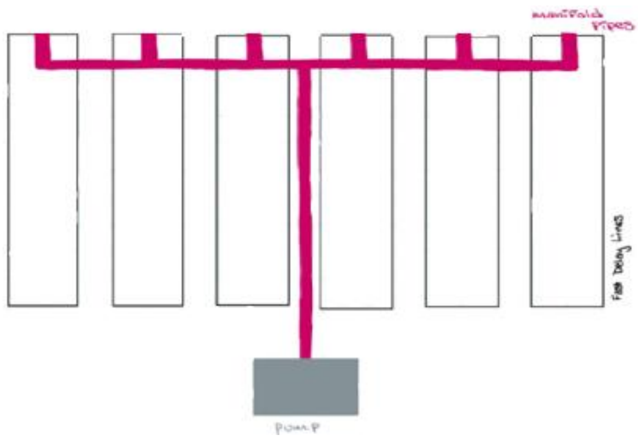

Figure 20: Manifold in Front Vacuum Pump In Back

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 21, we would remove the current connection of the vacuum manifold to the FDL's 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.

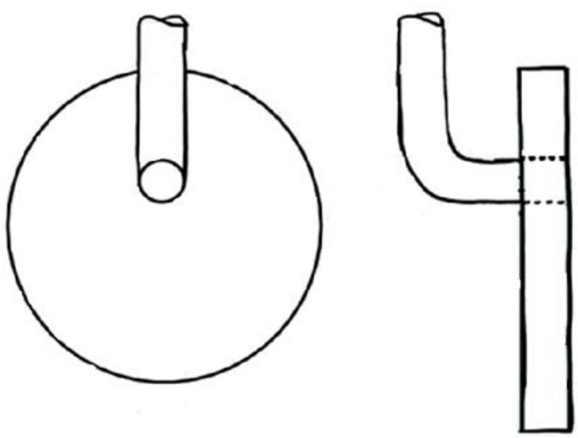

Figure 219: Simple Front plate

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, shown in Figure 22, each of the FDL lines would be attached to their own vacuum pump. These vacuum pumps would be attached to the back of the FDL and would be placed on rubber isolators.

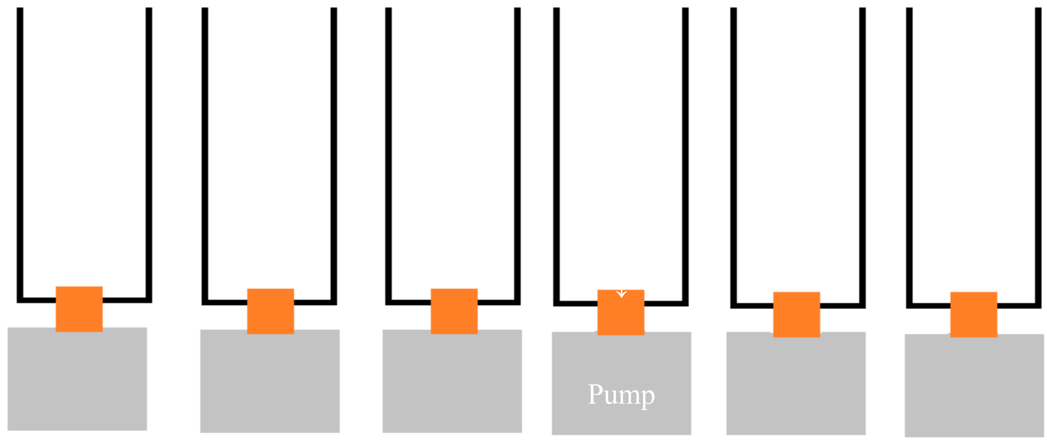

Figure 103: Pumps For Each FDL

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 11. 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.

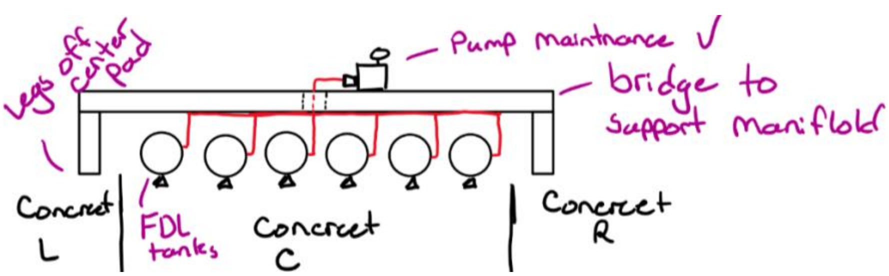

Figure 113: Front with support bridge

4.2.1.9 Design #7: Giant Lung

Error! Reference source not found.Error! Reference source not found.4 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 investigated 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.

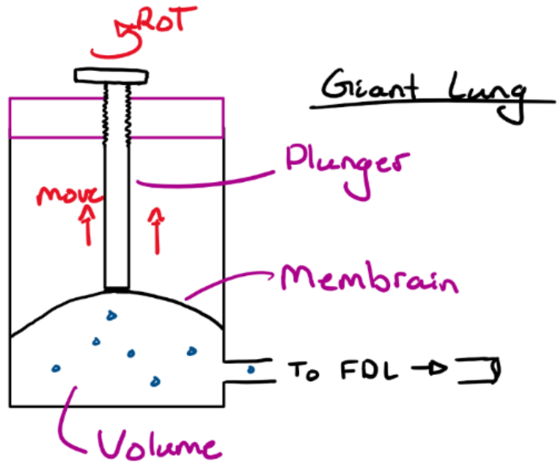

Figure 24: Giant Lung

5 DESIGN SELECTED – First Semester

This section contains the process that was used by the team to decide on the top design from the previous sections. In addition, this section also contains the rationale used to justify the designs that was 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 CRs were used to evaluate the designs because the client needs are of great importance and if a design fails to meet those CRs there is no point in evaluating them in reference to the ERs. The CRs that were used to evaluate the different concepts were safety, cost, reliability, ease of use, and future project integration. The first four listed CRs 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 ERs from the HoQ. The ERs 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 ERs were chosen as they represent some of the more important CRs that they were derived from. The weighting was chosen such that 40% would be with the two cost ERs 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. 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 CRs 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 2 below. The concepts go in order of how they were presented in Sections 4.1, 4.2.

Table 2: 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	+	-
∑+						3				
∑-	4	1	4	1		0	0	0	1	0
∑S	1	1	0	2		0	1	1	2	5
Total	0		1	2		5	4	4	2	0

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 concepts then went into our decision matrix using the previously mentioned ERs. The complete decision matrix can be seen in Table 3 below. For the two cost criterion, lower numbers indicate that the design would cost more.

Table 3: Decision Matrix

Criterion	Weight	Back Extension with Bridge RAW	Back Extension with Bridge WEIGHTED	Ribbon Cable Interconnect RAW	Ribbon Cable Interconnect WEIGHTED	Back Extension to Sid-Lab RAW	Back Extension to Sid-Lab WEIGHTED
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 like pressure sensors, valves, cables, etc. For the back extension the reliability was rated an eight because the vacuum pump was moved onto the bridge making it easier to maintain. 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 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 Initial CAD Model

Based on the top design the team created a 3D CAD model of the idea. To generate this CAD design the team took Engineering schematics of the existing NPOI FDL system and dimensionally accurate CAD components provided by Kurt J. Lesker Compony. Using Solidworks the team generated a dimensionally accurate (according to provided FDL schematics) CAD model shown in Figure 25.

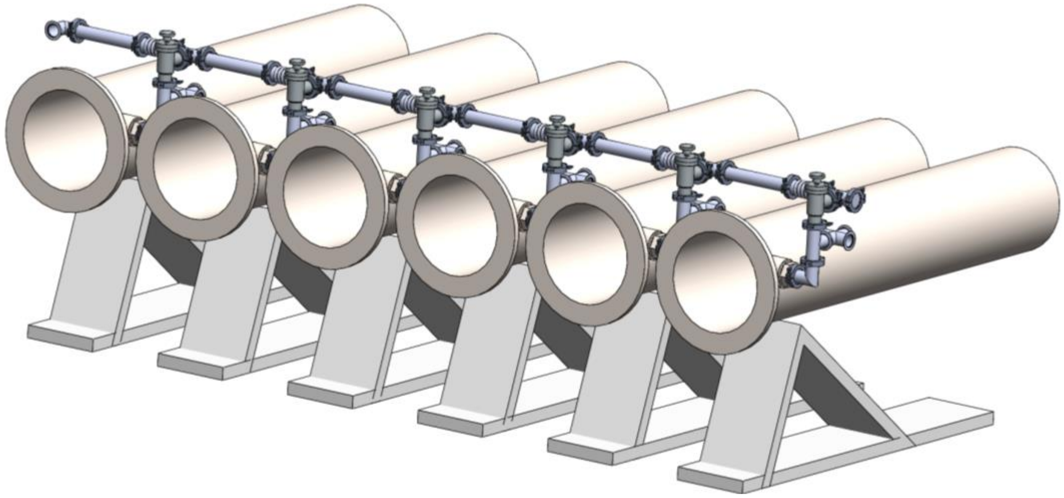

Figure 125: Isometric View Of Initial CAD Model

Figure 26 shows the front on view of the model. This image illustrates the compact design of the vacuum manifold and highlights some potential challenges in its assembly. The distance between the FDLs require the use of a 90° miter elbow fitting. The QF50 flange connection allows the team to assemble the structure despite the tight geometry. Additionally, the QF50 flange allows the rotation of each vertical section of the manifold to align with the top portion where other flange types would limit this ability.

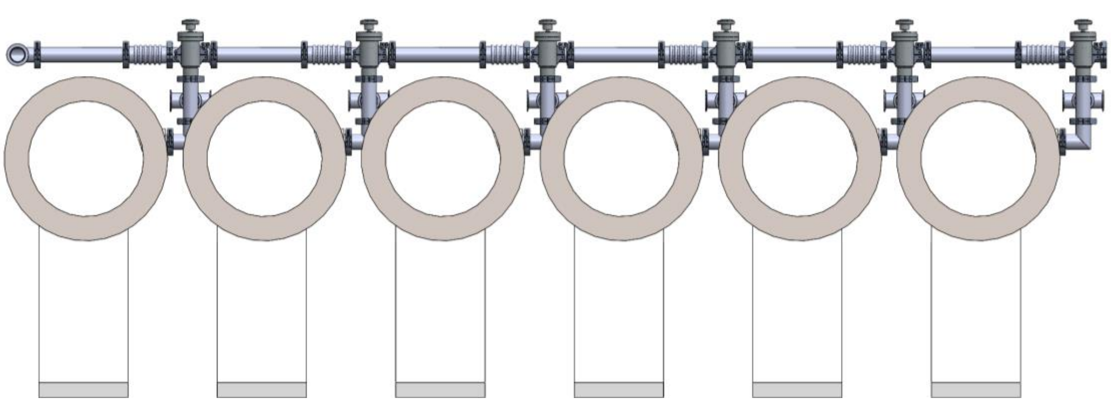

Figure 26: Front View Leading CAD

Figure 27 gives a close-up perspective of FDL 6 manifold connection. The top section of the manifold leads to the vacuum pump. A 90° valve is installed such that an isolated connection can be made to the individual tanks. Sine the team is consuming the existing electrical feed throughs, 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. This image also shows the implementation of a bellows to compensate for pipe misalignment, differences in the as built 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 of the system.

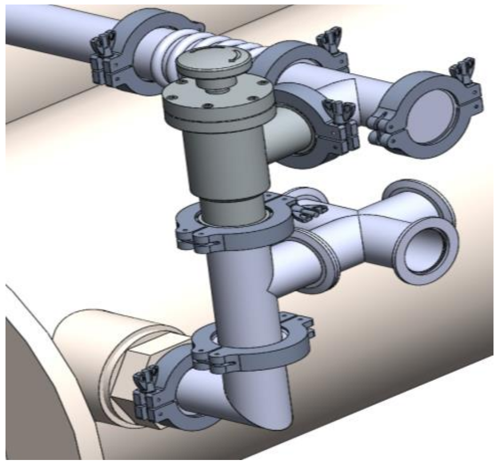

Figure 137: Isometric Close Look Leading CAD

5.4 Design Prototype

The initial prototype of part of our design is shown in Figure 28.

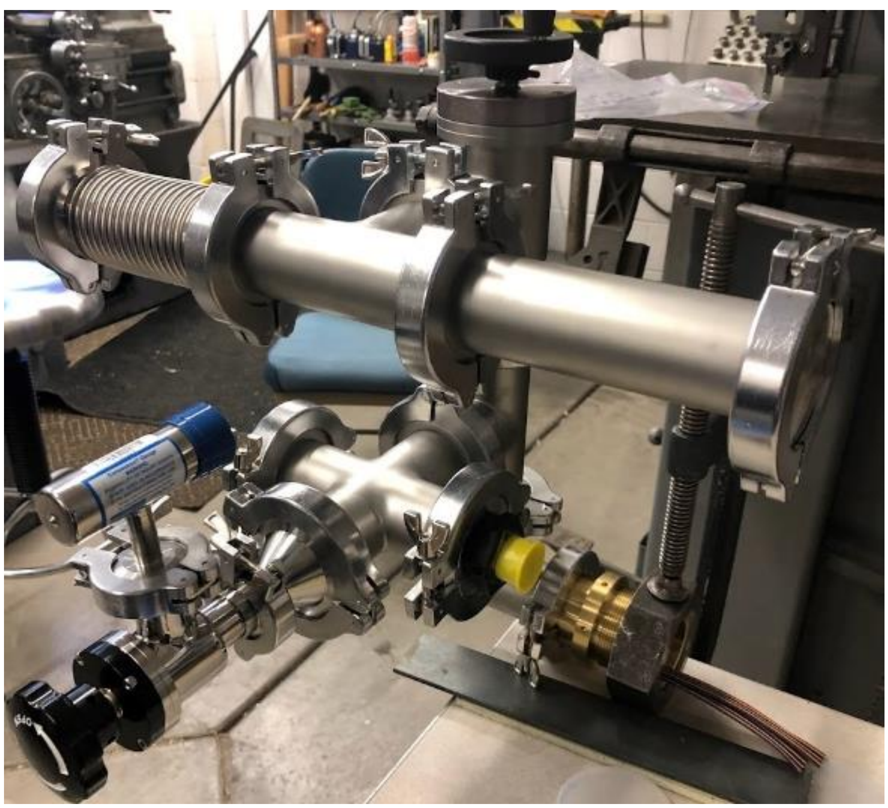

Figure 28: Prototype of One Section of The Manifold

This prototype demonstrated that the brass interface was able to hold the whole manifold in place without any rotation occurring. The team also worked on the method that would be used to "fish" the connectors through the various pipes when they would be installed onto the manifold. In the process of making this method to "fish" the connectors it was also discovered that there was not enough room inside of the cross pipe to hole both electrical connectors. This was solved by adding extensions to the electrical connection pieces on the outside to allow for more room on the inside of the cross.

6 Project Management – Second Semester

6.1 Gantt Chart

Figures 29-31 shows the Gantt chart that was used by the team from January 10, 2022, till May 5, 2022.

NPOI Vacuum Manifoild		For All	For Wyatt	For Cydny	For Alex
		On Track	On Track	On Track	On Track
		At Risk	At Risk	At Risk	At Risk
Project Start Date:	1/10/2022	Behind	Behind	Behind	Behind
		↑ Chart Legend↑			

Milestone description	Category	Assigned to	Progress	Start	End
Project Management Assignment	On Track	All	100%	1/10/2022	1/14/2022
Individual Analysis or Self Learning	On Track	Wyatt	100%	1/10/2022	1/26/2022
Individual Analysis or Self Learning	On Track	Cydny	100%	1/10/2022	1/26/2022
Individual Analysis or Self Learning	On Track	Alex	100%	1/10/2022	1/26/2022
Mill Blanking Plates For 1st Manifold	On Track	All	100%	1/15/2022	1/21/2022
Assembly Electrical parts for 1st Manifol	On Track	All	100%	1/15/2022	1/21/2022
Finish 2nd Brass Interface	On Track	All	100%	1/21/2022	1/29/2022
Mill Blanking Plates For 2nd Manifold	On Track	All	100%	1/21/2022	1/29/2022
ssembly Electrical parts for 2nd Manifo	On Track	All	100%	1/21/2022	1/29/2022
Assembly Completed Second Manifolc	On Track	All	100%	1/29/2022	3/25/2022
Combine 1st and 2nd Manifold	On Track	All	100%	2/4/2022	2/9/2022
Hardware Status Update - 33+%	On Track	All	100%	2/4/2022	2/11/2022
Machine 3rd Brass Interface	On Track	All	100%	2/11/2022	2/18/2022
Mill Blanking Plates For 3rd Manifold	On Track	All	100%	2/11/2022	2/18/2022
ssembly Electrical parts for 3rd Manifol	On Track	All	100%	2/11/2022	2/18/2022
Assembly Completed 3rd Manifold	On Track	All	100%	2/11/2022	3/25/2022
Website Cheeck #1	On Track	All	100%	2/14/2022	2/25/2022
Machine 4th Brass Interface	On Track	All	100%	2/18/2022	3/1/2022
Mill Blanking Plates For 4th Manifold	On Track	All	100%	2/18/2022	3/1/2022
ssembly Electrical parts for 4th Manifol	On Track	All	100%	2/18/2022	3/1/2022
Assembly Completed 4th Manifold	On Track	All	100%	2/18/2022	3/25/2022
Hardware Status Update - 67+%	On Track	All	100%	2/25/2022	3/4/2022
Machine 5th Brass Interface	On Track	All	100%	3/4/2022	3/11/2022
Mill Blanking Plates For 5th Manifold	On Track	All	100%	3/4/2022	3/11/2022
ssembly Electrical parts for 5th Manifol	On Track	All	100%	3/4/2022	3/11/2022
Assembly Completed 5th Manifold	On Track	All	100%	3/4/2022	3/25/2022
UGRAD's Registration	On Track	All	100%	3/7/2022	3/11/2022
Machine 6th Brass Interface	On Track	All	100%	3/11/2022	3/18/2022
Mill Blanking Plates For 6th Manifold	On Track	All	100%	3/11/2022	3/18/2022
ssembly Electrical parts for 6th Manifol	On Track	All	100%	3/11/2022	3/18/2022
Assembly Completed 6th Manifold	On Track	All	100%	3/11/2022	3/25/2022
Finalized Testing Plan	On Track	All	100%	3/18/2022	3/25/2022
Finish Final Section of Mnaifold	On Track	All	100%	3/18/2022	3/25/2022
Hardware Status Update - 100% Build	On Track	All	100%	3/18/2022	3/25/2022
Draft Of Poster	On Track	All	100%	3/25/2022	4/1/2022
Final Poster/PPT	On Track	All	100%	4/1/2022	4/7/2022
Initial Testing Results	On Track	All	100%	4/1/2022	4/8/2022
Final CAD Packet	On Track	All	100%	4/8/2022	4/15/2022
Operation/Assembly Manuel	On Track	All	86%	4/8/2022	4/15/2022
Product Demo and Final Testing Result	On Track	All	100%	4/15/2022	4/29/2022
Final Report	On Track	All	60%	4/15/2022	4/29/2022
Final Website Cheeck	On Track	All	80%	4/15/2022	4/29/2022
Client Handouff	On Track	All	70%	4/29/2022	5/5/2022

Figure 29: Milestone Names, Dates, And Chart Legend

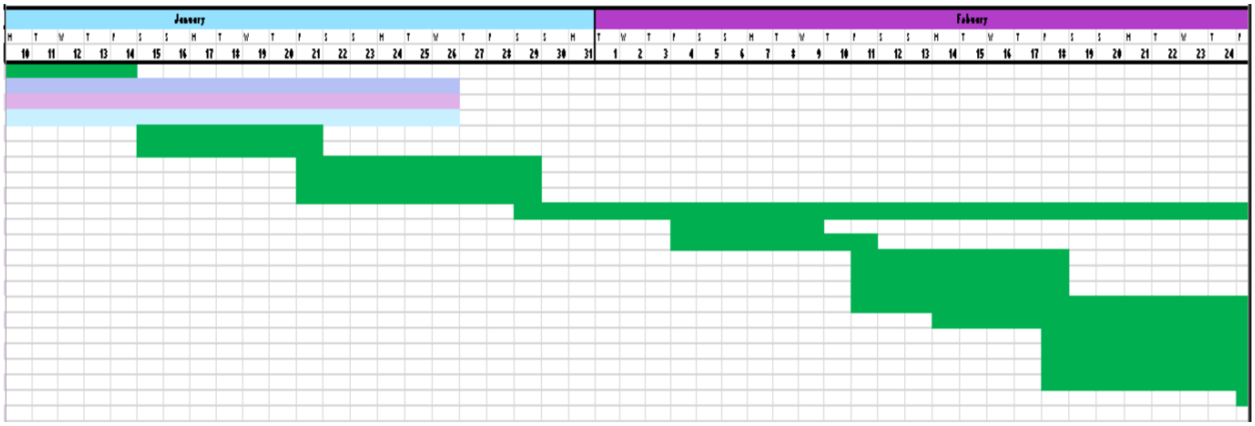

Figure 30: Milestone Deadlines For January 10 – February 25

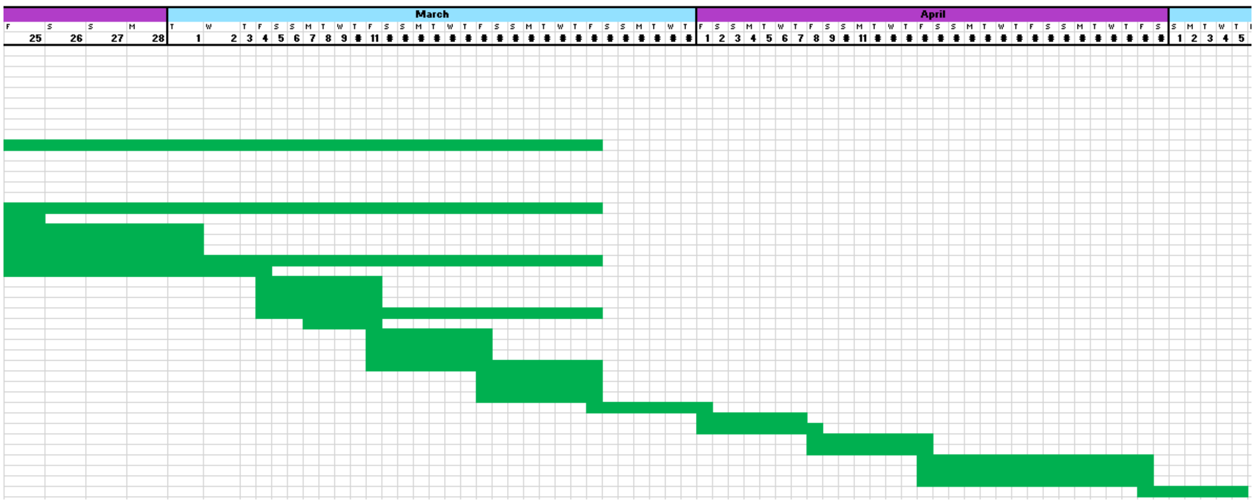

Figure 31: Milestone Deadlines For February 25 – May 5

The Gantt chart had the team working on one manifold at a time ensuring all the custom parts were made by a certain timeframe to complete that specific section. This pattern continued until the 100% build presentation which is when we should have had finished all of them by. From that point forward most of the time the team spent was on writing various reports and testing the system.

The only change that happened during the semester was regarding the finishing of the electrical section of the manifold. Because we needed to rely on Christina from NPOI to make the wire bundles for us, we initially fell behind on making the cables for the manifolds and as such we had to push out the completion of the manifold's subsections until the 100% build.

6.2 Purchasing Plan

The final list of items that were purchased by the capstone team can be seen in Figure 32. Compared to the purchasing plan that was presented at the begging of the semester the only differences are the prices of several items and the addition of tools needed to rethread the brass interfaces. The difference in prices from the original plan came about with how NPOI/Lowell sourced the requested parts. An example of this can be seen with the non-mitered 90° elbow that had a price difference of $55 between the supplier we had chosen and the cheaper one that was used.

Description	Make or	Primary Vendor	Part No.	Lead Time	Quanity Ordered	Unit Cost ($)	Expected	Actual Total ($)
4in DiaBrass Stcok (12in Segaments)	Buy	MidWest Steel Supply	N/A	In Stock	3	284.22	852.66	852.66
QF 50 Mitred 90° Elbow, Stainless Steel, 2"OD	Buy	Kurt J. Lesker	QF50-200E90M	In Stock	6	86	516	578.4
QF 50 Tee, Stainless Steel, 2" OD	Buy	Kurt J. Lesker	QF50-200-T	In Stock	12	146	1752	1753.8
QF 50 Cross, Stainless Steel, 2"OD	Buy	Kurt J. Lesker	QF50-200-X	KJLC will contact	6	220	1320	1318.2
QF50 TO QF25 Reducing Nippple, Stainless Steel	Buy	Kurt J. Lesker	QF50XQF25C	In Stock	6	81	486	484.8
QF 25 Clamp, Aluminium	Buy	Kurt J. Lesker	QF25-100-C	In Stock	6	9	54	52.8
QF 25 Centerning Ring, Stainless Steel	Buy	Kurt J. Lesker	QF25-100-SRV	In Stock	6	9	54	52.8
QF 25 Valve, Stainless Steel, FKM SEALED	Buy	Kurt J. Lesker	SA0100MVQF	In Stock	6	335	2010	2010
KF 25 Pressure GAUGE	Buy	Kurt J. Lesker	KJL275196	In Stock	6	175	1050	1050
QF 50 Blanking Plate, Stainless Steel	Buy	Kurt J. Lesker	QF50-200-SB	In Stock	19	20	380	213.75
QF 50 Centering Ring, Aluminium	Buy	Kurt J. Lesker	QF50-200-ARV	In Stock	61	12	732	747.25
QF 50 Clamp Aluminium	Buy	Kurt J. Lesker	QF50-200-C	In Stock	61	17	1037	738
QF 50 12.6'' Pipe, Stainless Steel, 2" OD	Buy	Kurt J. Lesker	QF50-200-NL	In Stock	6	89	534	534.6
6'' Bellows, Stianless Steel, 2" ID, .012" Wasll	Buy	Kurt J. Lesker	MH-QF-D06	In Stock	6	123	738	739.8
QF 50 Non Mitred 90° Elbow, Stainless Steel, 2"OD	Buy	Kurt J. Lesker	QF50-200-E90	In Stock	1	95	95	39.99
Smooth-Bore Seamless 304 Stainless Steel Tubing	Buy	McMaster-Carr	89895K794	In Stock	1	230.6	230.6	230.6
Flexible Coolant Hose	Buy	McMaster-Carr	5727K53	In Stock	3	20.66	61.98	61.98
Worm-Drive Clamps for Firm Hose and Tube	Buy	McMaster-Carr	5416K58	In Stock	2	14.47	28.94	28.94
Threaded-Rod-Mount Clamping Hanger	Buy	McMaster-Carr	2615T19	In Stock	6	3.15	18.9	18.9
Quick-Clamp High-Vacuum Fitting	Buy	McMaster-Carr	4518K14	In Stock	1	109.57	109.57	109.57
Carbide Tiped Lathe Tool	Buy	McMaster-Carr	3367A889	In Stock	2	15.52	31.04	31.04
Threads Per Inch And Center Identifier	Buy	McMaster-Carr	2072A11	In Stock	1	30.16	30.16	30.16

Figure 32: Purchased Items For Project

An improvement that could have been made would have been looking for more than one supplier for most of the materials that were used on the manifold. The main reason this was not done at the time was because the original supplier we had chosen of Kurt J. Lesker was a company that our client wanted us to use because he trusted the quality of their products as he has used them before at NPOI.

6.3 Manufacturing Plan

The final manufacturing plan that the team created can be seen in Figure 33. The major differences from the beginning of the semester is the addition of the blanking plate extension and the metal end support.

Description	Make or Buy	Lead Time	Quanity Needed	Unit Cost ($)	Expected Total ($)	Actual Total ($)
PAVE Standoff	Make	2hr Per Part	12	0	0	0
Brass Interface Adaptor Ring	Make	1hr Per Part	6	0	0	0
3in DiaBrass Stock (3.75in segments)	N/A	N/A	6	Donated	0	0
TankToKF50 Interface	Make	8hrs Per Part	6	0	0	0
Electrical Feedthrough Blanking Plate	Make	45 mins Per Part	12	0	0	0
Blanking Plate Extenstion	Make	1 hr Per Part	12	0	0	0
Metal End Support	Make	N/A	1	0	0	0
Cut 12.6in Pipe	Make	20min Per Part	2	0	0	0

Figure 33: Manufacturing Plan Used

7 Final Hardware

7.1 Final Hardware Images and Descriptions

The completed manifold that was installed at NPOI can be seen in Figures 35,36.

Figure 35: Overhead View of Repeating Section of the Manifold (Missing Metal “Snoot” Covers)

Figure 36: End Support of Manifold to Vacuum Pump

7.2 Design Changes in Second Semester

7.2.1 Design Iteration 1: Change in Electrical Connector

The original design that was going to be used for the electrical connector passthrough was just using the connector with a blanking plate that had an appropriate hole cut out of it which can be seen in Figure 37.


Figure 37: Original Connector Design

However, this design had to be changed when the team attempted to connect the inside cable connector to the passthrough and found that there was not enough room inside of the cross pipe to do this. To fix this an extension was added to the outside of blanking plate allowing there to be more room on the inside of the cross pipe. This extension was essentially a cylinder that had a grove on one side to allow for an O-ring which would allow the parts to have a vacuum. This iteration can be seen in Figure 38 in the red ovals.

Figure 38: Connectors with Their Extensions

7.3 Challenges Bested

7.3.1 Final Support Structure

The last part of our manifold was to take the pipe from FDL 1 and lead it to the vacuum pump that was above it. The problem with this was we could not design for the length of this pipe at the time because we could not build the actual section of the manifold piping that we needed to measure from. Because of this any design that involved custom length of tubing that had QF flanges on then could not be done as there was no guarantee that it would fit correctly. In addition to this problem there was also the issue that this last section of the piping needed to be support otherwise it would begin to rotate again.

To fix the first issue it was decided that a 6ft piece of stainless-steel pipe would be bought and then cut down to the correct size at NPOI. To connect it to the manifold with its QF flanges the best idea was to take some of the spare 12.6 pipe we had and to cut in half. Then to connect the custom 6ft pipe and the cut in half pipe some neoprene house would be placed around the outside of the seal and then clamped down. With that solution we would be able to make the last section of the manifold no matter what the dimension were.

To fix the other problem a tower was designed that would be able to support the horizontal section of the tubing with some mount hangers. This tower would then be bolted to the concrete to ensure that it did not move.

8 Testing

8.1 Testing Plan

A total of five test where run on the manifold. Figure 39 gives a brief overview of the test and the associated ERs and CRs that they cover.

Experiment / Test	Relevant Design Requirement
1. Front Plate Disassembly Time	CR3, CR5, ER3
2. Leak Rate Test	CR2, ER4
3. Cable Passthrough Setup	CR3, CR5, ER3
4. Cable Continuity Test	CR1, CR2, ER3
5. Pressure Gauge Calibration	CR2,CR3, ER3

Figure 39: Testing Overview

The purpose of the front plate disassembly test was to determine time needed to do remove plates for regular maintenance of FDLs. This would be done by following the previously established procedure for removing the front plates from the FDL tanks and timing this process

The leak rate test was to evaluate the ability of the manifold to maintain vacuum when pump system fails. This was done by isolating the tank from vacuum pump after it reached regular operating pressures and then recording the time taken to reach 30mTorr from the start of the isolation.

The passthrough test sought to understand time needed to disassemble and remove the cables for regular maintenance of FDLs. This process stated once the snoots and front plates have been removed. Then process of disassembling the cable connection and removing the cable that resides in the manifold will be timed.

The continuity test ensured that the cables were built correctly and could function with the FDL carts. This is a two-person job which requires testing at one end of outer cable and testing at the other end of inner cable. Using a digital multimeter each person will touch lead to one of 36 pins at the same time, starting at pin 1 and moving in ascending order.

The calibration test was used to authenticate the readings from the Pirani pressure gages. To do this each gauge is placed on the mass-spectrometer that produces 10^{-5} torr vacuum. Reading on display box is adjusted until it reads zero. Gage is then brought back to atmospheric where its box is adjusted until it reads 585 torr. This process is repeated to ensure values displayed are still correct.

8.2 Testing Results

For the front plate disassembly, the total time it took to take of the plate was approximately 10 min with another 10mins needed to reattach the plate. This total time of 20 mins represents a total time savings of 40 mins from the original manifold and is below the expected value for minimize downtime engineering requirement which is a good thing.

For the leak rate test the section of the manifold that was tested was able to hold operation vacuum for seven days which beats the previous record. Additionally, since this test has occurred the pressure readings inside the tanks have been lower than ever recorded indicating that if this test where to be performed again it is possible that it might last longer than seven days. This result beats the expectations set in our engineering requirement by an entire day.

For the cable passthrough setup it was found that it took only approximately 10 minutes to get the cables from the manifold into the FDL tanks and correctly working. When combining this with the time taken to remove the front plate that represents a total time of only 30 minutes to replace the cables which before could take several hours to complete. Once again this was below the expected value for minimize downtime engineering requirement.

The cable continuity test was able to show that each cable bundle that was created was done correctly as no faults were found during testing. Additionally, each FDL tank was able to move their respective carts further showing that there were no faults in the cable bundles.

The pressure gage calibration also went well with each black box showing the pressure data showing reasonable numbers compared to before the calibration occurred.

9 RISK ANALYSIS AND MITIGATION

An important step in the design project is accessing the risk of failure that the proposed design has and finding ways to mitigate it. To do this a failure mode and effect analysis (FMEA) was performed on selected design. The finalized FMEA for the design can be seen in Appendix B. Most of the failure modes identified result in failure to maintain vacuum pressure. Some components support the manifold structure and failure could result in loss of vacuum pressure and the collapse of the system.

9.1 Potential Failures Identified First Semester

9.1.1 Potential Critical Failure 1: Small Vacuum Leak

Small vacuum leaks are expected for not only the new manifold but also the FDL tanks. The current system requires 24/7 pumping to maintain vacuum pressure of 5 mTorr. We would consider leak rates that maintain operation pressure for 3 days without pumping negligible. Leak rates that lose vacuum pressure sooner than 3 days, and especially audible leaks to be small vacuum leaks. This type of failure is not catastrophic to system health but does require attention. Often improper assembly can be blamed for poor matting connections. It is also not uncommon for an O-Ring to go bad. These types of leaks can be found by listening for air whistling or by seeing frost on vacuum components. Bellows are notorious for frosting around small punctures. The first step is to reseat matting components. Then change O-Ring. If the below is damaged, then replacement is necessary. Mitigation would include proper assembly, clean surfaces before assembly, check for defects before assembly, take special care of fragile hardware such as bellows, O-Rings, matting surfaces, and brass components.

[Provide a brief description of the potential failure here, how that failure could be caused, the effect of the failure, and then discuss how the failure can be mitigated.]

9.1.2 Potential Critical Failure 2: Sudden Vacuum Loss

Suddenly losing vacuum is an unexpected and unlikely event. Regardless this event could happen and poses an extreme safety threat to people and machinery. Sudden vacuum loss could happen during improper operation of valves, if components were flawed before assembly, or if people abuse (climb on, hit, sit, shake) the manifold. Worst case scenario someone is pulled into the vacuum where serious injury or death is plausible. The more likely outcome of sudden vacuum loss is sand/oil blasting of optical components housed inside the FDL tanks. These components can cost thousands of dollars and take time to rebuild and align to the rest of the array. To mitigate this threat the new manifold is designed with large factors of safety, the valves are positioned out of the way of tour groups, and an operations guide will be provided along with the new manifold.

9.1.3 Potential Critical Failure 3: Support Disconnect

Should several companies fail simultaneously it is possible for the main horizontal section of the manifold to fall. This would result in structural loss, broken hardware, and loss of vacuum. This would be an incredibly unlikely event requiring several pipes to disconnect/server, the brass interface to spontaneously fracture, or the bellows to split. Events that could cause this include abuse from operators, neglect during assembly, or running into the manifold with the crane/other large objects. To mitigate this the team has designed in factors of safety, moved the manifold away from the heavy front plates and crane operations, and will be implementing an external support structure.

9.1.4 Potential Critical Failure 4: Electrical Discontinuity

The move to industry standardized electrical connectors should automatically reduce this risk over the existing design. Regardless, internal disconnect could result in loss of control of the optics cart and/or shorting 1000 volts of electricity to the FDL tank. These events pose a threat to the sensitive carts housed in the FDL tanks and to people touching the manifold/FDL tank when the system is turned on. Mitigation includes software control of high-power components, a new wiring harness which allows for regular inspection of connectors, and the new design provides engineers access to the electrical pass through for easy repair especially when compared to the existing system. The proposed new system increased the number of conductors available to engineers which may be used in future projects.

9.2 Potential Failures Identified This Semester

This section outlines the steps taken by students to preemptively mitigate systemic failures though comprehensive design changes made during the final semester of the capstone curriculum. This section also discusses failure modes experienced by the team during the design, manufacturing, and installation prosses and what corrective actions were taken.

Two major modifications to the design were made this semester to facilitate manufacturability and streamline assembly. The initial design did not take into consideration the length of a fully assembled PAVE and military shell connector. During a dry fit an interference was discovered between the apposing connectors inside the cross-member vacuum pipe. Subsequently aluminum spacer was designed and manufactured to move the connectors out and clear the internal interference. The spacers must seal against the body of the PAVE and steal blanking plate. To accommodate this requirement the spacer is machined with a vacuum flat surface on one side and grooved to fit an O-Ring on the other.

The second modification arose out of budgetary and geometric necessity. It became evident the approximate 6-feet of pipe connecting the new manifold to the existing vacuum system could not accurately be modeled due to variations in the as-built structure. Rather than ordering custom flanged pipe the team utilized large diameter neoprene tubing, commonly used in tractor-trailer radiator hosing, and saw cut steel pipe trimmed to size. This reduced the cost significantly and accommodated for variations in the as-built geometry. As a result of this design change and external support structure was added to this last stretch of manifold as the connection hose could not support the loads independently.

9.3 Risk Mitigation

As previously outlined a failure mode analysis was performed to assess the risks inherent to the design problem and proposed solution. The primary area of concern is generating a design with naturally static loading conditions. Bellows must be utilized as variations in the as-build structure must be accounted for. One disadvantage to bellows is the elimination of axial load compensation. This was the major design flaw in the previous manifold where the bellows supported a cantilevered unbalanced load resulting in system failure. The new manifold strategically positioned bellows tubes where axial loads are inherently balanced allowing the bellows to accommodate variations in design tolerance without sacrificing static loading integrity.

By combining the electrical passthrough with the new vacuum manifold the design obscures a full aperture air path. This design choice reduces the efficiency of pulling vacuum. Keep in mind the function of the manifold is to maintain low pressures not to expedite the procedure of pulling vacuum. While the ribbon increases time to achieve stable vacuum levels this design mitigates other potently more sever risks. NPOI has yet to implement an oil back stream trap. With time oil will spray from the pumps into the manifold and directly into the optical train. The positioning of the ribbon cable in conjunction with the vacuum manifold serves as a collection area for dust and oil. The ribbon baffling is not a substitute to a true oil trap but does work to preserve optical integrity and is a great improvement over the predicate system.

Additional design modifications made in the final semester include PAVE extensions. These components were necessary as physical interference prevented the electrical passthroughs from sealing in the cross member. The addition of these spaces increased the number of sealing surfaces with the inclusion of an additional O-Ring. An increase in the number of matting surfaces results in the increase of potential failure points. The modification was necessary and the parts have demonstrated though continual operation satisfactory levels of performance.

10 LOOKING FORWARD

10.1 Future Testing Procedures

As the system is used in continual operation unidentified failure modes may appear. It is critical the vacuum system be monitored and evaluated in accordance with the best practice and maintained to the level demonstrated by NPOI technical teams on other areas of the array. The utilization of segmented radiator hose for the connection between the manifold and vacuum pump has been demonstrated in past work at NPOI. The utilization of this material is not without disadvantage and therefore should regular be checked for necking, constricting, and deterioration. Long term testing and evaluation will determine the validity of these materials for use in other long-term applications.

The scope of this capstone project focused on ensuring the electrical system transmitted signals to though the vacuum barrier. Only a continuity test was performed on the wire. Due to the high voltages running in some of the wire inside of the electrical bundle a future test that could be performed is a HIPOT test. Additionally, an evaluation of signal degradation and interference should be performed as a benchmark used in identifying future problems with electro-optical systems.

10.2 Future Iterations

With the addition of more conductors passing though the vacuum barrier continued efforts may focuses on system control and interrogation technologies. Specifically, it is now easily possible to add encoders on the FLD cars; develop systems to detect problems with the internal take-up real and preemptively mitigate entanglement of the ribbon cable; add temperature or other sensors internal to the FDL tank system.

Presently, there exists six new vacuum valves isolating vacuum pressure sensors form the main manifold. The indented use for these valves is to allow calibration of the vacuum gauges without needing to vent the entire system. These ports, however, provide isolated connections to the FDL vacuum system. Testing equipment, expansion of the system, integration of new pumps, connection for new scientific instrumentation can all be integrated at these discreet isolated locations.

The external support structure is discreet and thus far performs well. Dependent on future work and testing results it may become necessary to add additional support structures elsewhere to the manifold. The current support boasts two pipe hangers, the implementation of a third could reduce stress between the manifold and turbo-pump.

Because the new vacuum manifold does not directly integrate with the snoots a critical deign upgrade should be made to the front plate and snoot system. The current plates are heavy and require a crane to life out of place. There are two types of front plates where a new design would create uniformity. The snoots are difficult to remove and position correctly and are an impedance of front-end maintenance. The metrology laser windows are small and make alignments more difficult than they need to be. Now that the manifold no longer connects to these systems a more comprehensive design should be investigated to improve the functionality at the front-end.

11 CONCLUSIONS

The capstone team was successfully at designing and implementing a new vacuum manifold system for NPOI. This system had demonstrated a strong performance thus far with braking records in both the recorded vacuum level as well as time stayed within operational conditions without vacuum assistance. Further, maintenance downtime of the FDL's has been reduced due to the removal of the manifold from the snoots and the implementation of standard electrical equipment. Finally, the team has also received affirmations from the staff at NPOI that our system has improved the quality of their operations. As the system continues to prove itself though regular use the team is excited to see future developments at NPOI facilitated by the new vacuum manifold.

11.1 Reflection

The Navy Precision Optical Interferometer is an instrument of global importance and recognition. Developments made at NPOI have been used in engineering and scientific institutions to improve the quality of science and discoveries. This capstone project had the unique opportunity to make a difference in the safety, reliability and performance of an instrument that will be used for years to come. The work performed on this capstone is open ended as are many projects ongoing at NPOI. The total gains have yet to be realized but already the project has impacted the individuals and organizations who work at the interferometer.

The mission of the interferometer changes, and the specific instruments are marvels of engineering. It is easy to take for granted the infrastructure needed to carryout monumental scientific achievement. A healthy portion of the infrastructure at NPOI has now been developed by NAU students. Our work will probably never be recognized in scientific magazines, or awarded ribbons of recognition, it is critical to remind ourselves the fundamental necessity of the manifold. It is a device designed to control the local environment. It protects optics, stabilizes air-path, and communicates directly with computer and robotic control systems. Without it the FDL carts could not operate, and no stellar observations would be made. This project encompasses a mission critical subsystem, regardless of what that mission is. The team and the staff at NPOI are proud of the work done and look forward to the work yet to do.

11.2 Resource Wishlist

Given the great success of the project already, additional resources would not have had a noticeable effect on the final result. Some of the design concepts would have cost an exuberant amount of money and time to complete. Although these designs had many advantages the challenge of staying on time and under budget pushed the creativity of the capstone team to deliver a working product.

The team achieved the goals laid out by the client with the tools and resources on hand. The learning opportunities of this project, especially in regard to half-century+ old manual machine tools, was unparalleled and we are grateful to have the mentorship and access. However, access to a modern CNC lathe would have greatly reduce time spent manufacturing components and would have provided different learning opportunities. NAU did not have a CNC lathe at the time of this capstone.

11.3 Project Applicability

Superficially, the team would often joke at how easy it would be to put some pipes together. After all, the manifold is simply a collection of pipes strung along with a few O-Rings scattered though. It may be known that often the simplistic, elegant designs are the most difficult to engineer. When everything is said and built, we know our job is does when the manifold fades into the background and doesn't cause problems.

The life and career skills learned from this project will stick with us for the rest of our lives. There are obvious skills we learned, using the lathe to chase threads, setting parts back up in the lathe to re-chase threads. We learned how to prepare our workstations to make assembly smooth. We learned the importance of clear communication, and we developed a healthy respect for vacuum and optical safety. As with any group project staying instep with another and keeping to a schedule proved challenging at times but we overcame those challenges by implementing team skills learned during our time at NAU.

Perhaps one of the most important skills taken from this project is being adaptable. No one gets the best design on their first try. On several occasions the team would be forced to make design changes even after hours had been spent perfecting drawings. One notable instance was the need to change from 4 inch diameter brass stock for the interface to 3 inch due to global shipping delays. Ultimately, this forced the team to be creative and flexible and generate a better product. Being adaptable makes us better team members but also better designers.

The manifold we build will stay in operation indefinitely. It will serve the scientific community and be witness to many future programs. While we move on to other things in life this capstone team will forever be part of the history at NPOI, NAU, and serves as physical evidence that we have what it takes to be mechanical engineers.

12 REFERENCES

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13 APPENDICES

13.1 Appendix A: House of Quality (QFD / HoQ)

Factor of Saftey					
Project Cost		3			
Minimize Downtime			1		
Leak Rate				3	
		Technical Requirements			
CustomerRequirments	**Customer Weights**	Factor of Saftey	Project Cost	Minimize Downtime	Leak Rate
Saftey	9	9	9		1
Cost	3	9	9	1	9
Ease of Use	3		1	9	9
Relyability	9	9	3	9	9
Repairability	9	3	3	9	3
Longjevity	3	9	1	1	3
Future Project Integration	1		1	1	
Technical Requirement Units		N/A	USD	Hours	Days ≤30mTorr
Technical Requirement Targets		2.5	10000	2	5
Technical Requirement Tolerance		±.5	±4000	±1	±1
Absolute Technical Importance		243	169	196	180
Relative Technical Importance		1	4	2	3

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

Back Extension with Bridge:

Bridge

Top of Bridge.

Dimensions: 12′ (length of FDL) by 1.5′ (width of pump + space for person).
Requires 9 2″ x 12″ x 12′ boards @ $28.12 per board [21] for total of $253.08

Railing for bridge

Dimensions: 36″ high (IRC standard [22]). Cost for one vertical 2″ x 2″x 3′ piece is 2.82 [23], cost for one horizontal 2″ x 12″ x 12′ piece is 28.12 [21] for total of $73.16

Steps for bridge

Assuming steps are vertical to simplify. Dimensions: 1.5′ x .5′ x 4′ (top of FDL is 3′ from ground and want bridge to be 1′ above FDL). 9 2″ x 4″ x 4′ needed. Cost for one piece is $4.68 [24] for total cost of $84.24

Stain

2 gallons stain. Cost for one gallon is $41.98 [25]. Total cost 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 [26]. Total Cost is $1620

Elbow Pipes

6 (One for every FDL) + 2 (up to vacuum pump) +1 (last turn to vacuum pump). Cost of one elbow is $96 [27]. Total Cost for elbows $864

Tee sections

4 (for 4 interior FDL pipes) + 1 (connection to final vacuum line that runs to pump) Cost of one Tee is $146 [28]. Total cost is $730

Bellows needed

6 (one for each FDL). Cost of one bellows is $123 [29]. Total cost is $738

Pressure Valves

6 (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 [30]. 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[26]]. 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 [27]. Total Cost for elbows is $672

Tee sections

5*1 (one fore each FDL expect last one). Cost of one Tee is $146 [28]. Total cost for tees is $730

Bellows needed

6*1 (one for each FDL). Cost of one bellows is $123 [29]. 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 [26]. 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 [27]. 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 [28]. Total cost for tees is $730

Bellows needed

6*1 (one for each FDL). Cost of one bellows is $123 [29]. 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>

13.3 Appendix C: Failure Mode and Effect Analysis FMEA

Product Name		Development Team: Alex McClinton, Cydny Clark, Wyatt Clark					Page No of			
System Name							FMEA Number			
Subsystem Name							Date			
Component Name										
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 "Interface"	Thermal Fatigue, Stress Fracture, Pressure vessel callops, Max bending stress exceded	Loss of vacuum, Destruction of optical componates	10	Poor design, Assembly error, User error, Fatigue loading	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	50	Replace seal and O-Ring.If no improvement replace complete componate.
QF50-200E90M "Miter 90 Elbow"	Scratched matting surface	Loss of vacuum, Destruction of optical componates, damage to manifold	8	Manufactureing defect, Impropor handaling of hardware	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	40	Replace O-Ring(s).If no improvement replace complete componate.
QF50-200-ARV "Centering Ring Al Viton"	UV/thermal/age/chemical degridation, scratch/cut, not proporly tightened -> tearing	Loss of vacuum, Destruction of optical componates	4	Manufactureing defect, Impropor handaling of hardware, environmental	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	4	32	Replace O-Ring(s).
QF50-200-C "Al Clamp"	Over tighten, hinge falure	No QF seal, Loss of vacuum	4	Manufactureing defect, Impropor handaling of hardware, environmental, load cycles	2	Visual	5	40	Replace Clamp
QF50-200-T "SS Tee"	Scratched matting surface	Loss of vacuum, Destruction of optical componates, damage to manifold	8	Manufactureing defect, Impropor handaling of hardware	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	40	Replace O-Ring(s).If no improvement replace complete componate.
QF50-200-X "SS 4-way Cross"	Scratched matting surface	Loss of vacuum, Destruction of optical componates, damage to manifold	8	Manufactureing defect, Impropor handaling of hardware	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	40	Replace O-Ring(s).If no improvement replace complete componate.
QF50XQF25C "SS Reducing Full Nipple"	Scratched matting surface	Loss of vacuum, Destruction of optical componates, damage to manifold	8	Manufactureing defect, Impropor handaling of hardware	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	40	Replace O-Ring(s).If no improvement replace complete componate.

WF25-100-SRV "SS Centering Ring 25mm"	UV/thermal/age/chemical degridation, scratch/cut, not proporly tightened -> tearing	Loss of vacuum, Destruction of optical componates	4	Manufactureing defect, Impropor handaling of hardware, environmental	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	4	32	Replace O-Ring(s).
QF25-100-C "Al Clamp 25mm"	Over tighten, hinge falure	No QF seal, Loss of vacuum	4	Manufactureing defect, Impropor handaling of hardware, environmental, load cycles	2	Visual	5	40	Replace Clamp
SA0100MVQF "SS RT Angle Valve"	Scratched matting surface, Damage the diaphram, Lubercant depletion	Loss of vacuum, Destruction of optical componates, damage to manifold, damage to sensor	8	Manufactureing defect, Impropor handaling of hardware, Impropor maintnance	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	80	Replace O-Ring(s). Lubercate. If no improvement replace complete componate.
KJL275196 "VAC Gauge"	Not calibrated, exposure to fluid, electrical malfunction, scratched matting surface, age	Loss of vacuum, Destruction of optical componates, damage to manifold, incorect emergency shutoff of system	5	Manufactureing defect, Impropor handaling of hardware, Impropor maintnance	3	Use *He* leak test to determine rate of leak. Visual and auditory inspection. Strange calibration results/readings	5	75	Replace O-Ring(s). Calibrate. If no improvement replace complete componate.
SA0200MVQF "SS RT Angle Valve"	Scratched matting surface, Damage the diaphram, Lubercant depletion	Loss of vacuum, Destruction of optical componates, damage to manifold, damage to sensor	8	Manufactureing defect, Impropor handaling of hardware, Impropor maintnance	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	80	Replace O-Ring(s). Lubercate. If no improvement replace complete componate.
QF50-200-SB "Blanking Plate SS"	Scratched matting surface	Loss of vacuum, Destruction of optical componates	7	Manufactureing defect, Impropor handaling of hardware, environmental	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	70	Replace O-Ring(s).If no improvement replace complete componate.
MH-QF-D06 "6" Bellows SS Thin"	Scratched matting surface, puncture wall	Loss of vacuum, Destruction of optical componates, collaps of manifold, human casualty	8	Manufactureing defect, Impropor handaling of hardware, environmental	2	Use *He* leak test to determine rate of leak. Visual and auditory inspection. Look for Ice.	5	80	Replace O-Ring(s).If no improvement replace complete componate.
QF50-200-NL "12.6" SS"	Scratched matting surface	Loss of vacuum, Destruction of optical componates, damage to manifold	8	Manufactureing defect, Impropor handaling of hardware, environmental	1	Use *He* leak test to determine rate of leak. Visual and auditory inspection.	5	40	Replace O-Ring(s).If no improvement replace complete componate.