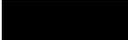# Design of Hydraulic Cylinder Test Apparatus

Final Design Report - Phase 3

Presented by

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Dear Dr. Labossiere:

Enclosed you will find the Final Design Report for the ███████████ Hydraulic Cylinder Test Apparatus Design Project.

The report begins by outlining the project introduction followed by the project background, problem statement, and project objectives. The scope of the project is defined using customer needs and specifications. The design report continues with the design concepts and selection section where the overview of the selected concepts is provided. The report then explains the details of the design including the design of different components and their features. The detailed design section also provided a visual interpretation of the design components. Lastly, the team summarizes the project and gives recommendations for future work. Several appendices are also attached to the end of the report detailing the technical drawings, detailed technical calculations, engineering bill of materials, and gantt chart.

Yours Sincerely,

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Kawaljeet Singh Banwait

Bhawanjot Sidhu

Kim Ochengco

Executive Summary

This report outlines the design of the hydraulic cylinder test apparatus requested by the client, ████ ████. This report first features an introduction section that showcases the project background, problem statement, and project objectives to ensure that the team understands the client's requirements. The report then outlines a summary of client needs and specifications along with engineering calculations required to select the concepts for measurement equipment, hydraulic system design, hydraulic cylinder mounting frame, and hydraulic cylinder shielding. The report then goes over the concept selection methodology for each component of the test apparatus followed by a detailed design section where details of design components are provided. Next, the report showcases recommendations that will allow the test apparatus to become more productive during the testing of the hydraulic cylinders, followed by the conclusion which includes the final design specifications of the test apparatus.

████████ utilizes hydraulic cylinders in their agricultural equipment such as headers and windrowers for position control. ████████ purchases hydraulic cylinders from external vendors and as per their purchasing agreement, ████ requires the vendors to perform quality assurance tests on the hydraulic cylinder in order to ensure that the cylinder meets ████ required specifications. ████ Industries sees value in developing an in-house hydraulic cylinder test apparatus to evaluate old and build relationships with new vendors. Therefore, the critical objective of the project is to develop a test apparatus that can be used to perform tests specified by ████████ The test apparatus is to have measurement devices that are within $\pm 2\%$ measurement tolerance. As per the deliverables, ████ requested CAD (Computer Aided Design) models, CAD drawings, BOM (Bill of Materials), and Hydraulic System Schematics of the test apparatus.

The test apparatus includes hydraulic cylinder mounting design which features the cap end bracket and rod end bracket. The cap end bracket is designed to mount different configurations of cylinders while sustaining the load exerted by the hydraulic pressure during the performance tests. The rod end bracket is designed to support the weight of various cylinders while providing clearance between the cylinder and testing table.

The test apparatus includes hydraulic cylinder shielding design which provides protection for the operators during performance tests. The design consists of L-shaped railings, handle, hinges and acrylic glasses.

The test apparatus also includes hydraulic system design which features hydraulic system schematics and hydraulic components. The components are sourced out from vendors. The components and vendor information is as follows: hydraulic hoses (Green Line Hose and Fittings), hydraulic adapters (Green Line Hose and Fittings), hydraulic reservoirs (Grainger), hydraulic filters (Grainger), hydraulic directional control

valves (Rexroth), ball valve (Parker), check valve (Tu-Lok), pressure relief valve (Hyvair) hydraulic oil coolers (Grainger), and hydraulic pumps (Parker).

The test apparatus also includes electrical system design which includes selecting an input layer in the existing data acquisition system of ███████ and selecting corresponding sensors what would interface with that layer and are hence compatible with the data acquisition system. The sensors were chosen based on the test requirements of ███████ and are all sourced out from a single vendor, Omega. The sensors included pressure sensor (for hose pressure measurement), LVIT (for rod displacement measurement) and thermocouple (for fluid temperature measurement). Each sensor required mounting adapters and electrical schematic to collect and output data. Mounting adapters were sourced out for pressure sensor and thermocouple and a custom design was developed for LVIT to mount to collect rod displacement data.

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1 Introduction

In this report, the student team outlines the detailed design of the hydraulic cylinder test apparatus. The design of the hydraulic cylinder test apparatus is composed of four main components: test apparatus electrical design, test apparatus hydraulic system design, hydraulic cylinder mounting design, and test apparatus shielding design. This test apparatus will be used to verify whether or not the hydraulic cylinders developed and designed by ██████ suppliers follow ██████ hydraulic cylinder specifications.

The first main section of the report outlines the project background, problem statement, and project objectives to ensure that the team understands the client's requirements while optimizing the design of the system.

The second main section of the report outlines a summary of client needs and specifications along with engineering calculations required to select the concepts for measurement equipment, hydraulic system design, hydraulic cylinder mounting frame, and hydraulic cylinder shielding.

The third main section of the report includes the concept selection methodology for each component of the test apparatus. In this section, the team summarizes concepts considered and selected for this project.

The fourth main section of the report includes a detailed design of each component of the test apparatus. This includes sourcing out vendors for different equipment needed for the apparatus, the team's design for mounting and shielding, and collaboration between all four components of the test apparatus such that the apparatus shows comparability.

The fifth main section of the report includes recommendations that will allow the test apparatus to become more productive during the testing of the hydraulic cylinders, followed by the conclusion which includes the final design specifications of the test apparatus.

1.1 Project Background

██████████ manufactures products such as combine headers (See Figure 1a) and windrowers (See Figure 1b) which are frequently improved in order to ensure that harvesting is made easier and more productive for farmers [1]. As ██████ products continue to evolve, the quality of the components supplied by ██████ suppliers needs to be evaluated to ensure the reliability of the products during operation.
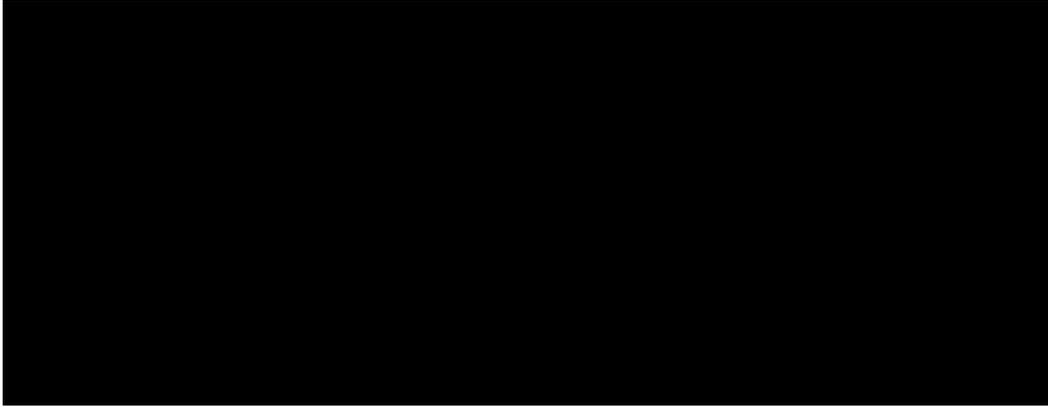
Figure 1: Examples of Selected Products Manufactured by ▆▆▆▆▆ ▆▆▆▆▆▆

One of the critical components of any product manufactured by ▆▆▆▆▆ is the hydraulic cylinders. The hydraulic cylinders are used to ensure position control of the product. As ▆▆▆▆▆ manufactures a variety of harvesting equipment, several configurations, rod types, lengths, and diameters of hydraulic cylinders are utilized in several products. The configurations include single-acting cylinders (See Figure 2a) and double-acting cylinders (See Figure 2b) with two types of rods, clevis, and threaded-type with various lengths and diameters. The lengths and diameters of the cylinders range from 7.75" to 60.5" and 1.5" to 4", respectively. The single-acting cylinders use only one port from which the fluid, generally hydraulic oil, can enter the cylinder to extend the rod of the cylinder. This configuration uses a mechanical device such as a spring in order to retract the extended rod of the cylinder. The fluid is withdrawn from the same port of the cylinder. The double-acting configuration uses two ports in order to extend and retract the cylinder rod by allowing the fluid to flow into one of the two ports.
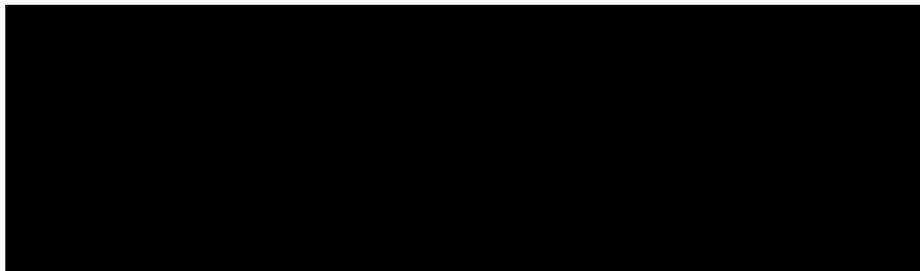
(a) Single-acting Hydraulic Cylinder [4]   (b) Double-acting Hydraulic Cylinder [5]

Figure 2: Configurations of Hydraulic Cylinders used by ▆▆▆▆▆ ▆▆▆▆▆▆

Since there are different configurations, rod types, lengths, and diameters of cylinders, ▆▆▆▆▆ requires quality validation tests done by the suppliers in accordance with the performance of the cylinders as a part of their purchasing agreement. In order to confirm the supplier's quality validation tests, accelerate testing, and evaluate potential new suppliers, ▆▆▆▆▆ ▆▆▆▆▆▆ desires to have an in-house hydraulic cylinder test

apparatus.

1.2 Problem Statement

The quality of the hydraulic cylinders supplied is very important to ████████ as they are critical to the function of the equipment. The quality of the hydraulic cylinder corresponds to the cylinder's integrity (i.e. cylinder's build quality), leakage resistance, seal effectiveness, and overall performance. A defective hydraulic cylinder can lead to the equipment being dangerous to the operator, dysfunctional, and can also lead to customer dissatisfaction. ████████████ does not currently have a testing apparatus to verify whether or not the supplier's hydraulic cylinder actually matches their specifications. Therefore, the team is tasked to develop a test apparatus that is capable of performing tests found in ████████ Hydraulic Cylinder Performance Specification – 252238 document for different configurations, rod types, lengths and diameters of cylinders [6].

This document outlines a series of standard tests (Hydraulic Cylinder Integrity Test, Hydraulic Cylinder No-Load Friction Test, and Hydraulic Cylinder Leakage Test) which contains critical measurements with specified tolerances that the apparatus must measure to verify and analyze the supplier's hydraulic cylinders. These measurements include temperature: pressure, leakage, time, and extraction length. These five parameters are vital to measuring as they are used to evaluate the performance of hydraulic cylinders.

1.3 Project Objectives

The objective of this project is to design a hydraulic cylinder test apparatus that is to be used to perform tests listed in ████████ Hydraulic Cylinder Performance Specification – 252238 document for different cylinder configurations, rod types, lengths, and diameters; these tests include SAE J1334:2003 Hydraulic Cylinder Integrity Test, SAE J1335:2009 Hydraulic Cylinder No-Load Friction Test, and SAE J1336:2014 Hydraulic Cylinder Leakage Test [6]. The apparatus will be used to measure the temperature of the oil, pressure in the cylinder, leakage of the cylinder, change in length of the rod, and time of each measurement with a specified tolerance ($\pm 2\%$) to evaluate old and new supplier's hydraulic cylinders by using a data acquisition system which is provided by the client. The final design is expected to have the following deliverables:

- CAD (Computer Aided Design) model of the test apparatus

- Engineering BOM including components used in the design from external vendors

- CAD Drawings to depict the layout and dimensions of the design

- Hydraulic System Schematics of the single-acting configurations for Mechanical Integrity Test and Leakage Test [6]

2 Client Needs and Specifications

After studying the scope of this project, 22 project needs were identified based on the expectations of the final design. The project needs were then discussed with the ▆▆▆▆ team. These needs are listed in Table I. Each need was given an importance factor number between 1-5 where 1 refers to the lowest priority needs and 5 refers to the highest priority needs. The needs were sorted out to reflect high priority needs first. The project needs table was reviewed by ▆▆▆▆▆▆▆▆▆ and recommended changes were made.

2.1 Summary of Client Needs and Specifications

Table I: PROJECT NEEDS DEFINED IN PROJECT OUTLINE AND THROUGH CLIENT MEETINGS

No.	Project Needs	Importance Factor
1	Test apparatus shall account for hydraulic cylinders from 7 ¾'' to 57" in length and 1.5" to 4" in diameter	5
2	Test apparatus shall be compatible for both single acting and double acting cylinders	5
3	A power pack for test apparatus shall be designed which shall provide custom configuration or single acting and double acting cylinders	5
4	Test apparatus shall be compatible with clevis and threaded rod ends	5
5	Test apparatus shall abide by the requirements for Hydraulic Cylinder Integrity Test Standard by MacDon (Document # 222538)	5
6	Test apparatus shall abide by the requirements for Hydraulic Cylinder No Load Friction Test Standard by MacDon (Document # 222538)	5
7	Test apparatus shall abide by the requirements for Hydraulic Cylinder Leakage Test Standard by MacDon (Document # 222538)	5
8	Test apparatus shall be safe for the operator in the event of a catastrophic failure	5
9	Test apparatus shall abide the 6 seconds cycle time constraint	5
10	Test apparatus shall have a minimum factor of safety of 2	5
11	Test apparatus shall be capable of measuring and displaying change in temperature of testing fluid within a specified tolerance	5
12	Test apparatus shall be capable of applying, measuring, and displaying hydraulic pressure within a specified tolerance	5
13	Test apparatus shall be capable of detecting any fluid leakage from cylinders	5
14	Test apparatus shall be capable of measuring and displaying time during testing within a certain tolerance	5
15	Test apparatus shall be capable of measuring and displaying change in length while cylinder rod is extending and retracting	5
16	Test apparatus shall have infinite life in fatigue loading	3
17	Test apparatus measuring components shall be easy to replace	2
18	Test apparatus shall fit on the standard tooling table of dimensions 95" x 35"	2
19	Test apparatus shall be within the budget of $10,000	2
20	Measurement devices to be used in the test apparatus shall be easily accessible to the user to facilitate easy data collection	2
21	Test apparatus surface shall be easily cleanable without disconnecting the measuring devices	1
22	Power pack configuration shall be easily changeable	1

The project needs in the above table were identified based on the requirements of this project and the ▮▮▮▮ team's expectations of the final design. The highest priority needs (i.e of level 4 and above) are based on the fact that these needs are absolutely necessary to achieve the goals of this project. Needs with rating 3 and below will be studied by the team after the high priority needs are satisfied. High priority needs such as the range of sizes of the hydraulic cylinders that the apparatus shall be compatible with and different types of rod ends were established by the team based on the engineering drawings of the hydraulic cylinders provided by ▮▮▮▮ Size range was decided based on the smallest and largest cylinder size and 2 types of rod ends were identified. Needs based on the ability of the apparatus to abide by the ▮▮▮▮ internal testing document (reflecting SAE standards) were established to match ▮▮▮▮ expectation of the apparatus to be used in their facility. ▮▮▮▮ also provided cylinder extending and retracting cycle time of 6 seconds which was identified as a need of the apparatus.

The apparatus is to be used for tests including performing proof pressure and integrity test during which a cylinder might burst if it fails the test. So, the team established a high priority need of operator being safe while working on this apparatus. ▮▮▮▮ team also had expectation of measuring crucial parameters such as temperature, pressure, leakage, length and time to satisfy industry testing standards. The team established additional measuring needs of the apparatus based on those expectations. ▮▮▮▮ team provided two configurations of hydraulic cylinders to be tested, single-acting and double-acting cylinders, because the apparatus must accommodate both configurations. The team also identified that a configurable power pack must be required so that the apparatus can operate with both configurations which was also established as a project need. ▮▮▮▮ team also provided expectations of minimum safety factor, fatigue life of the apparatus and budget which were also established as project needs by the team.

2.2 Hydraulic System Design Calculations Based on Client Needs

The client requires the cylinder to fully extend in three seconds followed by fully retracting in another three seconds, which makes the total cycle time six seconds for any configuration, length, and diameter of the cylinder. Therefore, preliminary calculations to satisfy the cycle time are needed to generate and then select concepts for the hydraulic system design. The following shows the preliminary fluid power calculations done by the team.

2.2.1 Hydraulic Hose Diameter

The table below depicts the different types of hydraulic cylinders used by ▮▮▮▮ These are the types that ▮▮▮▮ would like to test using the test apparatus.

Table II: CONFIGURATIONS OF HYDRAULIC CYLINDERS CORRESPONDING TO ▮▮▮▮▮ HYDRAULIC CYLINDER #

Configuration #	MacDon Hydraulic Cylinder #
Configuration 1	252934_A
Configuration 2	252934_A_C12-35A
Configuration 3	247900_B
Configuration 4	209789_B_658759_0P00
Configuration 5	308658_A
Configuration 6	273787_A_659829_0P00
Configuration 7	273284-C-C15-154A

Configuration 1 technical specifications are summarized in the table below.

Table III: TECHNICAL SPECIFICATIONS OF CONFIGURATION 1

Bore Diameter (d_{Bore})	1.504 inches
Rod Diameter (d_{Rod})	1 inch
Stroke (S)	3.375 inches
Half Cycle Time required (t)	3 seconds

The velocity is calculated using the following formula:

$$v = \frac{S}{t} \tag{1}$$

Where v is the velocity, in ft/s, S is the stroke of the cylinder, in inches, and t is the time to complete half cycle (extension), in seconds.

$$v = \frac{3.375}{3} = 1.125 \text{ in/sec} = 0.09375 \text{ ft/sec}$$

The required flow rate to satisfy the three second extension constraint is calculated as follows:

$$Q = \frac{v\pi(d_{Bore})^2}{4(0.321)} \tag{2}$$

Where Q is the flow rate, in gpm (US gallons per min), and d_{Bore} is the bore diameter of the cylinder, in inches.

$$Q = \frac{0.09375(\pi)1.504^2}{4(0.321)} = 0.51886 \text{ gpm}$$

The following parameters were obtained based on team's knowledge in the fluid power industry.

Table IV: ESTIMATES MADE BY THE TEAM

Viscosity of Hydraulic Oil (cSt) at 77ºC	15
Pressure Drop Across the Hose (psi)	5
Length of the Hose (ft)	4
Specific Gravity	0.86
Flow Type	Turbulent Flow

Using the required flow rate, the hose diameter required can be calculated using the following equation.

$$d_{Hose} = \left[\frac{\left[\frac{0.3164(L)(SG)(Q)^2}{74.3(\Delta P)} \right]^4 (\nu)}{3164(Q)} \right]^{\frac{1}{19}} \tag{3}$$

Where d_{Hose} is the hose diameter, in inches, L is the length of hose, in ft, SG is the specific gravity of the oil, ΔP is the pressure drop across the entire hose, in psi, ν is the kinematic viscosity of the oil, in cSt.

$$d_{Hose} = \left[\frac{\left[\frac{0.3164(4)(0.86)(0.51886)^2}{74.3(5)} \right]^4 (18)}{3164(0.51886)} \right]^{\frac{1}{19}} = 0.1735 \text{ in} = 0.19 \text{ in for standard hose diameter}$$

Following the methodology described above, the hose diameter required for other configurations can be calculated and the results are summarized in the table below.

Table V: HOSE DIAMETERS REQUIRED FOR EACH CONFIGURATION

Configuration #	Required Flow (gpm)	Required Hose Diameter (inches)	Standard Size Hose (inches)
Configuration 1	0.5189	0.1735	0.19
Configuration 2	0.3438	0.1491	0.19
Configuration 3	18.9786	0.6536	0.75
Configuration 4	13.7706	0.5808	0.63
Configuration 5	3.2276	0.3403	0.38
Configuration 6	1.3243	0.2451	0.25
Configuration 7	4.1870	0.3745	0.38

The minimum diameter required to compensate each configuration must be 0.6536in, which corresponds to 0.75in hose diameter for the standard sizes of hose diameters. This will also account for any flow and pressure reductions through the hydraulic adapters.

2.2.2   Suction Line Hose Diameter

Special consideration is required for the suction line hose diameter at the hydraulic pump's inlet. This is because if the velocity in the suction line hose exceeds 5ft/s then the risk of cavitation at the pump's inlet becomes inevitable, this reduces the life and efficiency of the pump. Thus, the suction line must be sized accordingly to prevent cavitation. The following shows the hose diameter calculation for the suction line.

$$d_{SuctionLine} = \sqrt{\frac{Q(0.321)(4)}{v(\pi)}} \tag{4}$$

Where $d_{SuctionLine}$ is the suction line diameter, in inches.

$$d_{SuctionLine} = \sqrt{\frac{18.9789(0.321)(4)}{5(\pi)}} = 1.246 \text{ in} = 1.50 \text{ in for standard hose diameter}$$

2.2.3   Hydraulic Pump Displacement Calculation

Determining the displacement of the hydraulic pump is critical for selecting which type of pump meets the specifications of this project. Selecting a pump that can produce the amount of flow needed in the system is a critical part of the test apparatus, therefore, the following preliminary calculation is done to ensure system stability.

$$D_p = \frac{Q(231)}{N(\eta_v)} \tag{5}$$

Where D_p is the pump displacement, in in^3/rev or cc/rev, N is the speed of the pump motor, in rpm (assumed to be 4250rpm), η_v is the pump's volumetric efficiency (assumed to be $\eta_v = 0.97$)

$$D_p = \frac{18.9789(231)}{4250(0.97)} = 1.0634 \text{ in}^3/\text{rev} = 17.4267 \text{ cc/rev}$$

The preliminary calculations results are summarized in the table below for the required parameters of the hydraulic system components.

Table VI: HYDRAULIC SYSTEM REQUIRED PARAMETERS SPECIFICATIONS

Required System Flow Rate (gpm)	18.97858
Minimum System Hose Diameter (inches)	0.75
Minimum Suction Line Diameter (inches)	1.50
Minimum Pump Displacement (in^3/rev or cc/rev)	1.0634 or 17.4267
Maximum System Pressure Required (psi)	6400

3   Design Concepts and Selection

This section includes a summary of concepts considered and selected by the team. The team was able to perform research and consult with the team advisor in order to generate at least two concepts for each sub-component for the respective project components. This is followed by selecting the concepts that best fit the client's needs and specifications. This section first goes over the summary of hydraulic cylinder mounting design concept selection, hydraulic cylinder shielding design concept selection, hydraulic system design concept selection, and lastly, electrical system design concept selection.

3.1   Hydraulic Cylinder Mounting Design Concept Selection

Three concepts were considered for hydraulic cylinder mounting system which are the L-shaped fixed bracket, lug and clevis bracket and chain vise grip. Based on the client's needs and requirements, the use of lug and clevis brackets for mounting the cap end side of the cylinders is selected for the mounting system. This selection is able to mount different configurations of cylinders while providing the appropriate level of security. Further analysis is performed and discussed in Section 4.1.

3.2   Hydraulic Cylinder Shielding Design Concept Selection

Portable glass barrier and mounted safety shield were the two concepts considered during the concept selection phase. Both meets the client's requirements but after meeting with the clients, the preferred concept is a design that can be mounted on the testing table. Based on the client's preference, the mounted safety shield concept is selected for safety shield design. Further analysis is performed and discussed in Section 4.2.

3.3   Hydraulic System Design Concept Selection

Hydraulic system design components include hydraulic hoses, hydraulic adapters, hydraulic reservoirs, hydraulic filters, hydraulic control valves, hydraulic oil coolers, and hydraulic pumps. Each of the hydraulic components has several configurations available in the market at several price ranges with unique benefits. The following subsections show the selected concepts and their selection methodology, the selected concepts will be used to source out different vendors in order to use the components for the test apparatus.

3.3.1 Hydraulic Hose

The flexible type is chosen over the rigid type hydraulic hose because the flexible type does not corrode easily hence it improves the life of the hose and the longer life of the test apparatus is expected by the client. The flexible type is well insulated which can maintain a constant oil temperature during operation. The flexible type also offers many different lengths and diameters of hoses which can meet the requirement of having different lengths and diameters of hoses. Flexible type is also easy to connect when it comes to connecting the hoses to hard-to-reach places. It also keeps the vibrations and noise level to a minimum which eliminates the need for the operator to wear earplugs. The flexible type is less expensive than the rigid type because they are made from rubber rather than metal which fits better within the project's budget constraint [7].

3.3.2 Hydraulic Adapters

The thread-type adapter is chosen over the quick-connect type because the price of quick-connect adapters is substantially more than the thread-type adapters. Also, the hydraulic hose requires a fitting to be installed at each end as it comes as a bulk hose (only rubber hose), so if the quick-connect type is chosen then the team would need to purchase both the fitting and the quick-connect adapters. Therefore, selecting the thread-type adapters would eliminate the need of having additional components such as quick-connects adapters, and would allow the operator to directly screw the hose (with purchased fittings) into the other hydraulic components [8].

3.3.3 Hydraulic Reservoir

Non-pressurized reservoir is chosen over the pressurized reservoir because the pressurized pump is more expensive due to the additional element which is needed to pressurize the reservoir and is not required for the project as the atmospheric pressure and gravity are enough to provide flow to the pump [9]. To keep the contaminants to a minimum, the team will use filters, thus selecting the pressurized type to keep the contaminants to a minimum is not a big incentive for the team. Therefore, the team chose a non-pressurized reservoir for the hydraulic system as it is also a cost-effective option.

3.3.4 Hydraulic Filters

Both bag and screen filters are viable options for this project, however, the screen filters give more flexibility to select pore sizes based on the application requirement. Selecting a larger pore size reduces the

cost of the filter. Meanwhile, the bag filter is offered in standard sizes and does not have as much flexibility as the screen filters. Also, since the bag filter pushes the flow through the cloth, the flow speed can be reduced slightly and that can negatively affect the flow rate of the system. Therefore, choosing the screen filter is an optimal choice [10].

3.3.5   Directional Hydraulic Control Valves

The solenoid-operated directional valve is chosen over the mechanical type because for this project, the amount of oil flowing through the valve needs to be controlled in a more precise manner, i.e., the diameter of the valve needs to be adjusted in smaller increments, the solenoid-operated directional valve must be used. The solenoid-operated directional valve uses an electrical signal to open or close the diameter of the control valve. The voltage is adjusted in order to achieve this. The solenoid-operated control valve allows the necessary amount of oil to flow through the valve in order to meet the three-second extension time.

3.3.6   Ball Valve, Check Valve, and Pressure Relief Valve

There are not many different concepts of ball valves that are available in the market, rather it is a very standard type of valve that is used in hydraulic applications [11]. Therefore, the team will simply choose a vendor for this type of valve based on the pressure and flow requirement which is discussed in Section 4.

Check and pressure relief valves are also standard types of valves where not many concepts are available in the market, rather they are very standard type of valves that are used in hydraulic applications [12]. The team will simply choose a vendor for these types of valves based on the pressure requirements which are discussed in Section 4.

3.3.7   Hydraulic Oil Cooler

The air-cooled oil cooler is chosen over the force-air oil cooler because the air-cooled type is economical compared to the forced-air type mainly because the forced-air type uses a motor-driven fan to cool the oil whereas the air-cooled type uses room-temperature air. Since the oil is maintained at a relatively low temperature of 77^oC, the need to have a forced-air cooler can be eliminated. Also, introducing a forced air cooler rather than an air-cooled cooler into the system would increase the cost by three-times for the hydraulic cooler alone. Given that the oil is at a relatively low temperature for all tests performed using the test apparatus, the team decided to select an air-cooled type hydraulic cooler.

3.3.8 Hydraulic Pump

It is important that the team select a hydraulic pump that can provide the required flow rate of at least 18.9786gpm and fixed displacement of 17.4267cc/rev based on the preliminary calculations done in Section 2.2. The pump must also be able to operate at 6400psi to satisfy the Mechanical Integrity Test listed in ████████ internal document [6].

The axial piston pump is chosen over the other three types of pumps (External Gear Pump, Axial Piston Pump, Bent Axis Piston Pump, and Internal Gear Pump) because it has the maximum pressure capability of 6530psi which is above the needed 6400psi, it has a maximum displacement capacity that ranges from 10-500cc/rev which meets the required displacement of 17.4267cc/rev, it costs almost the same external and internal gear pumps, it is also resistive to the contaminant and has overall efficiency range of 85% to 95% [13].

3.4 Electrical System Design Concept Selection

The following sections includes brief summary of different concepts developed for electrical system design and selections made in earlier phase of this project

3.4.1 Displacement Measurement Selection

Concepts of internal position sensor, digital scale and external position sensor were compared to measure rod displacement of test cylinder. Internal position sensor required drilling a hole on cylinder body to install internal position sensor.As this project focuses on testing of the hydraulic cylinders of the different configurations, it will take a lot of time and effort to install a sensor inside a cylinder bore for each cylinder to be tested. A digital linear scale consists of a track that would have to be clear of obstructions and would occupy about 30 inches of space on the tooling table while an external position sensor such as an LVIT can be connected parallel to a slave cylinder with an external connection with test cylinder. LVIT was chosen for measuring rod displacement as this option facilitates external connection (requires minimal effort and time to connect) and good space management on the tooling table

3.4.2 Pressure Measurement Selection

Concepts of a pressure sensor with digital guage and without any guage were compared. As there is a data acquisition system to be used to collect and analyze data, data can be viewed live from data acquisition unit itself. Furthermore, the pressure sensor might end up at a location where it might not be able to read

easily. It will not be ideal to rely on the gauge for pressure readings which is to be used for future analysis of the cylinders. This will not justify the added cost of a gauge being used. So, a pressure sensor with only voltage output will be used with a focus on providing best accuracy.

3.4.3 Temperature Measurement Selection

Concepts of using a custom threaded temperature sensor manufactured by KARTech and using a thermocouple were compared. Since the mounting configurations of both the sensors were identical, equal amount of time and effort would be required to connect and disconnect the sensors. The price of threaded temperature sensor by KAR Tech was about $ 70 CAD [14] and the price of the submersible thermocouple probe was about $110 CAD [15]. Thermocouple probe provides more flexibility in terms of choosing the length of the probe [15]. The probe of threaded sensor was fixed at 1/4 inches in length which might not completely submerge in the fluid while testing. Another adapter to extend the probe to ensure it is fully submerged in the fluid was required. Whereas, a thermocouple could be sourced out of a customized probe length to avoid this. Hence a thermocouple style sensor was chosen to collect temperature data from fluid.

3.4.4 Leakage Measurement Selection

Concepts of using flow meters and using rod displacement sensor were compared to detect leakages. Flow meters to be used in this project were limited by minimum flow detection capability of the flow meter. Flow meters to be used in high pressure lines (above 6000 psi) ranges from 2.113gpm (8 lpm) to 110.953gpm (420 lpm). The increment of measuring flow that the sensor has is 8 lpm which corresponds to $0.01709\text{in}^3/\text{min}$ ($0.28 \text{ cm}^3/\text{min}$). It is one of the crucial need to detect leakages of $0.01220\text{in}^3/\text{min}$ ($0.2 \text{ cm}^3/\text{min}$) or above and $0.01709\text{in}^3/\text{min}$ ($0.28 \text{ cm}^3/\text{min}$) is very close to that. Using a flow meter might not be ideal as it might not detect the change in flow in a case of very small leakage. Hence a sensor already being using to detect rod displacement could be used to detect change in rod displacement will conducting leakage test will would later be converted to change in volume and amount of fluid leaking.

4 Detailed Design

Once the concepts are selected for each component of the project, the concepts are then expanded further by providing details. This section first goes through hydraulic cylinder mount design which includes design of the cylinder mounts and mount manufacturability. The section then expands on the safety shield design of the test apparatus which includes the design of the shielding components and its manufacturability. This section then covers the hydraulic system design which goes over the sourcing out of all hydraulic components required for the test apparatus. Lastly, this section goes over the the sourcing out of the test apparatus' measurement sensors and all other sub-components required with the measurement sensors for the electrical system design.

The final hydraulic cylinder test apparatus design includes four main components which are the mounting system, safety shield system, hydraulic system and electrical system. Figure 3 shows the full assembly of the test apparatus.
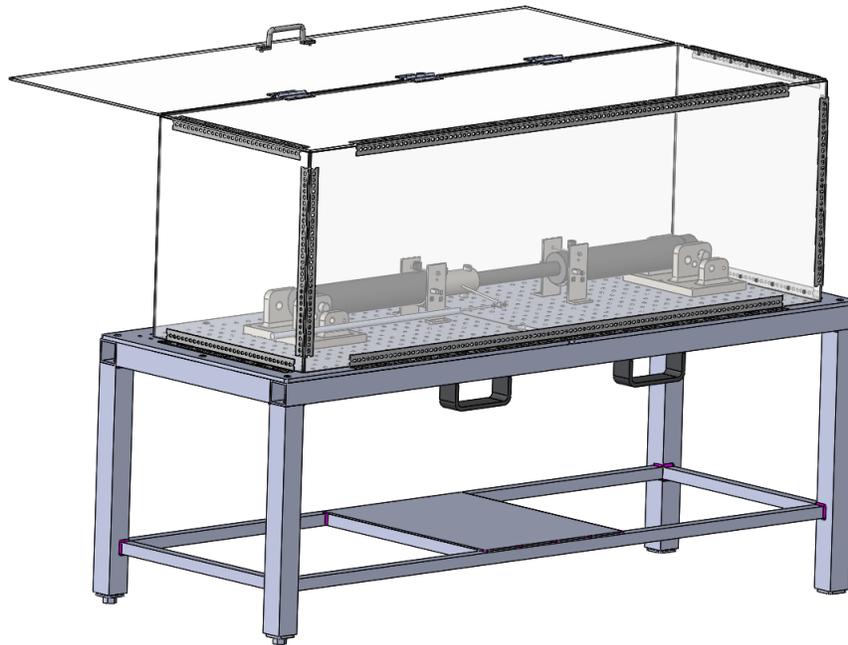
Figure 3: Hydraulic Cylinder Test Apparatus CAD Model

4.1 Mounting System Design

The hydraulics cylinders must be secured during the tests to provide accurate measurements and safety for the operators. The design needs to be capable of mounting different sizes and configurations of cylinders. The mounting system consists of cap end mounting and rod end mounting.

4.1.1 Cap End Bracket

The cap end bracket design revolves around being able to mount different configurations of cylinders. This consists of using three columns with different distances between them as well as holes for the different sizes of clevis pins. The heights of these holes have defined distances such that clearance is present between the hydraulic cylinders and testing table as shown in Figure 4.

(a) Cap End Bracket Isometric View   (b) Cap End Bracket, Clevis Pin and Cylinder Assembly
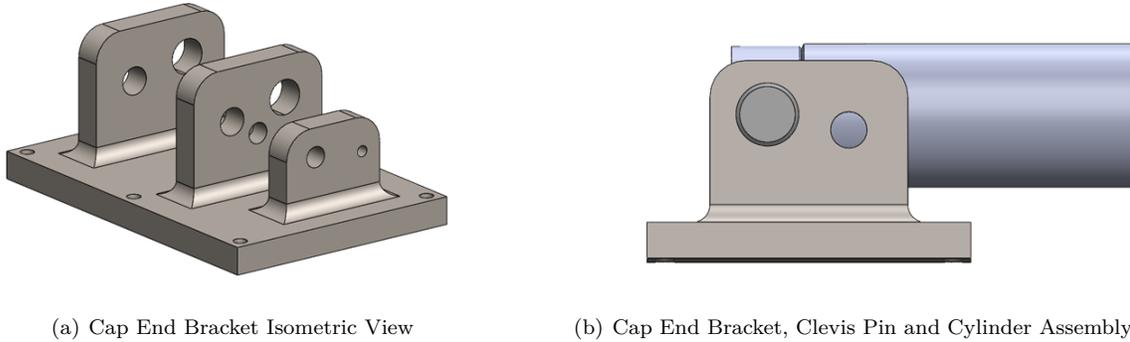
Figure 4: Isometric and Side View of Cap End Bracket

The cap end bracket will be manufactured out of AISI 4140H Alloy Steel plates and its material properties is shown in Table VII[16]. The manufacturing processes will consist of milling, drilling, grinding and welding. The columns and base of the bracket have slot and tab fixtures with full radius to minimize the stress concentration around the connection as shown in Figure 5. Fillet welds will be used to join the columns and base of the cap end bracket.
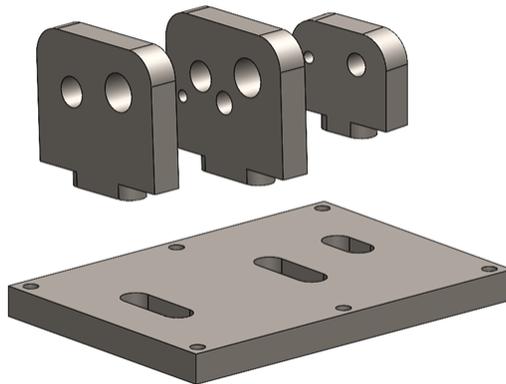
Figure 5: Slot and Tab Fixture of the Cap End Bracket

Table VII: AISI 4140H ALLOY STEEL MATERIAL PROPERTIES

Properties	Values
Density	0.284 lb/in^3
Tensile Strength	167000 psi
Yield Strength	152000 psi
Shear Modulus	11600 ksi
Elastic Modulus	29700 ksi
Poisson's Ratio	0.29

4.1.2 Cap End Bracket Analysis

To ensure the security of the cap end bracket design, both analytical and numerical analysis were performed. Normal stresses, shear stresses and weldment strength are the important aspects of this design as they prove the validity of this design's security. With a safety factor of 2, the following allowable stresses are shown below.

$$\sigma_{allow} = \frac{60200}{2} = 30100 \text{ psi}$$

$$\tau_{allow} = \frac{37926}{2} = 18963 \text{ psi}$$

Configuration 4 is the cylinder used for the analysis as it exerts the highest force during the proof pressure test with 5600 psi applied. This cylinder has a piston diameter of 3.5".

The force exerted for configuration 4 can be calculated as:

$$F = \frac{P\pi D^2}{4} \tag{6}$$

$$F = \frac{5600\pi 3.5^2}{4} = 53878.3 \text{ lbf}$$

4.1.2.1 Normal and Shear Stress

Consider a column of the bracket. The normal forces acting on it can be seen in Figure 6.
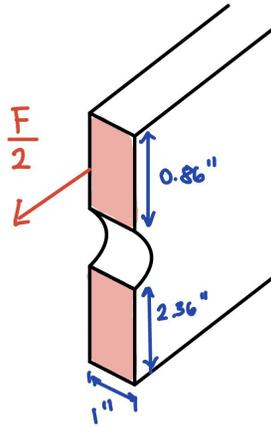
Figure 6: Section View of a Column of Cap End Bracket

Normal Stress can be calculated using the formula:

$$\sigma = \frac{F}{2(1(2.36 + 0.86))} \tag{7}$$

$$\sigma = 8366.2 \text{ psi}$$

Figure 7 shows the shear forces acting on the bracket.
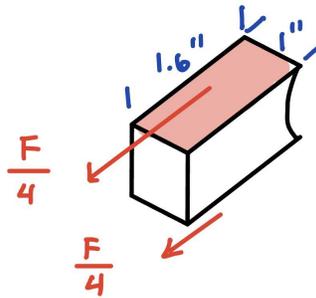
Figure 7: Section View of a Column of Cap End Bracket in Shear

The shear stress can be calculated using the formula:

$$\tau = \frac{F}{4A} \tag{8}$$

$$\tau = \frac{53878.3}{4(1.6 * 1)} = 8418.5 \text{ psi}$$

4.1.2.2   Numerical Analysis

Finite Element Analysis was conducted using SolidWorks to determine whether the cap end bracket design would be capable of sustaining the force applied during the proof pressure test. An advanced fixture is applied at the bolt locations constraining all directions. The material used for this simulation is AISI 4340 steel, normalized which has similar properties as AISI 4140H Alloy Steel. Split line is created on the holes for the pin so the force can be applied on the appropriate faces of the brackets. As shown in Figure 8, the purple arrow represents the remote load applied on the bracket which is located at the centre of where the clevis pin would be. Remote load is used for load application for more accurate load distribution on the brackets to achieve more accurate results.

X-Location (in):	-1.5
Y-Location (in):	3
Z-Location (in):	-1.5
Force - Z-Direction (lbf):	53,878.3
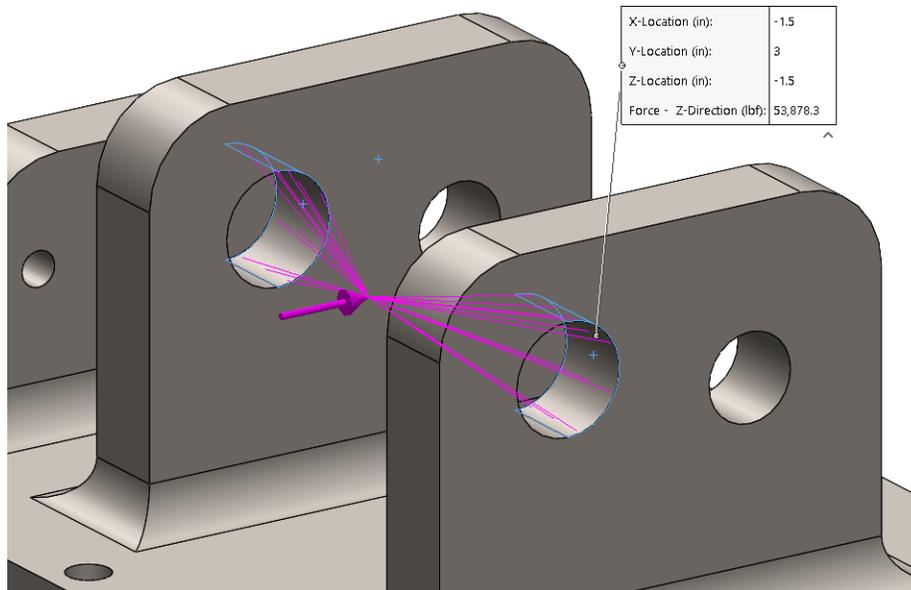
Figure 8: Force Application on Cap End Bracket

Table VIII and Figure 9 show the mesh settings and the mesh quality plot, respectively.

Table VIII: MESH SETTINGS

Item	Setting
Mesh Type	Blended Curvature-Based
Max Element Size	0.1 in
Min Element Size	0.01394 in
Total Nodes	1728271
Total Elements	1223107
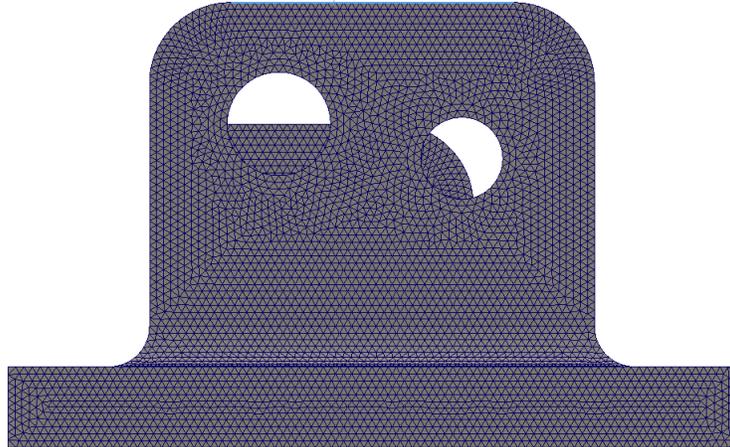
Figure 9: Mesh Quality Plot

The stress distribution present in the cap end bracket is shown in Figure 10 and Figure 11. The stress around the slot where the clevis pin goes is approximately 37500 psi. Lower stress is present around the hole with region of green and sky blue. Figure 11 proves that the cap end bracket can be used in either direction by showing similar stress distribution as the plot in Figure 10. This is a requirement because the same cap end bracket will be used for the slave cylinders during the performance tests.
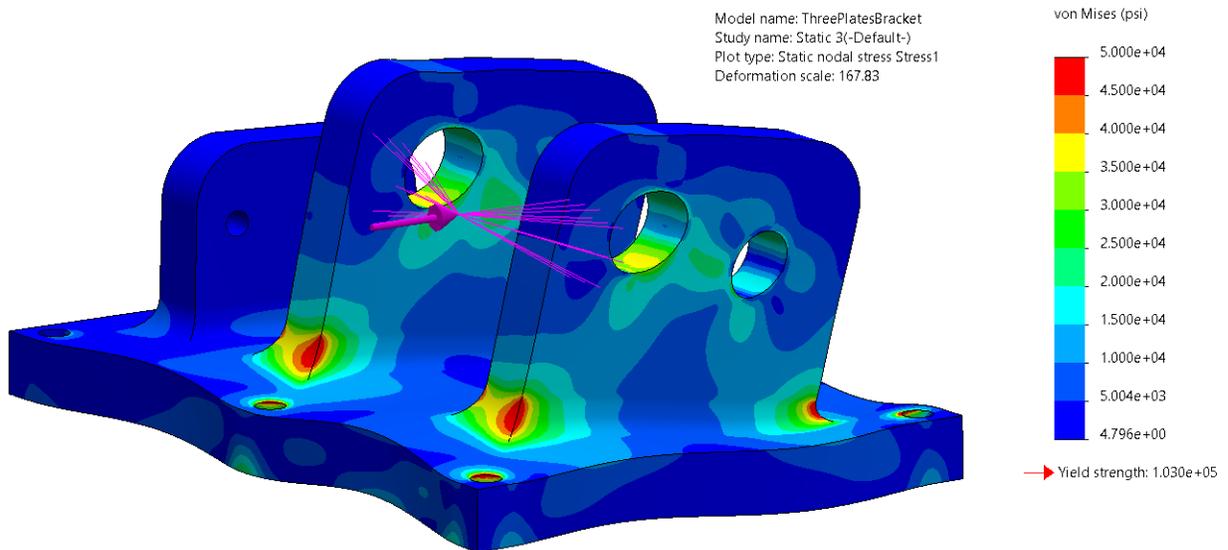
Figure 10: Stress Distribution Plot
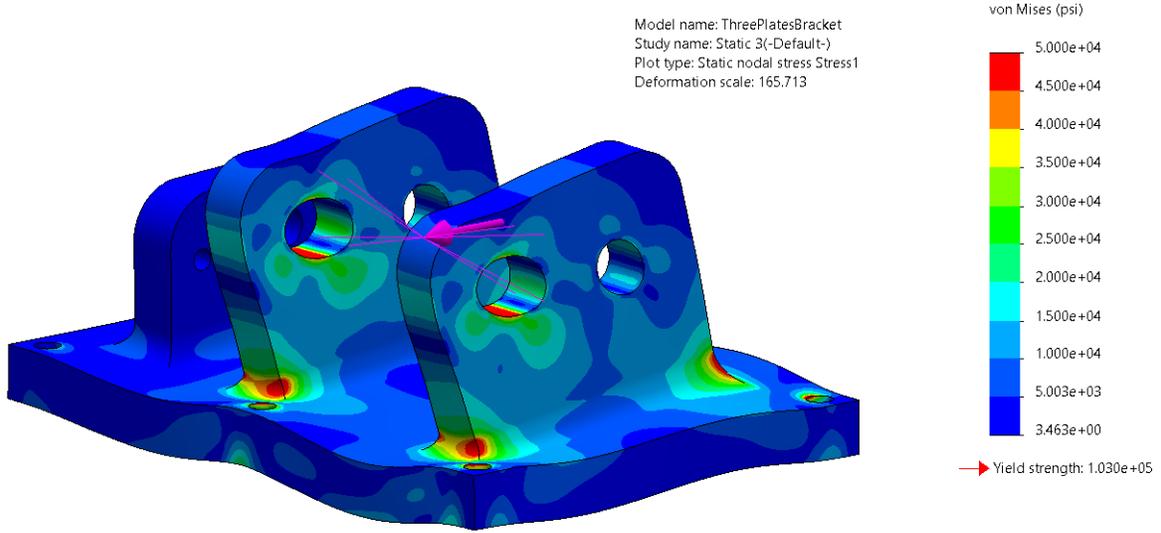
Figure 11: Stress Distribution Plot with Force Applied in Opposite Direction

4.1.2.3 Fatigue Analysis

Fatigue analysis is also performed on the mounting design in order to ensure that the mounting design meets the infinite fatigue life properties required by the client.

The pristine endurance limit was first determined using the following equations [17]:

$$S'_e = 0.5S_{ult} = 83500 \text{ psi} \tag{9}$$

Where S'_e is the pristine endurance limit and $S_{ult} = 167000 psi$, which is the ultimate tensile strength of the material.

Since the ultimate tensile strength of the selected material is 167000psi as mentioned in Table VII, the pristine endurance limit was determined to be 83500psi.

The actual endurance limit is then calculated using the following equations [17]:

$$S_e = S'_e \cdot k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \tag{10}$$

The variables in the above equation are described and calculated below.

$$K_a = aS^b_{ult} = 0.14713 \tag{11}$$

Where K_a is the Surface Modification Factor, $a = 2$ and $b = -0.217$ are obtained from below. [17]

Surface Finish	Factor a		Exponent b
	S_{ut}, kpsi	S_{ut}, MPa	
Ground	1.21	1.38	-0.067
Machined or cold-drawn	2.00	3.04	-0.217
Hot-rolled	11.0	38.6	-0.650
As-forged	12.7	54.9	-0.758

Figure 12: Surface Modification Factor (K_a) table

$$K_b = (\frac{d}{0.3})^{-0.107} = 0.9681434 \tag{12}$$

Where K_b is the Size Modification Factor [17] and $d = 0.406in$ for the smallest pin diameter.

$$K_c = 1 \; for \; bending \tag{13}$$

Where K_c is the Load Modification Factor obtained from [17].

$$K_d = 0.975 + 0.432(10^{-3})T_f - 0.115(10^{-5})T_f^2 + 0.104(10^{-8})T_f^3 - 0.595(10^{-12})T_f^4 = 1.000459 \tag{14}$$

Where K_d is the Temperature Modification Factor and $T_f = 71.6^o F$.

$$K_e = 1 - 0.08z_a = 0.814 \tag{15}$$

Where K_e is the Reliability Factor and $z_a = 2.326$ obtained from the table below [17].

Reliability, %	Transformation Variate z_a	Reliability Factor k_e
50	0	1.000
90	1.288	0.897
95	1.645	0.868
99	2.326	0.814
99.9	3.091	0.753
99.99	3.719	0.702

Figure 13: Reliability Factor (K_e) equation obtained from [17]

$$K_f = 1 \tag{16}$$

Where K_f is the miscellaneous Factor obtained from [17].

Using the variables from above in the actual endurance limit equation, the actual endurance limit, maximum stress, minimum stress, mean stress, amplitude stress can be calculated and are shown below.

$$S_e = S_e^{'} \cdot k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f = 9686.1325psi$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} = 6996.075psi \tag{17}$$

Where σ_m is the mean stress in psi, $\sigma_{max} = 13992.15psi$, and $\sigma_{min} = 0psi$.

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = 6996.075psi \tag{18}$$

Where σ_a is the amplitude stress in psi.

Using the Modified Goodman Approach, the team can determined if the mounting design is a safe design [17].

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ult}} \leq \frac{1}{n} = 0.76417 \tag{19}$$

Since the equation yields a value less than 1, the design is safe in terms of fatigue. Also, we can see from the S-N curve for 4140H Steel (see below) that at the maximum stress of 13992.15psi (96.47MPa) and actual endurance limit of 9686.13psi (66.78MPa), the material will have a fatigue life of over 1E10 cycles which can be considered infinite.
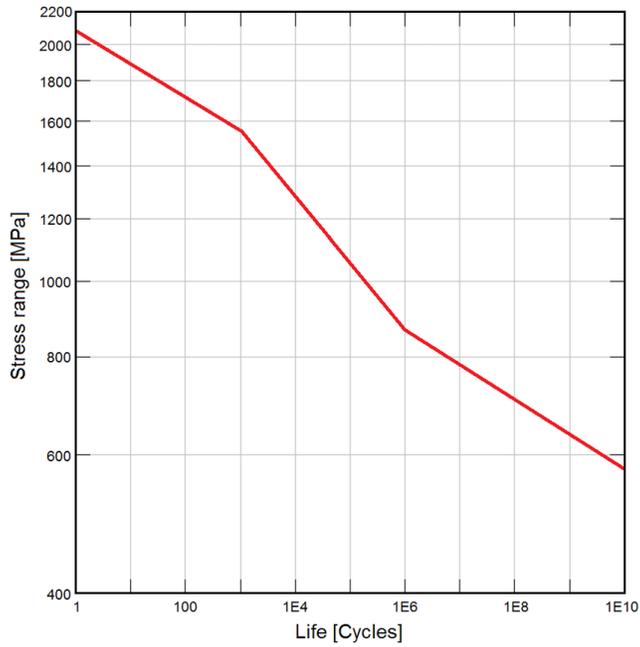
Figure 14: S-N Curve for 4140H Steel [18]

4.1.2.4 Weldment Strength

Weldment strength analysis is performed to ensure the connection of columns and base do not fail during the proof pressure test. Fillet welds will be applied around the base of the columns shown in green in Figure 15. Shear and bending will be the two type of stresses that will be exerted on the welds.
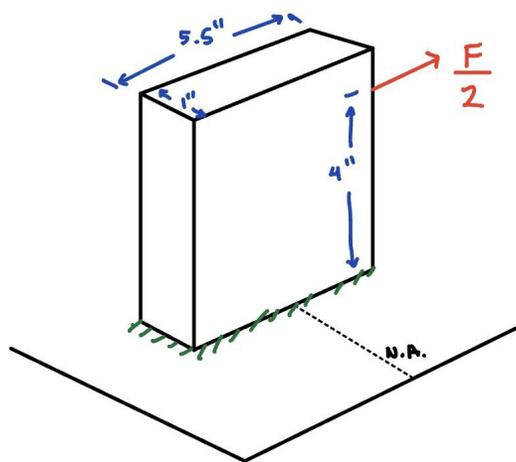
Figure 15: Weldment Strength Analysis Diagram

Considering one column of the bracket, the calculation of the shear stress is shown below.

$$\tau_a = \frac{F/2}{1.414h(1+5.5)} \tag{20}$$

where h is the size of the weld and is 0.5".

$$\tau_a = \frac{26939.15}{1.414*0.5*(1+5.5)}$$

$$\tau_a = 5862.1 \text{ psi}$$

Bending stress on the weldment is calculated as shown below.

$$\tau_b = \frac{Mc}{I} \tag{21}$$

where M is the moment acting on the column, c is the neutral axis of the bending, and I is the moment of inertia of the column.

$$I_u = \frac{d^2}{6}(3b+d) = \frac{5.5^2}{6}(3*1+5.5) \tag{22}$$

$$I_u = 42.85 \text{ in}^4$$

$$I = 0.707hI_u = 0.707*0.5*42.85 \tag{23}$$

$$I = 15.15 \text{ in}^4$$

$$\tau_b = \frac{(26939.15*4)2.75}{15.15}$$

$$\tau_b = 19559.8 \text{ psi}$$

$$\tau = \sqrt{\tau_a^2 + \tau_b^2} \tag{24}$$

$$\tau = \sqrt{5862.1^2 + 19559.8^2}$$

$$\tau = 20419.4 \text{ psi}$$

For AISI 4140H steel, the allowable shear strength for welding is:

$$\tau_{allow} = 0.3 * 152000 = 45600 \text{ psi}$$

$$n = \frac{\tau_{allow}}{\tau} = \frac{45600}{20419.4} = 2.23$$

4.1.3   Rod End Bracket

The rod end bracket holds the rod end side of the cylinder and prevents them from making any possible vertical motion. Forces acting on it are very minimal so further analysis for this design is not as important. The rod end bracket is also capable of mounting different sizes and configurations of cylinders. The design consists of two side brackets, half trunnion and threaded rod/nuts. The threaded rod is 18-8 Stainless Steel that has a 1/4"-20 thread size and is 6 inches long which can be ordered from McMaster-Carr [19].
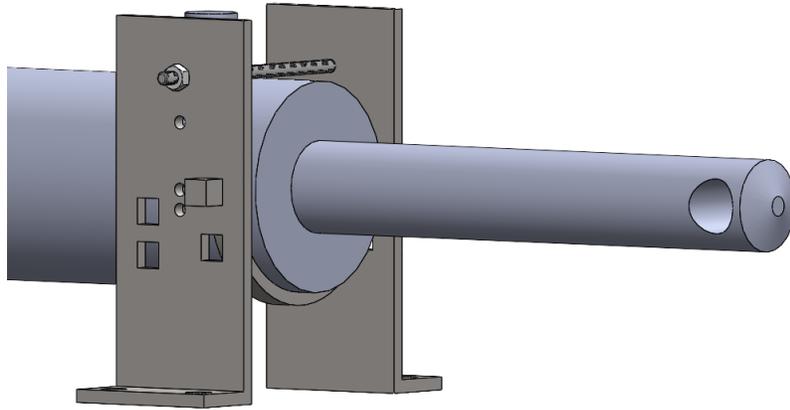
Figure 16: Rod End Bracket Attached with Configuration 4 Cylinder's Rod End Side

As shown in Figure 16, the distance between the side brackets can be adjusted since it is bolted onto the testing table. Several locations of square holes are present for different heights required due to difference in cylinder's diameter. There are also holes for the threaded rod for security of cylinders' rod end side. Multiple half trunnion brackets will be required to support the other cylinder configurations. The dimensions of the side brackets and half trunnions are shown in Appendix A.

4.2 Safety Shield Design

The safety shield designs provides protection for the operator just in case failure occurs during performance tests. Minimizing the amount of open areas around the test blocks the high oil pressure leaks which causes dangerous skin penetration. Mounting the design on the testing table protects the operator from hydraulic cylinder failure which may cause serious injuries. Figure 17 shows the safety shield setup on the testing table.
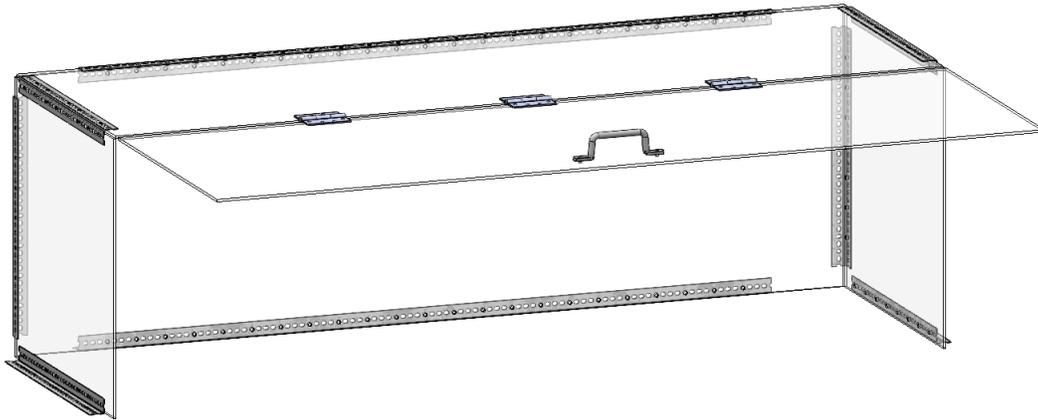
Figure 17: Safety Shield Design

The safety shield design includes glass, hinges and L-shaped frames. The glass is made out of acrylic and is a quarter inch thick. The dimensions of each side can be found in Appendix A. The following items required for the design can be ordered from McMaster-Carr:

- 304 Stainless Steel L-Shaped Rail, 1-1/2" x 1-1/2", 8' length[20]

- 304 Stainless Steel L-Shaped Rail, 1-1/2" x 1-1/2", 6' length[20]

- Unthreaded-Hole Round Pull Handle [21]

- 3 x Mortise-Mount Entry Door Template Hinge[22]

4.3 Hydraulic System Design

The hydraulic system design includes sourcing all the hydraulic components from different vendors. The vendors are chosen with client consultation such that the client has some relationship with the vendors from previous purchases. The components are selected based on the technical specifications required for the test

apparatus while considering the price point of each component. The figure below shows the hydraulic circuit schematic for the most complex test done by ▮▮▮▮ and all of the hydraulic components are required to make this test possible.
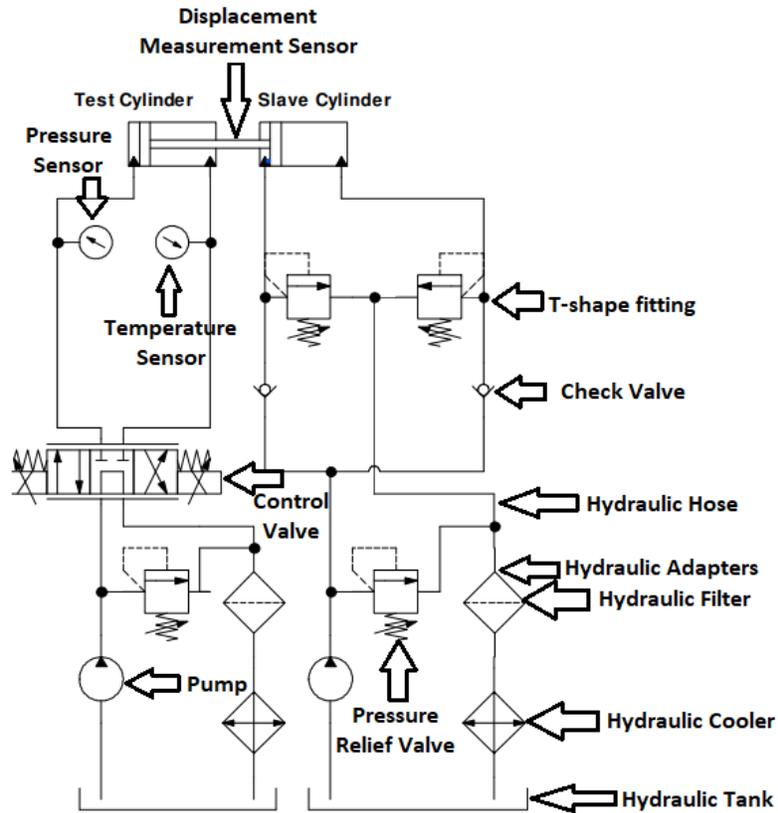
Figure 18: Hydraulic Circuit Schematic for Endurance Test [6]

4.3.1   Hydraulic Hose

The flexible hydraulic hose was chosen for the test apparatus. Based on the calculations done in Section 2.2, there are two hose diameters required for the test apparatus, 0.75" internal diameter (ID) for the pressure line hoses (general hoses used to connect different hydraulic components) and 1.5" ID for the pump suction line hose to avoid cavitation at the pump's inlet. The hydraulic hose must withstand 6400psi of pressure as the Mechanical Integrity Test is to be performed at 6400psi according to ▮▮▮▮ internal document – 252238 [6]. Green Line's *156PLUS-12 3/4" NOVA 15 6100 PSI* is chosen (See Figure 19). This hose is rated for a working pressure of 6100psi (which is also applicable for the operating pressure of 6400psi) with a burst pressure of 24400psi. This hose comes in both 0.75" and 1.5" ID with hydraulic part numbers -12 (Dash 12) and -24 (Dash 24), respectively. The operating temperature of the hose ranges from -40°F to 249.8^{o}F (-40°C to 121°C) which fall within the test apparatus working temperature of 170.6^{o}F ± 37.4^{o}F (77°C ±

3°C). The table below summarizes the technical specifications of the hose [23].

Table IX: TECHNICAL SPECIFICATIONS OF HYDRAULIC HOSE

Hose Part #	Hose ID	Hose OD	Working Pressure	Compatible Fitting	Temperature Range
-12	0.75''	1.20''	6100psi	4400 Series or 5000 Series Fitting	-40°F to 249.8°F (-40°C to 121°C)
-24	1.5''	2.25''	6100psi	4400 Series or 5000 Series Fitting	-40°F to 249.8°F (-40°C to 121°C)

Figure 19: Green Line's Hydraulic Hose [23]

4.3.2 Hydraulic Adapters

The thread-type adapters were chosen for the test apparatus. The hydraulic hose selected in the above sub-section requires a fitting to be installed as the hoses come in bulk, i.e., the fitting does not come pre-installed. The fittings come with different thread sizes and hose diameters. The fittings also come in either male-type or female-type. Since some hydraulic components such as directional control valves use different thread sizes than some other hydraulic components, the hydraulic hose fittings must be selected accordingly to show compatibility between the fittings and the hydraulic components. The table below summarizes different hydraulic fittings and adapters needed to connect various hydraulic components [24].

Table X: TECHNICAL SPECIFICATIONS OF HYDRAULIC FITTINGS AND ADAPTERS

Picture	Fitting/Adapter	Male/Female Type	Manufacturer	Thread Size	Product Style	Hose ID	Connection
	Fitting	Male	Green Line	3/4x14in NPT	Male NPTF Pipe - Rigid	0.75in	0.75'' Hose to Pump Adapter, Relief Valve Port, Filter, Oil Cooler Adapter, Check valve, Ball valve, T-shaped Fittings
	Fitting	Male	Green Line	1-1/2x11-1/2in NPT	Male NPTF Pipe - Rigid	1.5in	1.5'' Hose to Pump Suction Adapter
	Fitting	Male	Green Line	1/2x14in NPT	Male NPTF Pipe - Rigid	0.75in	0.75'' Hose to Control Valve
	Fitting	Female	Green Line	3/4x14in NPT	Female NPTF Pipe - Rigid	0.75in	0.75'' Hose to Cylinder Ports, Reservoir, Relief Valve Port
	Adapter	Female	Parker	3/4-14in NPT	Female Straight Thread Tee	N/A	0.75'' Hose to other 0.75'' Hoses
	Adapter	Male to Female	Surplus Center	1-1/16-12in ORB to 3/4-14in NPT	Male SAE to Female NPT	N/A	0.75'' Hose Male Fitting to Oil Cooler Ports
	Adapter	Male to Female	Eaton	1-1/2-11-1/2in NPT	Male ORB to Female NPT	N/A	1.5'' Hose Male Fitting to Pump Suction Port
	Adapter	Female	Parker	1.5in NPT	Female Flange	N/A	1.5'' Hose Male Fittings to Pump Suction Port
	Adapter	Female	Parker	3/4in NPT	Female Flange	N/A	0.75'' Hose Male Fittings to Pump Pressure Port

4.3.3   Hydraulic Reservoir

The non-pressurized hydraulic reservoir was selected for the test apparatus. The reservoir requires at least 19gallons of oil storage in order to ensure that system has enough oil available during testing. Grainger's hydraulic reservoir was selected for this project (See Figure 20). This reservoir has a total oil capacity of 38gallons which satisfies the team's need of requiring a maximum oil needed in the system of 38gpm for Mechanical Integrity Test [6]. This tank also features an in-tank oil filter, oil level gauge, oil temperature inductor, 4 suction ports, 4 return ports, and 4 drain ports. The thread size for each of the 4 ports on the tank is 2.00", 0.75", 0.5", and 1.25". The overall dimension of the tank is 22" in height and 28.354" in length. The table below summarizes the technical specifications of the tank [25].

Table XI: TECHNICAL SPECIFICATIONS OF HYDRAULIC TANK

Tank Capacity	38gallons
# of Suction Ports	4
# of Drain Ports	4
# of Return Ports	4
Thread Size for Ports	2.00'', 0.75'', 0.5'', 1.25''
Temperature Sensor	Yes
In-tank Oil Filter	Yes
Oil Level Gauge	Yes
Overall Dimension	28.354''L x 22''H

Figure 20: Grainger's Hydraulic Reservoir [25]

The drawing below shows how the tank is connected with hose.
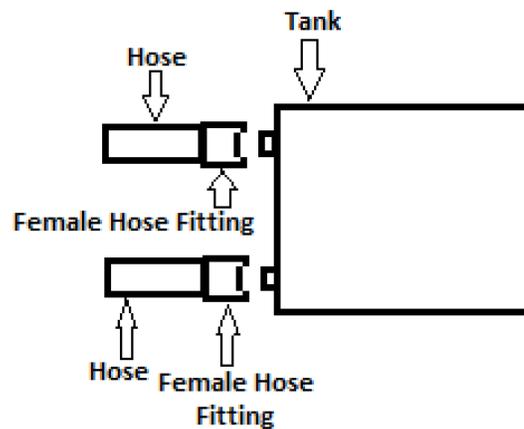
Figure 21: Drawing shows How the Tank is Connected to the Hose

4.3.4 Hydraulic Filter

The screen filter was chosen by the team for this project. The filter will stop any foreign contaminants to enter the system. The screen filter with 25micons pores will be sufficient to constraint the contaminants to enter the system in an indoor controlled environment. Grainger's *Hydraulic In-Line Filter,3/4in* is chosen to for this project (See Figure 22). This filter features a maximum pressure of 3000psi, 0.75"NPTF thread

size, and inline mounting condition. The filter is chosen because it does not need to satisfy flow and pressure requirements as it directly connects to the reservoir through the return line. The filter will not experience any more than 3000psi as it the larger pressure (6000psi) test is done via the pressure line and thus the return line would not see any more than 3000psi of pressure for any test for the hydraulic cylinder. The table below summaries the technical specifications of the filter [26].

Table XII: TECHNICAL SPECIFICATIONS OF HYDRAULIC FILTER

Maximum Operating Pressure	3000psi
Mounting Style	In-line
Pore Size	25microns
Thread Size	0.75'' NPTF
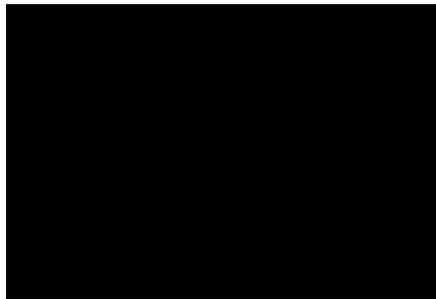
Figure 22: Grainger's Hydraulic Filter [26]

The drawing below shows how the filter is connected with hose.
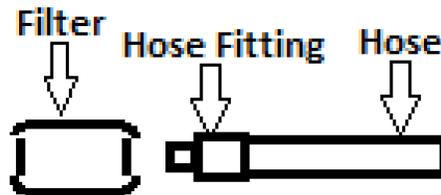
Figure 23: Drawing shows How the Filter is Connected to the Hose

4.3.5 Hydraulic Directional Control Valve

The solenoid-operated directional control valve is chosen for this project. The team requires a solenoid-operated directional control valve that has a tandem-style, open center, and 4way-3pos configuration (See Figure 24). The valve must allow at least 19gpm of flow through it, it should be able to operate at 170.6^oF (77^oC) and should have a voltage regulator to adjust the diameter of the valve to compensate for the flow allowance.

Figure 24: Rexroth's Hydraulic Directional Control Valve Schematic [27]

Rexroth's *R900561282 Directional Spool Valves* is chosen to meet the team's requirements (See Figure 25). This valve features a maximum flow of 21.134gpm, a maximum operating temperature of 180°C, and a 3-pole plug connection for each solenoid that can be mated with an M12 connector in order to adjust the voltage and consequently the diameter of the valve [27].

Figure 25: Rexroth's Hydraulic Directional Control Valve [27]

This valve requires a separate subplate to be installed at the bottom so that the hydraulic hoses can be connected to the subplate which allows the oil to flow from the hoses and through the valve. A compatible subplate was chosen so that valve aligns with the subplate seamlessly. Rexroth's *R900424447 Subplate* was chosen for the valve (See Figure 26). The subplate will be connected to the valve using four ISO 4762 – M5 – 10.9 hexagon socket head cap screws. The subplate will be clamped on the tooling table using 0.276" diameter bolts and nuts assembly [28].
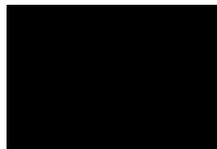
Figure 26: Rexroth's Hydraulic Directional Control Valve Subplate [27]

This valve also requires one separate 3-pole plug-in connector (See Figure 27a). The connector will be installed on the valve and will have an M12 connector cable (See Figure 27b) which connects the 3-pole plug-in connector to the 3 pins female to 4 pins male converter (See Figure 27c). The 3 pins female to 4 pins male converter will be attached to a 4 pins female to 4 pins female adapter (See Figure 27d). This adapter will be attached to the 4 pins male to 6 pins male adapter (See Figure 27e). The converters are required as ▮▮▮▮▮ data acquisition system uses 6 pins connection input in order to adjust the voltage of the solenoids on the valve. Rexroth's *R901207821 Double mating connectors for valves with two solenoids* is used along with McMaster-Carr's *Micro M12 Screw-Together Connectors* connector cable. This connector
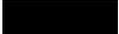
cable connects to B & H Electronics' *3-Pin Mini XLR Female to 4-Pin XLR Male Power Adapter Cable* which connects to the Audiopile's *DMX-4F4F 4 Pin FXLR to 4 Pin FXLR Barrel Adapter.* The Audiopile's adapter connects to the to connect to the B & H Electronics' *6-Pin to 4-Pin XLR Cable* which is finally connected the data acquisition system [29].

.

(a) 3-Pole Plug-in Connector [29]

(b) M12 Connector Cable [30]

(c) 3 Pins Female to 4 Pins Male Converter [31]

(d) 4 Pins Female to 4 Pins Female Converter [32]

(e) 4 Pins Male to 6 Pins Male Converter [33]
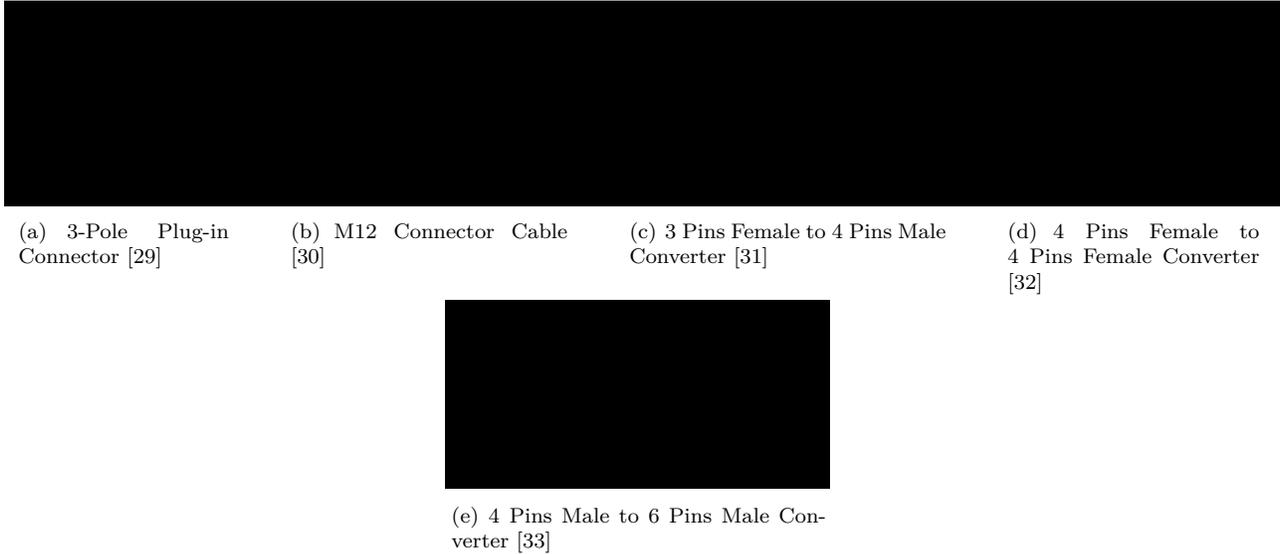
Figure 27: Additional Components Required to Change the Voltage of the Solenoids to Change the Diameter of the Control Valve

The table below shows the technical specifications of the hydraulic control valve and its additional components.

Table XIII: TECHNICAL SPECIFICATIONS OF HYDRAULIC CONTROL VALVE AND ITS COMPONENTS

Maximum Flow Rate	21.134gpm
Maximum Operation Temperature	356ºF (180ºC)
Control Valve Subplate Connection size	0.5'' NPT
Solenoid Connection	3 Pole Plug-in Connector
Plug-in Connector to Cable Connection	M12 Screw-Together Connector
Cable Connection to Converter	3-Pins to 4-Pins Converter
Converter to Converter	4-Pins Female to Female Converter
Converter to Converter	4-Pins to 6-Pins Converter
Converter to Data Acquisition System	Direct Connection

The drawing below shows how the control valve and its additional components are connected.
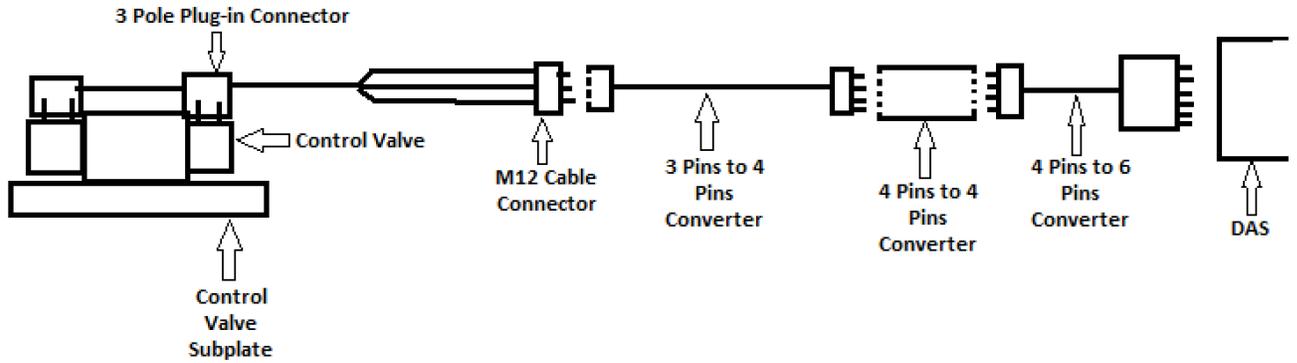
Figure 28: Drawing shows How the Control Valve and its Additional Components are Connected

4.3.6 Ball, Check, and Pressure Relief Valve

The ball valve is a standard valve available in the market. In order to select the adequate ball valve, the maximum pressure of 6400psi, the ID of 0.75", and an operating temperature of 170.6^{o}F (77°C) are needed. Parker's *Industrial Ball Valves - Carbon Steel* is selected in order to satisfy the requirements for the test apparatus (See Figure 29). This valve features operating pressure of 6500psi, ID of 0.75", and operating temperature ranges from -10°F (-23°C) to 210°F (98.8^{o}C), thread size of 0.75" NPT and lever-operated with inline configuration. The table below summarizes the technical specifications of the ball valve [34].

Table XIV: TECHNICAL SPECIFICATIONS OF HYDRAULIC BALL VALVE

ID	0.75''
Maximum Operating Pressure	6500psi
Thread Size	0.75'' NPT
Maximum Operation Temperature Range	-10ºF (23ºC) to 210ºF (98.8ºC)
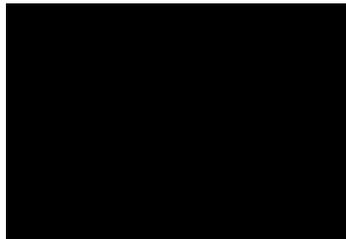
Figure 29: Parker's Hydraulic Ball Valve [34]

The check valve is also a standard valve available in the market. To select the adequate check valve, the maximum pressure of 6000psi, one-way flow, minimum ID of 0.75", and operating temperature of 170.6^{o}F (77°C) is needed. Tu-Lok's *6000psi Check Valve* is selected (See Figure 30). This valve features maximum operating pressure of 6000psi, 0.75" ID, operating temperature ranges from -40°F (-40°C) to 100°F (212°C),

thread size of 0.75" NPTF with one-way flow. Since this valve meets the team's requirements, the team has selected this valve for the project. The table shown below summarizes technical specifications [12].

Table XV: TECHNICAL SPECIFICATIONS OF HYDRAULIC CHECK VALVE

ID	0.75"
Flow	One-way
Mounting Style	In-line
Maximum Operating Pressure	6000psi
Thread Size	0.75" NPTF
Maximum Operation Temperature Range	-40°F (-40°C) to 212°F (100°C)

Figure 30: Tu-Lok's Hydraulic Check Valve [12]

The drawing below shows how the check valve is connected to the hose. This same idea is also applied to the ball valve connection.
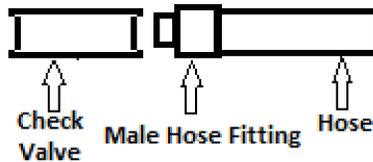
Figure 31: Drawing shows How the Check Valve is Connected to the Hose

The pressure relief valve is also a standard type valve available in the market. A spring-loaded pressure relief valve is chosen by the team. To select an adequate pressure relief valve, a maximum pressure of 6401psi is required. Once the pressure reaches 6401psi, the valve will open and allow the flow to travel from the pump to the reservoir. Hyvair's *FW1022 Series Direct Acting Relief Valve* is selected to achieve this (See Figure 32). The valve features variable pressure adjustable from 500psi to 6500psi (i.e., the spring within the valve can be adjusted to ensure that the relief valve will only open when it reaches any desired pressure between 500 to 6500psi). This will allow the valve to be used in different tests by changing the spring adjustment to the opening pressure (cracking pressure) of the valve. This valve also features a 0.75" male and female NPT thread size. The table below summarizes that technical specifications of the relief valve [35].

Table XVI: TECHNICAL SPECIFICATIONS OF HYDRAULIC PRESSURE RELIEF VALVE

Adjustable Pressure Setting	Yes
Adjustable Pressure Range	500psi –6500psi
Mounting Style	In-line
Thread Size	0.75'' NPTF (both male and female ends)
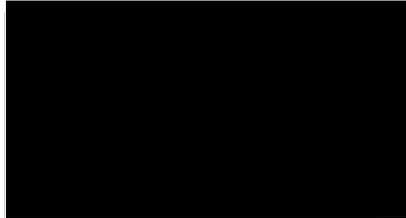
Figure 32: Hyvair's Hydraulic Pressure Relief Valve [35]

The drawing below shows how the pressure relief valve is connected to the hose.
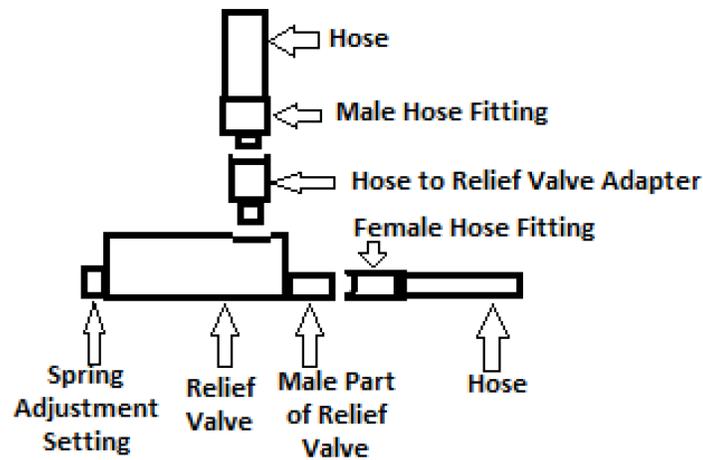
Figure 33: Drawing shows How the Relief Valve is Connected to the Hose

4.3.7 Hydraulic Oil Cooler

The air-cooled hydraulic oil cooler is chosen for this project. The oil cooler is needed to cool the heated oil as it travels through the system. The calculations shown below show the amount of heat that could be transferred to the oil due to the pump's inefficiency.

Power input required for the pump can be calculated using the following equation.

$$Power_{in} = \frac{PQ}{1714\eta_{tot}} \tag{25}$$

Where $Power_{in}$ is the power input to the pump in HP, P is the operating pressure of the pump in psi, Q is the flow rate produced by the pump in gpm, and η_{tot} is the total efficiency of the pump.

The pump's total efficiency can be calculated as follows.

$$\eta_{tot} = (\eta_{vol})(\eta_{mech}) \tag{26}$$

Where η_{vol} is the pump's volumetric efficiency ($\eta_{vol} = 0.99$ at 3200psi and $\eta_{vol} = 0.98$ at 6400psi [36]) and η_{mech} is the pump's mechanical efficiency ($\eta_{mech} = 0.95$ at 3200psi and $\eta_{mech} = 0.965$ at 6400psi [36]).

The pump's input power can be then calculated as follows:

$$Power_{in} = \frac{3200(18.9786)}{1714(0.99)(0.95)} = 37.674\text{HP}$$

The power out produced by the pump can be calculated using the following equation.

$$Power_{out} = (Power_{in})(\eta_{tot}) = (37.674)(0.99)(0.95) = 35.423\text{HP} \tag{27}$$

Where $Power_{out}$ is the power produced by the pump in HP. The wasted power can then be calculated which can be interpreted as the amount of power (heat) that will be absorbed by the oil.

$$Wasted\ Power = Power_{in} - Power_{out} = 37.674 - 35.423 = 2.242\text{HP} \tag{28}$$

Therefore, the oil cooler is needed to be selected such that it removes 2.242HP of heat from the oil. The table shown below summarizes the results for the pump operating at 3200psi and 6400psi.

Table XVII: SUMMARY OF HEAT TO BE REMOVED AT 3200PSI AND 6400PSI PUMP PRESSURES

Pump Operating at 3200psi		Pump Operating at 6400psi	
η_{vol}	0.99	η_{vol}	0.98
η_{mech}	0.95	η_{mech}	0.965
η_{tot}	0.9405	η_{tot}	0.9457
$Power_{in}$	37.6742HP	$Power_{in}$	74.9341
$Power_{out}$	35.4326HP	$Power_{out}$	70.8652
Wasted Power	2.242HP	Wasted Power	4.067
Heat to be removed	2.242HP	Heat to be removed	4.067

A maximum of 4.069HP of heat must be removed. Grainger's *Hydraulic Oil Cooler* is used to achieve this target (See Figure 34). This cooler features a maximum flow rate of 30gpm and 8HP of heat removed. This cooler meets the team's requirements as the system flow rate limited to 19gpm and the system's oil heat produced by the pump inefficiency is limited to the 5.236HP for the maximum pressure case. The table

below summarizes the specification of the oil cooler [37].

Table XVIII: TECHNICAL SPECIFICATIONS OF HYDRAULIC OIL COOLER

HP Heat Removed	8HP
Maximum Flow Rate	30gpm
Inlet Port Thread Size	Female SAE #12
Outlet Port Thread Size	Male SAE #12
Oil Cooler Adapter	Male SAE #12 to Female 0.75'' NPT
Mounting Style	In-line
Overall Dimensions	6.65''H x 17.91'' W x 1.77'' D

Figure 34: Grainger's Hydraulic Oil Cooler [37]

The drawing below shows how the hydraulic oil cooler is connected to the hose.
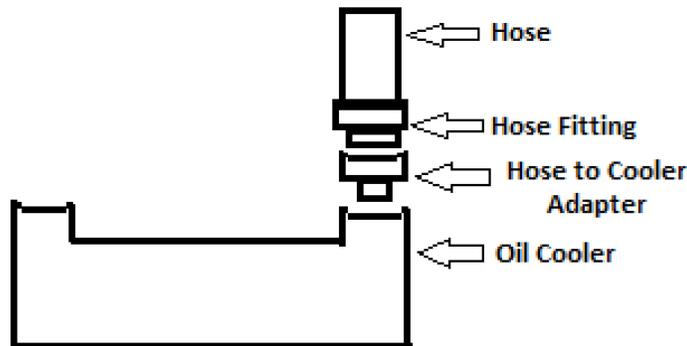
Figure 35: Drawing shows How the Oil Cooler is Connected to the Hose

4.3.8 Hydraulic Pump

The axial piston pump is selected for the test apparatus. Based on the calculations done in Section 2.2, the pump must have a displacement of $1.0634\text{in}^3/\text{rev}$ and the pump must provide a maximum pressure of 6400psi. Parker's *Axial Piston Fixed Pumps - Series Large Frame F12* is selected by the team to accomplish these requirements (See Figure 37). This pump can provide displacement of 1.83 in^3/rev with a maximum pressure of 6960psi [38]. This pump requires a flange adapter to be installed on the main ports of the pump in order to allow the suction hose and the pressure hose to connect to the pump. Parker's *ISO 6162-1/2*

SAE Full Flanges for Threaded and Cutting Ring Connections (See Figure 36a) is selected because it shows compatibility with the pump's connection configuration [39].

(a) Parker's Hydraulic Pump Flange [39]   (b) Suction Line Hose to Pump Flange Adapter [40]

Figure 36: Parker's Pump Additional Required Components

Two flanges will be installed on the pump's two main ports using four bolts flange connection for each flange. The bolt assemblies come with flanges. Once attached, the hose fittings can be installed to pump. Pressure hose fitting can be directly screwed onto the pump's flange since the thread size of 0.75x14in matches perfectly with the flange's thread size. However, the suction line hose fitting requires an additional adapter that connects the fitting to the pump's flange as the team was unable to find the thread size of the fitting that matches with flange's thread size since the pump's suction line diameter is 1.5" instead of 0.75" of the pressure hose [40]. The technical specifications of the pump are summarised in the table below [38].

Table XIX: TECHNICAL SPECIFICATIONS OF HYDRAULIC PUMP

Pump's Maximum Displacement	1.83in³/rev
Pump's Maximum Pressure Capability	6960psi
Pump Flange Connection	4 Bolt Assembly (included with the flange)
Flange 1 Thread Size (Pressure Port)	0.75'' NPT
Flange 2 Thread Size (Suction Port)	1.5'' NPT
Pressure Hose Thread Size	0.75'' NPT
Suction Hose Thread Size	1-1/2x11''-1/2 NPTF
Suction Hose Fitting to Flange Adapter	1-1/2"-11-1/2 Female to 1.5'' NPT Male
Flange Adapter to Flange	1.5'' NPT Male to 1.5'' NPT Female
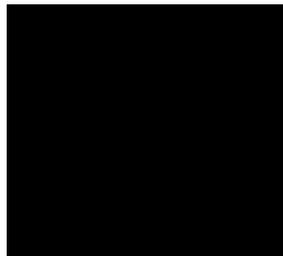
Figure 37: Parker's Hydraulic Pump [38]

The drawing below shows how the hydraulic pump is connected to the hose.
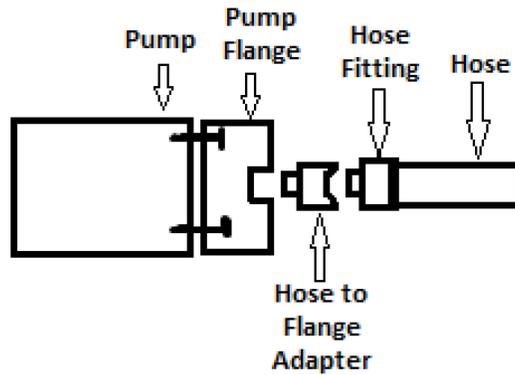
Figure 38: Drawing shows How the Pump is Connected to the Hose

4.3.9   Hydraulic System Schematics

During weekly meetings, ███████ specified that they only developed hydraulic system schematics for the double-acting cylinder configuration for all tests (Mechanical Integrity Test, Endurance Test, and Leakage Test) and only one schematic for the single-acting configuration for the Endurance Test. Thus, ███████ requested the team to build hydraulic system schematics for the single-acting cylinder configuration using the Automation Studios Software (See Figures 39 and 40).
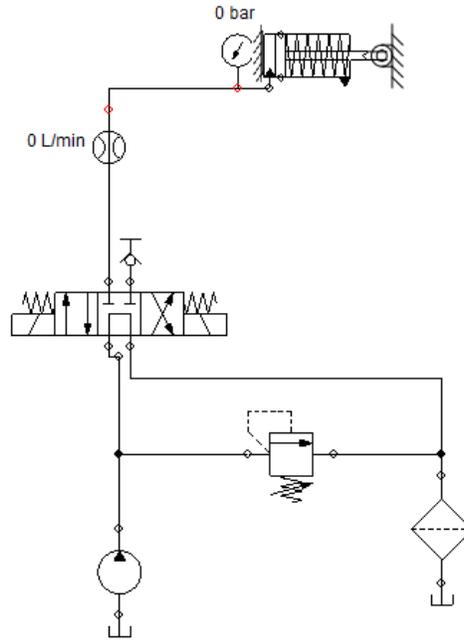
Figure 39: Hydraulic System Schematic for Leakage Test for Single-Acting Cylinder Configuration
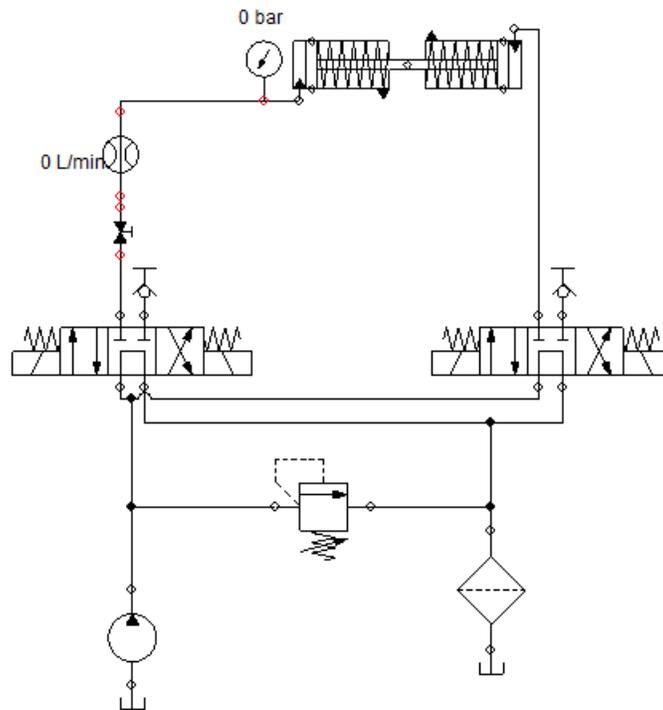
Figure 40: Hydraulic System Schematic for Mechanical Integrity Test for Single-Acting Cylinder Configuration

4.4 Electrical System Design

Electrical system design includes analysing the current data acquisition unit being used by the client and then sourcing out appropriate sensors that can collect required data and outputs data that is compatible with the data acquisition system.

To connect the sensors in the required location for the purposes of collecting data, adapters or mounting clamps will be needed. Any adapters or mounting clamps are included in their respective sensor's section later in the report

4.4.1 Data Acquisition Unit

The current data acquisition unit being used by the client is SoMat eDaq. SoMat eDaq is a microprocessor based data acquisition unit which features portable data collection system. SoMat eDaq has several input methods available including EBRG layer which inputs 16 simultaneous M8 - 6 pins connector. The SoMat eDaq features live display of data being collected and also has the ability to upload acquired data using web interface. The voltage output from sensors can interface with the EBRG layer of eDaq unit. For the purposes of this project, EBRG layer was analyzed as it was capable of accepting analog inputs. Below is a image of input layers of SoMat eDaq [41]
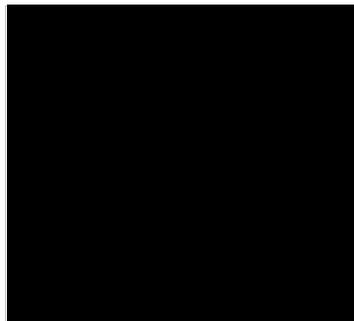
Figure 41: Input Layers of eDaq Unit [41]

As mentioned before that EBRG layer accepts analog signal inputs and has M8 - 6 pins connector point, this layer would be ideal for connecting pressure, temperature and displacement measurement sensors. A Schematic of EBRG layer of eDaq unit is as follows:

Figure 42: Schematic of EBRG Layer Illustrating 6 pin Ports [41]

SoMat eDaq has an internal clock and has the capability to present live data as it gets collected. All the sensors are selected are made compatible with input layers of eDaq.

4.4.2   Pressure Measurement

It was one of the critical needs of this project to collect pressure data to make sure hydraulic cylinders are being tested at right pressures. Below is the schematic of endurance testing from client's hydraulic cylinder performance document.
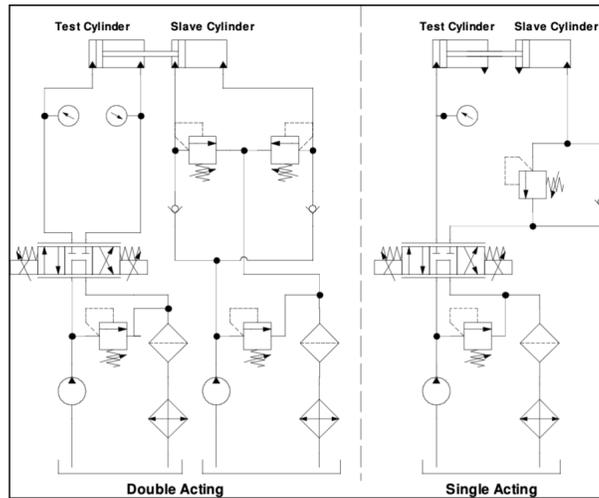
Figure 43: Test Set-up for Double Acting Cylinders [6]

It can be seen from the schematic that two pressure sensors are needed to collect pressure data from hoses for double acting configuration. First point of connection is at the input hose and second point of connection is at the return hose. A pressure transducer from Omega was chosen for this project (model number - PX359 - 100GV)[42]. This model has mounting threads so it can be mounted in such a way to sense pressure directly from the hose at points depicted in Figure 43. This model has accuracy of ± 0.25% which satisfies the need of this project to collect pressure data at ± 2 percent accuracy. Same sensor could be used at both locations as shown in Figure 43. This model has analog style output which can interface with EBRG layer of eDaq unit has discussed earlier. The method to mount this sensor to collect and output data are discussed in upcoming sections. An image of this model is shown below:
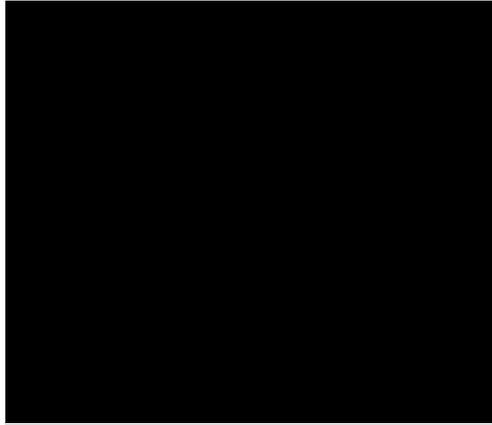
Figure 44: A Threaded Fluid Pressure Sensor [43]

Technical Specifications of this pressure sensor are summarized as follows:

Table XX: TECHNICAL SPECIFICATIONS OF PRESSURE SENSOR [43]

Output Type	Analog (0-5V)
Output cable	4 Pin M12 connector
Measuring Range	0-10000 psi
Accuracy	0.25%
Operating Temp	-40 to 85 degree celsius
Pressure Port Type	1/4" NPT Male

4.4.2.1 Connection of Sensor to Collect Data

As this sensor will collect data directly from the hose and has the ability to get threaded on, a T style threaded adapter would be ideal for connection with the hose. A T style female threaded adapter being used for hydraulic fittings can be used for this pressure sensor also. Details of this adapter were provided earlier in the report in Table X. The connecting threads available in this model is 1/4 NPT male threads, so an reducer to connect 3/4 NPT female to 1/4 NPT male will be used. This reducer was selected from McMaster Carr (model number: 48805K242) and is shown below [44]:

Figure 45: 3/4" NPT to 1/4" NPT Reducer [44]

4.4.2.2 Connection of Sensor with eDaq Unit to Output Data

The output of the pressure sensor is 4 pin M12 connector while eDaq accepts 6 pin M8 connection. A 10ft long 4 pin M12 to 6 pin M8 converter cable was selected in control valve components and is described in Figure 27. The schematic to connect pressure sensor sensor to eDaq unit is as follows:
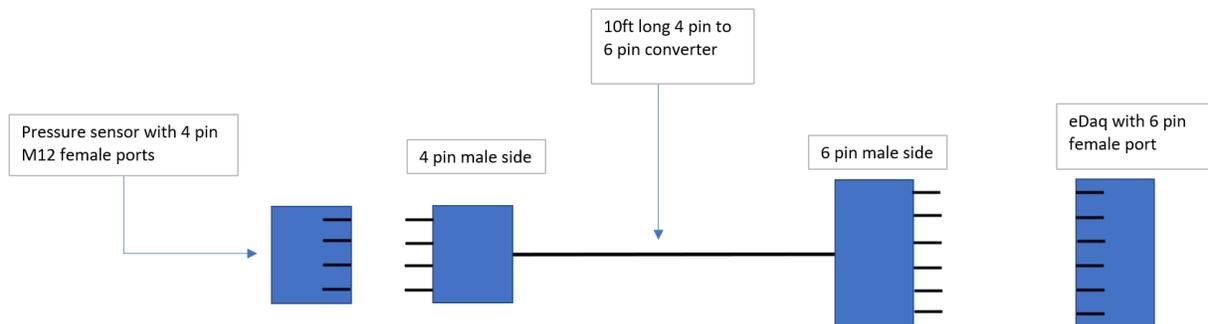
Figure 46: Schematic to Connect 4 Pin to 6 Pin Converter

4.4.3 Rod Position Measurement

It was one of the critical needs to monitor the rod displacement of the test cylinder. The rod displacement will also be used to detect leakages. While conducting leakage test as specified in ████████ test specification document [6], the rod of the test cylinder will move if there is any leakage. This displacement signal will be converted as volume change to detect leakages. The external mountable LVIT sensor was sourced out from Omega Ltd. (Model No.: LDI-619) An Image of the sensor is shown below:

46

Figure 47: LVIT Sensor [45]

This LVIT is capable of measuring max linear displacement of 30 in, which is enough for this project as maximum rod displacement is about 27 inches. The LVIT has accuracy of $\pm$ 0.15 % which satisfies the need of this project of measuring rod displacement with $\pm$ 2 % accuracy. This model outputs analog signal which can interface with EBRG layer of eDaq unit. The other technical specifications of this sensor are as below:

Table XXI: TECHNICAL SPECIFICATIONS OF LVIT [45]

Output Type	Analog (0-10V)
Output cable	4 Pin M8 connector
Measuring Range	Upto 30 in
Linearity error	0.15%
Resolution	0.03%
Operating Temp	-20 to 85 degree celsius
Housing Material	Stainless Steel

This sensor consist of a stainless steel housing and a pin that travels inside the housing. The signal of movement of pin inside the housing is transmitted as voltage output. The pin will be connected to the cylinder rod to measure its displacement. A design is developed in next section to connect the LVIT pin to cylinder rod.

4.4.3.1 Connection of sensor to collect data

Referring to Figure 43, which explains the set up required of test cylinder and slave cylinder to perform endurance testing and leakage testing. These testing requires the rods of both cylinders to be connected. The rods will move during these testings and it is one of the critical needs of this project to capture the

displacement of the rod.

To connect the cylinder rods and connect the LVIT to capture displacement, a custom sleeve was designed. The sleeve will have different dimensions for all 7 configurations of cylinders. A sample image of one of the sleeves is as following:
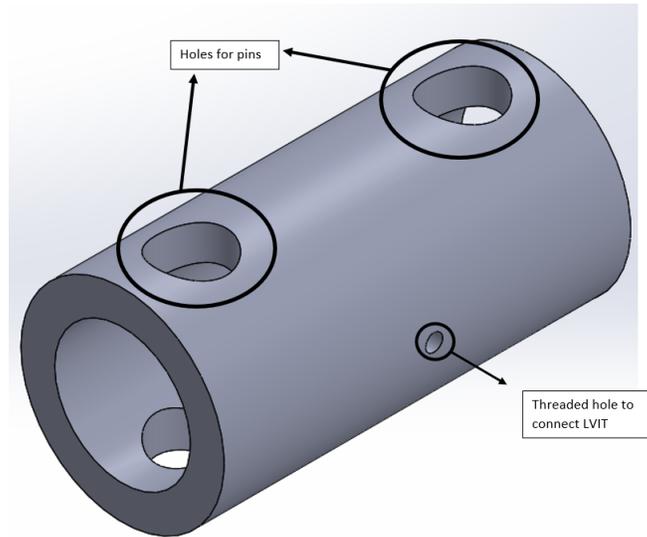
Figure 48: Sleeve to Connect Cylinder Rods

All the cylinder rods have holes which will be used to connect to the sleeve. As shown in the figure above, the sleeve consists of 2 holes which will line up against the holes of the rods. A custom pin is designed for all 7 configurations of rod and hole diameters. This pin will be used to connect 2 rods and the sleeve. The sleeve also has threaded hole to connect custom designed LVIT connector.

The table below was prepared and is to be used to design custom sleeves.

Table XXII: DATA TO DESIGN CUSTOM SLEEVES FOR ALL CONFIGURATIONS

Configuration	Rod Hole Diameter (in)	Min Center to Center Distance (in)	Rod Diameter (in)
1	0.406 ± 0.01	0.93622	1
2	0.406 ± 0.01	0.93622	1
3	1.265 ± 0.01	2.66	2.91
4	1.03 ± 0.01	1.86	1.86
5	1 ± 0.01	3.11	2
6	Sq 0.75 x 0.75	6.67	1
7	0.640 + 0.01 - 0.005	1.12	1.12

Since the force will be applied from the cylinder rod to the pin, the sleeves for all configurations must be designed for a specific thicknesses that can handle the loads that the pin will exert. The force applied

by each rod was calculated earlier in the report in section 4.1. Force analysis calculations were performed for each configuration using force calculations from Section 4.1. A sample calculation to determine optimal sleeve thickness with a safety factor of 2 for configuration 5 is shown below:

The general schematic of sleeve for configuration 5 is as follows:

Figure 49: Schematic of Sleeve of Configuration 5

$$\text{Hole Diameter} = 1\text{in}$$

$$\text{Force Applied} = 14762.2\text{lbf}$$

$$\text{Safety Factor} = 2$$

$$\text{Yield Strength} = 76000\text{psi(with safety factor 2 on 4041H steel)}$$

$$\text{Contact area req} = \frac{\text{Force Applied}}{\text{Yield Strength}} = 0.194in^2$$

$$\text{Sleeve Thickness req} = \frac{2 \text{ x Contact area req}}{\pi \times \text{Hole diameter}} = 0.124in$$

$$\text{Next nominal value after 0.124 in is 0.25 in}$$

$$\text{Pin Diameter} = 0.9 \pm 0.005in$$

$$\text{Pin Length} = 2.75in$$

The center to center distance was decided based on minimum center to center distance of the holes. The tooling table has holes every 2 inches so center to center distance of holes on the sleeves must be a multiple of 2 and bigger than the minimum distance as calculated in Table XXII. The pin diameter was calculated based on the rod hole diameter to have a clearance fit and pin length was calculated based on sleeve outer diameter (OD) and 0.5 in length at the top and bottom to connect cotter pins. After performing the calculations for all configurations, the highest required thickness was 0.437 in (from configuration 4) and the next nominal thickness of 0.5 in was selected for all sleeves. Sleeve inner diameter was selected based on rod diameter of

each configuration. Configuration 3 required the largest diameter (3in) which was selected for all sleeves. Refer to appendix B to see details of calculations for other configurations.

In order to allow for a flexible connection with LVIT, a ball joint connection was sourced out which accepts M5 x 0.8 type of threads. The image of a ball joint connection is as follows:
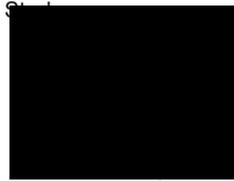
Figure 50: Ball Joint to Allow Flexibility [46]

From Figure 50, stud will go into LVIT connector hole and shank will accept LVIT pin threads.

The figures below provide better illustration of connection method of LVIT to the rods.
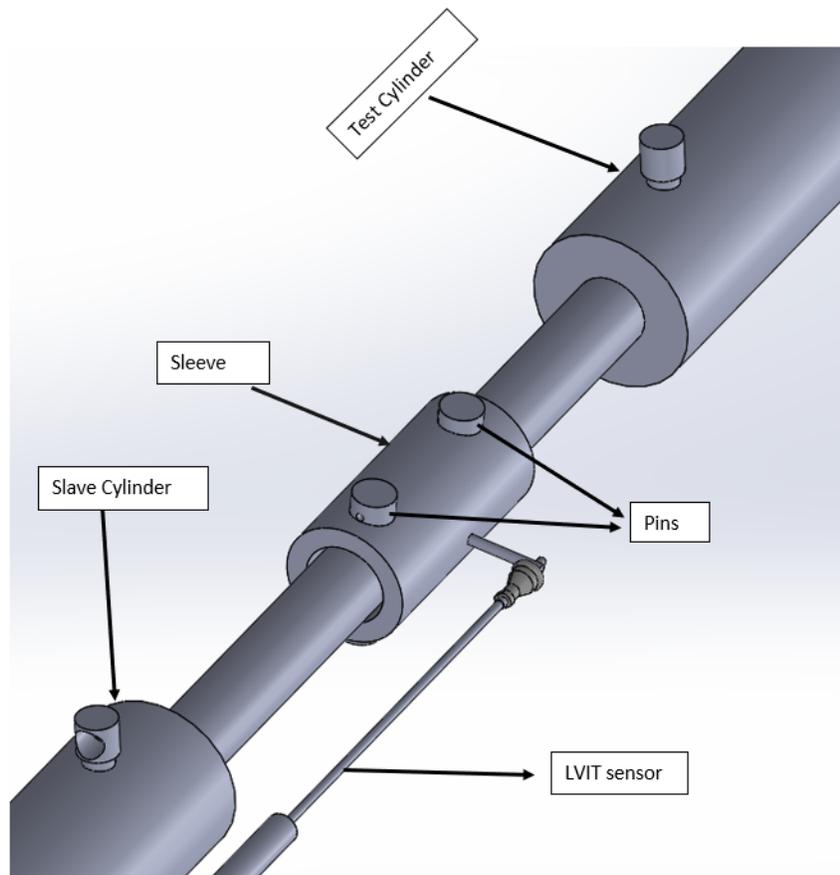
Figure 51: Close-up Image of Sleeve Connection
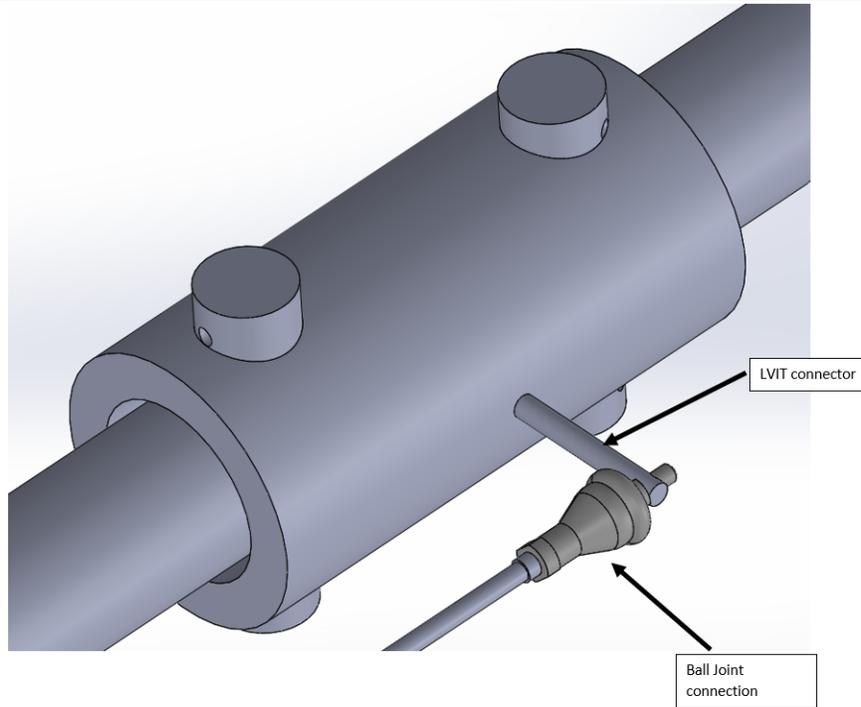
Figure 52: Close-up Image of LVIT Connection

Figure 53: Illustration of Test Cylinder Fully Retracted
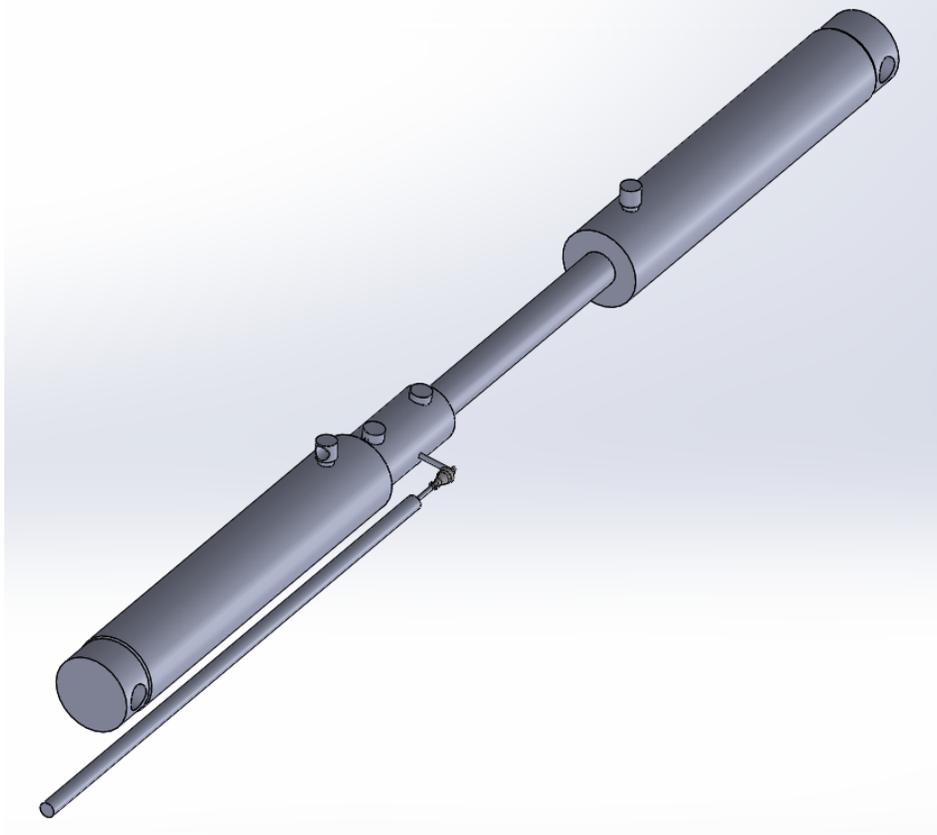
Figure 54: Illustration of Test Cylinder Fully Extended

A fixture is needed to hold LVIT in place while testing. A vise grip was sourced out which can accommodate the LVIT housing's diameter. An image of the vise grip is shown below:
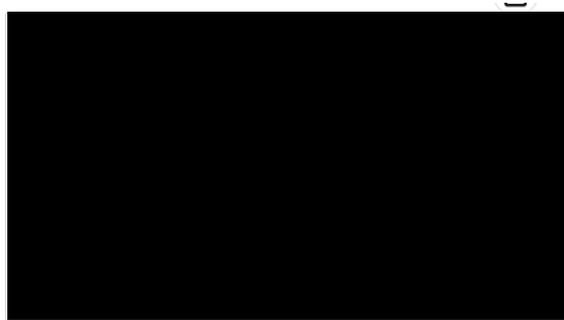
Figure 55: Vise Grip to Hold LVIT [47]

The vise grip shown above can be screwed to the tooling table to more support.

4.4.3.2   Connection of LVIT sensor to Output data

LVIT has a female 4 pin M12 port. Similar connector cable from pressure sensor is needed the schematic for which will be as follows:
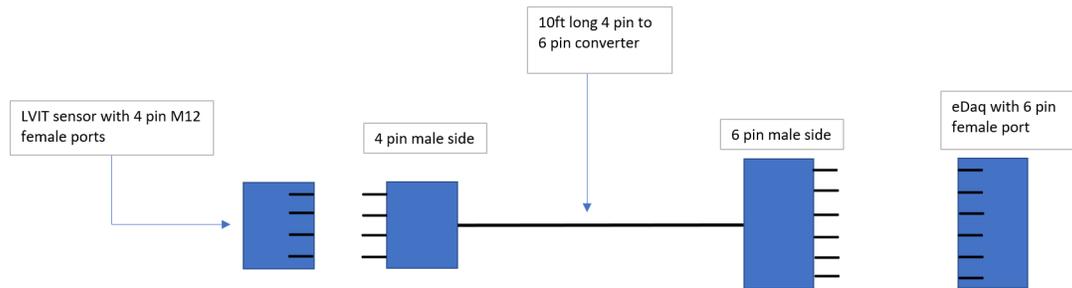
Figure 56: 4 Pin to 6 Pin Converter Schematic for LVIT

4.4.4   Temperature Measurement

Monitoring the temperature of oil is important to make sure that the oil temperature is maintained at 77 degree Celsius. From Figure 43, the input line to test cylinder would be an ideal location to get the temperature readings of oil. A immersion thermocouple probe with the ability of getting threaded on was chosen for collect temperature data. A threaded style immersion probe from Omega was chosen (model number: M12JSS-1/4-U-2-B). This thermocouple can be immersed directly to the hose using mounting threads to sense temperature of the oil. This model of thermocouple outputs analog signal which can interface with EBRG layer of eDaq unit. [15]. Methods to mount this thermocouple and collect data is discussed in next sections. An image of this model is shown below:

Figure 57: Immersion Thermocouple Probe from Omega [15]

Technical Specifications of this thermocouple is as follows:

Table XXIII: TECHNICAL SPECIFICATIONS OF THERMOCOUPLE [15]

Output Type	4 Pin M8 Connector
Thermocouple Type	Type J
Temperature Range	-40 to 600^0 C
Sheath Material	304 Stainless Steel
Mounting Threads	1/2" NPT Male

4.4.4.1 Thermocouple Connection to Collect Data

As the thermocouple probe has the ability to get threaded on, same T style fitting could be used to connect the thermocouple which was chosen for pressure sensor connection. This T style fitting is mentioned later in the report under hydraulic components section in Table X. This T style fitting is for 3/4" hose and hence 3/4" to 1/4" reducer would be required to connect the pressure sensor. The same reducer chosen for pressure sensor can be used, which was described in Figure 45

4.4.4.2 Thermocouple Output to eDaq

Thermocouple chosen for this project has a female 4 pin M8 port for output. Similar connector cable being used for pressure sensor and LVIT can be used for thermocouple as well, schematic for which will be as follows:
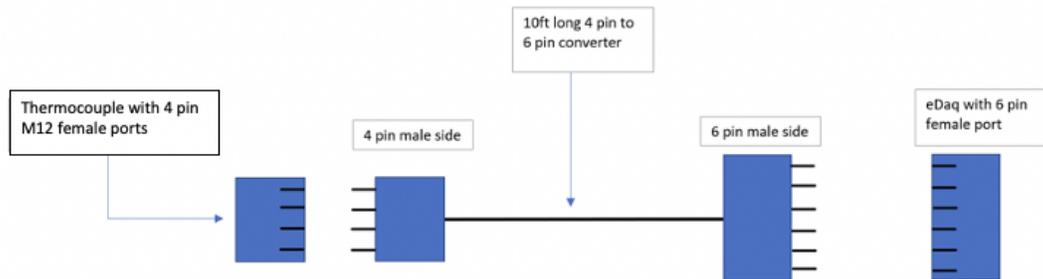
Figure 58: Thermocouple Output Schematic to eDaq Unit

5   Final Design Recommendations

The design of all components of the projects can be adjusted in the future in order to make the test apparatus more efficient and productive during the tests. The recommendations provided by the team enhance productivity however also impacts the cost of the project, thus the recommendations should be considered for future work only if the budget allows for it. The recommendations for each component of the project are summarized below.

5.1   Mounting System Design Recommendations

To improve the mounting system design, further numerical analysis can be performed to optimize the cap end bracket. Modal vibration analysis can be conducted to determine the vibration characteristics of the cap end bracket under dynamic loading conditions. Another recommendation would be having one hole (biggest pin diameter) instead of multiple holes for the clevis pins. Bearing spacers would be required for the smaller clevis pins to achieve the appropriate fit.

5.2   Shielding Design Recommendations

Polycarbonate would be able to sustain the impact load better than acrylic. However, due to cost constraint, acrylic was chosen for the design. Impact analysis can be performed on the glass to determine the optimal thickness of the glass. Bolting/connection analysis can be conducted to possibly minimize the numbers and sizes of the L-shaped railings required.

5.3   Hydraulic System Design Recommendations

In order to improve the hydraulic system design, the team recommends using a multimeter to adjust the voltage on the directional control valve. This would prevent the purchase of five additional pieces of equipment that are to be used to attach the directional control valve to the DAS which would result in reducing overall cost for the hydraulic components. To improve the productivity of the test apparatus, the team recommends using hydraulic quick connects adapters (quick couplers) instead of thread screw-in adapters. This is will increase the cost, however, the setup time for each test would be reduced significantly. The final recommendation for the hydraulic system design is to use one-unit hydraulic components. The directional control valve requires the control valve and an additional subplate to which the hoses can be connected, having a one-unit control valve (control and subplate together) would allow for simple assembly

and improve productivity during the tests.

5.4   Electrical System Design Recommendations

To further improve the electrical system of this project, the team recommends using a data acquisition system with more flexible connectors. The current data acquisition system has only M8 connectors while many sensitive sensors outputs in M12 wires which required a use of M8 to M12 connector wires. This lead to a lot of connection points and hence added more complications to collect data. The team also recommends using a wireless data acquisition systems. Wireless data acquisition system communicates and collect data wirelessly from the sensors and hence eliminates the need of connecting wires from sensors to data acquisition unit.

6 Conclusion

████████████ currently uses the suppliers' validation tests as a confirmation of their specifications being met for the hydraulic cylinders. The ████████ specifications are hydraulic cylinder performance is listed in ████████ Hydraulic Cylinder Performance Specification – 252238 document. The critical objective of this project is to design a test apparatus that could be used to verify these test results for different hydraulic cylinders configurations, lengths, and diameters. The configurations of the hydraulic cylinders include single-acting cylinders and double-acting cylinders with two types of rods, clevis-type and threaded-type, and a variety of lengths and diameters. The lengths and diameters of the cylinders range from 7.75" to 60.5" and 1.5" to 4", respectively. To simplify the project, the project was subdivided into four main components which include mounting system design, shielding design, hydraulic system design, and electrical system design.

The mounting system design is able to secure the hydraulic cylinders during the performance tests which would provide accurate measurements and safety for the operators. Based on the hand calculations and numerical analysis performed above, the cap end bracket is able to sustain the maximum load it will be subjected to, and meets the infinite fatigue life properties. The rod end bracket design is compatible with different sizes and configurations of cylinders. It also provides the clearance required between the cylinders and testing table.

The shielding system design provides the protection required for the operators during the performance tests. The glass is made out of a quarter inch thick acryclic glass. The sizes and location of holes can be found in Appendix A. The L-shaped railings, hinge and handle required for the design can be ordered from McMaster-carr.

The hydraulic system design features the selection of all hydraulic components in accordance to the client's hydraulic circuit schematics (Figure 18). The hydraulic components are selected such that they meet the client's 6000 psi pressure and 19gpm flow rate requirements. The components are also sourced out using vendors that the client has some previous purchasing experience with. The table below summarizes all of the hydraulic components required for the hydraulic system design.

Table XXIV: SUMMARY OF HYDRAULIC SYSTEM DESIGN COMPONENTS

Item	Vendor	Part #	Qty	Price/Qty	Total Cost
Hydraulic hose 0.75in ID	Green Line	797-12	60ft	29.6	1776
Hydraulic hose 1.5in ID* (Optional)	Green Line	797-24	2	178.41	356.82*
Hose Fitting (12-12)	Green Line	10177-12-12	44	16.02	704.88
Hose Fitting (24-24)* (Optional)	Green Line	10177-24-24	2	283.03	566.06*
Hose Fitting (8-12)	Green Line	10177-8-12	8	28.98	231.84
Hose Fitting (12-12 female)	Green Line	10277-12-12	6	33.03	198.18
Pump flange to hose adapter* (Optional)	Grainger	4VRW6	2	130.83	261.66*
Pump flange 1* (Optional)	Parker	PCFF63NSM	2	47.64	95.28*
Pump flange 2* (Optional)	Parker	PCFF36NSM	2	47.64	95.28*
Pump* (Optional)	Parker	F12-030-MF-IV-D-000-0000-P0	2	1750	3500*
Tank*(Optional)	Grainger	BUYSMR30S	1	1219	1219*
Filter	Grainger	WWG36L335	1	67.05	67.05
Cooler	Grainger	4UJD3	1	277	277
Cooler adaptor	Surplus Center	9-6405-12-12	2	3.55	7.1
Control Valve	Rexroth	R900561282	2	429	858
Control Valve Subplate	Rexroth	R900424447	2	208	416
Plug in Electrical Connector	Rexroth	R901207821	2	60.775	121.55
Plug in Connector to 3 pin connector	McMaster Carr	6897K27	2	15.18	30.36
3pin to 4pin converter	BH Photo Video	FA34PA	2	16.99	33.98
4pin to 6pin converter	BH Photo Video	TICBXLR42LE	2	80	160
4 pin to 4 pin converter	Audio Pile	DMX-4F4F	2	7	14
Ball Valve	Parker	V500HP-12	2	154.81	309.62
Check Valve	Tu-Lok	-	2	26.9	53.8
Pressure Relief Valve	Hyvair	FW1022 - 5500	4	79	316
T-Shape Adaptor	Parker	G5G5JG5-S	8	34.02	272.16
Total					5847.52

The electrical system design consists of appropriate sensors to collect rod displacement data, pressure data and fluid temperature data to satisfy the project need of collecting such data with 2 % accuracy. Specific models of pressure sensor (to measure hose pressure), LVIT (to measure rod displacement) and thermocouple to measure fluid temperature) were selected. All accessories required to mount the pressure sensor and thermocouple were sourced out and custom sleeve was designed to connect the LVIT to collect rod displacement data. The electrical system design also included selecting appropriate input layer in the existing data acquisition unit of ███████ that would interface with the sensors selected. The table summarizes the components for electrical system design:

Table XXV: SUMMARY OF ELECTRICAL SYSTEM DESIGN COMPONENTS

Item #	Item	Description	Vendor	Part #	Qty	Price/Qty	Total Cost
		Electrical System Design					
1	Thermocouple Probe	Thermocouple probe with mounting threads - 1/4 NPT	Omega	M12JSS-1/4-U-2-B	1	111.33	111.33
2	Pressure transducer	Stainless Steel Pressure Transducers - 1/4 NPT	Omega	PX359-10KG5V	2	471.81	943.62
3	LVIT	Linear Motion Sensor	Omega	LDI-619-750-A010S	1	1412	1412
4	3/4 NPT to 1/4 NPT adapter	3/4 NPT Male - 1/4 NPT female adapter	McMaster	48805K242	2	25.53	51.06
5	Table vise grip	Vise grip for LVIT	IRWIN - Amazon	226340	1	46.8	46.8
6	4 pin to 6 pin connector	10ft long M8 connector for eDAQ	B&H	TICBXLR42LE	4	80	320
7	Ball joint	Internally Threaded Inline Ball Joint Linkages	McMaster Carr	8412K17	1	10.93	10.93
	Total						2895.74

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Appendix

Appendix A - Technical Drawings

The dimensions of the cap end bracket's base and columns are shown below.
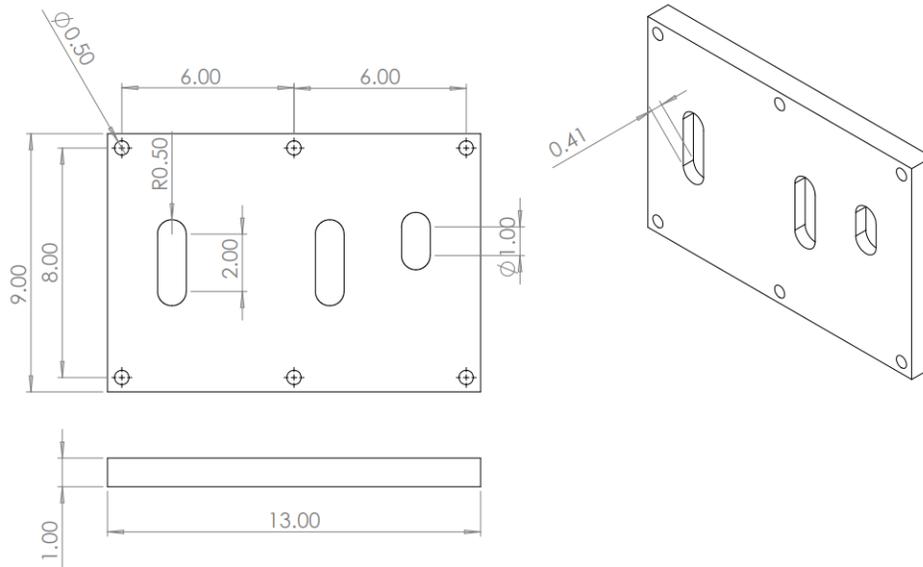
Figure 59: Cap End Bracket Base Drawing
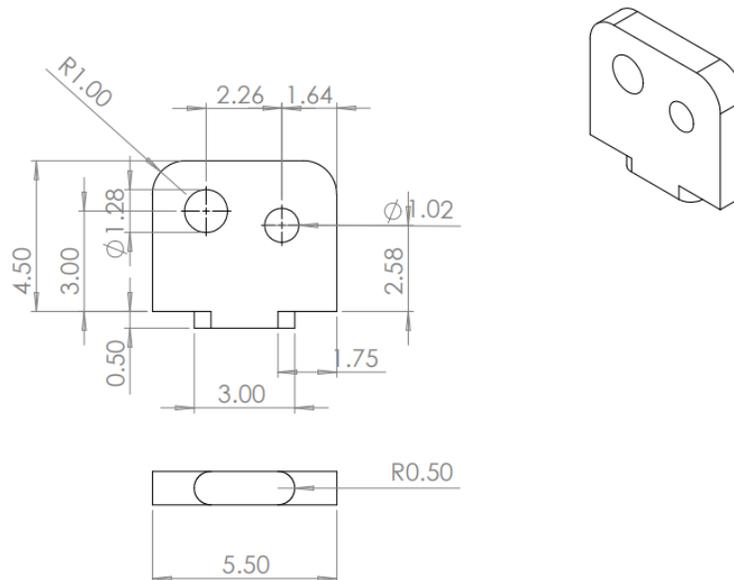
Figure 60: Cap End Bracket First Column Drawing
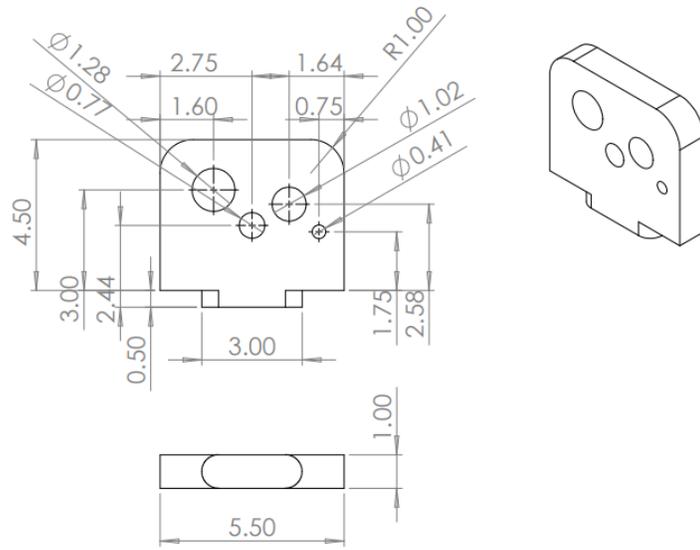
Figure 61: Cap End Bracket Second Column Drawing
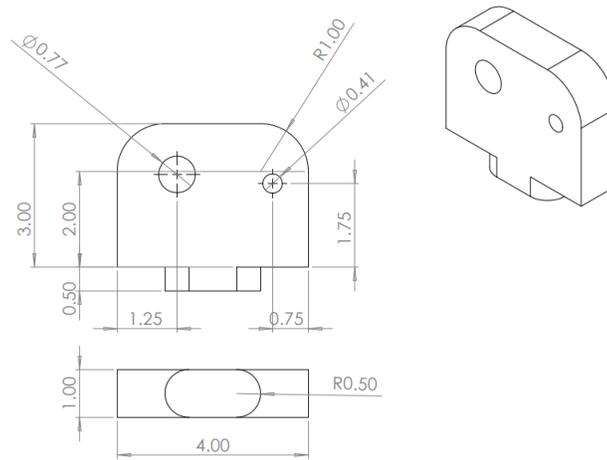
Figure 62: Cap End Bracket Third Column Drawing

The dimensions of the side brackets are shown below.
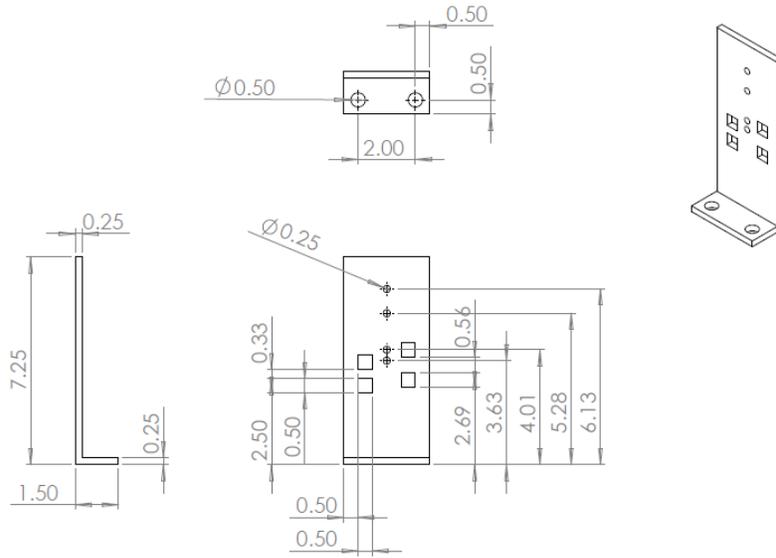
Figure 63: Right Side Bracket Drawing
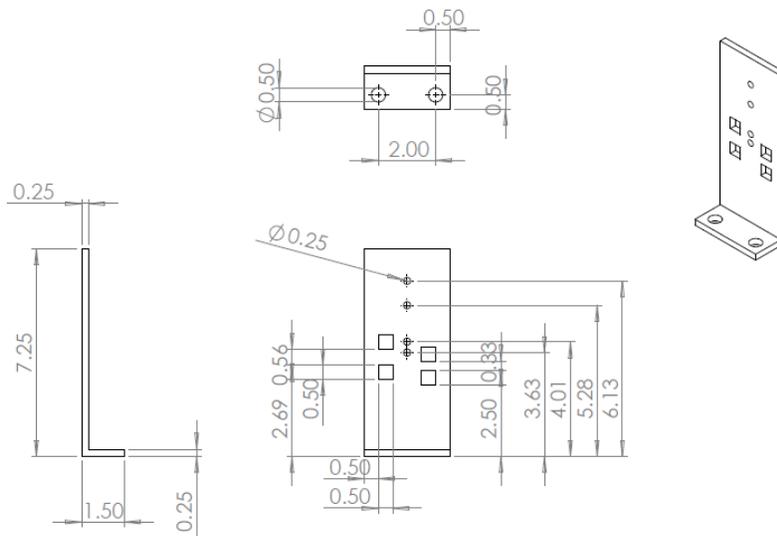
Figure 64: Left Side Bracket Drawing

For configuration 4 cylinder, the dimensions for half trunnion is shown below.
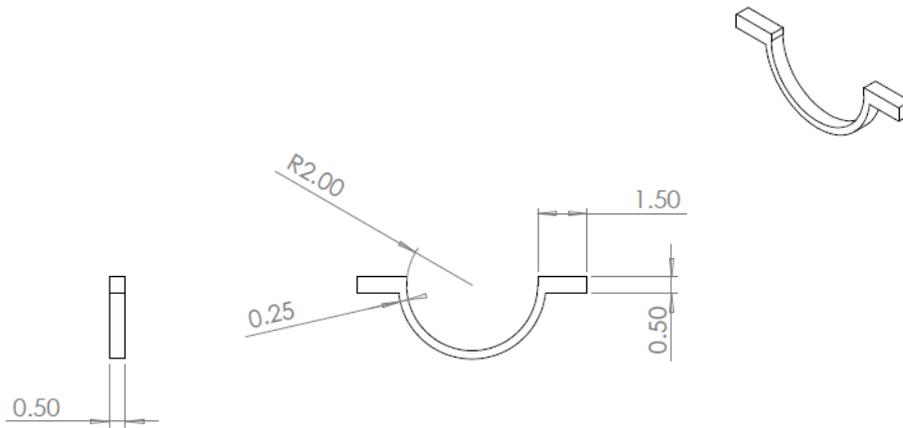
Figure 65: Half Trunnion Drawing

For the other cylinder configurations, only the radius differs from the half trunnion drawing in Figure 65. Table XXVI shows the radius of the other cylinder configurations.

Table XXVI: CYLINDER CONFIGURATIONS 1-7 RADIUS

Configuration	Radius
1	0.75"
2	0.75"
3	2.0"
4	2.0"
5	1.575"
6	0.94"
7	0.94"

For configurations 1 to 5 and 7 the dimensions to manufacture the custom sleeve are as follows:
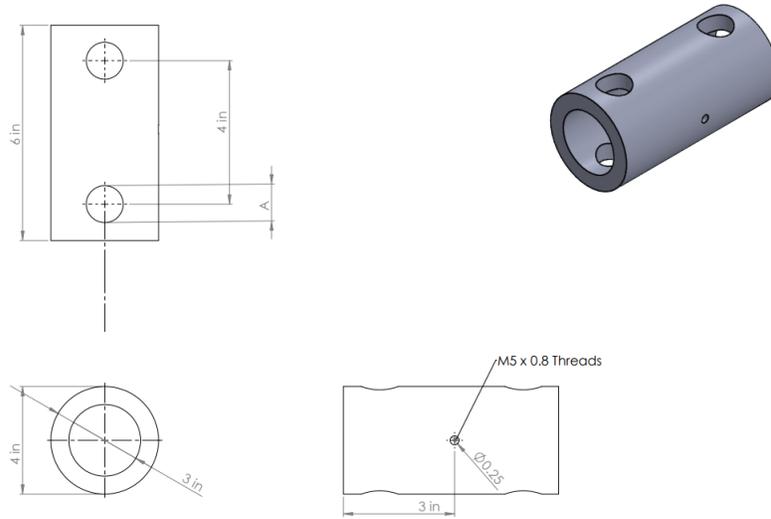
Figure 66: Sleeve Dimensions for all Configurations

Where dimension A is as follows for configuration 1 to 5 and 7.

Table XXVII: DETAILS OF DIMENSION "A" FOR CONFIGURATION 1 TO 5 AND 7

Dimension / Configuration	A
1	0.406 ± 0.01
2	0.406 ± 0.01
3	1.27 ± 0.01
4	1.03 ± 0.01
5	1 ± 0.01
7	$0.640 + 0.01 - 0.005$

Sleeve dimensions for configuration 6 is as follows:
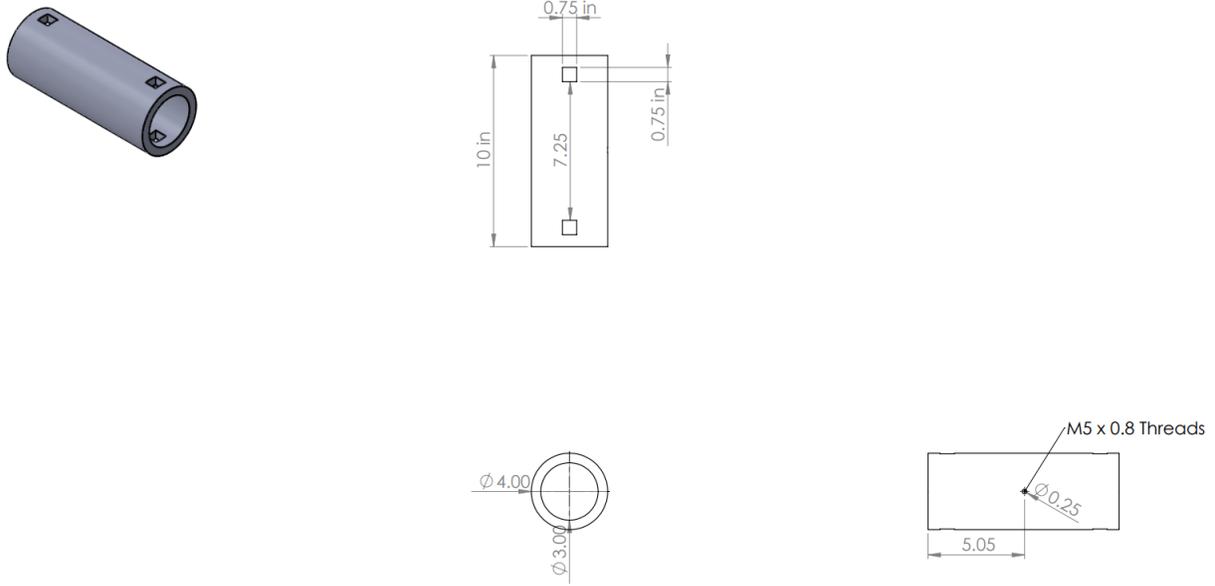
Figure 67: Sleeve Dimensions for Configuration 6

The dimensions of pin for configurations 1 to 5 and 7 are as follows:
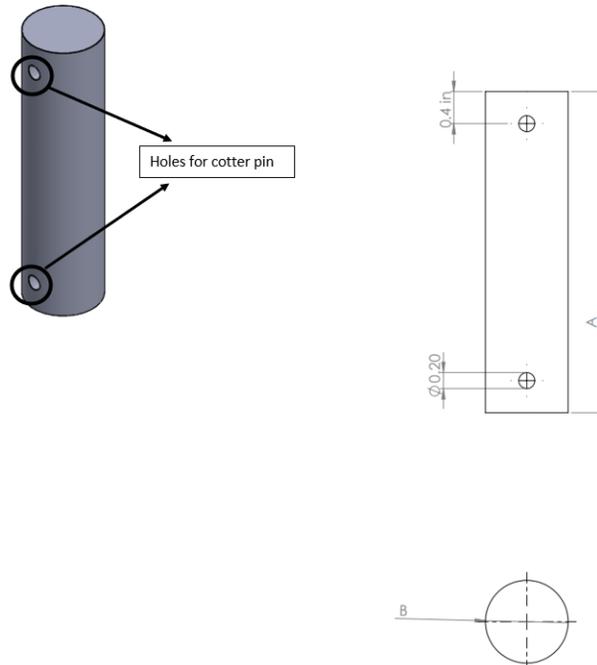
Figure 68: Pin Dimensions for Configuration 1 to 5 and 7

Where A and B will be as follows:

Table XXVIII: DETAILS OF DIMENSION A AND B OF PIN FOR CONFIGURATION 1 TO 5 AND 7

Dimension Configuration	A (in)	B (in)
1	0.405 ± 0.005	2.75
2	0.405 ± 0.005	2.75
3	1.26 ± 0.005	4.5
4	1.02 ± 0.005	4
5	0.9± 0.005	2.75
7	0.635 + 0.005 - 0.0005	2.75

The dimensions of pin for configurations 6 are as follows:
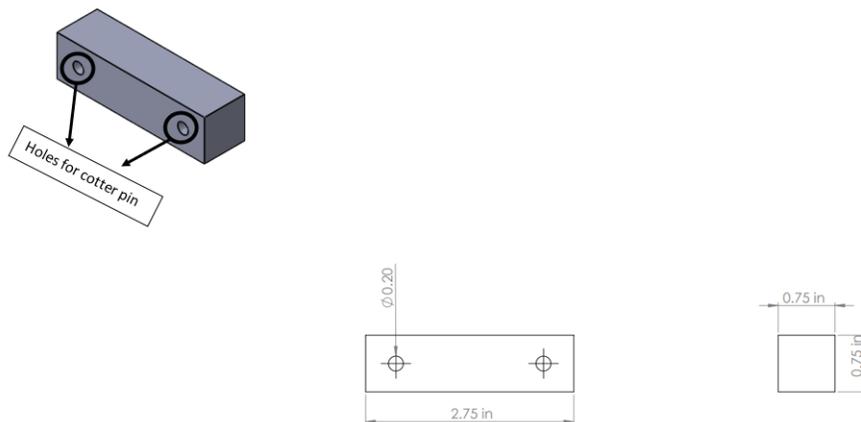
Figure 69: Pin Dimensions for Configuration 6

The dimensions of connector to connect LVIT is as follows for all configurations:
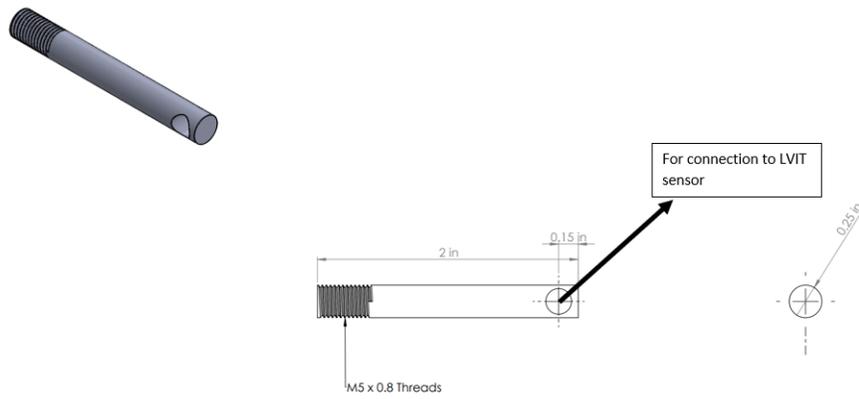
Figure 70: Dimensions of LVIT Connector

As shown in the picture above, LVIT connector has threads to connect to the sleeve and a hole to connect to the LVIT sensor.

Appendix B - Detailed Technical Calculations

The detailed fatigue calculations are shown below, it shows that the selected material and the design would yield a safe design in general and that the design will have a fatigue life of more the 1E10 cycles.

Pristine Endurance limit

$$S'_e = \begin{cases} 0.5S_{ut} & S_{ut} \le 200kpsi\ (1400\ MPa) \\ 100\ kpsi & S_{ut} > kpsi \\ 700\ MPa & S_{ut} > 1400\ MPa \end{cases}$$

Tensile Strength 655 Mpa
167000 psi

S'_e 83500 psi

Endurance Limit

$$S_e = S'_e \cdot k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f$$

Ka (Surface Modification factor)

$$k_a = aS_{ut}^b$$

Surface Finish	Factor a		Exponent b
	S_{ut}, kpsi	S_{ut}, MPa	
Ground	1.21	1.38	-0.067
Machined or cold-drawn	2.00	3.04	-0.217
Hot-rolled	11.0	38.6	-0.650
As-forged	12.7	54.9	-0.758

a   2
b   -0.217
K_a 0.14712976

Kb (Size modification factor)

$$k_b \begin{cases} \left(\dfrac{d}{0.3}\right)^{-0.107} = 0.879d^{-0.107} & 0.11 \le d \le 2\ in \\ 0.91d^{-0.157} & 2 < d \le 10\ in \\ \left(\dfrac{d}{7.62}\right)^{-0.107} = 1.24d^{-0.107} & 2.79 \le d \le 51\ mm \\ 1.51d^{-0.157} & 51 < d \le 254\ mm \end{cases}$$

d   0.406 in   (choose max dia)
K_b 0.968143399

Kc (Load modification factor)

$$k_c = \begin{cases} 1 & bending \\ 0.85 & axial \\ 0.59 & torsion \end{cases}$$

K_c 1

kd (Temperature modification factor)

$$k_d = 0.975 + 0.432(10^{-3})T_f - 0.115(10^{-5})T_f^2 + 0.104(10^{-8})T_f^3 - 0.595(10^{-12})T_f^4$$

tf   71.6 F
Kd   1.00045904

ke (Reliability factor)

$$k_e = 1 - 0.08z_a$$

Reliability, %	Transformation Variate z_a	Reliability Factor k_e
50	0	1.000
90	1.288	0.897
95	1.645	0.868
99	2.326	0.814
99.9	3.091	0.753
99.99	3.719	0.702

K_e 0.814 99% reliability

Kf (Misc factor)   1

Se	9686.13247	psi
sigma_max (σ_{max})	13992.15	psi
sigma_min (σ_{min})	0	psi
sigma_mean (σ_m)	6996.075	psi
sigma_amplitude (σ_a)	6996.075	psi
Life	>1E10	Cycles	From S-N Curve

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Modified Goodman Approach

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} \le \frac{1}{n}$$

0.764170108

Figure 71: Detailed Fatigue Life Calculations

Detailed calculations to calculate required sleeve thickness for each configuration is shown below:

Conf 1 and 2

6 in

4 in

ID: 1 1/4" in

hole diameter	0.406	in
F	7245.8	lbf
SF	2	
Yield strength	76000	psi	4041H steel
Area req	0.095339	in^2
Thickness req	0.149495	in
Next nomial size	0.25	in
Pin diameter	0.406 +- 0.005	
Pin length	2.75	in

Figure 72: Sleeve Thickness Calculations for Configuration 12

Conf 3

6 in

4 in

ID: 3 in

hole diameter	1.27	in
F	18850	lbf
SF	2	
Yield strength	76000	psi	4041H steel
Area req	0.248026	in^2
Thickness req	0.124329	in
Next nomial size	0.25	in
Pin diameter	1.26 +- 0.005	
Pin length	4.5	in
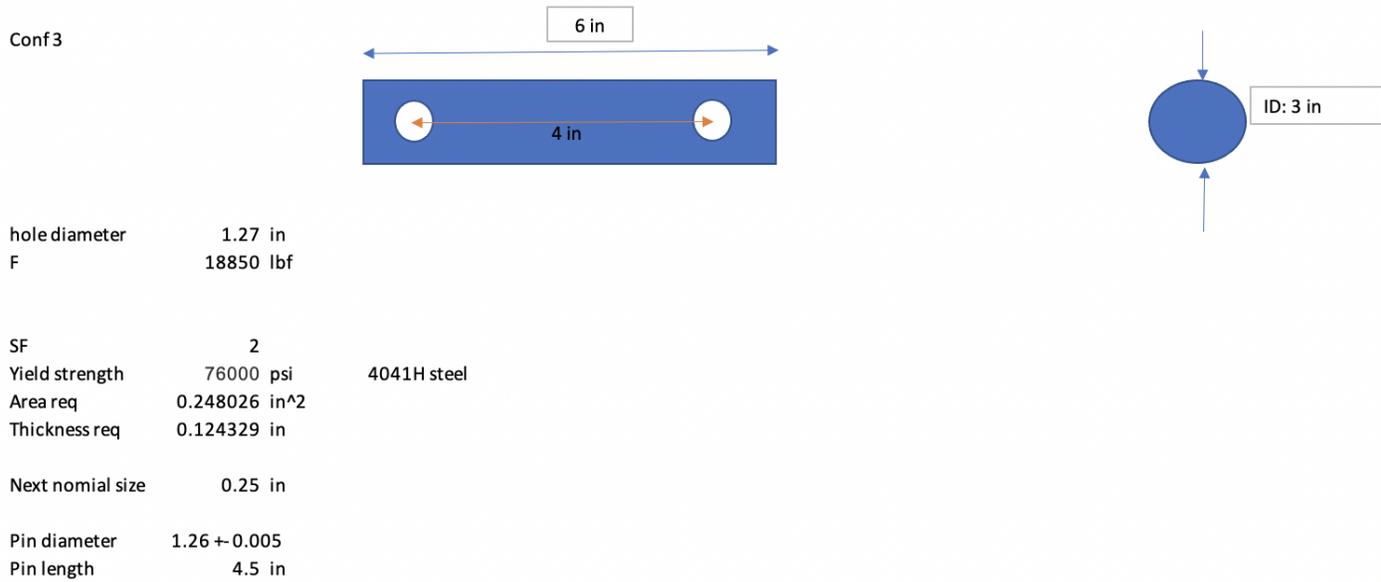
Figure 73: Sleeve Thickness Calculations for Configuration 3

Conf 4

6 in

4 in

ID:2 in
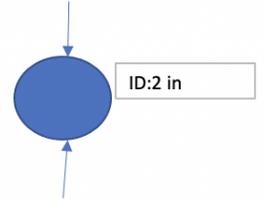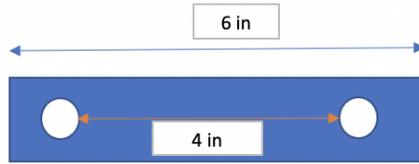
hole diameter	1.031	in
F	53878.3	lbf
Area		in^2

SF	2		
Yield strength	76000	psi	4041H steel
Area req	0.708925	in^2	
Thickness req	0.437746	in	

Next nominal size   0.5 in

| Pin Dia | 1.02 +- 0.005 |
| Pin length | 4 in |

Figure 74: Sleeve Thickness Calculations for Configuration 4

Conf 5

6 in

4 in

ID: 2 in
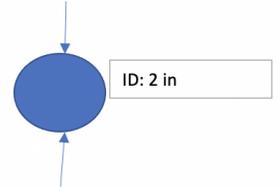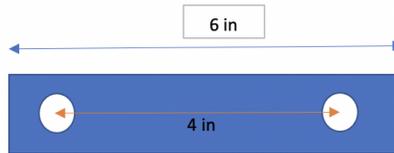
| hole diameter | 1 | in |
| F | 14762.2 | lbf |

| SF | 2 | | |
| Yield strength | 76000 | psi | 4041H steel |

$$\text{Area req} = \frac{F}{Yield\ strength}$$

Area req   0.194239 in^2

$$\text{Thickness req} = \frac{2 \times Area\ req}{\pi \times hole\ diameter}$$

Thickness req   0.123657 in

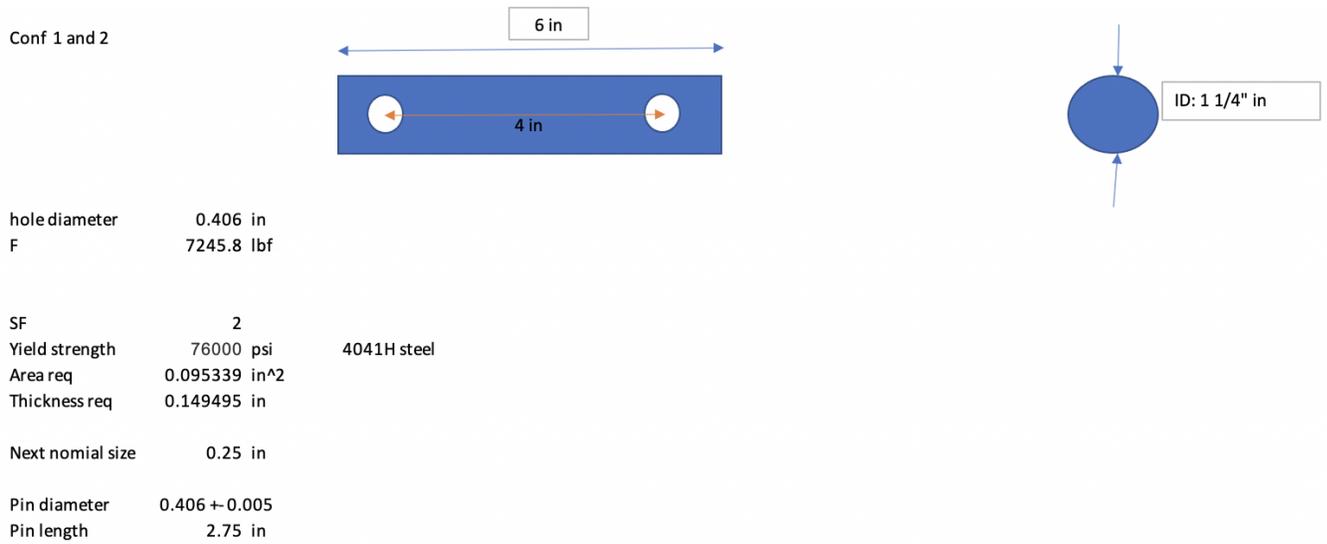Next nomial size   0.25 in

| Pin diameter | 0.9+-0.005 |
| Pin length | 2.75 in |

Figure 75: Sleeve Thickness Calculations for Configuration 5

Conf 6

10 in		
8 in		ID: 1 1/4" in

hole side   0.75   in
F   11309.7 lbf

SF   2
Yield strength   76000 psi   4041H steel
Area req   0.148812 in^2
Thickness req 0.198416 in

Next nomial size   0.25 in

Pin side   0.74 +- 0.005
Pin length   2.75 in
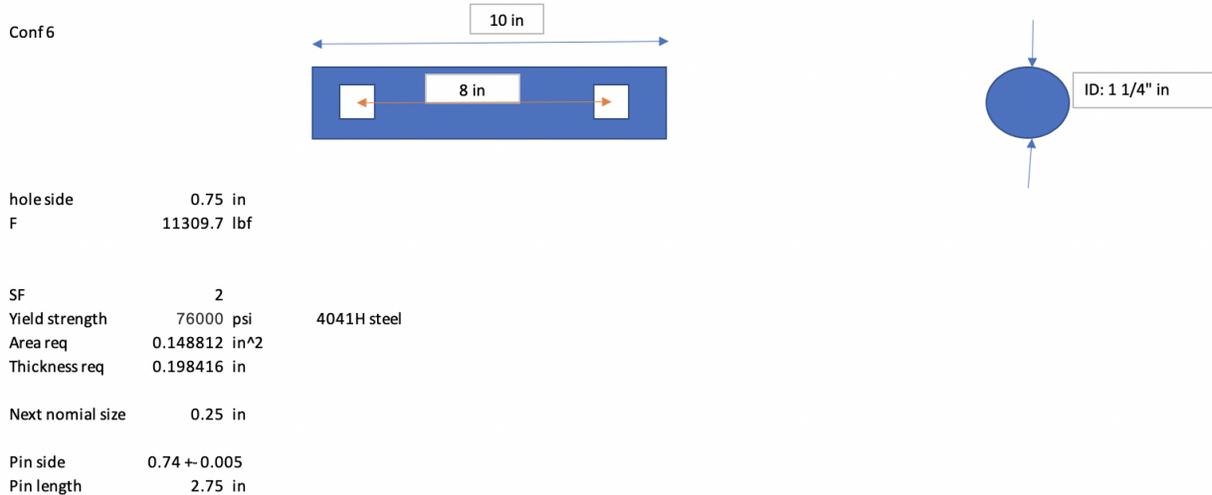
Figure 76: Sleeve Thickness Calculations for Configuration 6

Conf 7

6 in		
4 in		ID: 1 1/4" in

hole diameter   0.64 in
F   7245.8 lbf

SF   2
Yield strength   76000 psi   4041H steel
Area req   0.095339 in^2
Thickness req 0.094836 in

Next nomial size   0.25 in

Pin diameter   0.64 +0.005-0.0005
Pin length   2.75 in
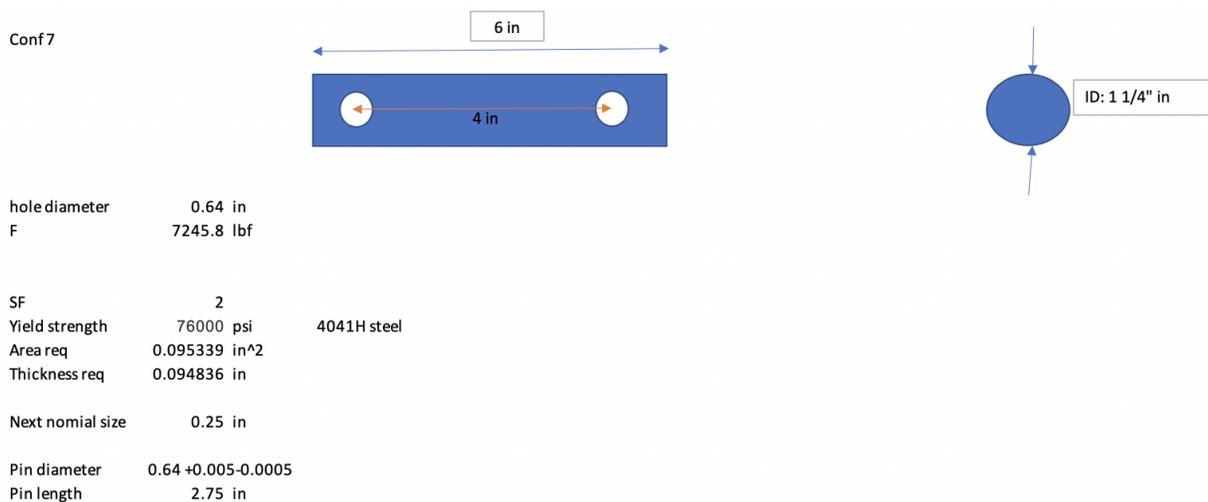
Figure 77: Sleeve Thickness Calculations for Configuration 7

Appendix C - Engineering BOM

An Engineering BOM was also requested by the client. The BOM is presented in one table with sub-headings for each component of the project. The BOM contains information about electrical system design components, hydraulic system design components, and manufacturing cost associated with the mounting and shielding design. The BOM starts with item number followed by item name, item description, supplier name, supplier part number, quantity needed for the project, price per component, and total cost for each component depending on the number of duplicates needed for the project. The total cost for project is

presented along with the total cost for each main component (electrical, hydraulic, mounting, and shielding designs) of the project.

Note that items labelled with an asterisk (∗) are excluded from the cost for the project as ███████ have similar items in-house that could be used for this project.

Item #	Item	Description	Vendor	Part #	Qty	Price/Qty	Total Cost
			Electrical System Design				
1	Thermocouple Probe	Thermocouple probe with mounting threads - 1/4 NPT	Omega	M12JSS-1/4-U-2-B	1	111.33	111.33
2	Pressure transducer	Stainless Steel Pressure Transducers - 1/4 NPT	Omega	PX359-10KG5V	2	471.81	943.62
3	LVIT	Linear Motion Sensor	Omega	LDI-619-750-A010S	1	1412	1412
4	3/4 NPT to 1/4 NPT adapter	3/4 NPT Male - 1/4 NPT female adapter	McMaster	48805K242	2	25.53	51.06
5	Table vise grip	Vise grip for LVIT	IRWIN - Amazon	226340	1	46.8	46.8
6	4 pin to 6 pin connector	10ft long M8 connector for eDAQ	B&H	TICBXLR42LE	4	80	320
7	Ball joint	Internally Threaded Inline Ball Joint Linkages	McMaster Carr	8412K17	1	10.93	10.93
	Total						2895.74
			Hydraulic System Design				
7	Hydraulic hose 0.75in ID	0.75" ID Flexible Bulk Hose	Green Line	797-12	60ft	29.6	1776
8	Hydraulic hose 1.5in ID* (Optional)	1.5" ID Flexible Bulk Hose	Green Line	797-24	2	178.41	356.82*
9	Hose Fitting (12-12)	0.75" ID Hose Fitting	Green Line	10177-12-12	44	16.02	704.88
10	Hose Fitting (24-24)* (Optional)	1.5" ID Hose Fitting	Green Line	10177-24-24	2	283.03	566.06*
11	Hose Fitting (8-12)	Control Valve Hose Fitting	Green Line	10177-8-12	8	28.98	231.84
12	Hose Fitting (12-12 female)	0.75" ID Hose Female Fitting	Green Line	10277-12-12	6	33.03	198.18
13	Pump flange to hose adapter* (Optional)	Hose to pump flange adapter for Pump flange 2	Grainger	4VRW6	2	130.83	261.66*
14	Pump flange 1* (Optional)	Pump Flange 0.75"	Parker	PCFF63NSM	2	47.64	95.28*
15	Pump flange 2* (Optional)	Pump Flange 1.5"	Parker	PCFF36NSM	2	47.64	95.28*
16	Pump* (Optional)	Pump	Parker	F12-030-MF-IV-D-000-0000-P0	2	1750	3500*
17	Tank*(Optional)	Tank	Grainger	BUYSMR30S	1	1219	1219*
18	Filter	Filter	Grainger	WWG36L335	1	67.05	67.05
19	Cooler	Cooler	Grainger	4UJD3	1	277	277
20	Cooler adaptor	Cooler adaptor	Surplus Center	9-6405-12-12	2	3.55	7.1
21	Control Valve	Control Valve	Rexroth	R900561282	2	429	858
22	Control Valve Subplate	Control Valve Subplate	Rexroth	R900424447	2	208	416
23	Plug in Electrical Connector	Plug in Electrical Connector	Rexroth	R901207821	2	60.775	121.55
24	Plug in Connector to 3 pin connector	Plug in Connector to 3 pin connector	McMaster Carr	6897K27	2	15.18	30.36
25	3pin to 4pin converter	3pin to 4pin converter	BH Photo Video	FA34PA	2	16.99	33.98
26	4pin to 6pin converter	4pin to 6pin converter	BH Photo Video	TICBXLR42LE	2	80	160
27	4 pin to 4 pin converter	4 pin to 4 pin converter	Audio Pile	DMX-4F4F	2	7	14
28	Ball Valve	Ball Valve	Parker	V500HP-12	2	154.81	309.62
29	Check Valve	Check Valve	Tu-Lok	-	2	26.9	53.8
30	Pressure Relief Valve	Pressure Relief Valve	Hyvair	FW1022 - 5500	4	79	316
31	T-Shape Adaptor	T-Shape Adaptor	Parker	G5G5JG5-S	8	34.02	272.16
	Total						5847.52
			Hydraulic Cylinder Mounting Design				
32	Clevis Pins		McMaster/In-house	-	5	30	150
33	Cap End Bracket		In-house	-	1	1000	1000
34	Rod End Bracket		In-house	-	1	500	500
35	18-8 Stainless Steel Threaded Rod		McMaster/In-house	95412A564	1	15.75	15.75
	Total						1665.75
			Hydraulic Cylinder Shielding Design				
36	Acrylic Glass		In-house	-	-	800	800
37	6' L-Shaped Railings		McMaster	-	1	97.15	97.15
38	8' L-Shaped Railings		McMaster	-	1	144.56	144.56
39	Hinges		McMaster	-	3	75.69	227.07
40	Handles		McMaster	-	1	34.35	34.35
	Total						1303.13
	Project Total						**11712.14**

Figure 78: Engineering BOM requested by the Client

Appendix D - Gantt Chart

The Gantt chart created from project definition phase has been reworked to include a more detailed breakdown of tasks for the final phase. First, the team optimized and finalized the design. Then, an engineering BOM, engineering drawings and CAD model are constructed before writing the final design report. A draft review with the advisor is scheduled before finalizing the final design report. After the report writing, poster and PowerPoint are constructed for the final presentation. Figure 79 shows the updated Gantt chart for the project.
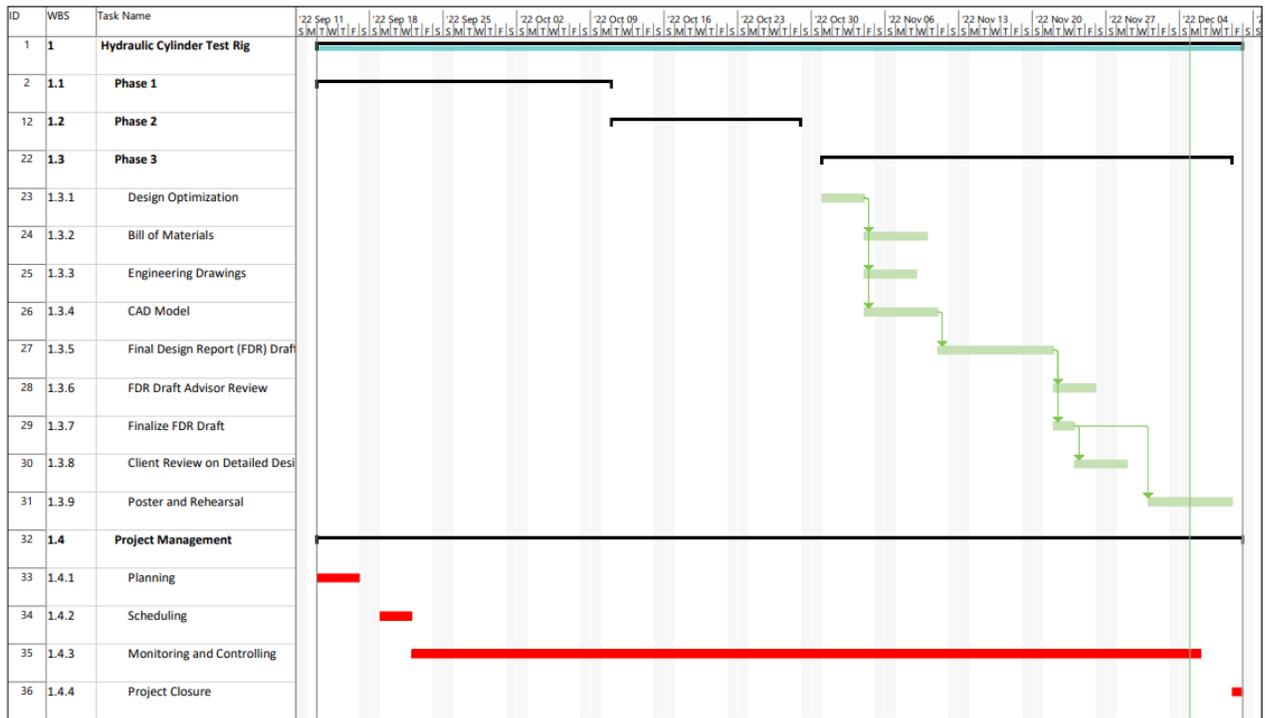

Figure 79: Phase 3 Project Gantt Chart