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THE DESIGN AND ADAPTATION OF AN EXPERIMENTAL TEST SETUP TO CHARACTERIZE METAL SPRING ENERGIZED SEALS

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THE DESIGN AND ADAPTATION OF AN EXPERIMENTAL TEST SETUP TO CHARACTERIZE METAL SPRING ENERGIZED SEALS

A THESIS APPROVED FOR THE
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BY THE COMMITTEE CONSISTING OF

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Table of Contents

List of Tables

List of Figures

Abstract

Fluid sealing technology is critical to the performance and longevity of equipment in a variety of industries. They prevent harmful fluids from being released into the environment, especially in the case of the oil and gas industry who commonly work with corrosive or toxic materials. Seals prevent harmful debris from entering internal areas of equipment which could damage internal components. It is important to test seals to better understand their level of performance for specific applications. The best method for characterizing seals based on their pressure limitations, fluid compatibility, or durability during dynamic sealing is to inspect them on a test stand. Typically, these tests stands are specific to each application and therefore are costly and time consuming to develop. To help save on project costs, an adaptation to an existing test system can be undertaken in order to test new or existing designs or apply new parameters.

This thesis presents the design approach enabled to adapt an existing test stand to characterize the performance of metal spring energized (MSE) seals under linear reciprocating motion. The test stand was adapted to meet new mechanical and data system requirements which were not capable of being met by the previous iteration.

Throughout the design and construction of the test stand, the following research objectives were achieved. The changes which needed to occur with the previous system were identified. New requirements were created, and the setup was adapted to meet them through the design and implementation of new components with a focus on minimal change to reduce project costs. Lastly, the adaptation to the setup was validated using data collected from initial tests showing proper function and its ability to meet system requirements.

Chapter 1: Introduction

1.1 Research Motivation

Fluid sealing technology is a critical component to many machines and equipment used throughout the oil and gas industry as well as many others because they provide a barrier to prevent debris from entering internal areas of equipment and keep fluid or gas mediums contained within a closed system. There are several types of sealing barriers to choose from and they differ by material type, shape, and desired purpose. When designing for or replacing a seal in a mechanical system it is critical to have pertinent information on the desired seals performance and durability. For example, a common sealing barrier that is used throughout industries is an O-ring. These are one of the most widely used sealing technologies because of their vast uses in both static and dynamic conditions and inexpensive nature. O-rings do have their limitations when exposed to harsh or extreme environments including high pressures, temperatures, or dynamic speeds. Characterization for various O-ring materials, shapes, and sizes are readily available for engineers integrating these components into their designs. The *Parker O-Ring Handbook* is an excellent example of the characterization of this type of sealing technology [1]. It provides a quick reference for engineers to better understand O-rings expected performance, where they are applicable, and how they can be properly integrated into systems to perform effectively. While designing a system, an engineer can call on the handbook and make a choice of seal and coinciding groove design knowing with full confidence how it will behave. The ability for engineers to make data driven design decisions is important to today's high standards of reliability and function. Therefore, having characterized information about the performance of seals as well as other components is necessary to limit failures.

Within the oil and gas industry, sealing barriers are commonly exposed to dynamic sealing scenarios and a harsh chemical and physical environment. O-rings can be used under some of these conditions; however, the nature of the oil and gas industry has influenced the continual development of new sealing technologies to withstand these conditions. In addition, environmental concerns and the safety of those working within it is at an all-time high. This means seals need to perform even more effectively to reduce harm to the planet and the people working around them. To achieve this, seals are vigorously tested under the expected conditions of this industry with the help of engineers. This allows them to understand their performance, ensuring the longevity of machines and equipment in which they are installed. Experimental setups, such as the one adapted due to the research of this thesis, are needed to help with this characterization and continued adaptations to new and existing designs.

1.2 Literature Review and Background Information

It is necessary for new and existing seal designs and configurations to be tested prior to being installed into field equipment or the harsh environments associated with the oil and gas industry. This prevents damage to expensive components and ensures the safety of those working around the equipment in the event of a seal failure. During testing, the performance of the seal is recorded and analyzed to better discern its limitations as to where the seal can be effectively and safely used. Testing equipment is typically specific to each application and is difficult to standardize between industries or even applications within the same industry.

To help characterize seals, it is best to understand their purpose in equipment. As mentioned in Chapter 1.1, the importance of fluid sealing technology is critical to equipment and machine performance. This chapter will further discuss this importance and provide a broader understanding of the use of this technology and application of various reciprocating seals as pertaining to the research of this thesis.

1.2.1 Overview of Fluid Sealing Technology

Fluid sealing technology can be described as a barrier between two surfaces “controlling and limiting the flow of fluids between” them [2]. Sealing barriers are present throughout the oil and gas, as well as others such as automotive and industrial, in the use of equipment and machines. These seals are critical to the performance and lifespan of this equipment and the industries as a whole. Different types of seals used include but are not limited to O-rings, gaskets, lip seals, and mechanical seals. They are typically made of elastomers, or rubbery like plastics [3], but often are required to be made from hard plastics, metal, or even a combination to ensure a proper seal due to high stress or corrosive environments. Material selection is important to the seals performance and will vary between equipment and environments based on their own specific conditions. The desired pressure, temperature, sealing fluid, type of motion, and total cost are all driving factors to help select the most applicable seal type and material [4]. All these conditions affect the sealing capabilities of the barrier and contribute to the overall function and reliability of the equipment in the field. If an improper seal type and material are selected, then an excess of fluid can drain from the equipment causing abnormal wear of internal components or harmful pollutants to leak into the surrounding area.

Seals can be split into two categories, static and dynamic seals. These seals are denoted by the condition that they experience during operation. Those that experience dynamic conditions such as reciprocating or rotary motion are dynamic seals [5]. Those under the condition where this motion is absent are static seals [5]. Proper seal type and material choice becomes more critical when looking at dynamic sealing which see increased wear resulting in shorter lifespans.

Within the oil and gas industry seals can be found in a wide range of equipment including but not limited to linear actuators, piston pumps, and valves. In this case there are many factors that can cause an increased failure rate of seals used within the field due to the harsh environment present. Because of this the continual development of enhanced materials and designs are a never-ending topic for research. The use of test equipment is vital to checking new ideas as well as confirming existing designs will be able to handle the elevated temperatures, pressures, and sometimes corrosive fluids typically seen within this industry. Additionally, an adaptation approach can be employed on existing test equipment to help test new or existing seal geometries under new conditions with the aim of saving on project costs.

1.2.2 Reciprocating Seals

Reciprocating seals are a type of sealing barrier found throughout industries, typically in hydraulic or pneumatic systems. These seals are distinguished by the motion which they experience, linear reciprocating motion, as the name suggests. For example, piston, rod, and wiper seals (Figure 1) commonly experience rectilinear motion in hydraulic actuators [5].

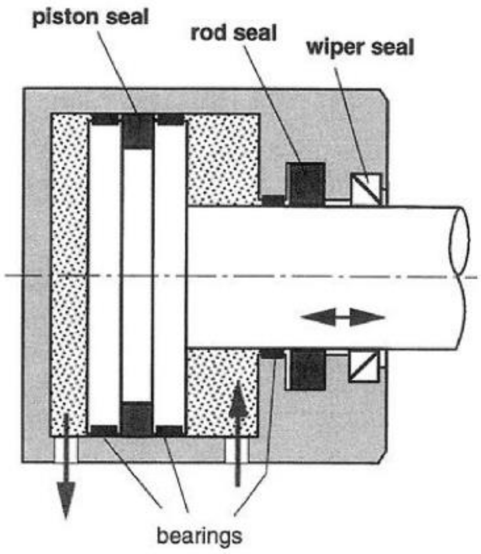

Figure 1: Typical piston and rod seal arrangement [5]

Reciprocating seals have many applications including piston rings in combustion engines and rod seals on hydraulic cylinders [4]. Due to the reciprocating motion, these seals often need to perform under both static and dynamic conditions. Under static hold they generally rely on an interference fit resulting in a compression against the desired sealing surface preventing fluid from passing through the barrier [4]. During reciprocation, they experience an additional frictional force due to the sealing surface sliding along the edge of the seal which can harm its performance if not designed with this motion in mind. For example, if O-rings are specified for this type of motion, they often roll or twist within their groove after experiencing some wear which is not ideal to performance. To help reduce this, typically when hydraulic fluid is present, reciprocating seals pull the sealing fluid along the surface to form a film [5] This helps to lubricate the seal and decrease the frictional force experienced during this movement thus increasing the lifespan of the seal. However, there is a disadvantage if the sealing fluid is a gas or one without much lubrication. In this case the friction can be extreme causing excessive wear and heat generation leading to an accelerated degradation of the seals. An external form of lubrication may be needed for this case, such as adding grease or a light oil during the seals assembly into equipment.

1.2.3 Metal Spring Energized Seals

Self-energized seals are widely used due to their versatility in various pressure ranges and sealing fluids. These are typically constructed out of elastomer or plastic to help with wear and keep frictional forces low when installed in reciprocating environments. Metal spring energized (MSE) seals are a category of self-energized seal that utilize a formed piece of metal or spring bonded within its interior (Figure 2). The seal body and metal spring typically are designed with a "U" shape to allow for additional sealing force to be applied to the sealing surface as fluid pressure is increased [4].

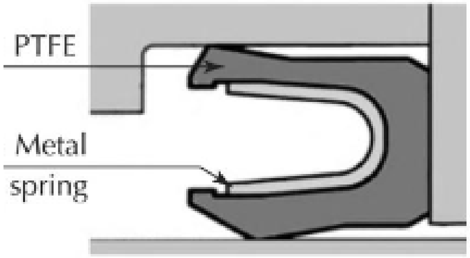

Figure 2: U configuration of typical metal spring energized seal [4]

The addition of the metal spring underneath the sealing surface, made of elastomer, allows for increased sealing force at low pressure ranges while retaining the low friction characteristics of elastomers. This design grants the seals the ability "to provide low dynamic leakage and positive static sealing" under both low- and high-pressure applications [4]. This seal type is found to be very helpful for the reciprocating case that needs acceptable performance under both static and dynamic conditions.

1.3 Research Scope and Objectives

The ability to accurately research new sealing technology and materials is critical for parts and machines to perform reliably when exposed to harsh environments. It also helps engineers make data driven choices during the design process to help limit harm to critical components within their respected system. Incorrect characterization or unfamiliarity with the sealing technology could prove detrimental to the overall performance and longevity of the equipment in the field.

Testing equipment is used to experimentally test the performance of seals under known parameters. Often the data collected is specific to their expected application and not transferable to other situations. With this in mind, creating a new setup for every small change in testing parameters to characterize the seal more broadly would be a costly and inefficient endeavor. In many cases an adaptation to an existing test setup will be undertaken in order to test new system parameters for other applications or accept new seal geometries. This can reduce funds needed for experimentation and provides faster turnaround for necessary data. Whether designing a testing setup from scratch or adapting an existing one, both have their own set of challenges that will need to be overcome.

This thesis will focus on the adaptation, implementation, and initial testing of an experimental test setup to characterize MSE seals under expected conditions. To do this, the current experimental setup will be adapted to form a new iteration that accepts MSE seals. Furthermore, it will expose the seals to new operating conditions which previously were unavailable in the original setup. For the purposes of this thesis, the adapted design and integration of an electromechanical system will be discussed up to the point of initial testing to validate the new design. Ensuring its function and ability to meet various system requirements provided by the sponsor. After much discussion with the project sponsors and considering the problem at hand, the following research objectives were created.

RO1: Identify changes with the current testing setup that need to occur for it to meet new system requirements.

RO2: Adapt the current setup through the design and implementation of new parts and components with a focus on minimal change.

RO3: Develop a process to validate the testing setup by showcasing data collected which correlates with the new system requirements.

1.4 Thesis Outline

To outline this thesis the chapters are organized to represent the design approach created for setup alteration and integration of new components (Figure 3). Chapter 1 starts with an introduction to the research and gives a general overview of sealing technology that pertains to the test setup. While doing so, the scope of the project and its objectives are explained.

Chapter 2 reflects Step 1 of the design approach. Here, the project expectations are introduced, and an analysis of the existing condition and purpose of the testing apparatus is conducted. After showcasing the intent of the original test stand, the new requirements are described for which the adapted electro-mechanical system must meet. After this discussion an explanation of the design approach developed to complete this process is conducted.

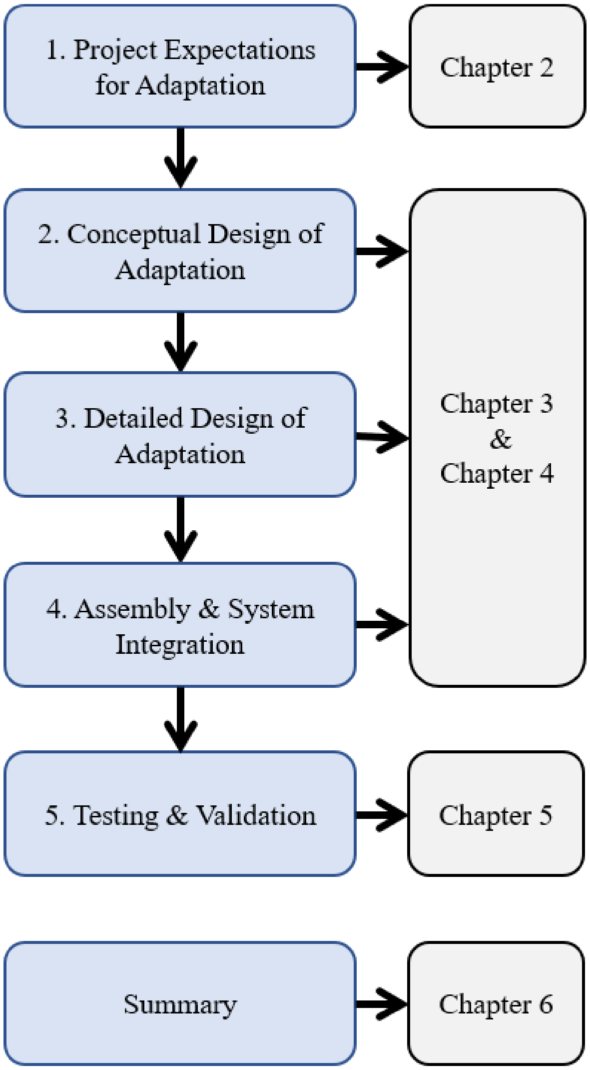

Figure 3: Overview of thesis discussion and approach

Chapters 3 and 4 describe the alterations made to the mechanical and electrical systems respectively. These chapters are structured to represent Steps 2-4 of the design approach. Each chapter will focus on an individual system and describe its overall design process. Initial concepts are shown and reasons for retained components are explained. Furthermore, the detailed design of the adaptations made to the test stand are included and important assembly steps are noted.

Next, Chapter 5 provides data collected from the system after assembly and initial troubleshooting. This data provides sufficient evidence for validating the adapted test stand against its expected performance as outlined in Chapter 2 and proves its overall function. Additionally, a description of the procedure created for running the experiments is brought forth to show the completion of Step 5 of the design approach.

Lasty, Chapter 6 provides a summary of the thesis and the efforts of this research. The research objectives are addressed and compared to the test stand's current status to see if they were appropriately achieved. Also, future recommendations for work or modifications to the test setup as well as the limitations of the research are provided to benefit the continuation of this project.

Chapter 2: Previous Iteration of Experimental Test Setup

As discussed, this thesis will focus on the adaptation of an existing setup to meet new system requirements. Before determining what alterations to the setup need to occur an analysis of the existing experimental setup must be completed to evaluate its condition and previous goals which it was trying to accomplish. Upon the completion of this analysis, new system requirements can be generated based off consulting with the project sponsors about the needs of the new test stand and the statis of the current iteration. To ensure the adaptation is capable of meeting the new needs of the sponsor the design approach mentioned within Section 1.4 will be discussed to see how it can help guide this process. An emphasis on minimal change to the test stand was requested by the sponsors to reduce project costs and time.

2.1 Existing Test Setup and Previous Requirements

The existing test stand was originally used to characterize the performance of O-ring rod seals exposed to hydraulic fluid and linear reciprocating motion. This test stand was designed with the intent of emulating the mechanics of a conventional positive displacement pump [6]. The main goals were to understand the leakage of hydraulic fluid past these sealing barriers and the frictional force experienced due to the linear motion. These rod seals were often tested to failure and their forces analyzed to help predict this failure before it occurred. Looking at the test stand, it can be broken down into both a mechanical and electrical system. The mechanical system consists of the drivetrain, test housing, piston, aluminum mounting, and hydraulic plumbing. The electrical system consists of the data acquisition device, various sensors, and wiring.

The mechanical system utilizes an AC induction motor and gearbox combination with variable speed controller to operate a cam-arm at a set RPM resulting in consistent linear travel of the reciprocating piston [6]. The cam-arm actuation consists of a 3-inch or 5.5-inch lever arm, depending on the configuration, to create a total of 6 or 11 inches of total travel per one cycle of the reciprocating piston (Figure 4).

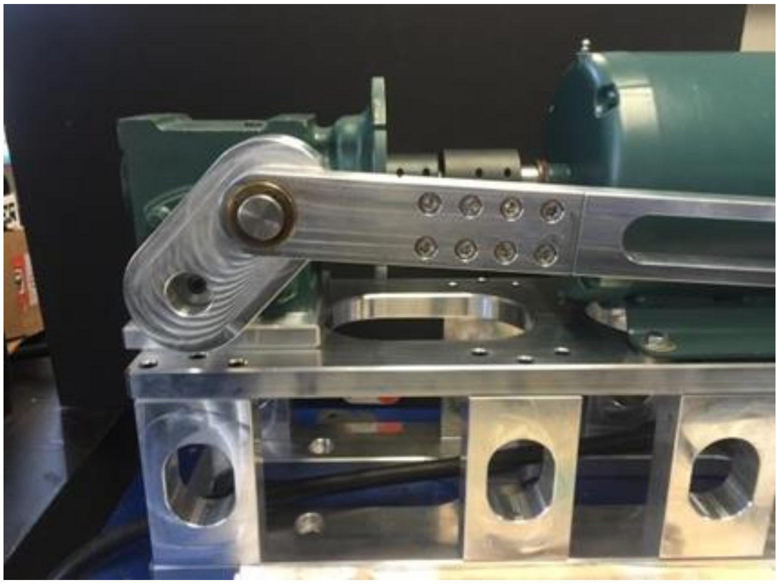

Figure 4: Existing drivetrain and cam-arm creating reciprocating motion [6]

This cam arm translates the rotary motion of the motor and gearbox combination to a linear motion provided by the piston (Figure 5). Linear travel is stabilized with resistance to binding thanks to a linear guide rail and ball bearing system [6]. Additionally, this setup utilizes a propriety housing with interchangeable cores which enables it to test variable O-ring gauges with limitations to a single seal inner diameter.

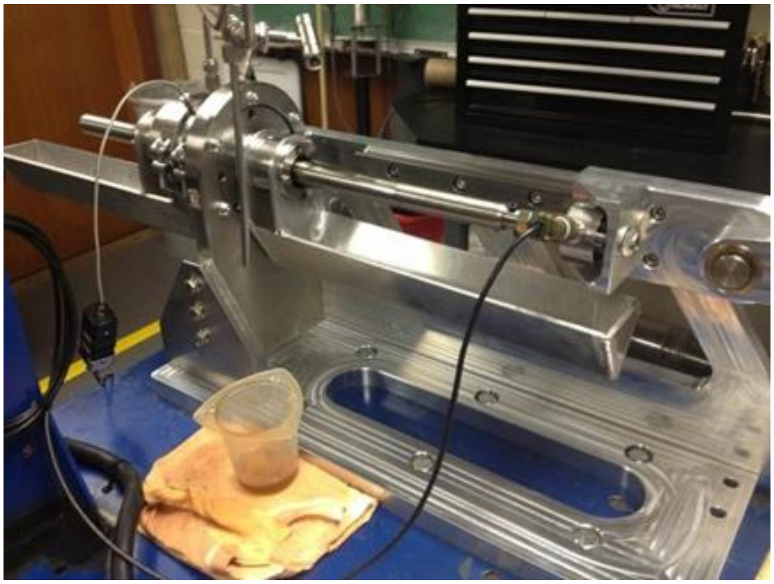

Figure 5: Existing O-ring test housing and piston assembly [6]

This iteration uses a thin hydraulic fluid as the test medium. This required the design of a hydraulic plumbing system capable of tracking fluid leak past the sealing barriers, and ability to energize the hydraulic fluid to the required pressure. To achieve a leak rate measurement, a linear variable differential transducer, or LVDT, was incorporated to accurately track fluid levels within the system (Figure 6). To charge the system to the expected pressures of less than 3,000 psig, a piston accumulator setup was incorporated with a gas cylinder to pressurize one side of the piston so that it can be transferred to the hydraulic fluid (Figure 5). A hydraulic pump was added to reverse the fluid flow within the LVDT and piston accumulator to force the internal pistons back to their original positions after tests were concluded.

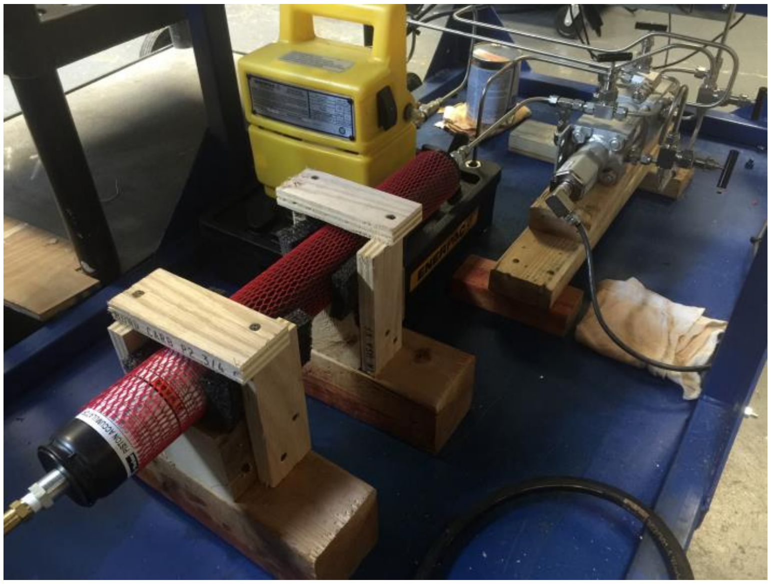

Figure 6: Hydraulic medium plumbing system [from old team presentation to sponsor]

For data logging the system incorporated an older National Instruments (NI) USB-series data acquisition device (DAQ). The system utilized a total of four sensors to monitor the testing environment. These include hydraulic fluid pressure, volumetric leakage, force, and housing temperature. Since tests were conducted using this iteration of the setup, the NI USB DAQ has received internal damage to the analog to digital converter as found out when taking inventory of the test stand. This was causing inconsistent readings on all analog input channels. Because of this, new components will be needed for replacement, or an entirely new electrical and data acquisition system will likely be needed in order to update it to accept newer and more compatible components.

After researching the previous use of the setup, the general requirements were found to be as follows.

1. Test O-ring rod seals exposed to reciprocating motion
2. Test medium required: Hydraulic fluid
3. Test Pressure: 0 – 3,000 psig

4. Translation length: 6 and 11 inches
5. Reciprocating speed: 30 cycles per minute
6. Measure frictional force due to reciprocation
7. Measure volumetric leakage past O-ring sealing barriers

2.2 New Requirements for Adaptation

Upon completing the analysis of the previous system, the status of the test setup was brought forth to the project sponsor. After which, multiple consultations with the sponsor were attended to discuss the new purpose and variables it was required to be able to measure. From these discussions, the end goal for the adapted setup was to determine the performance of MSE seals exposed to low-pressure Nitrogen gas and rectilinear motion. Both new MSE designs, and existing seals will be tested to help understand their performance under these known conditions.

For adapting the mechanical setup, some components were provided by the sponsors including an updated housing and reciprocating piston assembly which accepts the MSE seals desired for testing. Also, heating elements were sent for elevated temperature tests which were specified during the design of the test housing. To reduce both overall costs and the timeframe of the project, an emphasis on minimal change to the existing setup was encouraged. This meant primary system components would be kept if found satisfactory in helping to meet the adapted system's goals. Additionally, certain parameters were set based on existing drivetrain components, such as stroke length and cycle rate.

Due to the findings on the original setup, the main adaptation will involve redesigning the electrical and data acquisitions systems due to damaged and outdated parts. Additionally with the change in fluid medium required, many of the existing plumbing parts will be unable to be incorporated within the new adaptation. After understanding the general expectations of the test stand moving forward, new requirements for both the mechanical and electrical systems were developed and outlined in the following sections.

2.2.1 Mechanical Requirements:

1. Adapt a previously existing setup to meet new system requirements to conserve manufacturing time and overall costs
    a. Test a new seal geometry by integrating a new test housing and piston assembly
    b. Convert working fluid from hydraulic fluid to a gas medium
    c. Make minimum changes to existing setup while meeting new system parameters
2. Expose Metal Spring Energized seals to linearly reciprocating motion with a known stroke length and speed
    a. Stroke Length: 6 inches and 11 inches
    b. Speed: 2 cycles/min
3. Ability to apply 1,200 psig of Nitrogen gas to high-pressure chamber of housing
4. Ability to heat housing to elevated temperatures
    a. Ambient Temperature: ~75°F
    b. Elevated Temperature: 300°F

Safety Considerations:

5. Ensure pressure reliefs are pointed away from operator
6. Add heat shielding to areas to reduce chance of burning
7. Have Personal Protective Equipment handy to use during testing and assembly/disassembly

Below is a further explanation of each mechanical requirement (MR) listed that must be met in order to consider the updated mechanical system operational.

***MR1:* Adapt a previously existing setup to meet new system requirements to conserve manufacturing time and overall costs**

The previous iteration of the reciprocating system was updated to test new seal types and apply new experimental conditions that the previous iteration was incapable of testing. These conditions include accepting a new seal housing and piston assembly for testing the updated seal geometry; converting the system from hydraulic fluid to a gas medium; and lastly, incorporating a new electronic system for detecting and monitoring a low-pressure gas leakage past the sealing surface of the MSE seals. As requested by the sponsor to save on manufacturing time and cost, minimum change to the setup was required. This added extra constraints to what alterations could be done with the setup, but in the end total system cost was deemed more important.

MR2: Linearly translate Metal Energized Seals a known stroke length and speed

To test the seals under dynamic conditions, the system needs to be able to move the seals linearly in a reciprocating motion with a total stroke length of 6 and 11 inches. In addition to a linear reciprocating motion, a variable movement speed is needed with a slow cycle rate desired than the previous iteration. A minimum cycle rate of 2 cycles/min was agreed upon with the allowance of a faster cycle rate for future testing. The seals also need to be tested under static conditions, so this reciprocating movement needs the ability to be turned off so that each MSE design can be tested for this case.

MR3: Ability to apply 1200 psig of Nitrogen gas to high-pressure chamber of housing

The test setup must energize the MSE seals with a steady low-pressure environment. The objective high pressure for these “low-pressure” experiments was set at 1200 psig. This value will be used to design the plumbing subsystem for the experimental setup and commission its ability to detect low-pressure leakage and force with the effect of varying housing temperatures at this pressure range.

MR4: Ability to control housing temperature

The system must be capable of altering the test housing temperature to test the seals at both ambient and elevated temperatures. The temperatures necessary for this iteration of the setup include the range from room temperature, approximately 75°F to 300°F. Characterizing the leak rate and force at elevated temperatures is important, as the MSE seals are expected to be exposed to these temperatures during their lifespan.

MR5: Ensure pressure reliefs are pointed away from operator

For overall system safety, any pressure zones must have reliefs pointed away from the operator during testing in case of an over pressure situation.

MR6: Add heat shielding to areas to reduce chance of burning

For overall system safety, any hot areas or components must be covered with heat shielding to reduce chance of operator burning oneself.

MR7: Have Personal Protective Equipment Handy to use during testing and assembly/disassembly

To prevent personal injury, at all times the operator must use Personal Protective Equipment to reduce chance of bodily injury resulting from working around pressurized equipment and moving components.

2.2.2 Data Requirements

1. Measure leakage past sealing surface of two individual barriers simultaneously
2. Measure frictional force required to reciprocate seals linearly
3. Monitor temperature at various points of the test housing

4. Log all system data including pressure, temperature, and force
5. Account for temperature fluctuation in housing when tracking total leakage of gas past sealing surfaces
6. Design and write a LabVIEW code to aid in data collection and provide a better user interface

Safety Considerations:

7. Have automated solenoids for pressure relief to reduce damage to sensors and reduce over pressure of test housing and plumbing system
8. Set force and temperature limitations to reduce chances of setup losing control

Again, further details for each data requirement (DR) are provided.

DR1: Measure leakage past sealing surface of two individual barriers simultaneously

The main characteristic of the MSE seals desired from this testing is the leak rate as a function of number of cycles. The new test housing and piston assembly requires two seals to be tested at one time. This means each individual leakage measurements needs to be taken simultaneously throughout the experiment to monitor the leakage past both seals. This enables the ability to test two different seal types at once. Because a gas medium is used, the compressibility of the fluid must be considered when determining the best way for measuring the leakage past the sealing surface, so direct volume sensors such as an LVDT or MTS sensor are not suitable. This must be adapted from the previous iteration.

DR2: Measure frictional force required to move seals linearly

This requirement is retained from the existing system as it pertains directly to the adaptation. The forces required to move the seals linearly back and forth within the test housing must be measured. This value will help characterize the MSE seals and determine equipment requirements if commissioned for industry use.

DR3: Monitor temperature at various points of the test housing

The experimental setup needs the capability of monitoring the gas temperature or temperature of the housing at various points where necessary. These include the overall test housing temperature and both low-pressure chambers for use in controlling the desired test temperature and post experiment analysis.

DR4: Log all system data including, pressures, temperatures, and force

A new data acquisition system and program needs to be designed and implemented due to damaged existing components and major test setup alterations. The data acquisition system must be able to monitor and log all pressure, force, and temperature data for post experiment analysis, as well as have the ability to control the linear actuation of the seals during the experiment. In addition to these features, the data acquisition system should be able to turn on and off the supply pressure from the gas reservoir and relieve the low-pressure chambers if the pressure becomes too great.

DR5: Account for temperature fluctuation of housing when considering total leakage of gas past sealing surface

To ensure an accurate leak rate measurement is taken, low-pressure housing temperatures must be captured and considered during the volume analysis for determining the leak rate of the seals over time. Thermal insulation should also be considered where possible to reduce outside temperature influences on the system during testing.

DR6: Design and write a LabVIEW code to aid in data collection

National Instruments LabVIEW was chosen as the best method for monitoring and logging all system parameters for post analysis, based on compatibility with NI devices and various sensor types. Major aspects of the existing system are changing, therefore a new program for data collection and system control will be programmed.

DR7: Have automated solenoids for pressure relief to reduce damage to sensors and reduce over pressure of test housing and plumbing

In conjunction with MR7, pressure reliefs must be automated to help with over pressure situations and to reduce chance of damaging expensive electrical and mechanical system components. This was not integrated into the previous test stand.

DR8: Set force and temperature limitations to reduce chances of test setup losing control

Within the LabVIEW program there must be limitations for excessive force and temperature conditions to reduce chance of damaging critical test components or the operator. When these conditions are met and sensed by the program, it should enforce a shutdown protocol for the reciprocating motion and heating elements, as well as prevent excess Nitrogen from being leaked to the atmosphere.

2.3 Detailed Design Approach for Adaptation

To help incorporate the desired changes and meet the new system requirements, a design approach was developed. Figure 7 illustrates an explanation of the design steps taken during the research project from initial concept to completion.

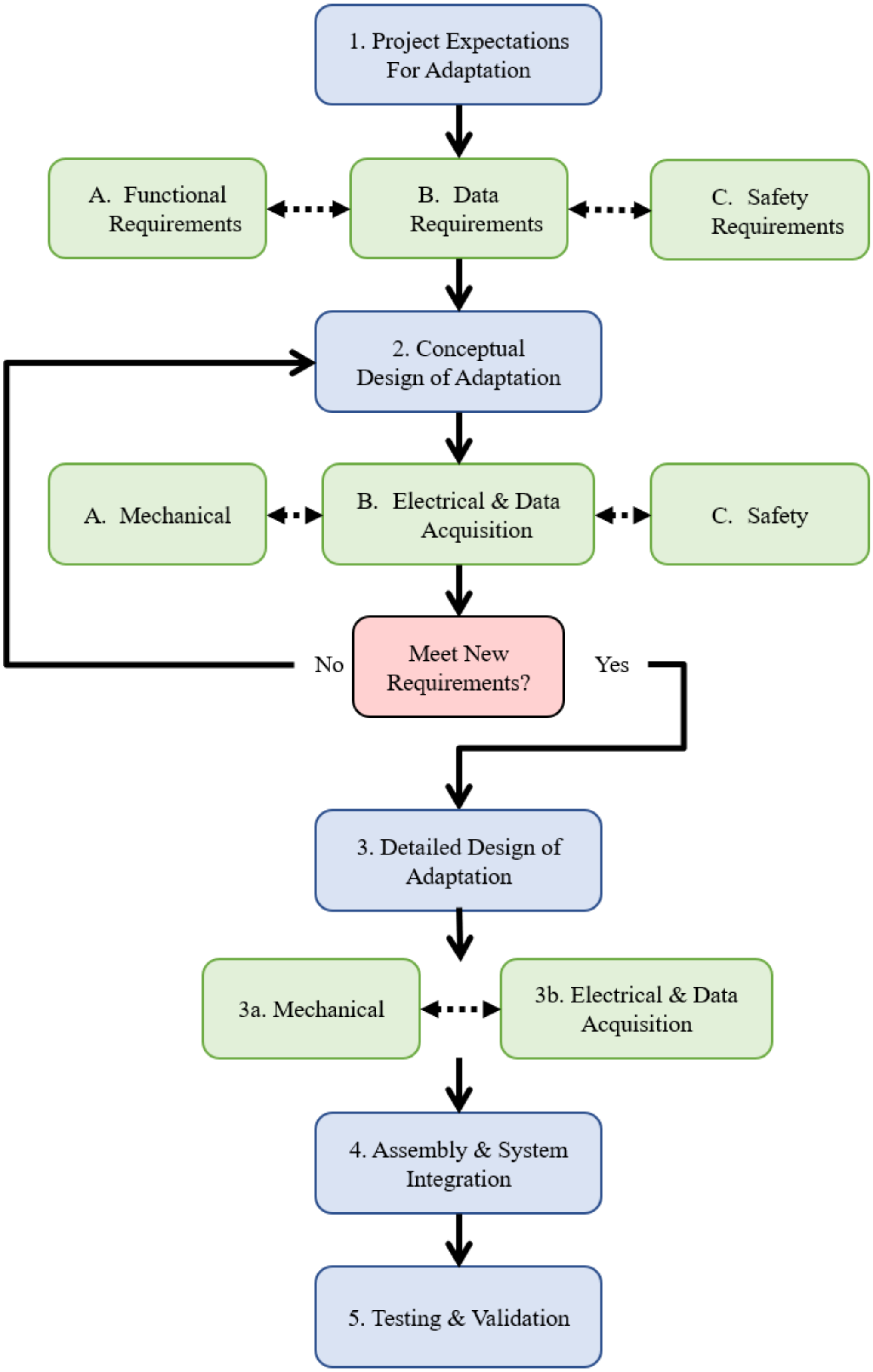

Figure 7: Detailed design approach flow chart

The initial step, *Project Expectations for Adaptation*, is similar to the start of many other design processes that engineers in industry use today. At this stage the general purpose of the adapted setup and the requirements which it needs to complete per the sponsor were defined. Defining the expectations or requirements that the test stand needed to fulfill were crucial to ensuring the research would be considered a success upon its completion. These requirements help build a general understanding of the project and set objectives which need to be met. The requirements have therefore been split up into three subcategories: functional, data, and safety requirements. This helps to focus the intent of each individual system and how they aid in meeting them.

Functional requirements characterize the actions that the electro-mechanical system had to be able to complete during testing, such as using the desired working medium or having the ability to achieve the desired pressure to test the sealing barriers against. Data requirements helped drive how the data acquisition system needed to perform, such as what data needed to be monitored and collected for analysis. Lastly, safety requirements were established to ensure the setup's operators and high-cost equipment would not be damaged if a seal or other component should fail during testing. Considering the functional, safety, and data requirements was an important step before conceptualizing an idea of what the setup design would be. Disregarding these at this point, could have led to incorrect function of the adapted test setup or a safety hazard forming, resulting in harm to the operator or damaged equipment.

Continuing with the design approach presented in Figure 7, the second major step is *Conceptual Design for Adaptation*. This phase included creating a basic drawing of how the system could potentially be built, focusing on the main components of the system. The general idea and requirements determined in the previous step were considered and helped drive the initial concept of the system design. This step was broken down into two sub systems correlating to the Mechanical and Electrical and Data Acquisition Design. Included within these sub systems, safety considerations for the system overall were prioritized. The Mechanical Design included specifying components for the plumbing system and ensuring existing components would work with testing the new seal type. The Electrical and Data Acquisition Design included determining what data would be collected which in turn would drive sensor type and location. Here, different ideas for collecting data and adding in automated control of the plumbing system was discussed for safety purposes. During this phase as ideas were being drawn and components were specified for each sub system, they were checked against the different requirements discussed in Step 1. If they were thought to be extraneous or did not fit within a requirement they were discarded, and a different idea was brainstormed or part was considered. Once a general idea for how the system would work and complete the desired requirements was obtained, both systems were subject to a more detailed design process.

Step 3, *Detailed Design of Adaptation*, was broken up into two systems, Mechanical and Electrical and Data Acquisition Systems. During Step 3, the best components and sensors were chosen based on the set conditions of the experiment, to fulfill each requirement. The plumbing system was designed based on the fluid medium and expected pressures. Code was written in LabVIEW to help log all system data and let the operator view system data in real time. After a final design was chosen and build of materials was made for each subsystem, the project was moved to Step 4, the *Assembly and System Integration* phase. During this step the two major systems were brought together, and correct operation was confirmed. If issues arose, revisions were made and reverified. Further, mechanical parts were assembled onto the test stand and the plumbing system was installed and checked for leaks. Careful consideration for alignment of moving parts was considered. The data acquisition system was wired, and sensors were integrated into their desired location. In addition, the LabVIEW program was setup to collect necessary data for seal characterization and add automated control to the experimental setup for ease of use and added safety.

Lastly, Step 5, Testing and Validation comprised of evaluating the system for proper mechanical operation, correct calibration of sensors, and running a multitude of initial tests on different MSE seal types to validate the system was working properly and able to meet system requirements. Additional troubleshooting took place to help eliminate small issues and to setup a common test procedure for consistency between tests and different seal designs. In addition, raw data was analyzed and plotted to check the system against each mechanical or data requirement determined during Step 1.

Chapter 3: Design and Implementation of Mechanical System

With a general understanding of the fluid sealing technology being used and the expectations of the sponsor, the initial conceptualization of the experimental test setup can begin. Using the design approach described in Chapter 2, each major system will be discussed individually showing how they were adapted, designed, and integrated into a single setup. Starting with the Mechanical System, the design decisions and parts used will be discussed in detail as it has been adapted from its current state.

3.1 Initial Mechanical Concept of Adaptation to Test Stand

After carefully considering the expectations, existing system restraints, and the mechanical requirements for the project as discussed in the previous chapter, an initial concept of how the new mechanical system iteration should look and operate was developed (Figure 4).

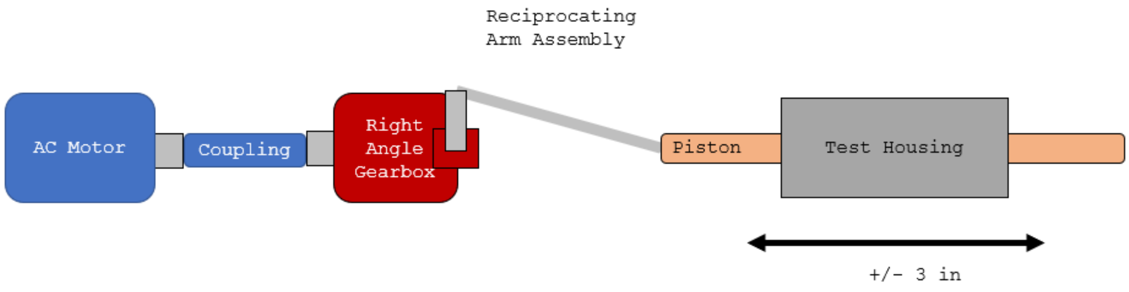

Figure 8: Initial concept of mechanical system and test housing configuration

As can be seen, it is very similar to the previous iteration discussed in Chapter 2. Alternative methods for driving reciprocation were raised but were rejected as they involved changing out critical drivetrain components which would add substantial costs to the project. Additionally, to incorporate these proposed changes in components, major redesigns of mounting would result in additional time and costs outside of the project timeline. Ultimately, it was deemed inefficient to change the manor for which the seal was reciprocated through the housing and thus the existing drivetrain components were retained. Features such as the motor and gearbox, cam arm, guide rails, and mounting solutions of the previous iteration were to remain which made the initial concept simple to visualize. The major change is incorporating the new test housing and piston assembly.

A new component as provided for testing by the sponsor is the piston and test housing assembly. These were designed around the existing setup and would easily be integrated into the current mounting solutions. Another reason to keep the current method for reciprocation. These components allow for appropriate testing of the MSE seals to help with their characterization. Figure 5 provides a diagram presenting a simplified view of these components.

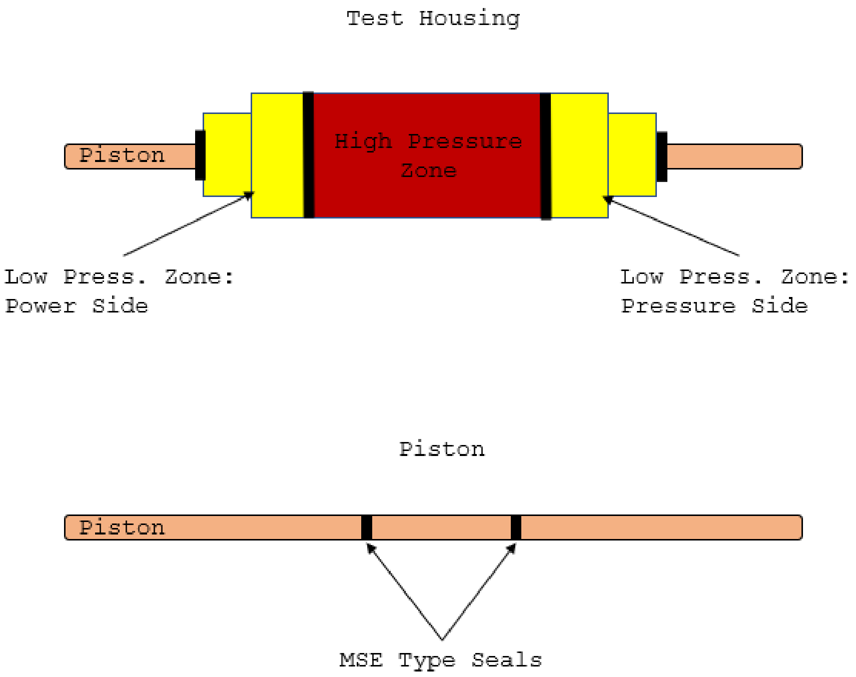

Figure 9: Simplified diagram of test housing and piston assemblies

Within this assembly, the MSE seals are installed in a piston configuration, within a seal groove cut into the high-pressure piston. The piston will then be reciprocated through the smooth bore of the housing in a back-and-forth motion. This new test housing and piston will allow for the use of existing mounting solutions and parts but will require new designs for both the plumbing and electrical and data acquisition systems since changes to the testing parameters and physical attributes of the test housing, when compared to the previous iteration, has occurred.

With a change in test housing and working medium, the plumbing system needed to be modified or changed. The initially concept of the gas plumbing system is represented in Figure 10.

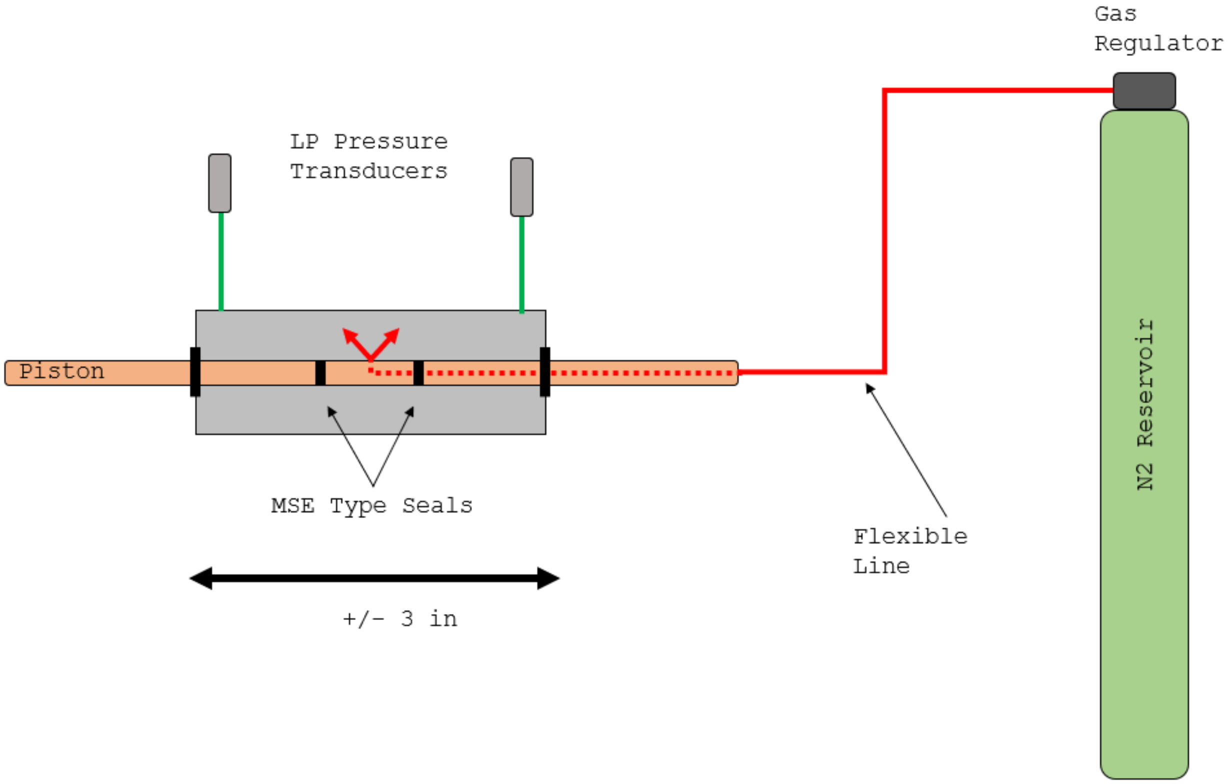

Figure 10: Initial gas medium plumbing

Since the pressure desired for testing is below 3,000 psig it is possible to charge the system using a gas cylinder containing Nitrogen. This eliminates the need for a pump to charge the system, reducing its overall complexity. Additionally, the plumbing system cannot be rigidly mounted around the test housing since the Nitrogen gas is required to be charged through the centerline of the piston assembly which will be moving during an experiment. This calls for a flexible line between the high-pressure piston and gas cylinder with a regulator to control the pressure. Lastly, additional lines on the back sides of each seal for collecting volumetric leakage is known to be needed. Connecting pressure transducers to these regions was considered to be the best method for tracking this buildup over the entirety of a test.

Within the piston and test housing assembly there are three main pressure regions: two individual low-pressure regions and a single high-pressure region. To help distinguish the low-pressure regions apart, they were given names relating to their position within the experimental setup. The low-pressure region located near the cam arm and drivetrain assembly is denoted as the Power Side, while the side closest to the supply pressure bottle which feeds into the piston is the Pressure Side. The single high-pressure region will simply be labeled the high-pressure supply.

3.2 Mechanical System Components

After conceptualizing both major mechanical systems and obtaining the new components necessary for testing, a more detailed design could be completed knowing the project is heading in the right direction to meet various system requirements. At this point a detailed design was conducted and main components of the experimental setup were identified to meet the various mechanical requirements. In addition to new components chosen, parts retained from the previous setup iteration are further discussed in detail. During this stage, if any limitations for testing the new MSE seals were discovered, a new method would be considered, and the existing design would be altered as needed.

3.2.1 Drivetrain Components and Considerations

As mentioned, these parts were decided to be retained based on the minimal change requirement associated with *MR1: Adapt a previously existing setup to meet new system requirements to* *conserve manufacturing time and overall costs*. Driving the linear actuation of the seals from the previous setup iteration was a Baldor AC Motor (Figure 11) with ABB ACS150 Drive. The variable frequency drive limits the motor speed and controls torque by varying the supply load and frequency to the motor [6]. The drive itself is controlled using a 0-10V analog voltage input. This enables the operator of the setup to vary the reciprocating cycle rates and reach the low speed required for testing. The Baldor motor is directly linked to a Dodge Tigear-2 gear reducer (Figure 12) with a 10:1 ratio. The Tigear-2 reducer is a right-angle gearbox that helps to both increase the torque output of the motor while reducing its overall RPM. With this combination of motor, motor controller, and gearbox, the system can achieve the low 2 cycles/min rate needed to meet part of requirement *MR2: Linearly translate Metal Energized Seals a known stroke length and speed.* Furthermore, using the ABB controller the cycle rate can be increased for future adaptations to test parameters.

Figure 11: Baldor AC Induction Motor [7]

Figure 12: Dodge Tigear-2 Right Angle Gear Reducer [8]

In addition to these existing components, other methods for linear actuation were considered as mentioned in Chapter 3.1. These methods included: a ball screw assembly or linear actuator to drive the piston through the housing. All three drivetrain systems have their advantages and disadvantages, but eventually the existing motor and gearbox assembly were chosen based on its ability to meet and maintain the cycle rate requirement while being the most cost-effective option. Furthermore, this combination of drivetrain components was believed to have a suitable torque capacity for overcoming the frictional forces between the new MSE seal and test housing at the expect test RPM. This variable was unknown at this phase of the process since the seals being tested had not been subject to linear motion beforehand. This value is a large reason for testing.

3.2.2 Potential Gearbox Iteration

A potential failure point was discovered within the existing drivetrain assembly from researching it's specifications. It was found that the horsepower (HP) rating of the gearbox, 1.67 HP, was not sufficient for the output power of the AC motor, 3.0 HP, as specified by the manufacturer [7,8]. Currently this motor HP will not be achieved due to the slow RPM desired under the current testing parameters however, this could cause potential problems with the drivetrain, if the RPM for testing were to be increased or even decreased in a future adaptation. If increased to a high enough speed internal damage of the gearbox could occur. While decreasing the RPM could cause excessive current through the motor and electrical drive straining the system and reducing its life. Due to this discovery – and the potential for future adaptability of the system – a more suitable gearbox was researched and selected. Designing and analyzing this potential update created an opportunity to research a mechanical change to the pre-existing system, that could lead to future testing alterations to further study the MSE seals under different conditions. CAD models were created for integrating the new larger gearbox into the existing assembly.

The newly selected gearbox assembly was designed within the previous iterations CAD assembly to ensure proper alignment between the new and existing mechanical components. This existing assembly was made by prior members of the research team. The gearbox selected is a Baldor Tigear 2 right angle gear reducer with a 20:1 ratio [8]. This part was chosen based on its motor input rating of above 3.0 HP and similar configuration as the smaller gearbox currently on the setup. Additionally, the larger gear box utilizes the same size input shaft diameter so the motor couplings can be retained. The larger gear reduction does decrease the RPM, however there is more room to increase the input of the motor speed through the ABB drive. This gearbox provides the opportunity for the system to test larger diameter seals or material types which may require more force for reciprocation and guarantees the durability of the system. This gearbox utilizes a larger frame, compared to the existing gearbox, for increased torque capacity.

Using SolidWorks, detailed solid models were created for adapting the current motor and existing test stand to accept the larger gearbox option. This included designing an adjustable base for the AC motor, adapter plate for mounting the larger gear reducer to the existing aluminum mounting structure, shorter supports between the top and bottom mounting plates, and 3.0-inch and 5.5-inch lever arms which interface with the larger output shaft of the gear reducer. Figures 13 and 14 presents these parts within the assembly and highlights them in color compared to the existing parts which remain grey.

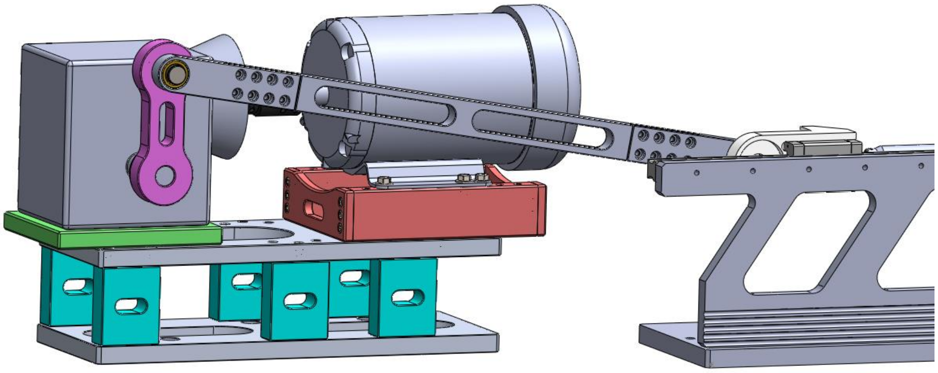

Figure 13: Large Gearbox Assembly – 5.5-inch Cam-arm Alignment

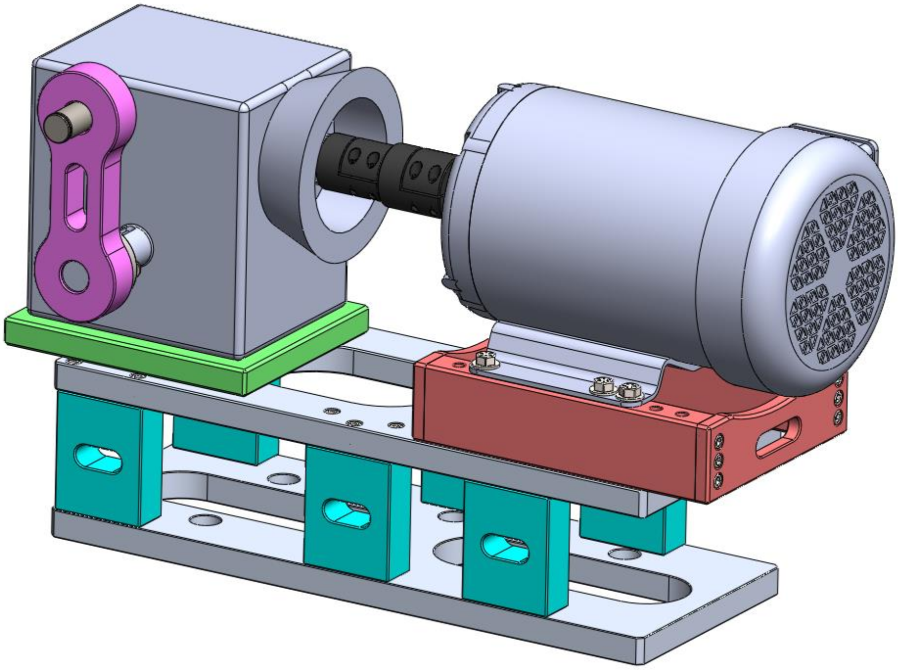

Figure 14: Large Gearbox Drivetrain Assembly

Aluminum 6061-T6 was selected to manufacture these parts because of its strength, weight, and machinability, as well as being similar in material to the pre-existing components of the setup. Existing fasteners were utilized to easily integrate the new parts within the existing mounting structure where possible. Proper alignment for rotating equipment was the driving factor for height and location of the gearbox output shaft. Gearbox position then drove overall height for the supports and motor base. Both the 3-inch and 5.5-inch arms were designed to accept a quick disconnect bushing which integrates with the keyed output shaft of the larger gearbox. The bushing is split and designed to fit within the 1.871” bore cut into both arms (Figure 15).

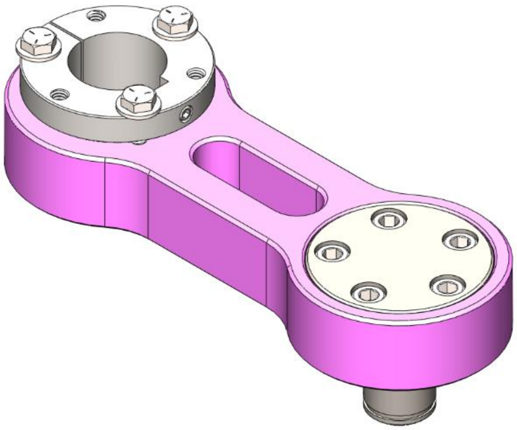

Figure 15: Split keyed bushing used [mc] *Figure 16: 5.5-inch Arm Assembly*

This bushing is then bolted to the aluminum arm causing it to squeeze the output shaft of the gearbox tightly, preventing the assembly from sliding off. The 5.5-inch arm assembly with necessary hardware is provided in Figure 16.

To show the process of validation on critical parts, finite element analysis was conducted on the 5.5-inch motor arm under the condition of the motor stalling. In this case, a cause for failure would be the binding of the cam-arm or piston assembly, causing the motor to stall. The stall torque of the motor is 34.2 ft-lbs [7]. This torque will be multiplied through the gearbox by a factor of 20 increasing its value to 684 ft-lbs or 8,208 in-lbs. This value, in addition to the material properties for 6061-T6 aluminum, were used to test the arm's deformation and safety factor in the worst-case scenario [9]. Results for the safety factor (Figure 17) and deformation (Figure 18) of the 5.5-inch motor arm are 2.6 and 0.016 inches respectively. These values are acceptable for the performance expectations of the arm under these conditions.

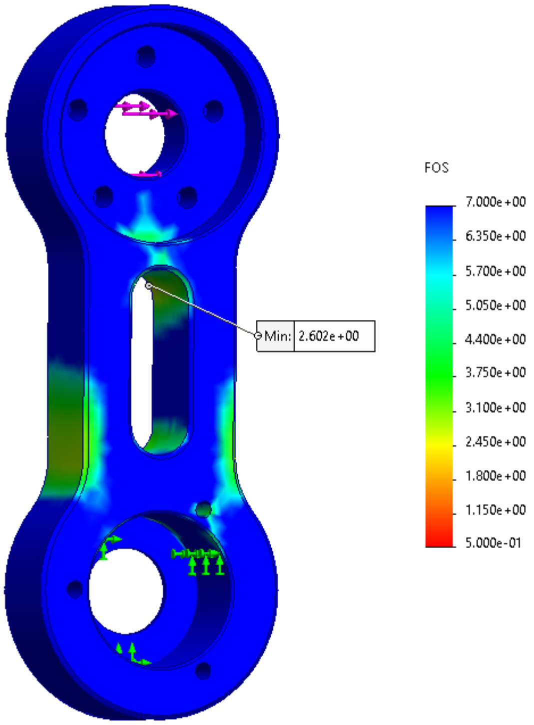

Figure 17: 5.5-inch arm safety factor plot

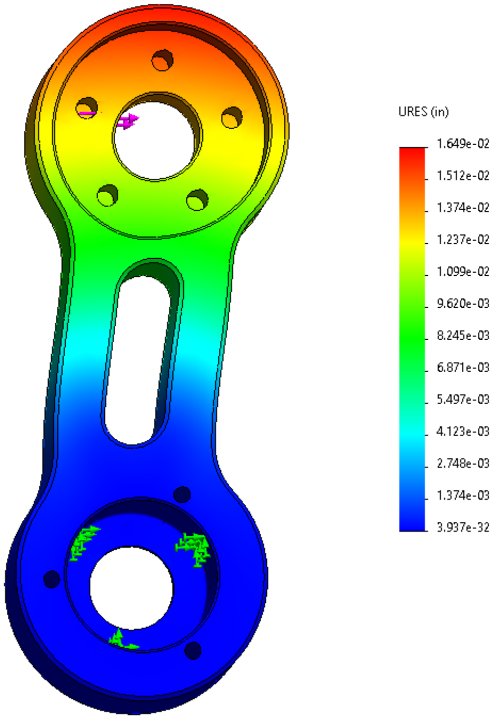

Figure 18: 5.5-inch maximum displacement chart

Lastly, another node of failure for this part would be the bolted connection between the bushing and aluminum arm. This assembly uses three Grade 8, 1/4 – 20, bolts which have tensile strength of 150,000 psi [10]. The bolt pattern is 2.25” in diameter. Using the expected maximum torque value, the shear stress experienced by the bolts can be calculated. A safety factor of 2.42 was found illustrating that the bolts under a single shear case have more than enough strength to resist failing due to shear under the condition of the motor stalling.

Even if these parts are not used, planning for this potential failure will provide future research team members with a starting point for future adaptability of the system to apply new testing parameters with a reduced chance of damaging the drivetrain. Currently these changes have not been integrated, due the existing gearbox performing effectively, and the overall costs associated with the new parts manufacture and implementation. However, if the desire to further adapt the system arises in the future and increased torque capacity or higher piston cycle rates are needed, these parts are available.

3.2.3 Mechanical Linkages

The AC motor and gearbox are mechanically linked with a combination of keyed shaft reducers. Connecting the output of the gearbox to the piston assembly is a cam style arm (Figure 19) which transitions the rotary motion of the gearbox to the required linear movement that the seals will be tested under. The arm is rigid helping remove any compliance from the system. By adjusting the cam length, the stroke length can be increased or decreased based on the lengths desired for testing. The previous iteration used a stroke length of 6 inches and had available a 5.5-inch arm to increase this value to 11 inches. This entails the existing cam arm assembly can meet the length requirements associated with *MR2: Linearly translate Metal Energized Seals a known stroke length and speed,* making it suitable for commissioning the new MSE seals after the system has been assembled and issued for testing. The cam arm is directly connected to a carriage (Figure 20) which supports the high-pressure piston within the housing assembly. This carriage utilizes a Rexroth ball rail linear guide system to help with support while allowing movement of the piston. It also helps keep the piston concentric within the bore of the housing. The guide rail helps reduce the chance of extraneous forces acting on the system that would cause the piston from becoming unaligned with the bore of the housing during reciprocation.

Figure 19: Retained drivetrain components

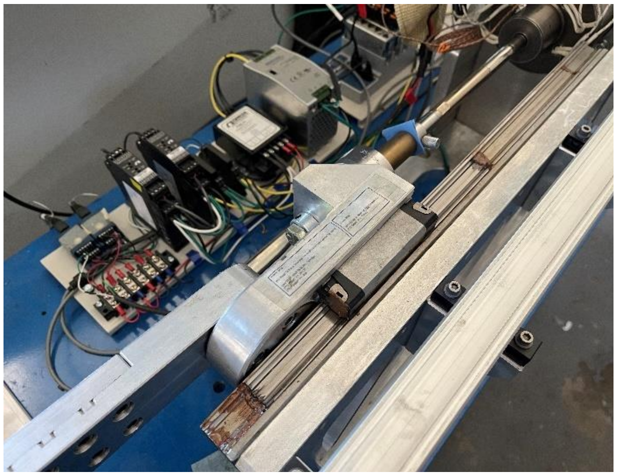

Figure 20: Linear Guide rail and carriage

3.2.4 Existing Mounting Solutions

The main system components were supported using a machined aluminum structure that linked the parts together with proper alignment and stiffness. These parts again were left alone to reduce overall project costs as they proved to be a reliable system within the existing setup showing no signs of excessive stress. This adds constraints to what can be added to the system in the future, but also gives the ability to return to the previous seal type if desired by the sponsors. Figure 21 shows the existing mounting solutions used for holding the new test housing and retained drive train components.

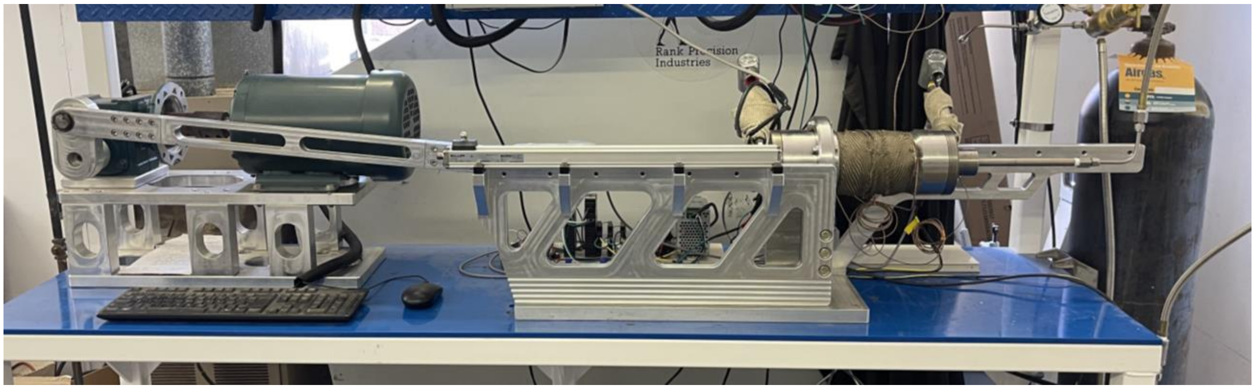

Figure 21: Previous mounting and drivetrain with new test housing and piston assembly

3.3 Plumbing Subsystem Adaptation

To meet mechanical requirements *MR3: Ability to apply 1,200 psig of Nitrogen gas to high-pressure chamber of housing*, the existing plumbing system needed to undergo a redesign to ensure it could charge the high-pressure supply with a Nitrogen gas instead of a hydraulic fluid. It was important to retain the ability to move back to charging the test housing with hydraulic fluid incase the MSE seals also need to be tested with a hydraulic medium. Figures 22 shows the newly designed gas plumbing system with the flow of Nitrogen gas starting from the Nitrogen cylinder through the test housing and past the MSE sealing surface before entering its respected low-pressure region.

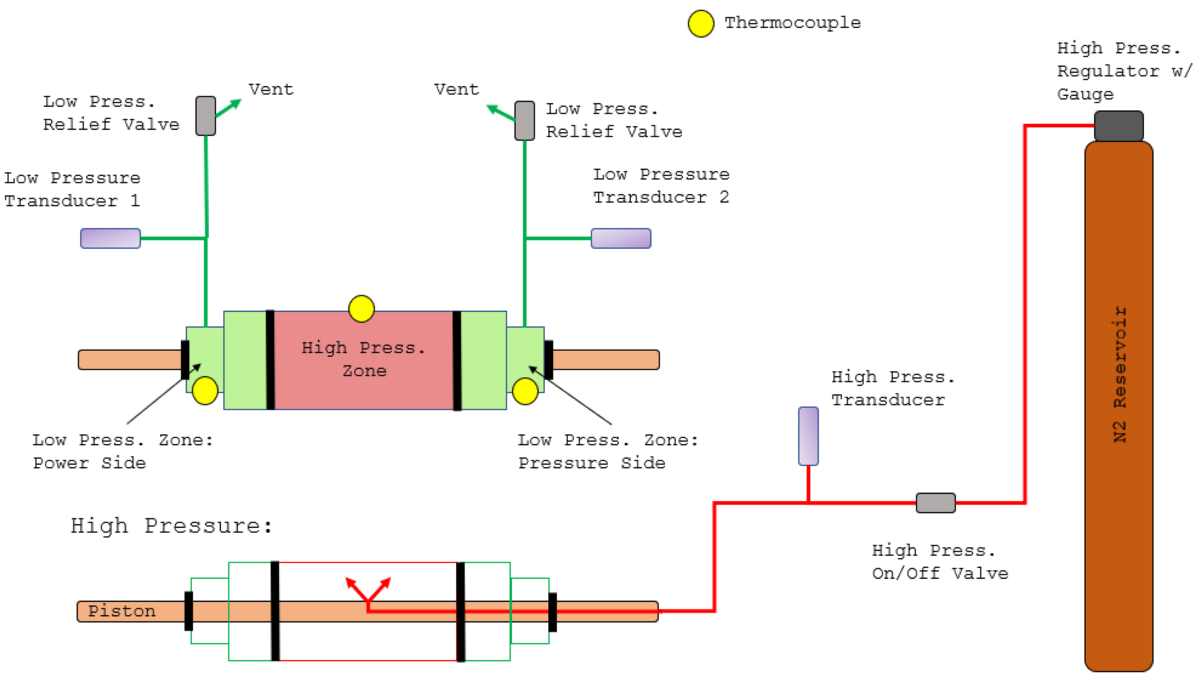

Figure 22: Final gas medium plumbing for new iteration

All lines, transducers, and fittings were selected with requirement MR3 in mind. Ensuring that 1,200 psig of Nitrogen gas could be applied to the test housing without a risk of rupturing a line or fitting. A safety factor of at least 2.5 was considered to ensure the overall safety and reliability of the system when at an operating pressure of 1,200 psig. Furthermore, the chosen safety factor considers a failure with the high-pressure regulator resulting in the system being charged with the full Nitrogen bottle pressure received for the experiments, typically no more than 3,000 psig. A combination of rigid stainless-steel tubing and flexible braided hosing was used throughout the system. Both compression tube and NPT fittings were utilized as they were necessary to incorporate both the pressure transducers and solenoid valves specified and to achieve proper alignment of fittings and components. For enhanced safety and to add automated control of the system, 24V solenoid valves were integrated into the gas medium plumbing system. These valves allow the operator to relieve pressure in each individual low-pressure region and turn the high-pressure supply on or off in the event of a critical seal failure without standing directly near the test stand. Furthermore, these valves in conjunction with the data acquisition system were used for automated pressure relief and high-pressure supply shut off in the event a seal or mechanical failure is sensed during testing. This adds an additional layer of safety to the test stand by allowing the operator to remain at a safe distance. Also, this feature can save on project costs as it reduces excess gas medium from being lost to the atmosphere.

With the addition of the Nitrogen gas plumbing system, a new challenge was presented. The previous setup used a noncompressible hydraulic fluid, allowing the leak rate to be measured directly using a LVDT located in line between the piston accumulator and test housing. Because the medium has switched to a compressible gas, an LVDT is unable to reliably track the volume of fluid moving through the test housing. In this case, a new way to track the volumetric leakage past the seals is needed. It was concluded that the most feasible way to track the gas leakage through the test housing was to monitor the low-pressure buildup in each low-pressure region. The pressure in each region is tracked by two individual highly sensitive pressure transducers. This means the volumetric leakage past both seals can be monitored separately. This method does require more steps during post processing but can reliably result in the total millimeters that have leaked past both seals. Further discussion and example calculations will be presented within Chapters 4 and 5.

3.4 Assembly of Mechanical Systems

The assembly and integration of the major mechanical components involved mounting the new test housing to the existing aluminum mounting and plumbing the gas medium system. At this point, proper system alignment was checked. After proper alignment was obtained the reciprocating motion was verified to work as intended with the new test housing and piston assembly. If the system was not aligned mechanically, meaning the motor and gearbox or cam arm and piston assemblies were not within proper alignment, invalid force measurements could be witnessed or worse, the piston could bind within the test housing. Lack of precision could cause damage to moving parts including galling between surfaces of metal components or scratches to critical sealing surfaces. Replacing these parts would prove expensive and increase the overall project costs. In addition, improper alignment could inhibit the accuracy of the data collected and harm the validity of the setup to characterize the sealing barriers being tested.

While installing the plumbing system it was found to be important to add Teflon tape or another type of sealant to NPT threaded components to reduce chance of leakage and to ensure all fittings were sufficiently tightened. Pressure relief valves, including those controlled by a 24V signal were pointed in a safe direction away from the operator. Insulation and heat shielding was added to the surface of the test housing to reduce chance of personal injury and to provide some thermal insulation to the test housing limiting the effects of the environment.

Chapter 4: Design and Implementation of Electrical and Data Acquisition System

With the detailed design of the mechanical system completed, the next step involved determining the final design of the electrical and data acquisition system. This chapter outlines the steps taken throughout designing and implementing the electrical and data acquisition system to adapt the test stand to meet the sponsor's goals and requirements.

4.1 Initial Concept of Electrical and Data Acquisition Adaptation

Following the design approach outlined in Chapter 2, an initial concept (Figure 23) for the wiring and data acquisition system was created to help visualize the system and understand its basic needs.

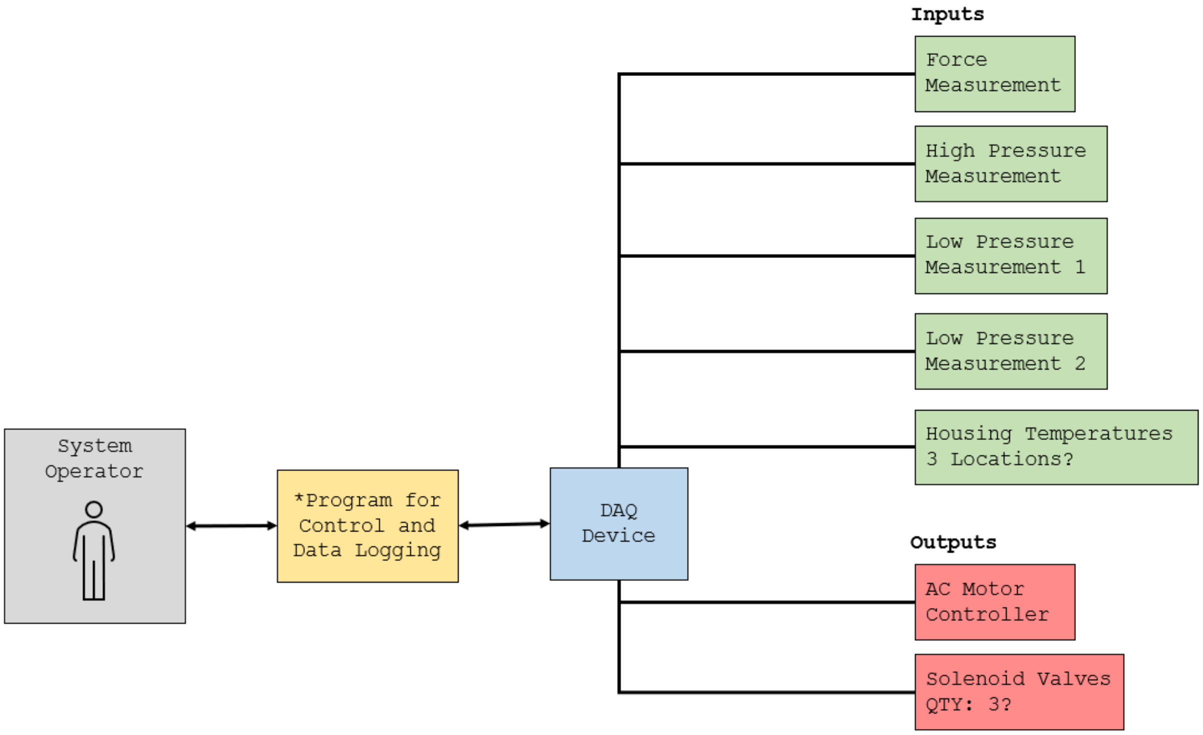

Figure 23: Concept drawing of electrical and data acquisition function

During the concept phase the data requirements were analyzed and the necessary inputs and outputs of the data acquisition system was determined. These parameters included the need for measuring force, pressures, and temperatures. Additionally, the system needed to be able to control outputs to open pressure valves and adjust the motor speed. Power distribution for various sensors and system components will be determined after individual parts are selected during the detailed design phase. With the general I/O determined, parts could be specified to meet the requirements of the system.

4.2 Electrical System Part Selection

The process for selecting the best components to use was critical to ensure accurate data could be collected without overextending project costs. For example, there was a large emphasis on capturing the total volumetric leakage past the seals while they are subjected to a gas medium. With this requirement in mind, a method for capturing this leak had to be determined, the most suitable sensor needed to be identified, and the best way of collecting the data produced from that sensor needed to be enabled. This thought process was used to walk through each data requirement listed, for selecting the best components for the system, allowing it to perform with accuracy and repeatability. Table 1 and 2 provide a list of the main components and software used within the electrical system.

Table 1: Main components selected for use in electrical system of adapted test setup [11]

Instrument	**Manufacturer & Model #**	**Description**	**QTY**
Data Acquisition System 1	NI cDAQ-9174	Compact DAQ Chassis (4 Module)	1
Strain Bridge Module	NI-9237	4 Channel Strain/Bridge Input Module	1
Analog Input Module	NI-9219	4 Channel Universal Analog Input Module	1
Digital Output Module	NI-9472	24V, 8 Channel Digital Output Module	1

Thermocouple Module	NI-9210	4 Channel Mini-TC Temperature Input Module	1
Data Acquisition System 2	NI USB-6341	Multifunction I/O Device, Used for motor control	1
Low Pressure Transducers	Omega PX429-150GV	0 – 150 psig Pressure Transducer (0 – 100 mV)	2
High Pressure Transducer	Omega PX409-5.0KG5V	0 – 5000 psig Pressure Transducer (0 – 5 V)	1
Load Cell	Omega LC213-1K	± 1000 lbF Load Cell (± 2mV/V Sensitivity)	1
Thermocouples	Omega 5TC-TT-K-24	K-type Thermocouple, 32 – 500°F	4
Signal Conditioners	Omega DMD4380	Configured 0 – 10 V output to amplify LP transducer signals	2
DC Relays	Crydom DRA-1 Series	3 – 32 VDC Input 3 – 60 VDC 3A Output	3
24V Solenoid Valves	McMaster Carr P/N: 1190N23	High-pressure compact solenoid valves	3
Heating Elements	Tempco P/N: HDC06225	Cartridge Style, 3/8” x 12” OAL, 120VAC Input	4
PID Controller	Omega CN16DPT-144-EIP	2 channel PID controller for Temperature devices	1
Omega Relay	Omega SSRL240DC25	3-32 VDC Input 24-280 VAC 25A Output	1
24V Power Supply	Altech Corp. PS-12024	120VAC Input 24VDC Output	1
10V Power Supply	Omega PSS-10	115VAC Input 10VDC Output	1

Table 2: Software used for data acquisition and control [11]

Software	Manufacturer	Description of Use
LabVIEW	National Instruments LabVIEW 2020	Data logging and system control
TDM Excel Add-in	National Instruments Excel Add-in	Opens TDMS files directly in Excel
NI MAX	National Instruments Measurements and Automation Explorer	Test raw signal inputs of sensors to check wiring

Further discussion of the major components of this system, including the reasons for their use and specifications are provided in Sections 4.2.1 through 4.2.7.

4.2.1 DAQ and Software Choice

Figure 24: NI cDAQ 4-slot Chassis 9174 [12]

National Instruments cDAQ-9174 chassis (Figure 24) and corresponding modules were chosen for their ease of integration with NI LabVIEW software and ability to be customized to fit the unique experimental setup. The selection of input and output modules that can be bought and utilized by the NI cDAQ chassis system is expansive and allows for the integration of a multitude of sensors and output devices. The NI cDAQ modules selected helped to fulfill data requirements and are interchangeable within the cDAQ chassis system. The cDAQ chassis allows individual channels to be customized to meet sensor I/O requirements including various sensor input ranges, such as 0-5 V or 4-20 mA. With this chassis system, inputs could be monitored, and outputs could be controlled via LabVIEW to help add safety through automation of the electrical system. Future expansion for this setup will be limited since the chassis purchased is only a four-slot compared to one of their larger models. Overall cost drove this selection, but in the future can be easily swapped and integrated into the existing LabVIEW code if more I/O. The NI cDAQ module selection was driven based on expected sensor inputs and outputs. The selection of using the NI cDAQ chassis system and LabVIEW software provided a basis for the test stand to meet all data requirements.

In addition to the new cDAQ device, the previous USB-series DAQ device, NI USB-6341, was utilized. Additional outputs were needed to help with controlling the motor and to save on overall project costs. The damaged unit from the previous setup iteration was found to be useful as the damage was isolated to the analog input region of the device, thus allowing the output channels of the device to still be utilized. This worked perfectly for retaining the motor controller wiring which saved the costs of purchasing a larger cDAQ chassis and additional module for analog output capabilities.

4.2.2 Low Pressure Leakage Measurement

To track the total leakage past each seal, a method for capturing this was required. Since a gas medium is being used, the initial concept of using pressure transducers was further developed since it was determined to be the best method. After a test is completed, an analysis using the known volume of each low-pressure region and the increase of pressure over time, could be performed to predict the total volume of gas past each MSE barrier being tested. In this case, the critical component is the low-pressure transducer. The transducer needed to be sensitive enough to pick up on small pressure changes with low signal noise to accurately track the total leakage to characterize the sealing barriers performance. Omega PX429-150GV pressure transducers (Figure 25) were selected as these can measure gauge pressure with an overall range of 0 to 150 psig with an accuracy of ±0.8% and provide a 10mV/V output [13]. These have a relatively small pressure range thus being more sensitive to small pressure changes when compared to a transducer utilizing a larger range such as 0 to 5,000 psig. This allows it to pick up on subtle changes in pressure, while still having a large enough range to allow for a measurable amount of volume to build up within the low-pressure region. To reduce noise and amplify the mV/V output signal, Omega DC to DC signal conditioners were added in line between each transducer and the NI analog input module (Figure 26). This helps amplify the output signal of the transducers to 0-10V to be accepted by the DAQ device. This combination of transducer and signal conditioner will provide the system the ability to meet *DR1: Measure leakage past sealing surface of two individual barriers simultaneously*.

Figure 25: Omega PX429 Series Pressure Transducer [13]

Figure 26: Omega DC to DC Signal Conditioner [14]

4.2.3 High Pressure Supply Measurement

For the system to reliably record the supply pressure from the Nitrogen cylinder, a pressure transducer was selected. The safety factor was the driving force for selecting the pressure range of the transducer. Here, a 0 to 5,000 psig pressure transducer was selected. Namely, an Omega PX409-5.0KG5V which has an output range of 0-5V. This sensor is highly accurate with the same accuracy expectancy as the low-pressure transducers [13]. The larger pressure range was selected based on its safety factor of 4.2 when comparing to the experimental pressure of 1,200 psig and safety factor of and 1.7 when comparing to the typical charged nitrogen cylinder received for the experiments of less than or equal to 3,000 psig. Using this transducer, the high-pressure supply could be monitored throughout the experiment to ensure there were no leaks within the system and that a constant pressure was being applied throughout the reciprocating range of the test housing.

4.2.4 Force Measurement

Another critical data point for characterizing these barriers included the amount of compressive and tensile force required to translate the MSE seals through the smooth bore of the housing. The previous system had a load cell capable of tracking this measurement, so it was repurposed to save on costs. The inline load cell is an Omega LC213-1k, which has a load range of ±1,000 lbF (Figure 27) [15]. The load cell mounts at the end of the piston assembly between it and the cam arm. Once attached, it can be zeroed and used to ensure proper alignment within the system, overall cycle rate of the seals, and measure the required forces. With this load cell the setup will meet requirement *DR2: Measure frictional force required to move seals linearly*.

Figure 27: Omega 2" Miniature Inline Load Cell [15]

4.2.5 Temperature Measurement

To ensure the system achieves requirements *MR4: Ability to control housing temperature* and *DR3: Monitor temperature at various points of the test housing*, a method for monitoring housing temperatures was needed. K-type thermocouples were utilized because of their relatively robust nature and ease of integration into the NI cDAQ chassis. K-type thermocouples have a compatible temperature range for the experiments with a process temperature range of 32 to 500°F for the prebuilt ones selected [16]. The temperature is limited because off the PFA wire insulation used during their construction [16]. With the expected experiment temperature ranges being room temperature, 75°F, and 300°F, these sensors were a suitable choice. A total of four K-type thermocouples were utilized to monitor test housing temperatures at different points. These include the temperature of each individual low-pressure region as well as the exterior of the housing. Two thermocouples were used on the exterior of the housing, one for data logging and the other provided control for the PID controller running the heating cartridges.

4.2.6 Heating Elements and Control

The test housing was designed with the intent of using four heating elements inserted equally spaced within the test housing. This provides sufficient heat to maintain the seals at an elevated temperature throughout the experiment. Heating rods or cartridge heaters were chosen to accomplish this and were provided by the sponsor with the test housing. To complete the system, a method of control was needed. A PID controller, specifically an OMEGA Platinum Series, was selected to control when power is supplied to the heating elements. A 25-amp solid-state relay was incorporated to allow for the DC output of the PID controller to control the AC supply needed by the heating rods. This controller was expected to provide stable control of the test housing temperature with a temperature stability of 0.05°C/°C [17]. With the parts selected the setup will meet requirement *MR4: Ability to control housing temperature*.

4.2.7 Automated Pressure Relief

To ensure critical electrical components were not damaged and the safety of the operator while around the system, automated pressure relief valves were needed at different points of the plumbing system. Incorporating these valves will meet *DR7: Have automated solenoids for pressure relief to reduce damage to sensors and reduce over pressure of test housing and plumbing*. The NI cDAQ and corresponding module made this easy to integrate by allowing for digital outputs to be controlled via the LabVIEW program and real time data. The pressure relief valves selected were normally closed 24V solenoid valves (Figure 28), meaning they would open or relieve the pressure when excited with 24 volts. They are rated for 3,000 psig [18]. Because the digital output module selected for the cDAQ chassis would only output a maximum voltage of 5 volts, Crydom solid-state relays were integrated to provide direct power from a 24-volt power supply to each solenoid. The cDAQ digital output module triggers the relay based on real-time data or operator control thus opening the solenoid valve. Wiring the solenoid valves in this manner reduces the chance of running excess current through the cDAQ chassis limiting damage to the equipment. Utilizing real-time data for controlling the solenoids adds automation to be integrated into the system by allowing it to open individual values automatically based on individual sensor readings. For example, during a critical seal failure, where full high-pressure supply passes into the low-pressure region, which will damage the low-pressure transducer, the low-pressure relief valve would be triggered relieving the pressure before damage to the transducer can occur. These valves were designed to be mounted pointed away from the operator while routing the plumbing system to reduce risk of the operator when releasing pressure.

Figure 28: 24V Normally Closed Solenoid Valve [18]

4.3 Power Distribution and Wiring

After component selection the wiring process can begin. Considerations for proper wire gauge based on expected amperages was considered along with proper crimping techniques and isolation of individual connections to reduce chance of electrical shorts. To ensure the proper operation of these components, their input parameters must be known, and correct supply voltages given. A power distribution diagram was created to show the necessary inputs and outputs expected based on the sensors and components chosen for implementation. Figure 29 provides the flow of power from three individual power sources to major components. These sources include 120V AC, 24V DC, and 10V DC.

A single 120V AC source provides power to the NI cDAQ chassis system and signal conditioners, along with the 24V DC and 10V DC power supplies, while a separate 120V AC source provides power to the heating elements and drivetrain. This reduces the amperage draw seen by each individual circuit and separates the “high-power” components from the data acquisitions system. This reduces the potential for excess electrical noise to be detected by input channels due to the effects of high current flow. It is important to note that the previous AC motor and controller wiring was left untouched.

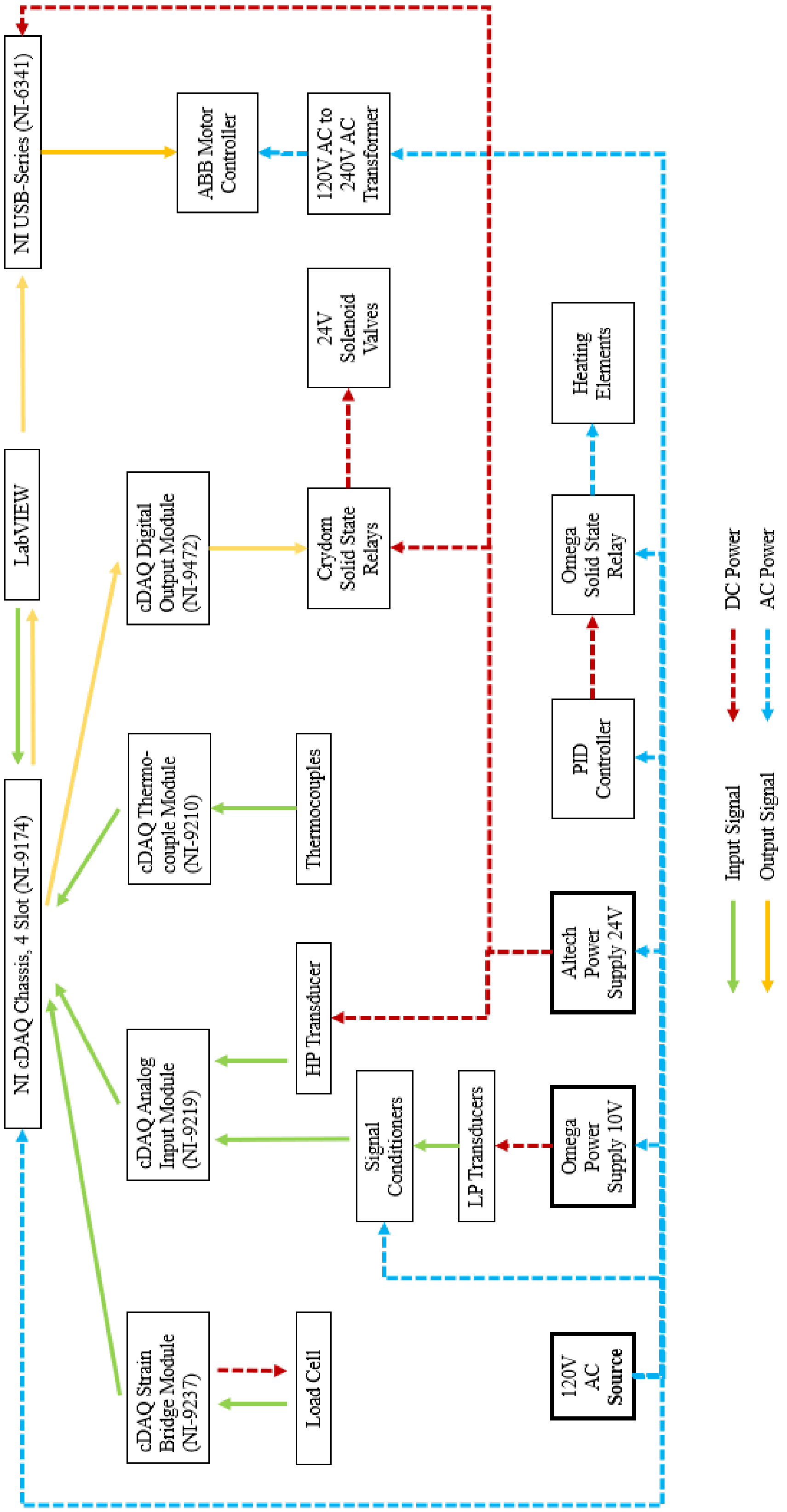

Figure 29: Diagram of basic power distribution and I/O of electrical system

For power to individual sensors and relays, both a 24V DC and 10V DC power supply was integrated. The 24V DC power supply provided the correct supply voltage to the high-pressure transducer and the proper load power for each Crydom solid state relay. For triggering these relays, a 5V output from the NI cDAQ Digital Output module would be used, allowing the 24V DC source to open each normally closed solenoid valve. Additionally, 24V DC power was required to supply the previous iteration DAQ device to allow for an analog output source to be sent to the motor controller. Further, both low-pressure transducers were required to have a supply voltage of 10V which was provided by the 10V DC power supply.

Lastly, the load cell and thermocouples did not need external excitation for proper function. The load cell utilized the internal excitation function of the NI cDAQ Strain Bridge Module, which can be specified through LabVIEW. This value was set to 10V to obtain accurate force values as specified by the manufacturer. For temperature measurement, the K-type thermocouples do not need power supplied and can be directly plugged into the NI cDAQ Thermocouple Module.

To conclude the wiring process, all inputs and outputs were wired into their appropriate module and their placements were noted to aid in initializing the channels within LabVIEW. Figure 30 provides a glimpse into the wiring process to showcase some of the wiring completed and components used.

Figure 30: Bench wiring of power supplies, signal conditioners, and sensor leads

4.4 Data Acquisition System Using LabVIEW

NI LabVIEW programs are separated into two sections, the first being the Virtual Instrument or VI. This area of the software encompasses the code driving the data collection, controlling outputs, and logging data to a local save file. The second is the User Interface or UI which is the front screen that the operator will interact with to turn outputs on and off and view graphs showing live system data. This section will discuss the program that was written with NI LabVIEW to control and log data from the experimental test setup.

4.4.1 Virtual Instrument

Since the setup has seen many mechanical and electrical adaptations, a new program was needed to monitor additional sensors, help control motor speed, and to be able to easily add more future customization as needed. The basic structure of the program uses sequence frames to ensure components turn on and off in an appropriate manner under startup and shutdown of the experimental setup. In addition to this sequence, the code utilizes individual "while" loops to log data to a .TDMS file for future analysis, update the front panel with live data, and automate or control the AC motor and 24V solenoid valves [10]. Within the code, safety parameters can be set for pressure, temperature, and force to enforce the automated shut down of the experimental setup. If any of the maximum values set are sensed, the shutdown process proceeds to shut off the Nitrogen gas supply, open 24V solenoid valves to relieve pressure, turn off the heating elements to prevent heating the test housing to a harmful temperature, and shut down the motor to halt the reciprocating motion [10]. This feature ensures safety of both the mechanical and electrical components as well as the operator running the equipment if excessive pressures, temperatures, or forces are sensed indicating a mechanical or electrical failure with the test setup.

For data logging and future analysis, all necessary data is recorded at the specified start and stop time set by the operator to limit the file size for each experiment. In addition to this the name can be specified to help with file organization while running multiple experiments in one sitting. All data is written to high speed .TDMS files and later converted to Excel using an importer for data analysis. Within Excel further calculations can be performed and graphs can be created showcasing the data for each experiment to help with seal characterization.

The use of LabVIEW, the NI cDAQ chassis system, and the method for structing the code written allows for future upgradability if more sensors or additional data points are needed after further experimentation. Someone familiar with writing LabVIEW VIs should be able to easily initialize new DAQ channels and record the required data by easily following along with the flow of data as laid out within the program. Additionally, the code is commented to help both current and future project team members to understand what each section is trying to accomplish if an issue arises.

4.4.2 User Interface

The user interface was designed with simplicity and ease of use in mind. This ideology limits the amount of information filling the screen to keep the attention of the operator on the important information pertaining to the experiment at hand. Figure 31 shows the main user interface screen developed to control and monitor the experimental setup.

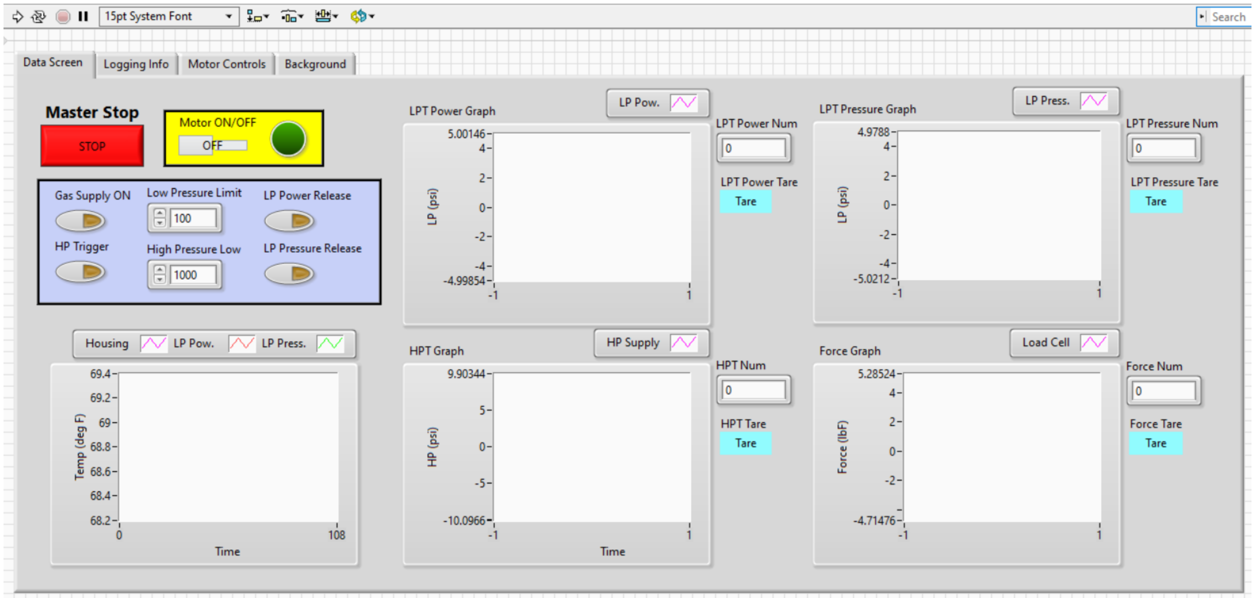

Figure 31: LabVIEW program user interface for adapted setup [10]

The user interface consists of 4 sperate tabs or pages. The first shows only necessary controls, limiters, and data to allow the operator to monitor the experiment and ensure the barriers and system are running smoothly. If an unusual force or pressure is witnessed within the live graphs, such as unequal force in compression and tension, the system can be shut down and checked before continuing the test. The second tab allows the operator to set the file location and logging information. The third tab allows the user to set the motor speed and direction if its current state needs to be modified for a future experiment. The motor parameters are usually kept constant, so they were removed from the main tab. Lastly, the final tab shows background information pertaining to the speed and sample rate of data collection within the program.

4.5 Assembly of the Electrical and Data Acquisition System

During assembly and integration of this system, the wiring was completed and checked using NI MAX, the proper I/O for the NI cDAQ chassis within the LabVIEW program was initialized, and correct sensor placements were located within the plumbing and test housing. Using NI Max during the wiring process proved useful for checking sensor outputs. This software allows the user to tap into the cDAQ firmware to check raw input readings or test outputs of each module installed. After connecting the sensors and other components to their designated terminal of each DAQ, a reading can be taken and checked for correct function utilizing this software. This step was completed to isolate and verify the wiring of individual sensors and solenoid valves by removing the LabVIEW code from the picture. After confirming proper function of sensors and outputs, the LabVIEW code was opened, and correct sensor calibrations were added. The program was allowed to run, and each input was confirmed visually for function within the live data screen. Motor control and solenoid valve operation was checked and confirmed at this stage. Further, pressure measurements of the various transducers were verified with an analog gauge to ensure an accurate reading was being recorded.

Lastly, a multitude of initial tests were conducted to help troubleshoot any issues witnessed while running the system. These tests were helpful for finding system leaks, misalignment between moving components, and problems with data logging through the LabVIEW program. After the program was operating smoothly, the correct motor speed was found. Adjusting the analog input voltage to the ABB drive while monitoring pressure and force data confirmed the time required to complete one full cycle of the piston. In addition, the stroke length was confirmed by physical measurements of the piston at different positions within the test housing. With this, both the mechanical and electrical systems were brought together, meaning the adaptation to the setup was completed and validation of system requirements can begin.

Chapter 5: Testing and Validation Against System Requirements

This chapter will discuss the established procedure for testing to ensure consistency between data sets and seal types. Using the procedure, initial tests were conducted to validate the experimental test setup showing its ability to meet individual requirements.

5.1 General Test Procedure

With the adaptation to the test setup designed, assembled, and working as intended; MSE tests could begin to ensure the setup is capable of meeting each system requirement discussed in Chapter 2. A test procedure was developed to allow for consistency between tests so that each seals performance can be compared between each other. This will likely be adapted as tests continue in the future and more information is gained on how tests can be improved but will work for validation of the system at its current state. Each test was broken down into three parts: Back Pressure Testing, Dynamic Testing, and Static Testing.

5.1.1 Part 1: Back Pressure Testing

For part one of the test procedure, the back pressure test is enacted to accomplish two things, to ensure the test housing’s low- and high-pressure regions are sealed before the dynamic tests are set to begin, and secondly to determine the minimum and maximum volumes of each low-pressure region. Determining the volumes is a critical step for calculating an accurate volumetric leakage measurement apart from just a pressure buildup in these regions. The steps outlined below are followed in order to complete an initial back pressure test.

1. Assemble piston with MSE seals into test housing and zero sensors as needed
2. Begin with Piston in Neutral Position (*Both low-pressure regions at similar volumes*)
3. Set Temperature of Housing (*Allow at least 1 hour to let housing temperatures stabilize if heating*)

4. Apply approximately 200 psi of Nitrogen gas to HP supply
5. Apply approximately 25 psi of Nitrogen gas to both LP chambers
6. Let housing temperatures stabilize after charging
7. Hold for 15 minutes with Piston in neutral position (*If pressures are stable, move to next step)*
8. Rotate Piston to far-left position
9. Hold for 15 minutes
10. Rotate Piston to far-right position
11. Hold for 15 minutes
12. Center Piston back in neutral position
13. Hold for 15 minutes

During this procedure set, the high-pressure piston is rotated throughout the housing to the neutral, far-left, and far-right positions. These positions are demonstrated in Figures 32 through 34. Rotating the piston from the far-left to the far-right position will change the volume of each low-pressure region from their minimum to maximum values or vis versa. Each piston position is found by using a digital level on the machined cam-arm to locate its position at 0 or 90 degrees. This correlates to cam-arm being at the 12, 9, or 3 o'clock position.

Figure 32: Piston in Neutral Position

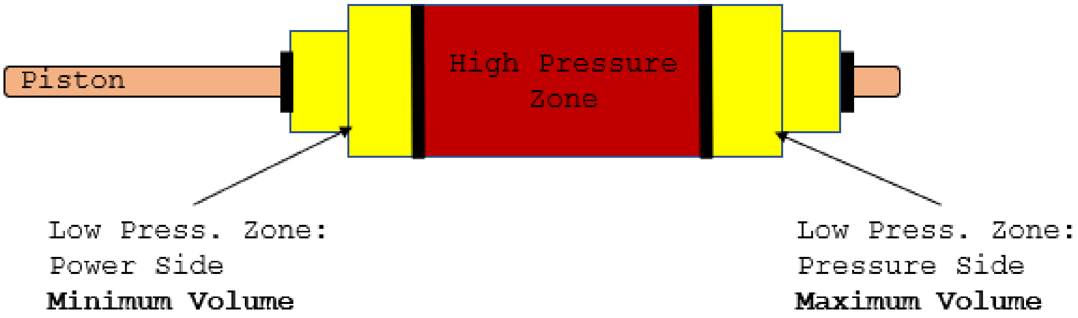

Figure 33: Piston in Far-Left Position

Figure 34: Piston in Far-Right Position

Positioning the arm in either the far-left or far-right position will ensure the minimum and maximum vales are found accurately and consistently at the start of each test. The initial and final hold at the neutral position is established to check for leaks within the test housing O-rings or damage to the MSE seals before moving forward with a dynamic test. Cycling the piston to the far-left and far-right position will corollate to a pressure change of the original 25 psi of Nitrogen gas applied to both the Power Side and Pressure Side low-pressure regions. By tracking how the pressure changes at these specified piston positions, the volume at these points can be calculated using the inverse relationship between pressure and volume (Equation 1).

$$P_{min}V_{max} = P_{max}V_{min} \tag{1}$$

Thus, the resulting pressure change can be used to calculate the minimum and maximum volumes of both the Power Side and Pressure Side low-pressure regions. These values are then noted and used to calculate the total volumetric leakage of gas past each individual sealing barrier using the ideal gas law (Equation 2).

$$PV = nRT \tag{2}$$

Estimating the total volumetric leakage is critical for evaluating seal performance and can be the main factor to disqualify a seal design after testing.

5.1.2 Methodology for Volumetric Leakage Conversion

Below is a sample calculation for how the raw pressure data collected during a back pressure test was converted to a total volumetric leakage. First the average pressures over time were calculated at the minimum and maximum volume positions of each low-pressure region. For this example, the Pressure Side sealing barrier and low-pressure region were being analyzed for total volumetric leakage. Figure 35 shows the raw pressure data collected over time during an initial back pressure test. Test parameters included ambient temperature and the 3-inch cam arm installed allowing for 6 inches of total piston travel. Pressures were applied in accordance with the procedure.

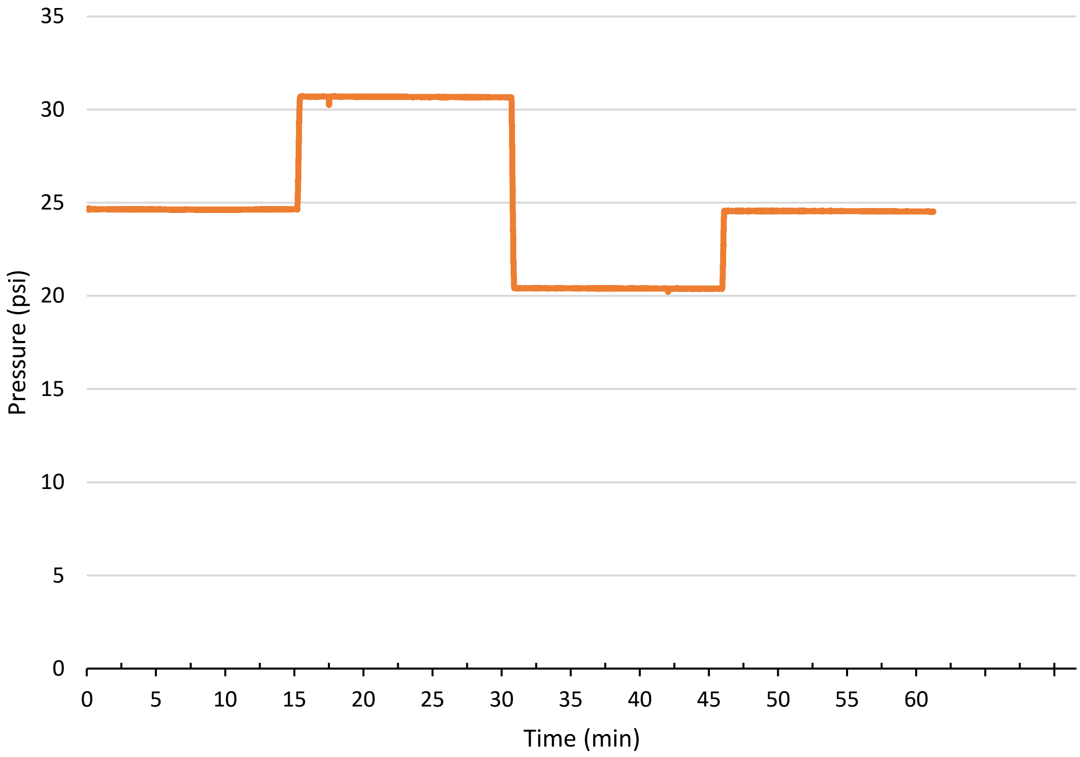

Figure 35: Pressure Side low-pressure vs time during Back Pressure Testing

Starting with the raw data, average values for pressure were taken for each 15-minute interval corresponding to the maximum and minimum positions. With these pressure values, the minimum or maximum volume is needed in order to determine the other. Each low-pressure region is cylindrical in shape with a 0.625-inch bore. The volume of a cylinder (Equation 3) can be used,

$$V_{cyl} = \pi r^2 h \tag{3}$$

where r is the radius and h is the height of the cylinder respectively. For the minimum volume case, Equation 3 was modified as such.

$$V_{min} = \pi r^2 h + line\ volume \tag{4}$$

Here, r is the bore radius of the test housing and h is the height of the low-pressure region. The line volume between the test housing, pressure transducer, and relief valve is unknown. For the maximum case, Equation 4 was modified and can be seen below.

$$V_{max} = \pi r^2(h + 6) + line\ volume \tag{5}$$

For this case, the total 6-inch reciprocation length was considered a part of the cylinders height representing the low-pressure region. Using Equations 4 and 5 the following relationship between V_{max} and V_{min} can be found.

$$V_{max} = V_{min} + 6\pi r^2 \tag{6}$$

Substituting Equation 6 into Equation 1 will yield a relationship for V_{min} in terms of r and the average pressure values, P_{min} and P_{max}, measured.

$$V_{min} = \frac{6\pi r^2}{\frac{P_{max}}{P_{min}} - 1} \tag{7}$$

Table 3 shows the calculated values for Power Side and Pressure side volumes at their minimum and maximum positions using the equations derived.

Table 3: Average pressure and volume calculation example values

Piston Position	***Power Side***		***Pressure Side***	
	Pressure (psi)	***Volume (in^3)***	***Pressure (psi)***	***Volume (in^3)***
Neutral Position	26.014	-	24.633	-
Far Right	21.320	3.879 (Min)	30.669	5.493 (Max)
Far Left	31.439	5.719 (Max)	20.391	3.652 (Min)
Neutral Position	26.010	-	24.536	-

The average volume can be calculated by averaging the minimum and maximum values. This process can be repeated for the Power Side low pressure region. The volumes can then be used later to help determine the total volumetric leakage over the longevity of the test. It is important for this procedure and volume calculation to be performed prior to each test after new seals have been installed in the housing to account for discrepancies in seal geometry.

5.1.3 Part 2: Dynamic and Static Testing

Part two of the test procedure is Dynamic and Static Testing. During this step the MSE seals are observed under a constant cycle rate, pressure, and temperature to a desired number of cycles, stopping periodically to measure static leak rate. If a failure occurs the test would need to be stopped and the system diagnosed. During Dynamic Testing the following steps are followed with test parameters of 1,200 psig for high pressure supply, 6 inches of reciprocating length, a cycle rate of 2 cycles per minute, and a goal of 1000 total cycles. This test should be conducted immediately following the Back Pressure Test.

1. Ensure housing temperatures are stable from Back Pressure Testing
2. Increase High Pressure Supply to 1,200 psig and let temperatures stabilize
3. Turn motor on at 2 cycles/min
4. Let run for 100 minutes
5. Stop after ~200 cycles

Using the cycle rate of 2 cycles per minute, the setup was allowed to run for 100 minutes, roughly 200 total cycles, or until a critical seal failure is noticed. During cycling, the frictional force and low-pressure buildup are monitored to characterize seal performance during constant reciprocation. After 200 cycles has been completed, the motor is turned off and a static test would be completed following the steps below.

6. After 200 cycles, move piston to neutral position, still holding supply pressure (1,200 psi)
7. Hold for 15 minutes

8. Move piston to far-left position
9. Hold for 15 minutes
10. Move piston to far-right position
11. Hold for 15 minutes
12. Center piston again in neutral position
13. Hold for 15 minutes

This process is the same as that of the initial back pressure test. During this procedure the sealing barriers are checked for excessive leak throughout their entire cycle range under static conditions after wear of the seal has likely occurred due to reciprocation. This is valuable information to know for equipment which may not be used continuously in industry. This allows for subsequent leak rates to be measured and the effects that start up and shut down have on the barriers themselves. This two-part procedure is repeated until the total number of cycles has been reached.

5.2 Validation of Electro-mechanical System to Meet System Requirements.

The system implemented to test the MSE seals can be further validated by looking at and analyzing the data logged through the Data Acquisition System and LabVIEW program. To do this, initial tests were conducted following the procedure outlined in the previous section. A single data set from these tests was selected and will be discussed in this section. The experiment consisted of testing two individual MSE sealing barriers at both room temperature and 300°F for a total of 1,000 cycles at each temperature. The .TDMS file exported by LabVIEW was then imported into Excel using TDM add-in which efficiently delimited the data stream into individual channels for further analysis. The following sections showcase figures providing actual data monitored by the system throughout the test. Each figure will be presented as a function of time or cycle depending on the results shown. The total number of cycles was determined based on experiment run time and cycle rate of the AC motor. MATLAB programs were later developed by fellow research team member, Milad Najafbeygi, to validate the total number of cycles the seals experienced per dynamic test and create force plots to help with overall analysis time. However, for the purposes of validating the system's overall function, the Excel plots generated will prove adequate. This available data proves satisfactory for validating Requirements *DR4: Log all system data including, pressure, temperature, and force* and *DR6: Design and write a LabVIEW code to aid in data collection*. Sections 5.2.1 through 5.2.5 will discuss these figures proving the proper function of the adapted setup to meet major data system requirements, such as sustaining high pressure supply or monitoring reciprocating forces.

5.2.1 High Pressure Supply

To show the system is capable of meeting *MR3: Ability to apply 1,200 psig of Nitrogen gas to high-pressure chamber of housing*, the following raw data was captured and presented in Figure 36.

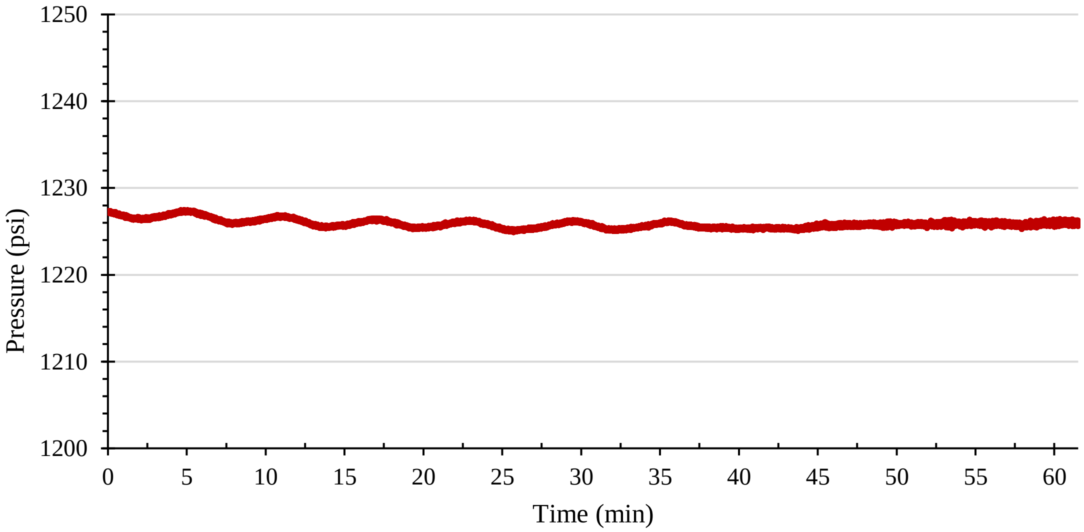

Figure 36: Raw Data – High Pressure Supply

As shown in this example, the high pressure was able to stabilize at 1,226 psig within 40 minutes of initial charging. Once stabilized, the system was able to hold a steady pressure without sporadic readings from the high-pressure transducer, regardless of static or dynamic conditions.

5.2.2 Low Pressure Buildup

To meet data requirement *DR1: Measure leakage past sealing surface of two individual barriers simultaneously*, Figures 37 and 38 were generated to show two individual signals captured by the Power Side and Pressure Side low-pressure transducers during the room temperature test.

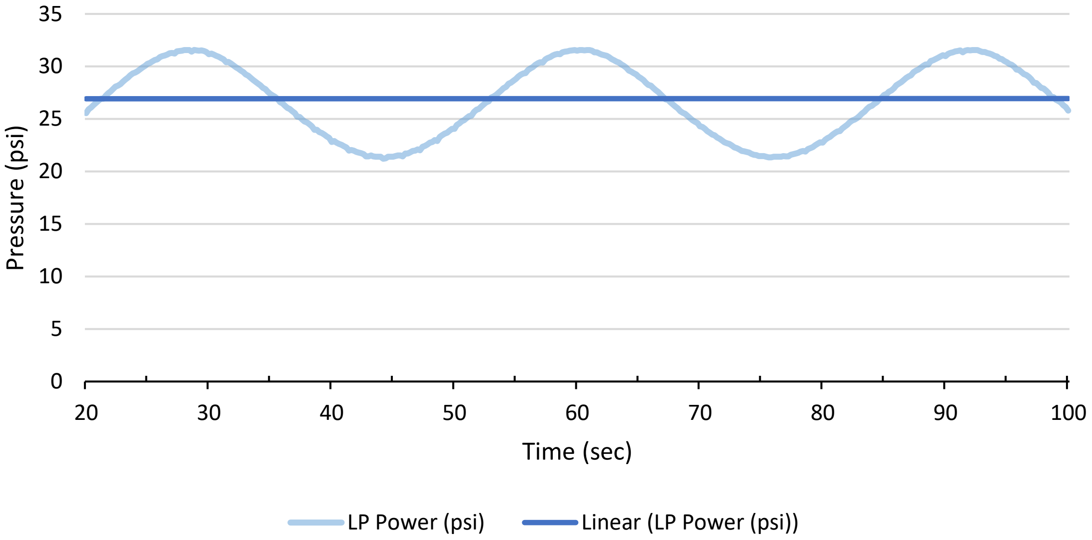

Figure 37: Raw Data – Low Pressure Buildup – Power Side

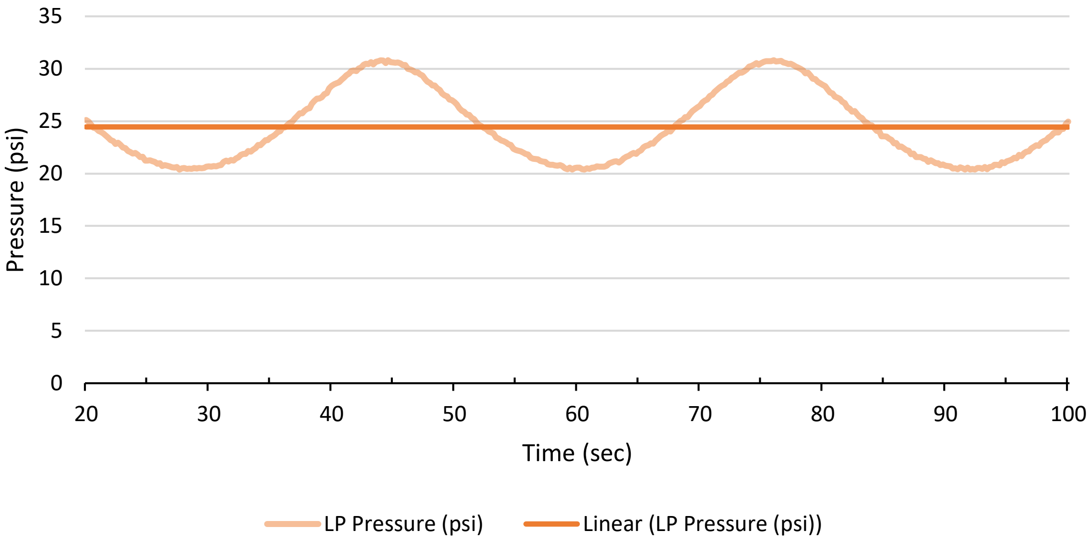

Figure 38:Raw Data – Low Pressure Build up – Pressure Side

In each low-pressure graph 80 seconds was examined to show how the pressure within these regions changed over time. A sinusoidal waveform was generated during each piston cycle as the volumes within each low-pressure region change.

To prove the setups ability to track individual volumetric leakages over the course of a dynamic or static test, the method discussed earlier in this chapter was implemented. To track total volumetric leakage within these areas, the change in pressure over time at the minimum, maximum, and average volume positions must be monitored. After plotting each 200-cycle portion of pressure data, a linear trendline can be taken to represent the pressure buildup at the average volume position. The volumetric leakage was then calculated based on the function for change in pressure over time, the average room temperature, and the average volume for each respected low-temperature region. Figures 39 and 40 represent the total volumetric leakage calculated for the average volume position throughout the duration of the 1000 cycle test under ambient conditions.

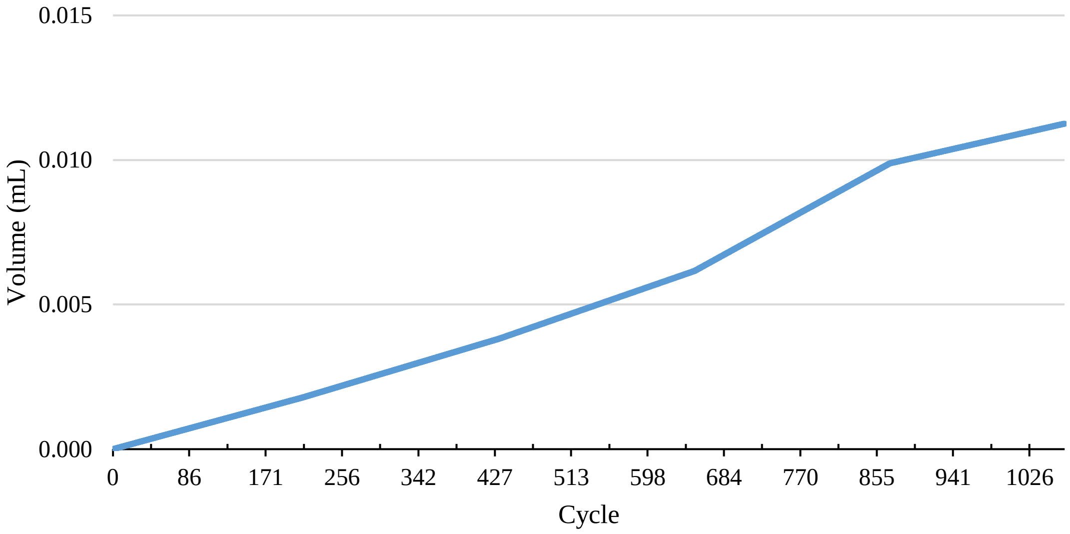

Figure 39: Power Side Accumulated Leakage vs Cycle at Room Temperature

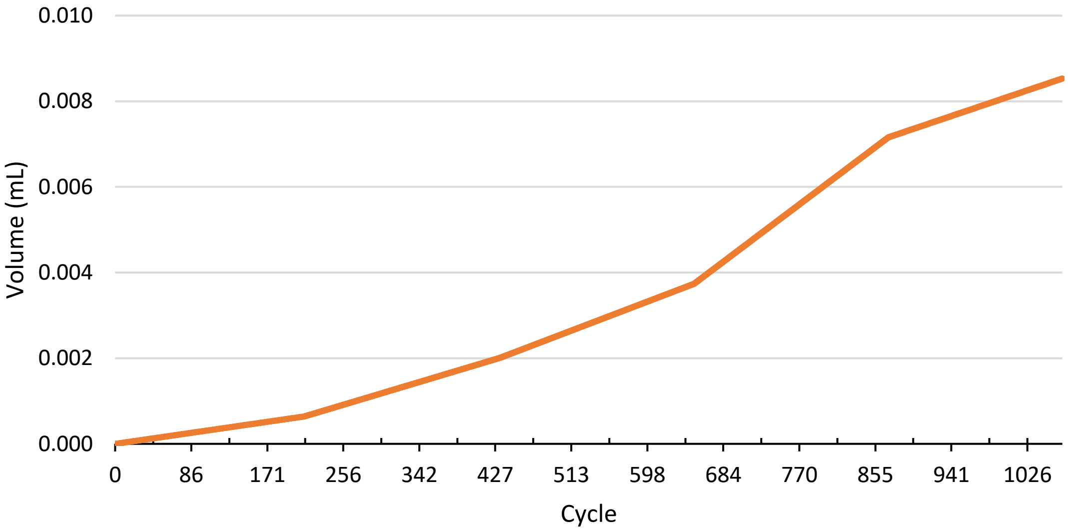

Figure 40: Pressure Side Accumulated Leakage vs Cycle at Room Temperature

The volumetric leakage data can be further analyzed to account for fluctuations in housing temperatures. By relating the change in temperature to the change in pressure at each data point back to the original value, the corresponding volumetric leakage change can be removed due to temperature fluctuation. This yields the actual volumetric leakage past each seal without outside influence from the environment.

5.2.3 Temperature Measurements and Control

The housing temperature is monitored at three separate locations on the outside surface of the test housing. The first of which is located at the center of the test housing to monitor overall housing temperature during heating. The other two are located on each low-pressure region to represent the interior temperatures of these regions. These positions can be seen in Figure 41 and are represented by the yellow dots.

Figure 41: Thermocouple Locations on Test Housing

These thermocouples are taped to the outside surface of the test housing rather than having machined thermocouple ports. This is a detriment to accuracy when tracking low-pressure region temperatures and should be noted during analysis. For the scope of this thesis, this does not disprove the setups ability to measure necessary temperature values as these parts were provided by the sponsor and can be modified at a future date. To account for this, large dwell times during heating were necessary to ensure an even heating of the test housing. In addition to this, insulation was wrapped around the test housing and low-pressure lines to help with more consistent temperature readings. To show the setup is capable of meeting system requirements *MR4: Ability to control housing temperature* and *DR3: Monitor temperature at various points of the test housing*, Figures 42 and 43 were generated from the ambient and elevated temperature tests conducted.

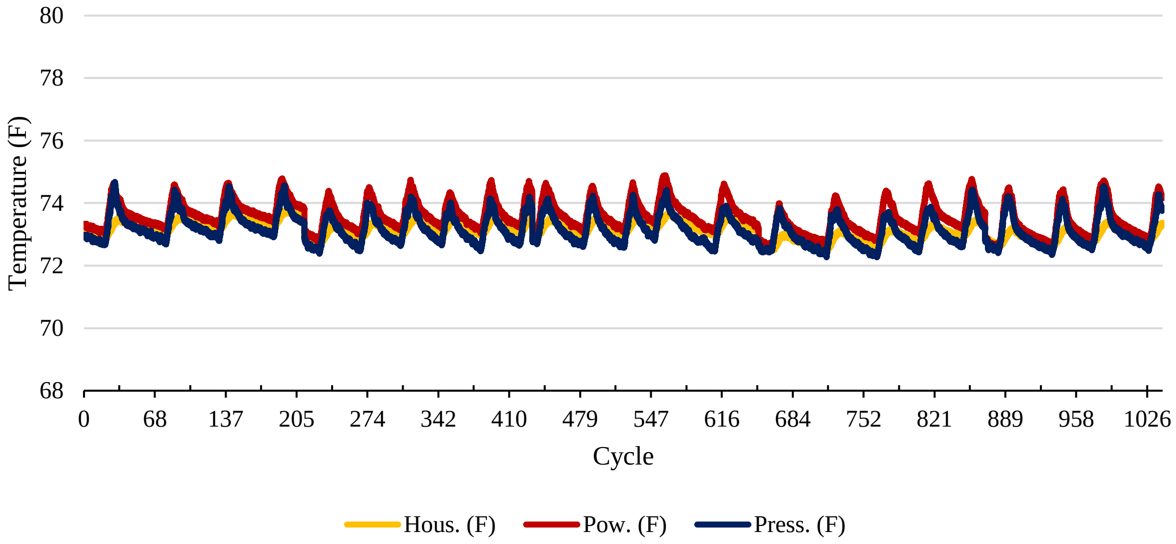

Figure 42: Raw Data – Housing Temperatures

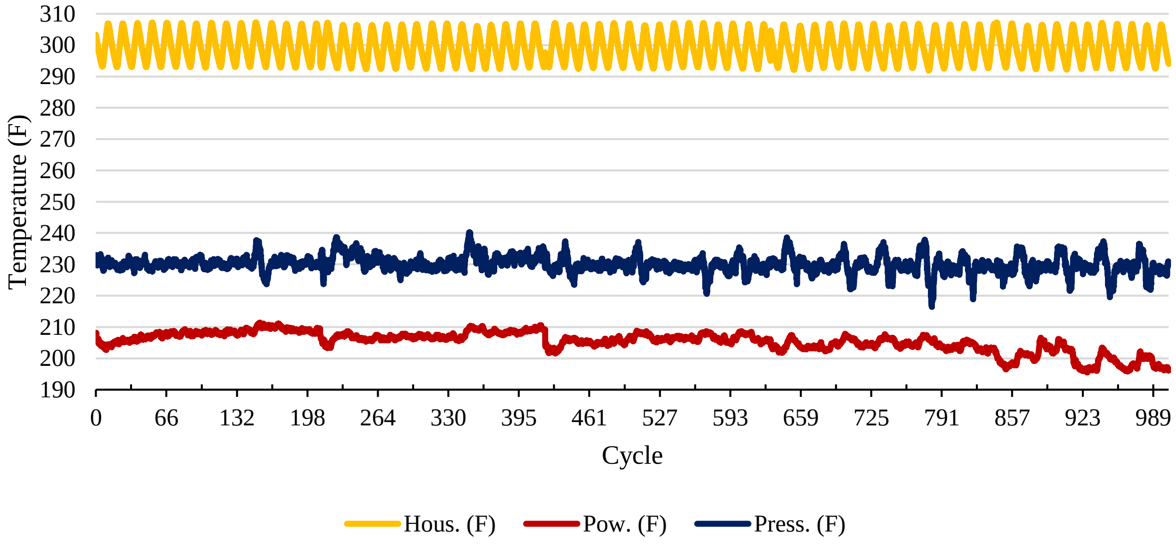

Figure 43: Combined Temperature Graph vs Cycle at Elevated Temperature

Both figures represent the housing temperatures during the entirety of the 1000 cycles of their respected test. As shown in the figures, the temperatures can be accurately monitored and do not fluctuate more than ± 2°F at all housing locations during the ambient temperature test. The temperatures have a larger variation at elevated temperature due to the nature of the PID controller and location of the heating elements within the test housing. The variation at elevated temperature is less than ± 5°F at all locations which was deemed acceptable by the sponsor for consistent housing temperatures.

5.2.4 Force Measurement

For both compressive and tensile force measurements, a plot was created from the ambient experiment to show one complete cycle after the system had run for at least 150 cycles. Figure 44 shows the force measurements taken from the load cell mounted to the piston.

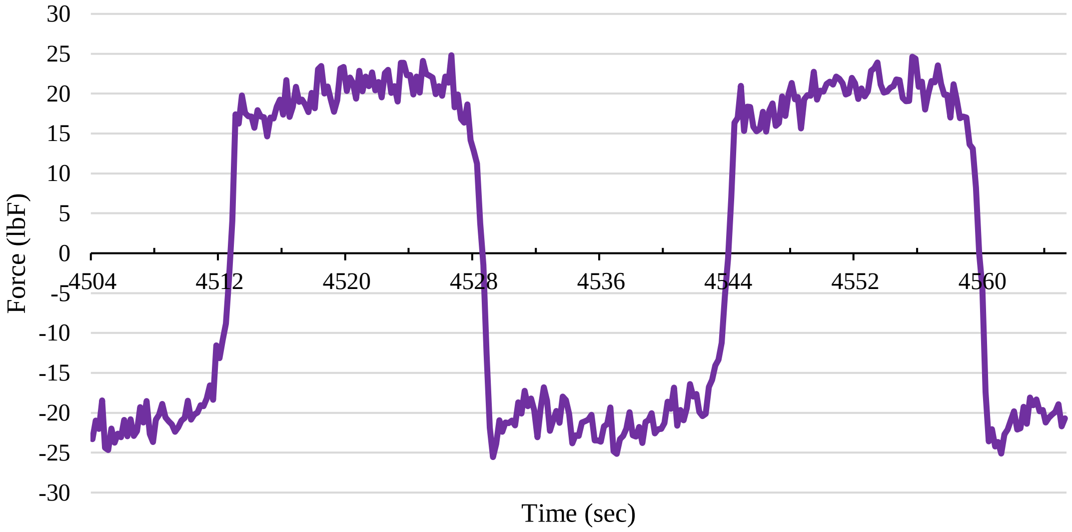

Figure 44: Raw Data – Compressive and Tensile Force After 150 Cycles

This plot shows the overall force acting on the system and confirms it to meet system requirement *DR2: Measure frictional force required to move seals linearly*.

Additional tests were conducted on the housing without the MSE seals installed. This provided insights into the forces acting on the piston which were not provided by the MSE seals. These forces include added friction from housing O-rings which retain low-pressure buildup and the resistance of the linear guide rails though minimal. With roughly 25 psig of pressure applied throughout the system and 500 cycles completed, average forces of 5.94 lbF and 7.55 lbF were witnessed at ambient and elevated temperatures respectively.

5.2.5 Motor Parameters

While looking at the prior force data, the motor speed can be estimated. Looking at Figure 44, the start time for the cycle is 4,512 seconds or as the piston changes from being in compression to tension. The end time for the cycle can be seen at 4,544 seconds. Subtracting these numbers yields 32 seconds which when converted equals 1.9 cycles per minute. This cycle rate was satisfactory to meet requirement *MR2: Linearly translate Metal Energized Seals a known stroke length and speed*.

Chapter 6: Conclusions, Limitations, and Recommendations

6.1 Thesis Summary

In conclusion, this thesis showed the process of adapting an electromechanical setup in order to characterize metal spring energized seals in a low-pressure environment. Sponsor specifications and the expected environment of these seals were the driving factors for selecting system requirements for which it needed to meet. Cycle rate, pressure, temperature, frictional force, and volumetric leakage were important parameters which were needed to properly characterize the performance of the reciprocating seals tested.

Beginning with the design process, a five-step design approach was developed. The initial step was understanding the existing system and determining the new expectations of the project. This included the desired function of the adapted test setup and determining different system requirements for which it needed to meet. Secondly, the concept phase involved generating rough designs and ideas for how the mechanical and electrical and data acquisition systems should function and look. Next, the detailed design was completed, and the best components and sensors were chosen to be able to fulfill each requirement. Finally, both systems were assembled, and initial testing was completed helping to validate the test stands ability to characterize MSE seals at low pressures. The data included provides proof of the adapted systems ability to meet the new requirements set forth by the sponsor.

A new plumbing system was needed to convert the last iteration of the setup from a hydraulic fluid to Nitrogen gas. This tested the seals under the worst-case scenario, a medium with small molecules and a lack of lubrication, which will inherently leak more than one tested with a larger molecule gas or hydraulic fluid. Solenoid pressure relief valves were utilized to reduce the risk of those working around the equipment. With the integration of a new plumbing system the existing electrical and data acquisition systems were inoperable, thus a new National Instruments cDAQ chassis system was wired, and additional sensors were selected. A LabVIEW program was written allowing for complete control over the setup using the I/O of the cDAQ chassis and modules to let the operator stand at a safe distance while a test was being conducted. In addition, the program allows for live data monitoring through a graphical interface and logs all required data for further post processing.

A methodology for determining the leakage past each individual sealing barrier was determined. Highly sensitive pressure transducers were used to track the pressure buildup within two individual low-pressure regions. This data was collected through LabVIEW and later post processed to determine the total volumetric leakage past each seal. This variable was critical for showing whether the seals would perform acceptable under the adapted conditions.

6.2 Research Objectives

RO1: Identify changes with the current testing setup that need to occur for it to meet the new system requirements.

Objective 1 was achieved by understanding the parameters and purpose of the previous setup iteration and comparing them with the new expectations for an adaptation to the existing setup. An analysis of the existing setup was conducted to better understand the previous system requirements and a generalized list was presented showing its intended purpose. After many consultations with the sponsor, new requirements and expectations for the adaptation were developed. Using the knowledge gained from researching the existing setup and the expectations of the adaptation, alterations to the setup which were needed became clear.

RO2: Adapt the current setup through the design and implementation of new parts and components with a focus on minimal change.

Objective 2 was achieved through the process of choosing acceptable parts to meet new system requirements while incorporating a minimal change mentality. Though drivetrain components and mounting systems were retained, a substantial savings in overall costs and the reduction in the timeframe of the project was achieved as requested by the sponsor. Only necessary additions were incorporated including new plumbing to accept the gas medium, and the redesign of the electrical and data acquisition system to replace damaged critical components. Additional sensors were added to meet new system expectations, and their selection was discussed including their abilities for meeting certain mechanical and data requirements. An entirely new LabVIEW program was written to help with system control and log data since a new data acquisition device was incorporated. Lastly, a potential iteration for adapting the setup to use a larger gearbox was designed after a potential problem with the HP rating of the current gearbox was discovered. The parts designed were not used, however are available granting future adaptability of the setup to apply larger torques due to seal geometries or material changes.

RO3: Develop a process to validate the testing setup by showcasing data collected which correlates with the new system requirements.

Objective 3 was met based on the data collected from the system. This showcased its ability to perform as required by the sponsor. This proved that a successful adaptation of the previous iteration was accomplished and the new system was able to meet necessary data requirements to aid in characterizing MSE seal performance. Parameters such as force and volumetric leakage can be measured under known conditions of cycle rate, pressure, and temperature.

6.3 Future Work and Recommendations

Recommendations for future work to this research include decreasing the time needed for data analysis, implementation of thermocouple porting within test housing components, and increasing the size of the cDAQ chassis for more flexibility and I/O. Compared to analyzing data in Excel, other methods for post processing such as MATLAB can be used to decrease analysis time and increase productivity of the research team operating and running MSE experiments in the future. Next, thermocouple port machining is needed within test housing components to allow for more accurate seal or low-pressure zone temperature readings. This will add additional accuracy to leakage measurements and better consistency between tests, as the tip of thermocouples could be consistently mounted within the test housing compared to reading exterior housing temperatures. Additionally, multiple thermocouple ports can be added to low-pressure regions to add redundancy in case of a thermocouple failure to ensure lengthy tests are not wasted. Lastly, a larger cDAQ chassis could be employed to allow for future expansion and removal of the NI-USB series device to consolidate the system under a singular DAQ device. Cost limitations prevented this, but the budget could be increased in the future as tests continue and data is collected.

6.4 Research Limitations

As mentioned throughout, the limitations of this research were associated with total costs and time. The expected total costs and timeline of designing a new test setup to achieve the expected outcome were the driving factors for starting with a previously built non-working setup. The mention of minimum change posed a challenge since this required only replacing or redesigning parts if necessary. This allowed the sponsor to save on total costs for this project and reach the initial testing phase sooner but ultimately lead to many of the mechanical system parts having to remain the same.

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