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THE DESIGN OF A TEST SETUP FOR THE TESTING AND EVALUATION OF ROTARY SHAFT SEAL FAILURE

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THE DESIGN OF A TEST SETUP FOR THE TESTING AND EVALUATION OF ROTARY SHAFT SEAL FAILURE

A THESIS APPROVED FOR THE

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BY THE COMMITTEE CONSISTING OF

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Abstract

An experimental setup was designed and assembled to test the performance of a rotary seal stack under industry conditions. The system is composed of five subsystems: the DUT and drive system, the pressure system, the cooling system, control and data acquisition, and the frame. The setup can hold up to 3 seals pairs that can be arranged in different configurations. The main parameters recorded for the system are the pressure differential, the DUT shaft speed, the torque applied, and the temperature of the working fluid, DUT surface, and DUT interior. It is imperative that each subsystem works together to meet different requirements of the rotary seal test setup.

Rotary seals are seals used in machinery with rotating or oscillating motions around a rotating shaft. Rotary seals are widely used in various industries to increase long-term performance and the lifespan of mechanical equipment. The seals are designed to create a barrier around a rotating shaft and their purpose is to withstand high temperatures, hold high flow, and prevent leakage of fluids or lubricants out of machines while also protecting internal components from contaminants such as dust or mud. There are various cross section designs for rotary seals, and they can be made from many different types of materials. The main parameters determining performance and lifespan of the rotary seals are operating speeds and heat production from the seal lip. This setup focuses on being able to evaluate both the effect of operating speeds and heat production on the rotary seals throughout experimental tests.

This thesis will explore the design and manufacturing process of the test setup for rotary shaft seals. The goal of the setup was to be able to test the rotary seals at high temperature, hold high flow, and operate at high speeds until failure of the seals. An iterative design process was

followed to recreate operation conditions used in industry with the requirements of being able to control the shaft speed, the pressure, and maintain operating temperature. The test setup was able to record data on pressure, operating temperature, speed, flow, leakage rate, and current data to evaluate the performance of multiple differing rotary shaft seals until failure.

Chapter 1: Introduction

1.1 Problem Statement

Rotary shaft seals are made in various cross section geometries and made of varying materials due to their vast applicational usage. Depending on these factors, they have different expected lifespans since they are generally built for very specific applications. Some applications require more extreme conditions than others such as operating under high pressures and high temperatures. However, the main parameters that determine the lifespan of rotary shaft seals are the operating speeds of the system and heat produced by the seal lip of the rotary shaft seal. Therefore, designing a test setup to record the effects of these parameters on rotary shaft seals can provide useful data to better understand how these parameters affect different types of rotary seals.

There is also limited literature and research done on the performance of rotary shaft seals. Real-world testing can lead to expensive operations and can heavily limit the amount of useful and accurate recorded data. Since real-world applications would have more complications to record speed, pressure, or temperature data, testing in a controlled environment where all the parameters are easily monitored would provide a better understanding of how different environments affect rotary seals. A designated test setup that can be used repeatedly to experiment with different configurations, different materials, and varying geometries of rotary shaft seals could expand the possibilities for the evaluation of rotary shaft seals. Having the versatility of testing multiple types of rotary shaft seals with one setup can minimize hours of design work, costly manufacturing, and construction hours needed to build different setups. This test setup can also monitor and record torque, temperature, pressure, and leakage rate in real time to evaluate the performance of seals throughout operations more easily than in real-world applications.

1.2 Research Objectives

This research focuses on the process of creating a test setup that is able to mimic real-world applications of rotary shaft seals. The test setup will be built to test and evaluate rotary shaft seals until they fail. This means the setup should be able to operate under extreme environments of high-pressure levels, high flow rate, and high temperatures while being able to control and record data from these parameters throughout short-term and long-term testing. The setup needs to be modular for easy access to any part of the setup. This will also make for easier control of the system and the ability to improve specific parts of the setup throughout the iterative design process. Since the setup needs to test the rotary seals until failure, it should be able to conduct short-term or long-term tests with reliable power and monitoring. It is also important to set in place safety features to shut off the system if it reaches dangerous levels that would damage any part of the setup.

1.3 Overview of Approach

The first step in creating a test setup is to do extensive background research to understand how rotary shaft seals work in different machines and what kind of environments they operate in. After gaining that understanding, it is also useful to be aware of related research in testing rotary seals to prevent mistakes or oversights. Then, the design process begins. The design process of the test setup will utilize the design process by first identifying the requirements of the system, brainstorming ideas for the setup, creating an initial design, manufacturing the design, testing and evaluating the design, optimizing the design, and repeating the last three steps until the test system adequately meets the requirements of the test setup. The design process is discussed in further detail in Chapter 3 of this thesis. After the setup is finalized, testing of rotary shaft seals are conducted to gain data to evaluate the system. Comparing multiple tests will improve the understanding of the capabilities of the setup as well. Lastly, evaluation of the setup are made and limitations are identified to recommend improvements to the setup.

1.4 Outline of Thesis

Chapter 1 introduces motivation for the research conducted in the thesis and specifies the research objectives. It also outlines each chapter of the thesis. Chapter 2 presents the background of rotary shaft seals by showing the industrial applications and purpose of rotary seals. It shows the typical geometry of a rotary shaft seal to show how they work and to develop an understanding of how they operate. It also discusses design considerations that go into manufacturing rotary seals and related research that have been conducted to understand the relationship between some aspects of rotary seals. Chapter 3 identifies the requirements of the rotary shaft seal test setup and describes the iterative design process used to create the setup. It also shows the final design and describes the function of each subsystem, detailing safety considerations taken throughout the design process. Chapter 4 describes the test procedure used to test the performance of the rotary seals with the test setup. It also evaluates the results for the conditioning test of the rotary shaft seals and shows how other tests have performed in comparison. Chapter 5 summarizes the thesis, identifies the limitations within the research, and provides recommendations for improvements of the system.

Chapter 2: Background of Rotary Seals

2.1 Industrial Applications

Rotary shaft seals are utilized across numerous industries, resulting in numerous types of shaft seals. These industries span from automotive to food processing because of their versatile applications. Some of the most prominent industries where rotary shaft seals are utilized are the automotive, aerospace, oil and gas, manufacturing, and food processing industries (Sullivan, 2023). The use of rotary seals in the automotive industry prolongs the lifespan of components such as engines, transmissions, axels, and differentials. In the aerospace industry, the seals help precisely maintain control over fluid flow in aircraft engines or landing gear systems. Rotary seals in the oil and gas industry are utilized in pumps, compressors, and valves to ensure operation under extreme environments. Machinery in the manufacturing industry such as pumps, couplings, gearboxes, and mixers use rotary seals since they can handle high rotational speeds and adequate sealing performance. Safety and quality standards are maintained in the food processing industry by using rotary seals to block any contaminants from entering processed food. They are typically designed to withstand pressures of about 300 psi and temperatures up to 500 degrees Fahrenheit (Sullivan, 2023). The unique application in each industry has resulted in many customization options of rotary seals to cater to the demands of each specific use.

2.2 Purpose

The primary function of rotary seals is to prevent leakage of fluids while protecting internal components from contaminants such as dust, dirt, and more. Rotary shaft seals have a complex relationship between friction, wear, lubrication, and surface interactions, as all these components play a part in how surfaces move relative to each other. There are two key mechanisms for the sealing properties of the rotary shaft seals. The first mechanism is lubricant retention as the rotating shaft acts like a pump to assist the seal to push lubricant into the sealing lip also known as the sealing edge and shaft (Nieuwenhuizen, 2024). The second mechanism is contaminant exclusion where the seal prevents any external materials from entering the lubricant (Nieuwenhuizen, 2024).

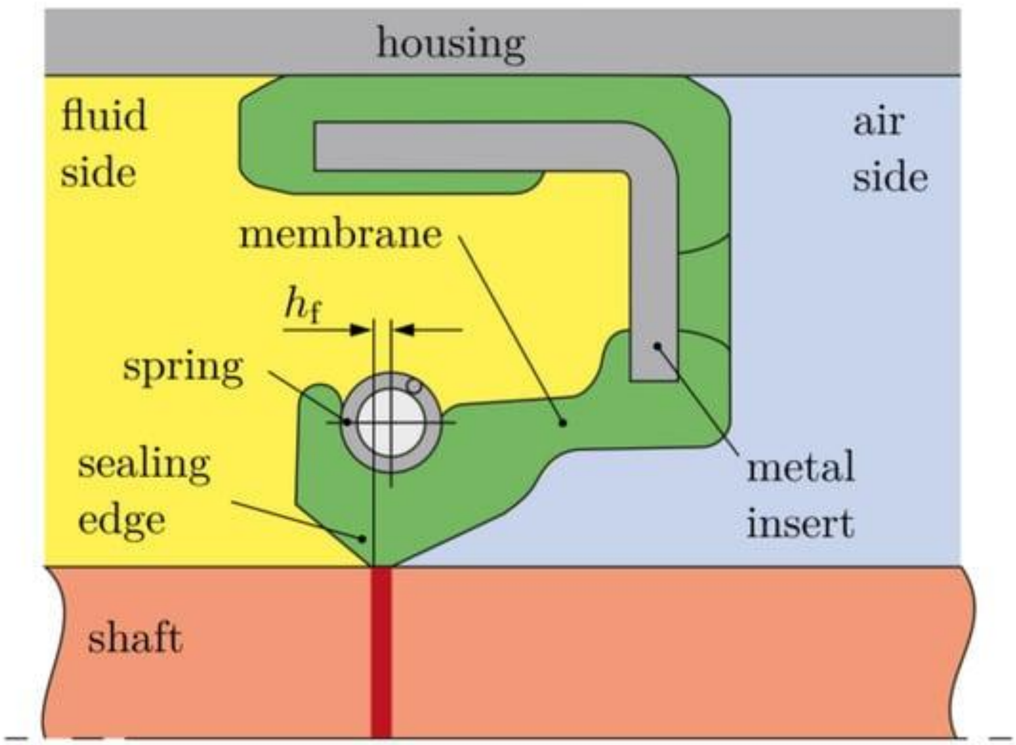

Figure 1: Schematic of Sealing Mechanism (Grun, Gohs, & Bauer, 2023)

Figure 1 depicts the different components of the rotary stack seal sealing mechanism (Grun, Gohs, & Bauer, 2023). The system needs to be able to seal the fluid while in ambient static and operating conditions. The friction between the inner diameter of the sealing ring and the outer diameter of the shaft and the friction caused by the spring pressing the sealing edge to the shaft surface seals the lubricant while the system is static. The relative movement of the sealing edge and the shaft surface while it is in operation results in the lubricant being pumped from close to the air side to the fluid side in the axial direction (Grun, Gohs, & Bauer, 2023). This serves as the sealing mechanism while the system is active.

2.3 Design Considerations

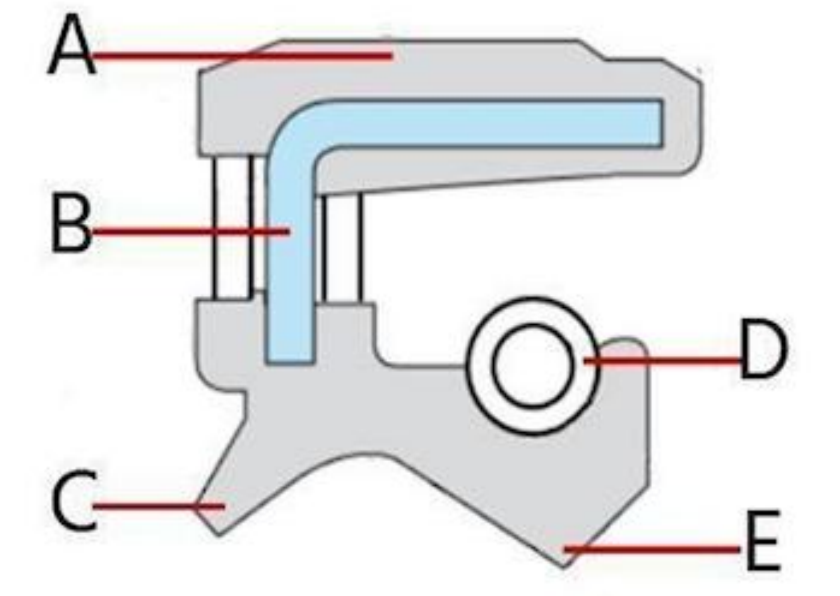

Figure 2: Basic Cross-Section Design of a Rotary Shaft Seal (Kolstad, 2024)

Figure 2 shows a basic cross section design of a shaft seal (Kolstad, 2024). The section labelled A is the outside covering which acts as a seal against the housing and is typically made of rubber or metal. B is a metal ring that ensures stability and strength. The part labelled C is an optional dust lip that blocks any dirt or dust to protect the sealing edge. Having a dust lip can increase the lifetime of the rotary shaft seal. Part D is a garter spring providing load around the sealing circumference which keeps the sealing lip tight against the shaft surface. Lastly, the section labelled E is a sealing lip that creates a seal against the shaft. This area is usually made as small as possible to reduce generated heat from the seal.

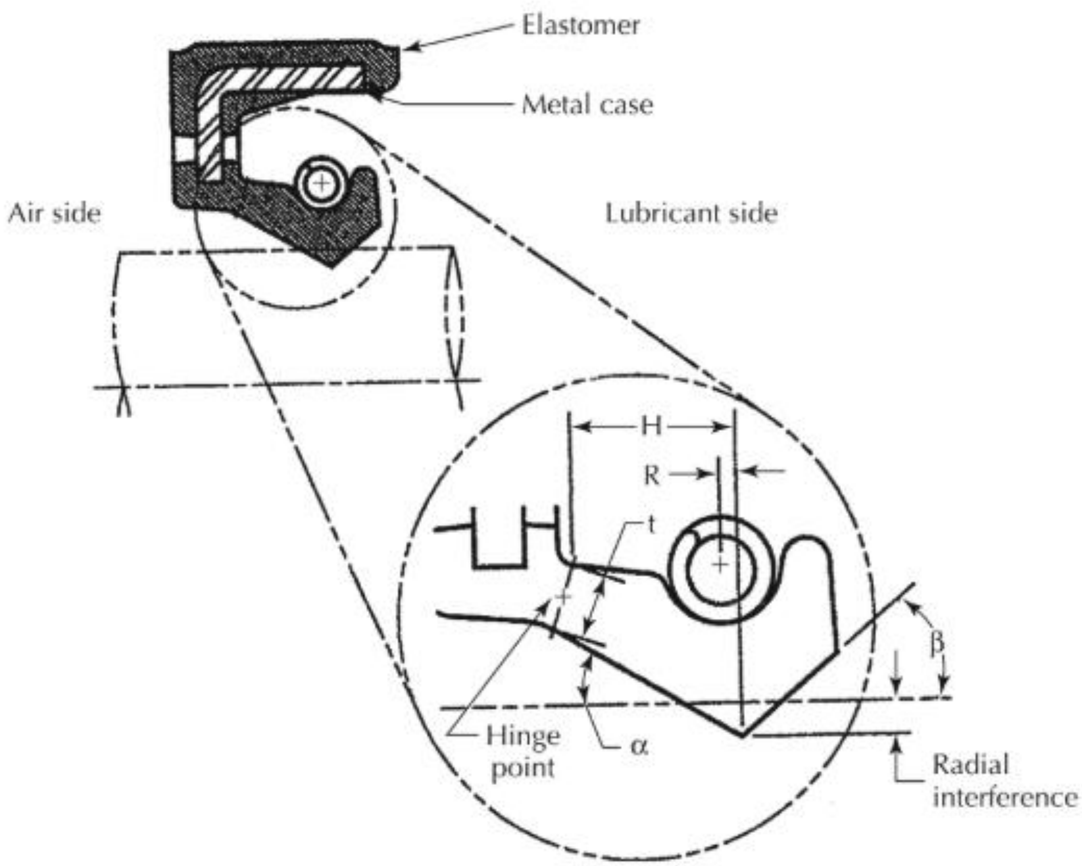

Figure 3: Cross-Section of a Basic Lip Seal Design (Flitney, 2007)

Figure 3 shows an expanded view of a basic lip design (Flitney, 2007). The details of individual seal designs will vary widely but all have the same overall design principle. The seal lip is manufactured to be sharp and in contact with the shaft. In Figure 3, the outside covering is labelled as elastomer, a common material for the outside covering to be made of. On the lubricant side, the outside covering is steeper compared to the air side. The angle β represents this angle and is typically in the range of $40 - 45°$ while the angle on the air side is represented as α and is typically in the range of $25 - 30°$ before being installed on the shaft (Flitney, 2007). A $10°$ angle change is possible on either side once the seal is installed on the shaft.

The center of the spring is offset from the contact line of lip depicted by R. The distance of R is typically 10% of the lip length represented by H (Flitney, 2007). This offset towards the air side is important since it helps provide the correct amount of direct loading to the lip and contribution to the asymmetric geometry while preventing excessive lip distortion. If the spring offset distance, R, is manufactured or installed incorrectly with an offset to the oil side, this will result in potential tilting of the lip and leakage. The most common type of spring found in a rotary seal is a garter spring because of its localized circumferential spring force in the required location (Flitney, 2007).

The lip length, H, and the thickness at the hinge point, t, determine the flexibility of the rotary seal. It is common for the thickness, t, to be 50% of the lip length, H (Flitney, 2007). To withstand larger shaft radial deflections, the seal must be more flexible. This can be achieved by increasing the lip length. Contrastingly, for operations at high pressures, the thickness, t, should be increased while the lip length, H, should be decreased. The outside casting is molded to the metal ring and can be entirely covered or partially covered. This supports the lip and creates a static location for mounting the seal.

The limits of rotary seal performance depend on a combination of parameters such as the seal design, flexibility, lip load, materials, and more. One of the major limiting factors is the heat generated under the lip. Since the seal is continuously running in a localized section of the shaft, friction in that area generates heat. "Seals and Sealing Handbook" by Robert Flitney showcases three graphs depicting the relationship of the shaft diameter and maximum temperatures for various lubricants in figure 4, shaft surface speed limits for elastomer lip seals in figure 5, and performance limits of different lip seal materials in figure 6 (Flitney, 2007).

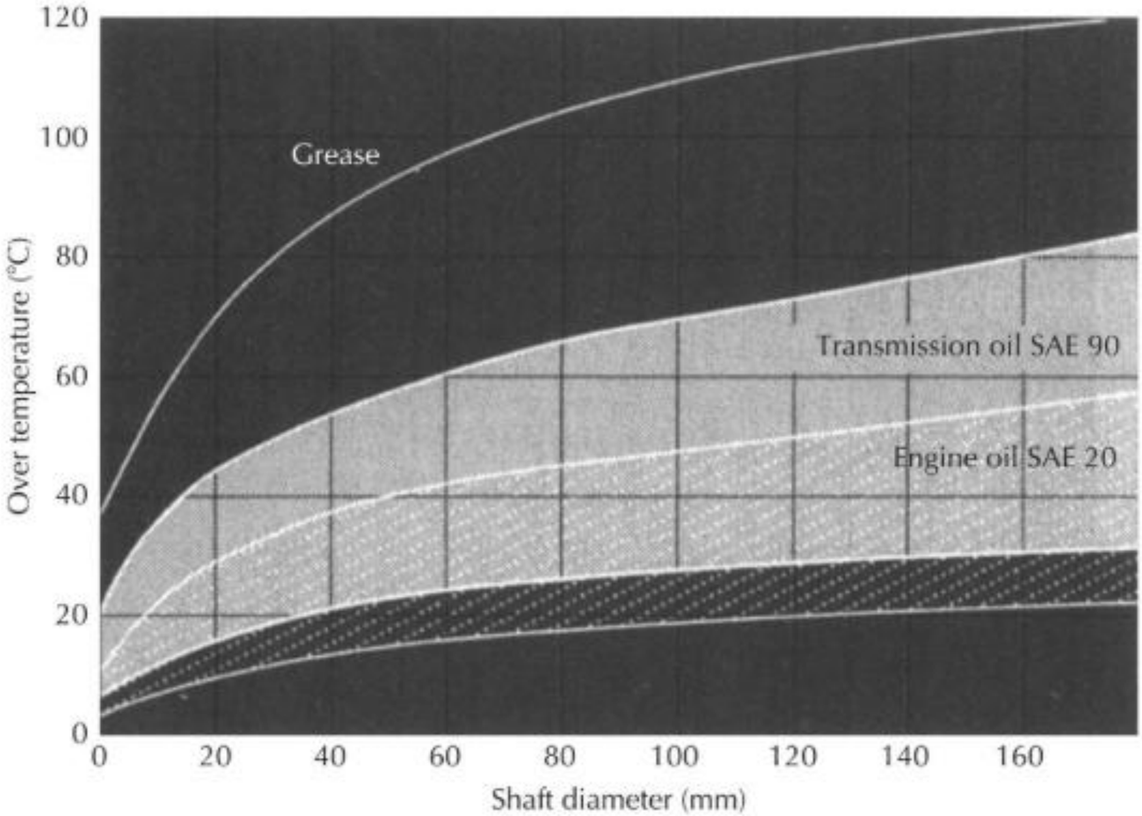

Figure 4: Over Temperatures at Different Shaft Diameter for Various Lubricants (Flitney, 2007)

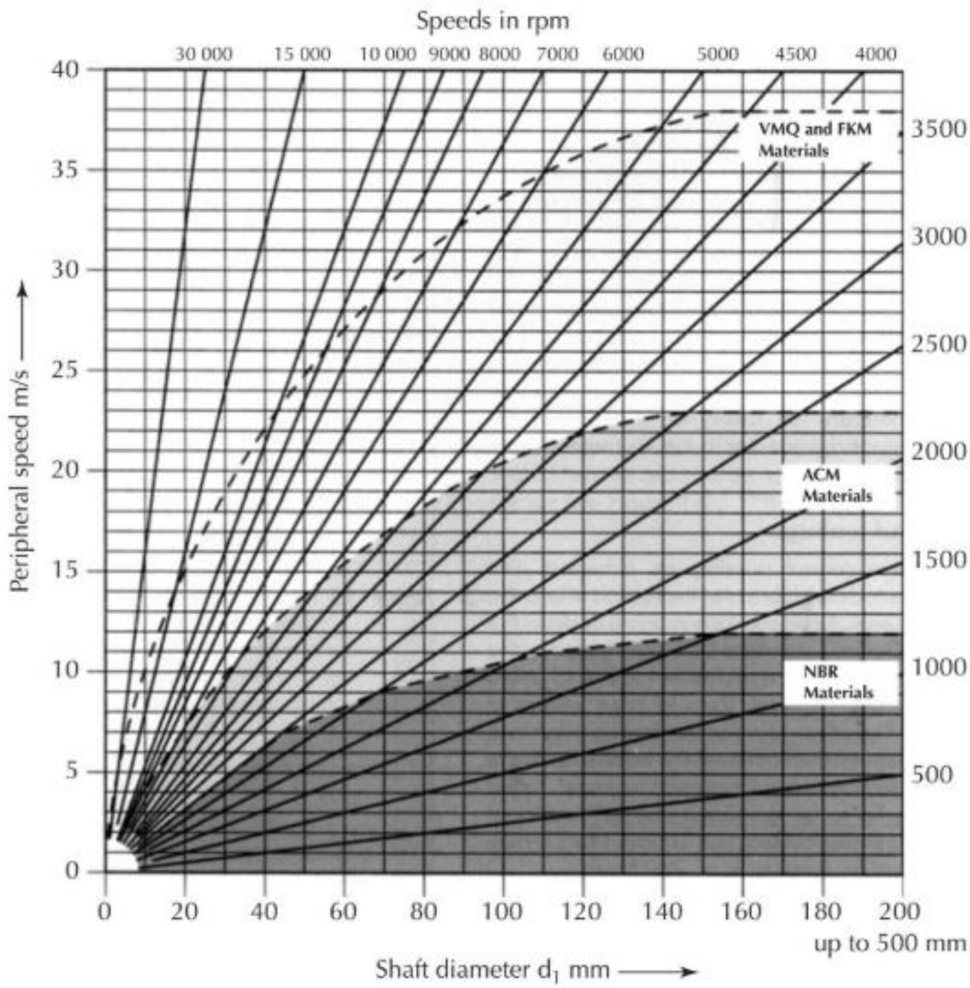

Figure 5: Shaft Surface Speed Limits for Elastomer Lip Seals (Flitney, 2007)

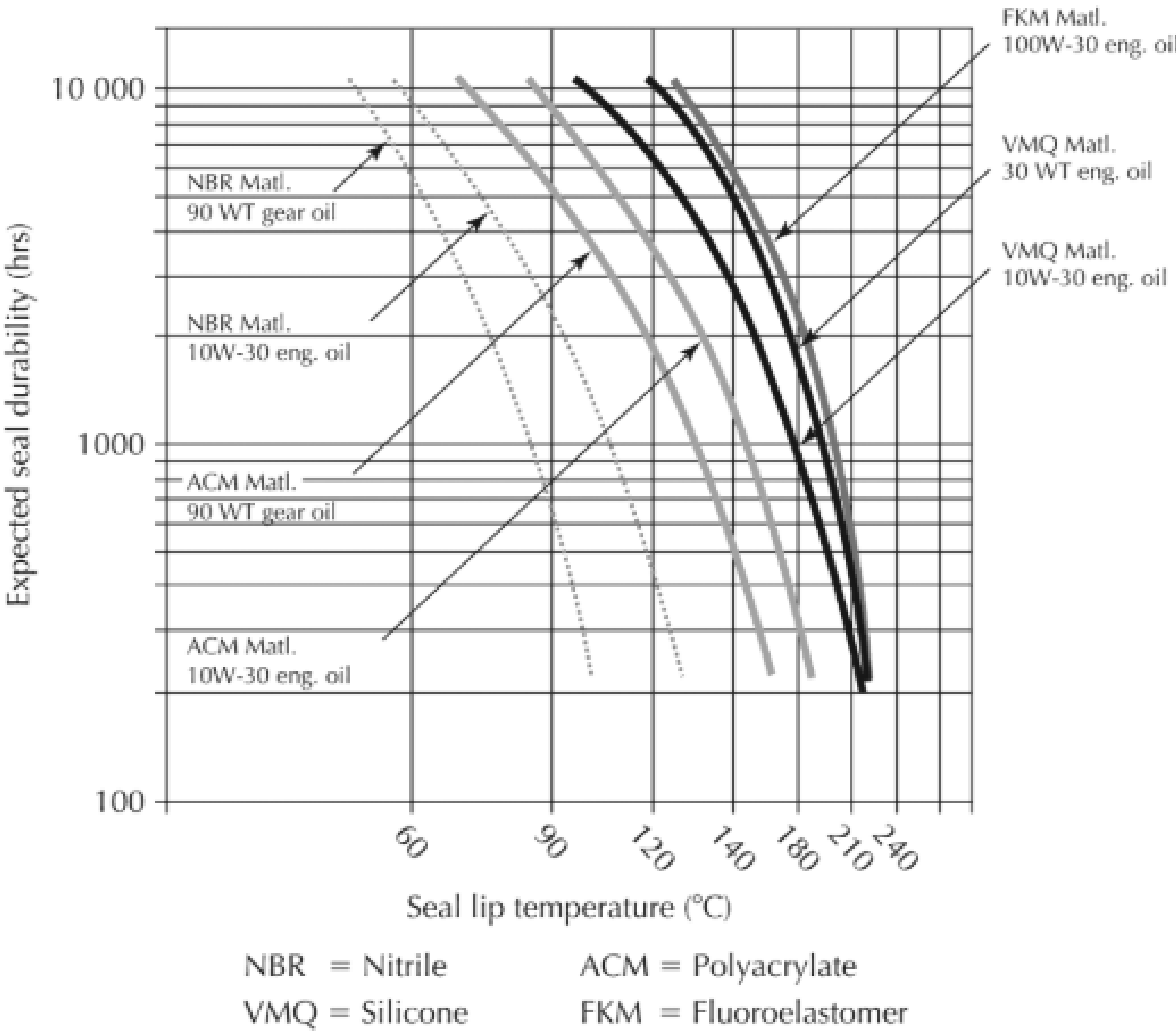

Figure 6: Performance Limits of Different Lip Seal Materials (Flitney, 2007)

These figures show that many factors play a part in the longevity of rotary seals and material selection is crucial to their performance limits. Figure 4 shows at what shaft diameter the seals exceed the maximum temperature for different lubricants. This is important for not only lubricant selection and shaft diameter but also seal materials as the rotary seals will need to withstand these temperatures also. Figure 5 highlights the speed limits of different elastomers. It shows that the materials that can withstand higher temperatures also have higher speed capabilities. Figure 6 outlines how the material and lubricant can also affect the durability of the seal as heat is produced by the friction of the seal lip. This shows how material selection directly affects the thermal limit, speed capability, and duration until failure of the seals.

2.4 Related Research on Rotary Seals

Many considerations must be taken into account when designing a test setup for rotary shaft seals. A study titled, "Numerical Simulation and Experimental Study on Sealing Performance and Frictional Property of Rotary Lip Seal" by Dong and Hu discussed the influence of the viscosity of lubrication, rotational speed, surface roughness, and contact load on the performance of rotary shaft seals (Dong & Hu, 2021). Their study revealed that viscosity decreases as the temperature increases, especially at high shaft rotational speeds. The viscosity of the lubricant plays a part in the pressure distribution on the oil film, which affects the reverse pumping rates and friction torque.

For the influence of rotational speed, it was found that the reverse pumping rate of the rotary seal increased as the rotational speed increased. However, it was discovered that the relationship between the reverse pumping rate and the rotational speeds was not a direct relationship. Instead, there was an indirect relationship since higher rotational speeds led to higher film thickness resulting in the increase of the reverse pumping rate. The results of the study also showed that the friction torque increased relative to the increase in rotational speeds, but the friction torque increases slower past the rotational speed of 2500 revolutions per minute (Dong & Hu, 2021). It is also important to note the effect of the contact load as it increases when the reverse pumping rate decreases. This happens because more contact load increases pressure in the gap of the seal, which means fluid particles need to overcome higher pressure to pass from the oil side to the air side (Dong & Hu, 2021). They also found that the average film thickness decreases as the contact force increases, which results in the increase of the viscous shear friction of the fluid. This is important as different fluids like water and oil are used as lubricants and have different characteristics that can effect contact force.

Looking at the influence of the surface roughness of the lip, they found that the reverse pumping rate increases as the friction torque decreases. The friction torque also decreases as the root mean square deviation of the lip surface increases (Dong & Hu, 2021). This shows that sealing performance is affected by the surface roughness of the lip and that seals with rougher wear tracks have better reverse pumping rates and excellent reliability when it comes to service. However, if the surface roughness of the lip is increased too much, the service life will be very poor. This shows that it is important to consider how all these factors come into play with each other while designing a test setup.

Another important factor when creating a test setup for rotary shaft seals is the alignment of the seals. Hand et al. examined the effects of seal alignment in a study titled, "Experimental testing on the influence of shaft lip seal misalignment for marine hydro-kinetic turbine." In the study, they tested rotary seals that were aligned with the shaft axis, as well as rotary seals that were misaligned by 1º to compare the performance (Hand, et al., 2022). It was found that the misaligned seals showed a higher rate of wear compared to the aligned seals up to a maximum width difference of 97.60% and a maximum depth difference of 103.13%. However, the aligned seals reached higher chamber temperatures of almost 20ºC higher compared to the misaligned seals. This is important to consider while assembling the test setup as even a 1º misalignment can affect wear and heat production that could accelerate the failure of rotary shaft seals.

Understanding the industrial application, the purpose, design considerations, and related research of rotary shaft seals is important when designing a test setup for rotary shaft seals. Knowing the ways rotary shaft seals are used and how they operate helps to understand what components are necessary to design a system to test them properly. Design considerations outline the typical designs and materials of the seals which ensure that the design of the setup will be able to mimic typical operating environments, hold typical pressure levels, and withstand expected heat production. Related research includes different ways the seals fail and allows the design of the setup to account for these considerations to prevent repeating mistakes from previous research and increasing efficiency. The main parameters determining performance and lifespan of the rotary seals are operating speeds and heat production from the seal lip. Therefore, the test setup will focus on accurately testing these parameters.

Chapter 3: Design of Test Setup for Rotary Seals

3.1 Design Process

Creating a test setup from scratch is a lengthy and involved process. Extensive background research is required to ensure that no parameters are overlooked during the design process. Based on obtained knowledge on the previous related research on rotary shaft seals and developing an understanding on the way the seals operate from chapter 2, design requirements for an appropriate test setup were determined. Identifying clear design requirements for the test setup is important because it establishes a foundation for the system and provides a clear desired outcome. After establishing all the requirements, further design concepts and iterations were underway to complete the design and manufacturing of the complete test setup.

3.1.1 Requirements

Designing a test setup for industrial applications can be complex and require multiple iterations to create a final design that produces quality results. To ensure completion and quality of the final product, a design process that clearly outlines each necessary step can be utilized. The design process is not a purely linear process as it requires reviewing designs, evaluating and testing the results of the design, and continuously identifying the limitations of the design and improving on them. Each step is necessary to ensure the final design meets the requirements and produces desired outcomes.

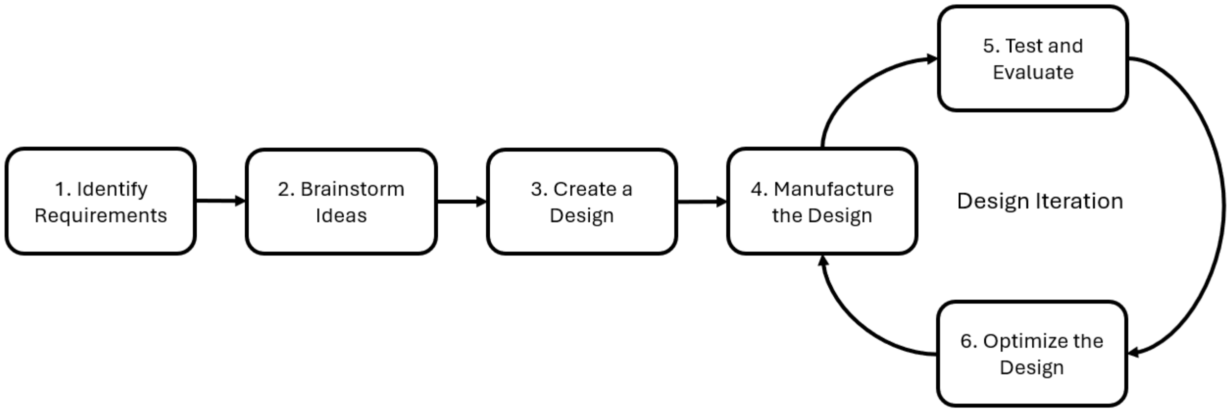

Figure 7: Design Process Block Diagram

The design process used for the rotary shaft seal test setup is illustrated with a block diagram in figure 7. The first step of a design process is to identify what requirements or goals the setup should meet. This is necessary to set clear aims and outcome expectations for the test setup. After the requirements have been identified, brainstorming ideas on different design concepts should take place. This is when research is done to understand how the system should operate and ensure the design will meet the requirements. Then, design concepts should be refined to produce a preliminary design. After that, the fourth step is to construct a prototype of the design. The prototype should be tested to prove the design's functionality and its reliability. The limitations should also be identified to learn what areas of the design need to be improved. This is part of the design iteration process because as limitations are identified, improvements should also be established to create a better design. Then the design can be manufactured, tested, and improved upon as many times as necessary until the obtained data can validate desirable performance of the design.

The goal of the research was to design and assemble an experimental setup to test rotary shaft seals and record operational variables. For the rotary shaft seal test setup, the requirements of the setup were to:

- Withstand high temperatures
- Operate at high speeds
- Hold high flowrates

Since the test setup should be able to test various types of rotary shaft seals, it should be able to operate at high ranges of speed, pressure, and temperature. A few calculations are necessary to establish what the ranges for these parameters should be based on guidance from a third-party sponsor. According to Kalsi Seals Handbook, the equation to convert rpm to surface speed in feet per minute is

$$S_s = \frac{D_s * \pi * rpm}{12} \tag{1}$$

where S_s is surface speed, D_s is the diameter of the seal, and rpm is revolutions per minute (Dietle, Gobeli, Schroeder, Richie, & Kalsi, 2015). Converting it to SI units, results in the equation

$$S_s = \frac{D_s * \pi * rpm}{12} * \frac{0.3048\, m}{1\, ft} * \frac{60}{2\pi} = \frac{1.524 * D_s * rpm}{\pi}$$

The third-party sponsor provided the seals with a diameter of 11.8 inches or 0.9833 feet and the range of 0 to 200 revolutions per minute or 0 to 20.94 radians per seconds targeted speed. Inputting the selected maximum revolutions per minute the setup needs to meet and the diameter of the seal, results in

$$S_s = \frac{1.524 * 0.9833 * 200}{\pi} = 95.45 \frac{m}{s}$$

This means the maximum surface speed is approximately 95 meters per second for these parameters.

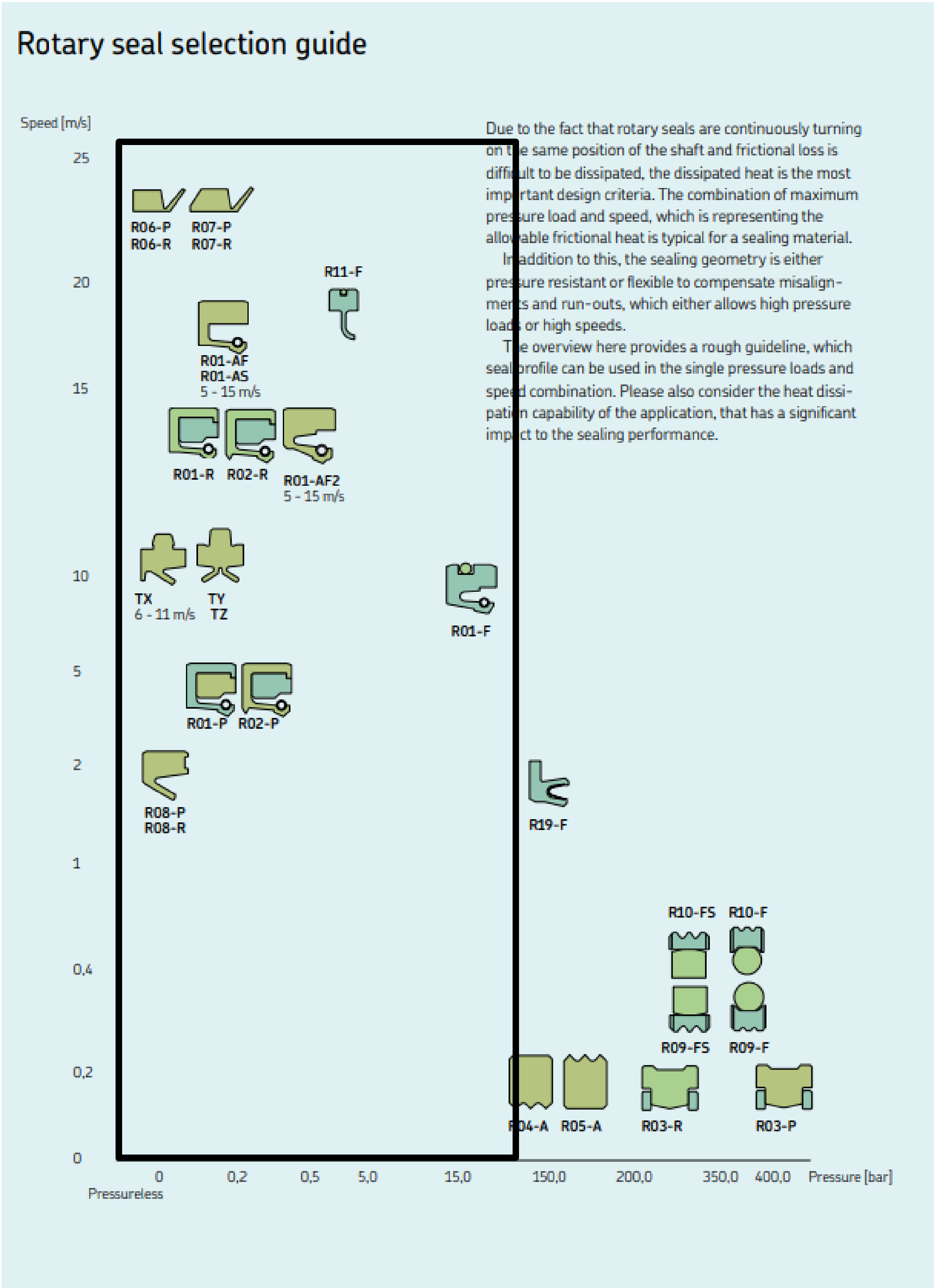

Figure 8: SKF Rotary Seal Selection Guide (SKF, pg. 50)

SKF is a company that manufactures a wide range of seals. They make numerous types of rotary seals profile depicted in figure 8 (SKF). Each profile has multiple seals varying in materials for the seal, retainer ring, and spring, providing dozens of seals that fit within any given range. Basing the rest of the requirements to focus on speed and heat produced by the rotary seals as stated in chapter 2, a range of high-speed seals were chosen. A requirement of 68.95 bar or 6,895 kilopascals was selected to adequately handle all the high-speed seals. The black outlined box in figure 8 shows what seal profiles can be tested until failure with the selected speed parameters and pressure parameters.

Table 1: Test Setup Requirements

Parameter	**Requirement**
Temperature	93 ℃
Speed	0 − 21 rad/s
Pressure	0 − 6,895 kPa
Flow Rate	0.126 L/s

Table 1 shows the requirement for each parameter of the test setup. The test setup must hold up to 3 rotary seal pairs, withstand temperatures of up to 93 degrees Celsius, allow for operating speeds of 0 to 21 radians per minute and a pressure range of 0 to 6,895 kilopascals, have a flowrate of 0.126 liters per second, and be able to test the seals until failure. The system must also have temperature and pressure monitoring to maintain safe operating levels. A safety shutoff feature also needs to be in place. For data acquisition, there must be sensors for pressures and temperatures at different locations in the setup as well as torque sensors, leakage rate monitoring, and current monitoring.

Table 2: Data Requirements for Test Setup

Input	**Output**
Control Variable Rotational Speed Torque Sensor	Rotational Speed Data Current Data
Control Different Pressure Levels Pressure Sensors	Pressure Differential Data
Control Cooling System	Maintaining Operating Temperatures
Temperature Sensors	Temperature Data
Flow Sensors	Flow Data
Leak Bucket Scales	Leakage Rate Data

Table 2 shows the requirements for data acquisition for the rotary shaft seal test setup. The test setup must have controllable variable speed, the ability to operate under high pressure, and maintain operating temperature. This means the setup should be able to monitor and record these parameters to evaluate the performance of the setup. It is also important to record data on flow, leakage rate, and current data to evaluate the performance of the rotary seals. Having both sets of data will show the effectiveness of the test setup with testing rotary shaft seals, making it imperative for the test setup to have control or monitoring of all the parameters listed above in Table 2.

3.1.2 Initial Design

The initial design of the test setup included a modular design of five subsystems. The subsystems include the control and data acquisition, the pressure system, the cooling system, the device under testing (DUT) and drive system, and the frame. The DUT is the housing for all the rotary shaft seals designed and provided by a third party and treated as a black box throughout the design process. The rest of the setup was designed with a modular concept to accommodate simple assembly of the setup, disassembly of the setup, the ease of replacing different parts, and fixing items that would otherwise be difficult to reach.

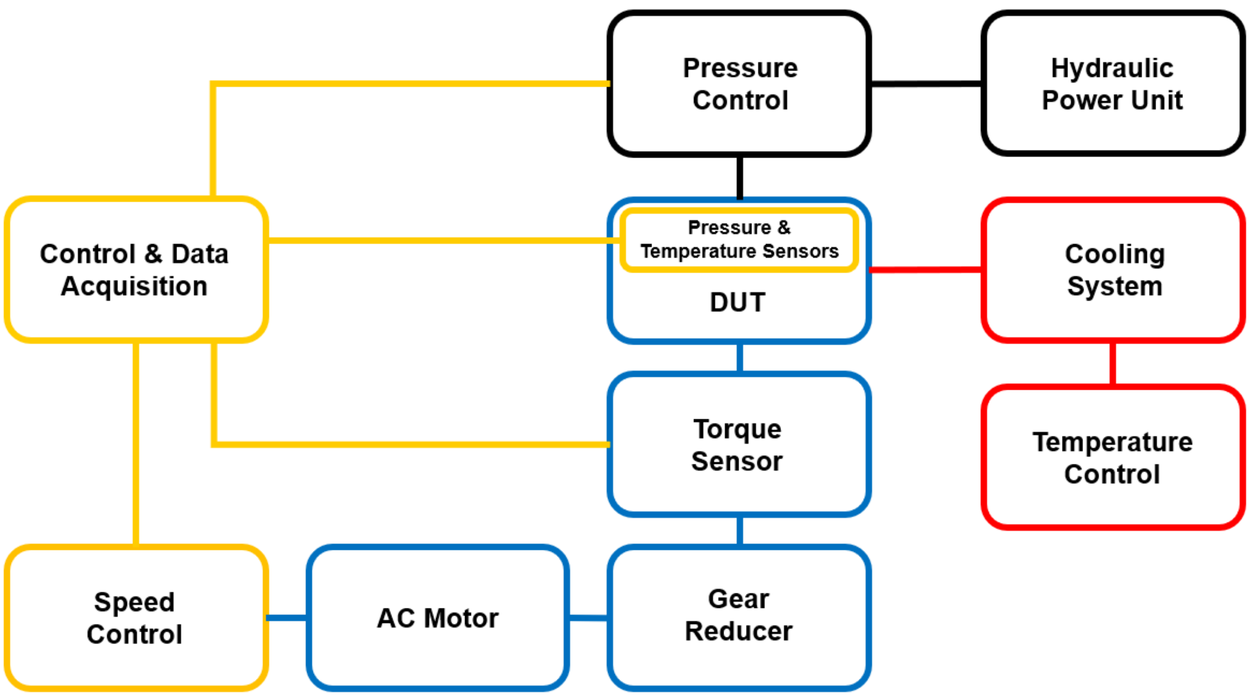

Figure 9: Initial Test Setup Subsystems Block Diagram

Figure 9 shows the initial block diagram of the subsystems for the test setup, except for the frame. The figure shows how all the subsystems interface with each other to ensure they are integrated together to get desirable testing conditions and results. The frame is modular, designed to hold all the subsystems while allowing easy access to any specific part of the setup. The blue boxes in figure 9 represent the DUT and drive system, the yellow boxes show the control and data acquisition subsystem, the red boxes represent the cooling system, and the black boxes are the pressure system. The drive system includes a motor mechanism to drive the rotary seal stack assembly and create the desired operating speeds using a gear reducer. The torque sensor records data of the rotary seals and acts as a safety measure for the setup. The hydraulic power unit supplies pressurized liquid to the system. Pressure control allows for the levels of pressure in the system to be adjustable to desired values. Temperature and pressure control allows for precise control over the temperature and pressure to replicate real world application testing. The cooling system includes circulating cold water internally and externally of the DUT to prevent overheating and damage to the seals. The control and data acquisition subsystem includes numerous sensors for temperature and pressures at various locations of the system to record data and maintain safe operating conditions.

Table 3: Requirements for Components in the DUT and Drive System

Component	Required Input	Input Range	Required Output	Output Range
DUT	Provided by a Third Party			
Motor	Electric Power	440 VAC 40 HP	Variable Speed	0-3,600 rpm
VFD	Speed Control	Digital Signal		
Gearbox	Motor Torque		Gear Ratio	Speed Range
Torque Sensor	Electric Power Measurement Range	DC Voltage	Analog Signal Signal Resolution	

The required output and input of the test setup for the DUT and drive system are provided by table 3 as well as the input and output range of each component. To test the effectiveness of the test setup with running experiments on rotary shaft seals, there must be constant rotation that can be controlled. The selected motor for the design must also be able to run at high speeds, which a right-angle gearbox connects with the motor to assist with running operations at these high test condition speeds. A right angle gearbox allows torque from the motor to be transmitted perpendicularly to the DUT.

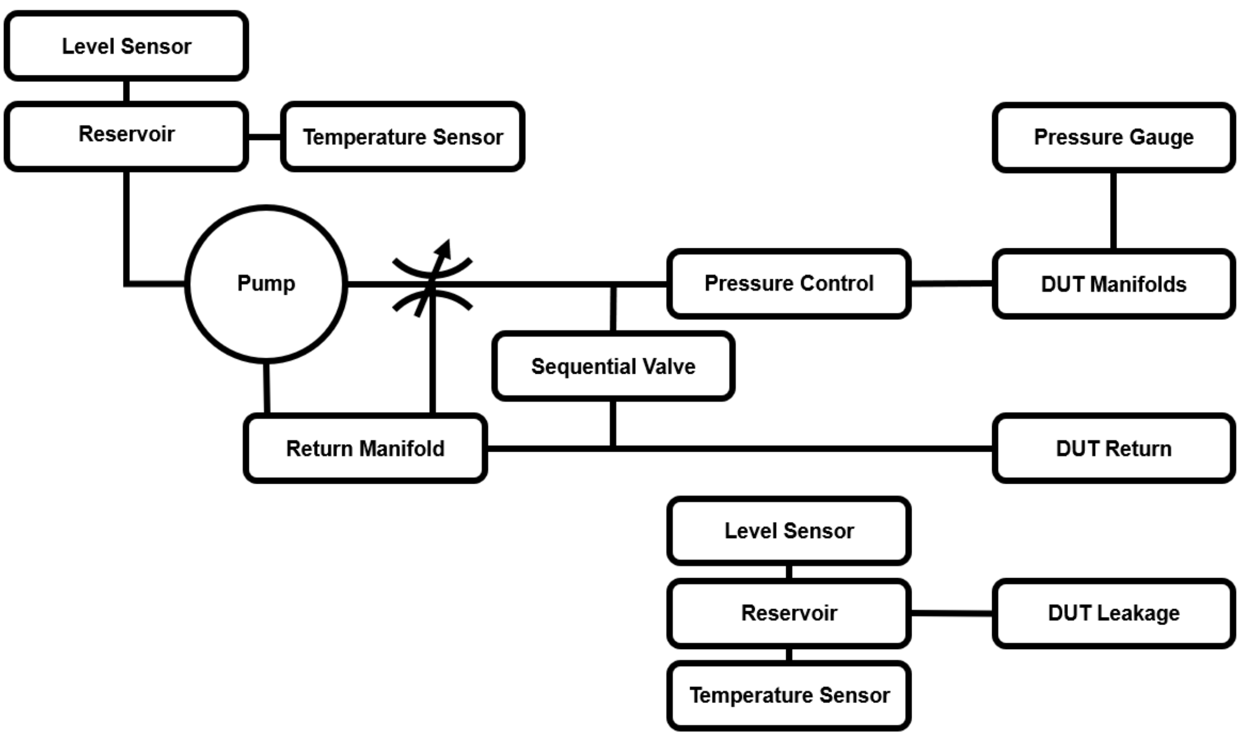

Figure 10: Pressure Subsystem Block Diagram

Figure 10 shows the block diagram of the pressure subsystem. A pressure differential will be created on the rotary shaft seal stack as pressurized fluid circulates through the DUT. The pump provides constant flow to the system while the manifolds and sequential value allows for altering how much pressure goes into the system. The pressure gauge allows for monitoring of pressure at the DUT. The level sensor and temperature sensor are connected to a reservoir to monitor any leakage from the DUT. The setup of the pressure subsystem allows for flow control while being able to monitor flow, temperature, and leakage.

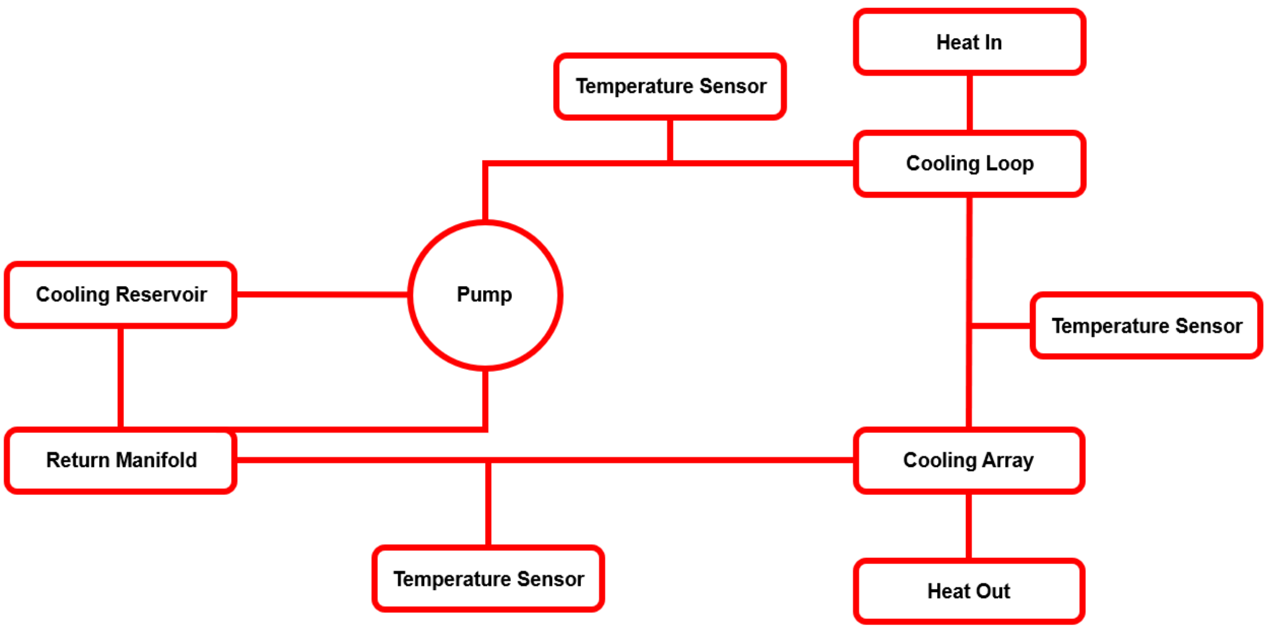

Figure 11: Cooling Subsystem Block Diagram

Figure 11 illustrates the block diagram of the cooling subsystem. Coolant will be circulated throughout the system using a PID controller and a centrifugal pump. The cooling loop allows for heated liquid from the system to be deposited and cycled through a cooling reservoir to ensure cool liquid is circulated through the system throughout testing. A cooling reservoir allows any heated liquid to be cooled down before being circulated through the system to prevent continuous heated liquid from looping. This will dissipate heat produced through any testing operations and multiple temperature sensors help to monitor the effectiveness of the cooling process.

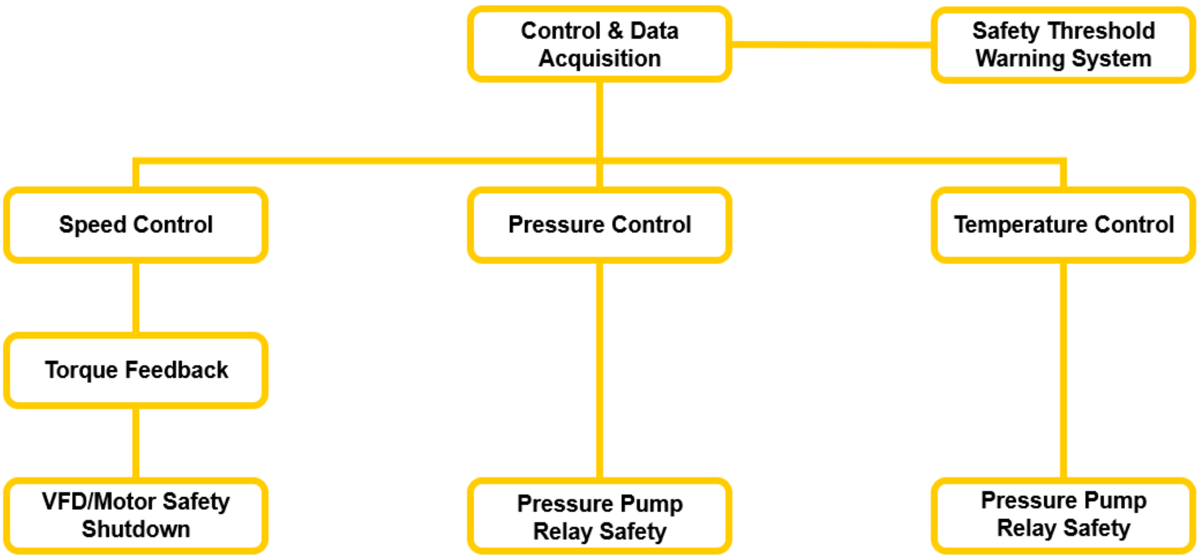

Figure 12: Control and Data Acquisition Subsystem Block Diagram

Figure 12 showcases the block diagram of the control and data acquisition subsystem. A data acquisition module is connected to different channels to output physical data into digital data. The data acquisition module is utilized along with NI LabVIEW to control the speed of the motor as well as record the data being collected through the various pressure and temperature sensors on the setup. Since safety thresholds for force applied and significant pressure drops will be programed onto LabView, the program will shut off the setup if it exceeds any thresholds as a safety mechanism.

3.1.3 Intermediate Design

After running multiple experiments using the initial design, there was insufficient control and monitoring of pressure, temperature, and flow. Numerous changes to the system were made iteratively to provide better results of rotary shaft seal testing. Changes in the pressure system, cooling system, and control and data acquisition were made, specifically.

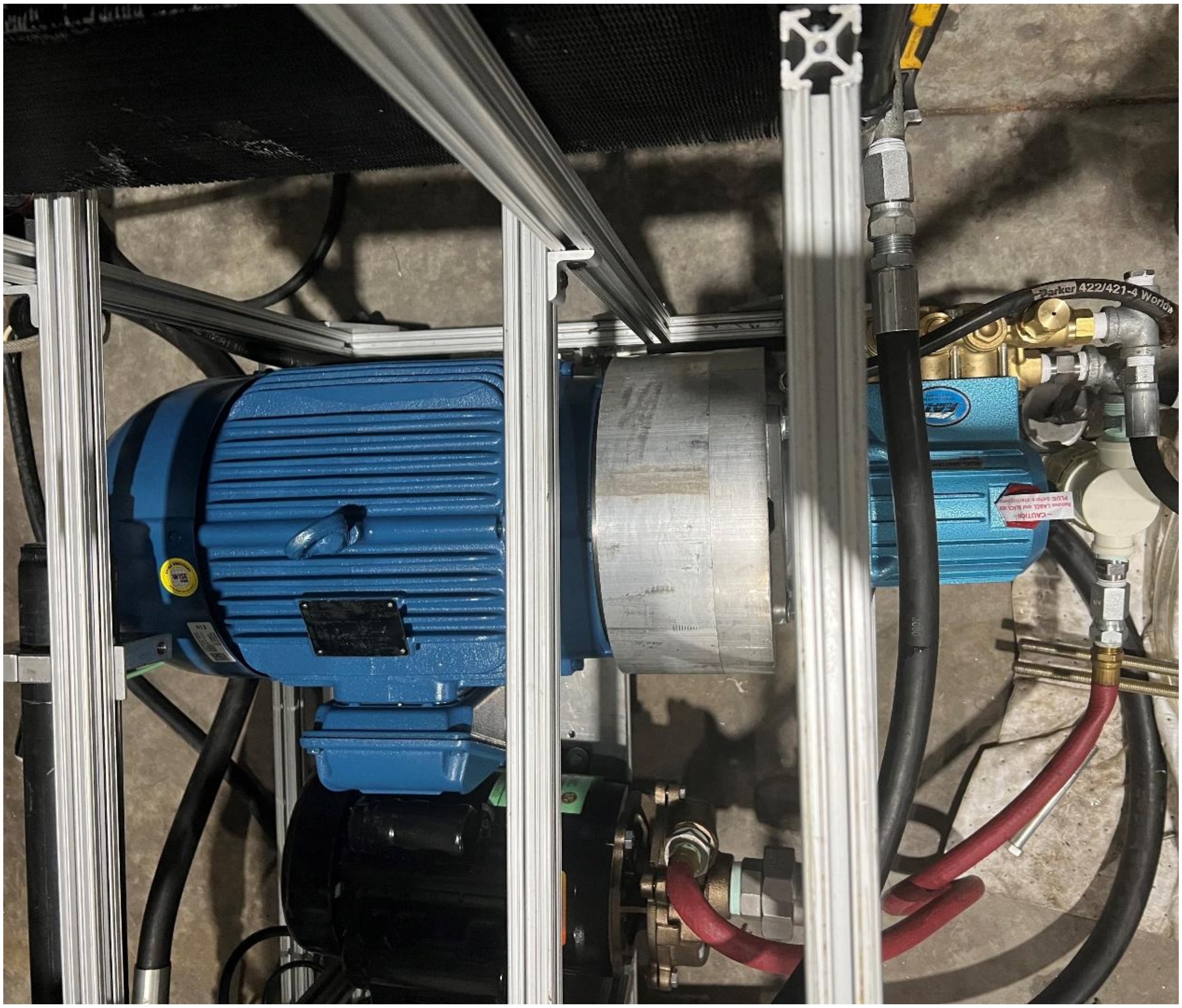

Figure 13: Centrifugal Pump and Triplex Pump

For the pressure system, the centrifugal pump alone was not providing sufficient pressure to the system. To combat this, a triplex pump was integrated to the pressure system shown in figure 13. This addition increased pressure and flow capacity as well as increased reliability. Pressure regulator valves and ball vales were added to the inlet of the DUT and flow control valves and ball valves were added to the outlet of the DUT to provide better monitoring and control of the pressure levels. The different valves were interchanged to find easy controllability of pressure with better accuracy.

Figure 14: Chiller Added to the Cooling System

Figure 15: Copper Coils Around the DUT

For the cooling system, the water reservoir was not cooling the system as expected during operations. The water circulating through the system was not cooling sufficiently with the water reservoir. Instead of the circulation through the reservoir allowing time for the water to cool and circulating cool water, the water circulating was warm and continuously added warm water from the DUT to the reservoir that did not cool at high speeds. A chiller was added to the circulating pump to ensure the water was cooling to a set temperature before circulating back to the DUT shown in figure 14. A water pump and flow control valves at the inlet and outlet of the DUT were also added to the cooling system to more accurately maintain the flow level in the DUT. An external copper coil around the DUT was added to provide external cooling of the system shown in figure 15.

3.1.4 Final Design

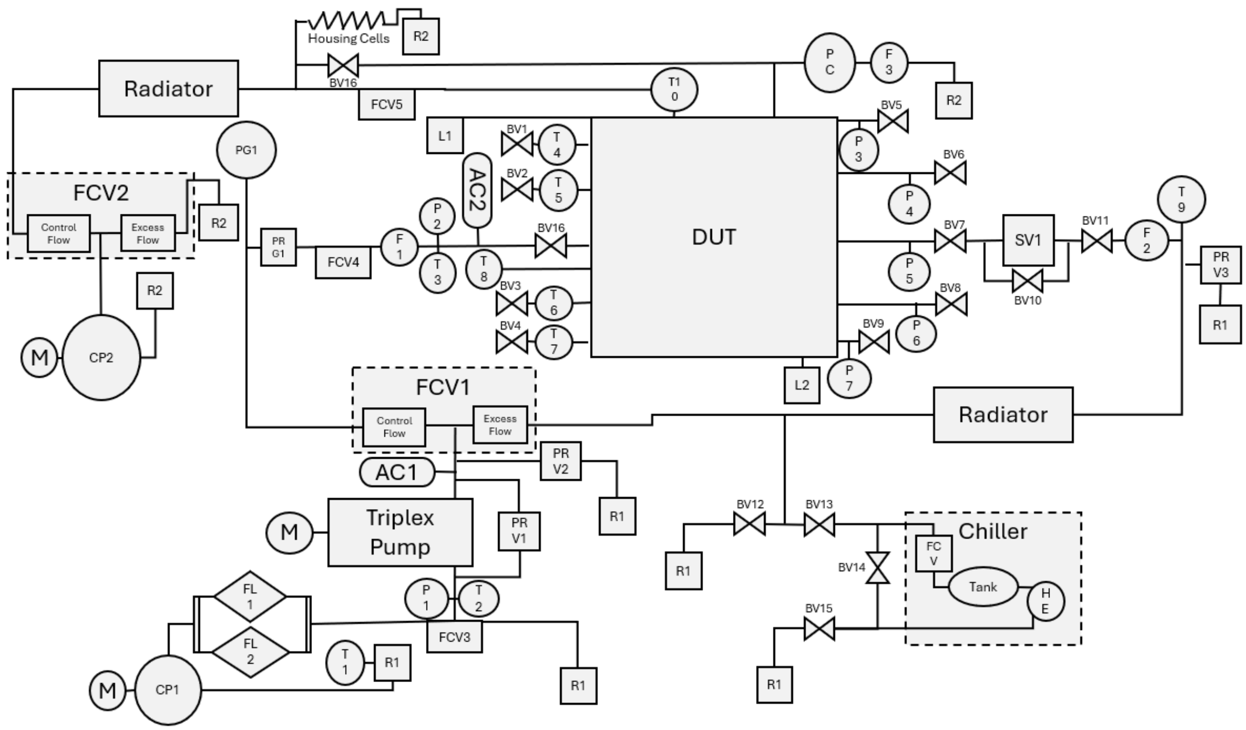

Figure 16: Block Diagram of the Final Test Setup Design

Table 4: Block Diagram of the Final Test Setup Design Key

COMPONENT	COMPONENT NAME
DUT	Device Under Testing
M	Motor
CP1-2	Centrifugal Pump 1-2
FL1-2	Flow Level 1-2
T1-10	Temperature Sensor 1-10
P1-7	Pressure Sensor 1-7

FCV1-5	Flow Control Valve 1-5
R1-2	Reservoir 1-2
PC	Pump Cooling
PRV1-3	Pressure Relieve Valve 1-3
AC1-2	Pressure Accumulator
PRG1	Pressure Gauge at Regulator Inlet
PG1	Pressure Gauge 1
SV1	Sequence Valve
F1-3	Flow Meter 1-3
L1-2	Leak Measurement 1-2
HE	Heat Exchanger

Figure 16 shows the block diagram of the final test setup design and table 4 explains each component's name. Figure 16 is also in appendix A for easier view. The final test setup design shows how all the subsystems are connected and work together. It also shows how the system is a loop since water is circulated through the entire system. The final design of each subsystem will be further discussed in section 3.2.

3.2 Overall Setup

3.2.1 Functions of the System

The test setup was designed and constructed to support testing of rotary shaft seals until failure. The setup has a hub to hold up to 3 seal pairs, variable speed control, adjustable pressure levels, and high flow control to mimic real world applications of rotary shaft seals. The hub supports different configurations and geometries of rotary shaft seals to support versatility in testing as well. The setup consists of five different subsystems to accommodate these functions. Each subsystem of the test setup works in conjunction with one another to obtain desired experimental results of rotary shaft seal testing.

3.2.2 Subsystems

3.2.2.1 The Device Under Testing (DUT) and Drive System

Rotary shaft seals must be able to function properly while interfacing with rotating components. The performance of the setup depends on maintaining high rotational speeds and torque to model real world applications of rotary seals. This is why having a reliable and controllable drive system is imperative for the functionality of the setup.

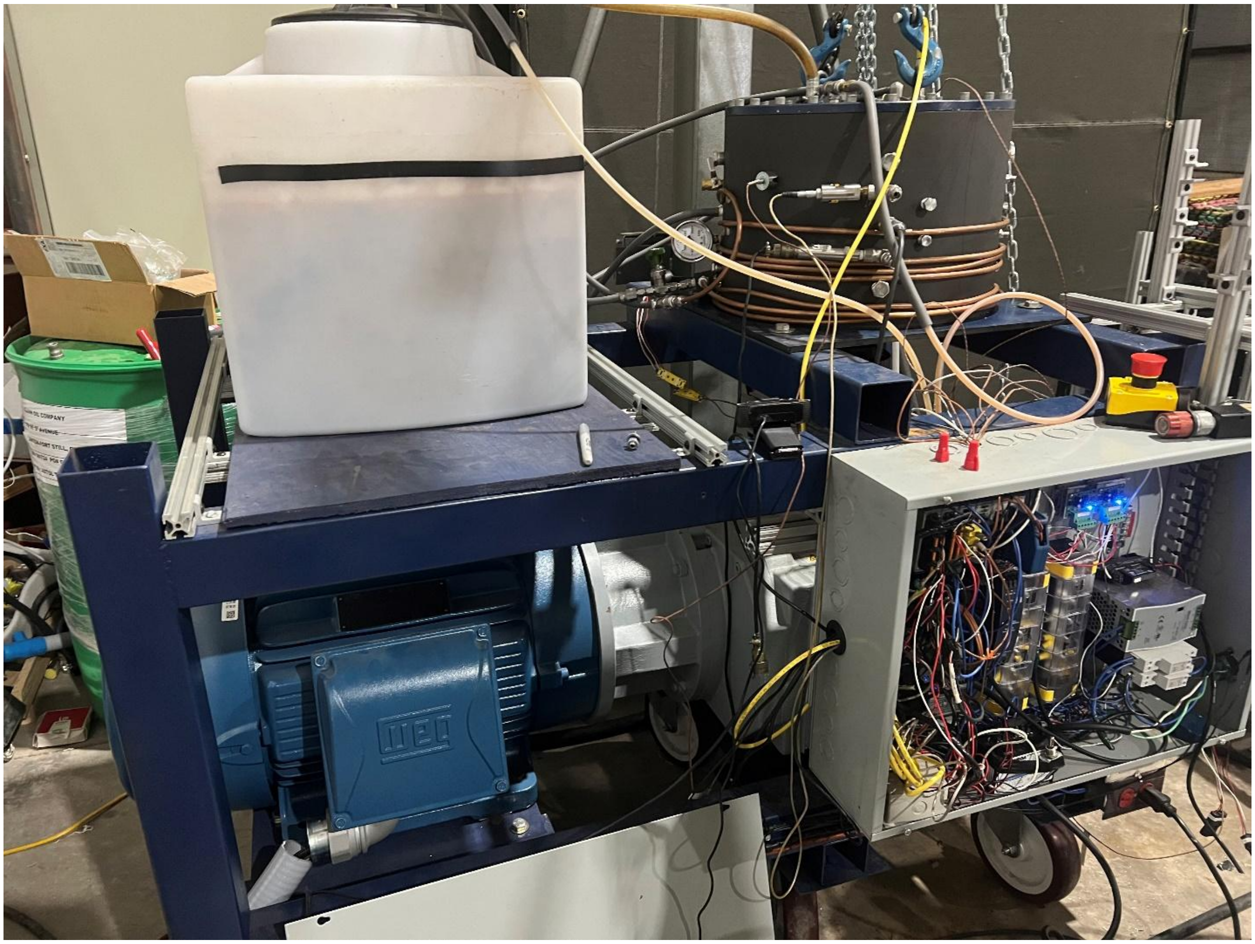

Figure 17: DUT and Drive System on the Frame

The device under testing or DUT is the encompassing hub that holds all the rotary shaft seals, designed and provided by a third party. It is connected to the drive system that powers the components to rotate the seals within the hub. Figure 17 shows the DUT in the upper right-hand corner. The drive system consists of a motor and gearbox. This is shown on the lower section of the frame with the motor on the left and the gearbox on the right.

The motor is an AC motor that operates on a 440 alternating current and generates 40 horsepower. It also has a speed of up to 3,600 revolutions per minute. There is also a 90-degree gearbox reducer to provide the desired amount of torque and speed for testing rotary shaft seals.

The gearbox can handle a maximum of 90 horsepower and has a 7.93 gear ratio. The rotational speed is controlled through data acquisition module, which takes an analog signal from the motor to a variable frequency drive or VFD which configures frequency to control the speed of the motor.

3.2.2.2 The Pressure System

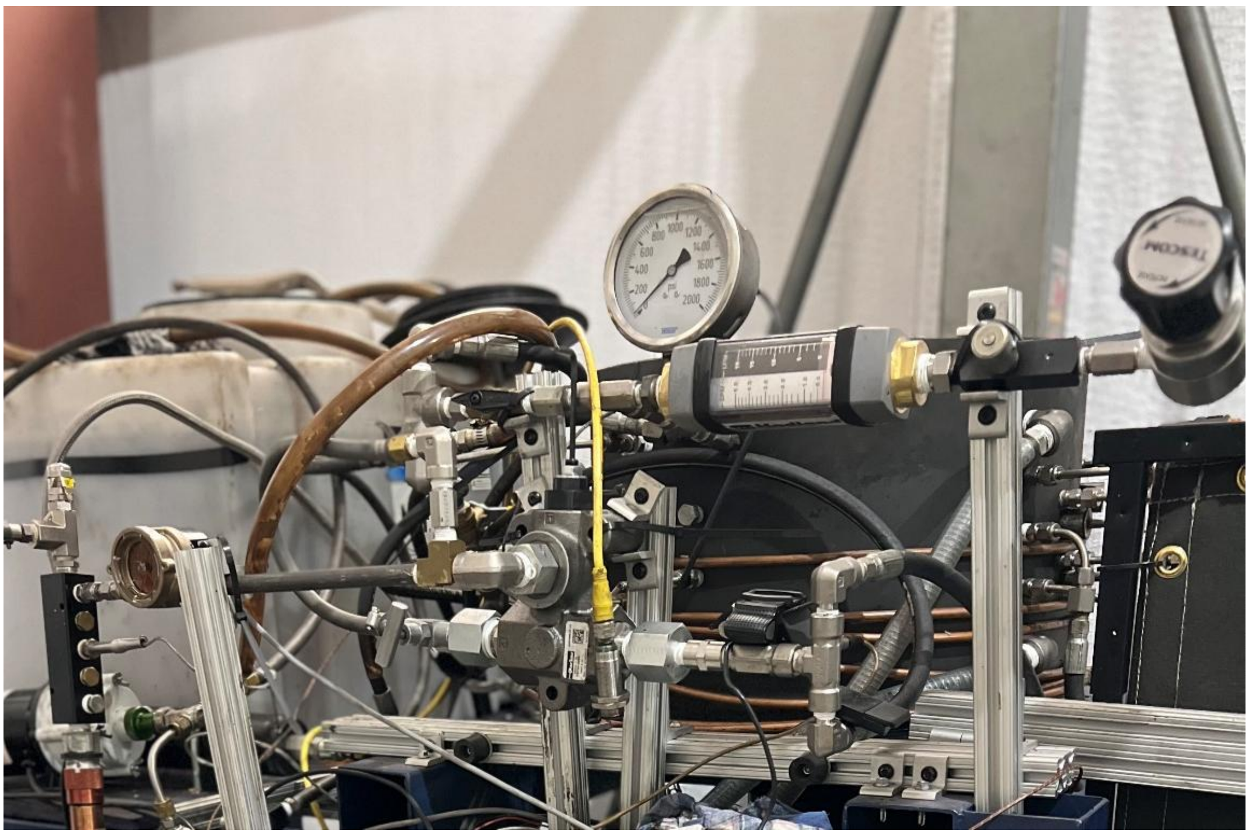

Figure 18: The Pressure System Connected to the DUT

The pressure system consists of a centrifugal pump, a triplex pump, a hydraulic control unit, numerous different types of valves, hoses, and different adapters. Figure 18 shows various pressure system components that are connected to the DUT. The specifications of the triplex pump are that it can pump 1.4 gallons per minute, can provide up to 2,000 pounds per square inch, has a horsepower rating of 2 horsepower, and operates on a 440 alternating current. The hydraulic power unit provides pressurized liquid to the system that is controlled with varying valves. It can hold a maximum of 3,000 pounds per square inch and has a 15-gallon reservoir capacity. There are four different valves in the pressure system including pressure regulator valves, sequence valves, flow control valves, and ball valves. The pressure regulator valve provides control over the level of pressure entering the DUT during testing. The sequence valves are used to direct flow from the DUT to flow control valves. The flow control valves make sure the pressure is constant while traveling through the system. Connected to the pressure regulator valves and flow control valves are ball valves. The ball valves open or close a pressure line to either maintain pressure or relieve pressure from the system.

3.2.2.3 The Cooling System

Figure 19: Various Components in the Cooling System

The cooling system includes a water circulating pump, 2 radiators, an external coil around the DUT, 3 fans, a water reservoir, a chiller, hoses, and adapters. Figure 19 shows the chiller, the water reservoir, a fan, the radiators, and some other components of the cooling system interfacing with the whole system. The water circulating pump works on 220 VAC, a maximum flow rate of 10 gallons per minute, a maximum pressure of 7 pounds per square inch, and has a temperature range of 35°F to 150°F. The two radiators in the cooling system help keep the system cool by dispersing heat from the circulating fluid through the fins of the radiator to the surrounding air. An external copper coil is wrapped around the DUT to keep the hub cool to mitigate damage of the seals and prolong testing times before the seals break. There are flow control valves in the cooling system to help regulate the flow of the circulating fluid through the system.

3.2.2.4 The Control and Data Acquisition

Four data acquisition modules are used in the control and data acquisition system. The first module has digital output and 16 channels. It is used for controlling 3 speeds to measure the DUT shaft speed. The second module gives voltage output and has 32 channels. It controls variable speeds of the motor. The third module takes voltage measurements and has 32 channels. It measures the motor speed, pressure sensors, and torque sensors. Lastly, the fourth module is used for temperature measurements and has 16 channels. It is connected to the temperature sensors throughout the system. These modules relay information digitally which is recorded using NI LabView. LabView is then set up to display the data for monitoring throughout the test, record the data, and output the data for analysis of the performance of each experiment.

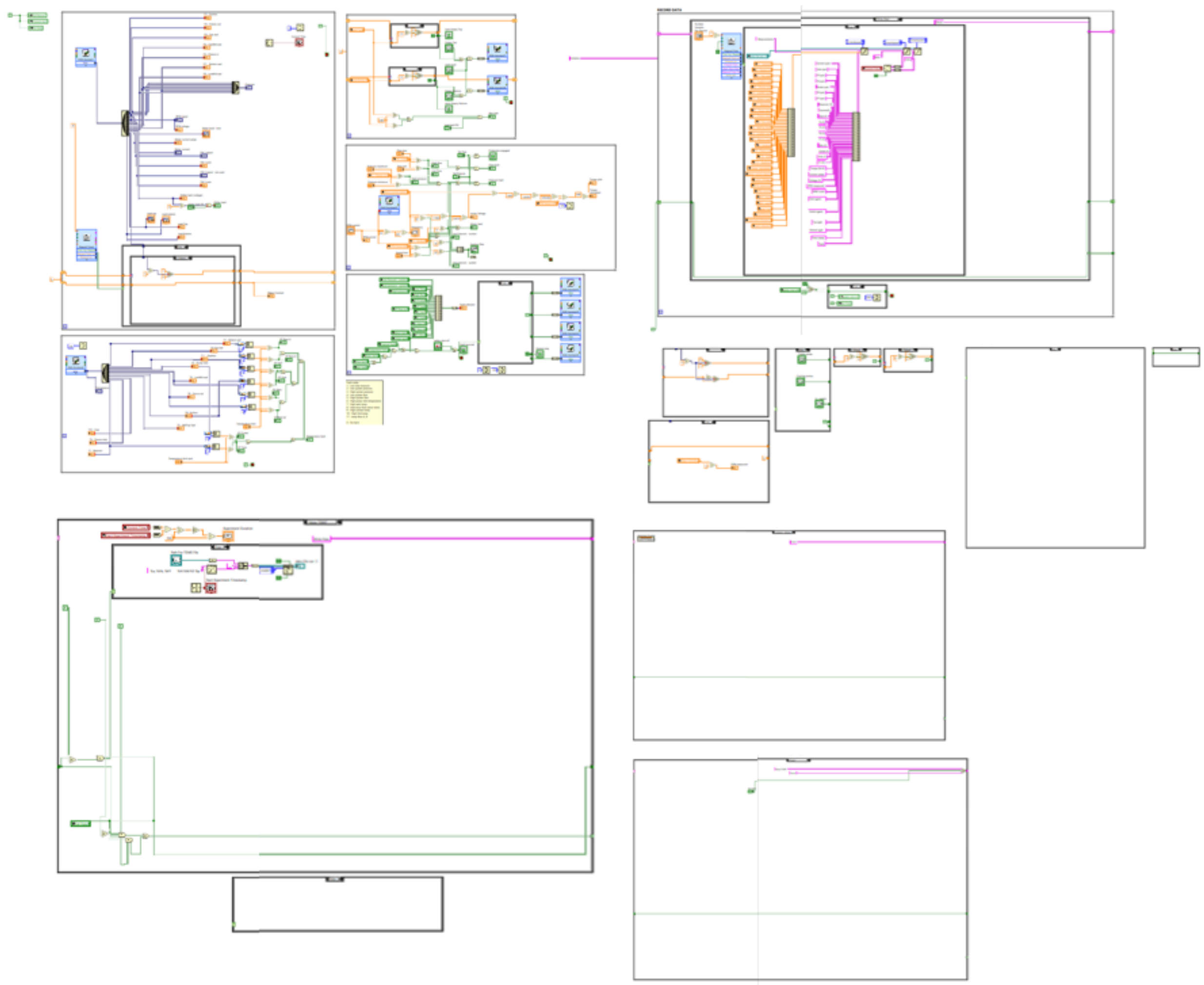

Figure 20: LabView Control Panel

Figure 20 shows the LabView control panel. The control panel is where all the channels in the DAQ are configured to display data using LabView and where the safety shut-off features are added. The pressure, temperature, speed, current, and leak rate data are acquired from sensors in the VFD and additional measurements while the frequency and motor voltage are proportional to the speed of the motor. Using this data ensures there is enough data to calculate for the torque data throughout the test. Torque is calculated using the electric motor torque equation

$$T = \frac{(I * V * \eta)}{100 * 60} * \frac{2\pi}{rpm} \quad (2)$$

where I is the current in amps, V is the voltage in volts, η is the efficiency of the motor, and rpm is the rotations per minute, which is shown in English units in the LabView control panel. The control panel also provides user input to set the flow rate, pressure, and temperature limits that cause the system to shut down if any of these values are exceeded.

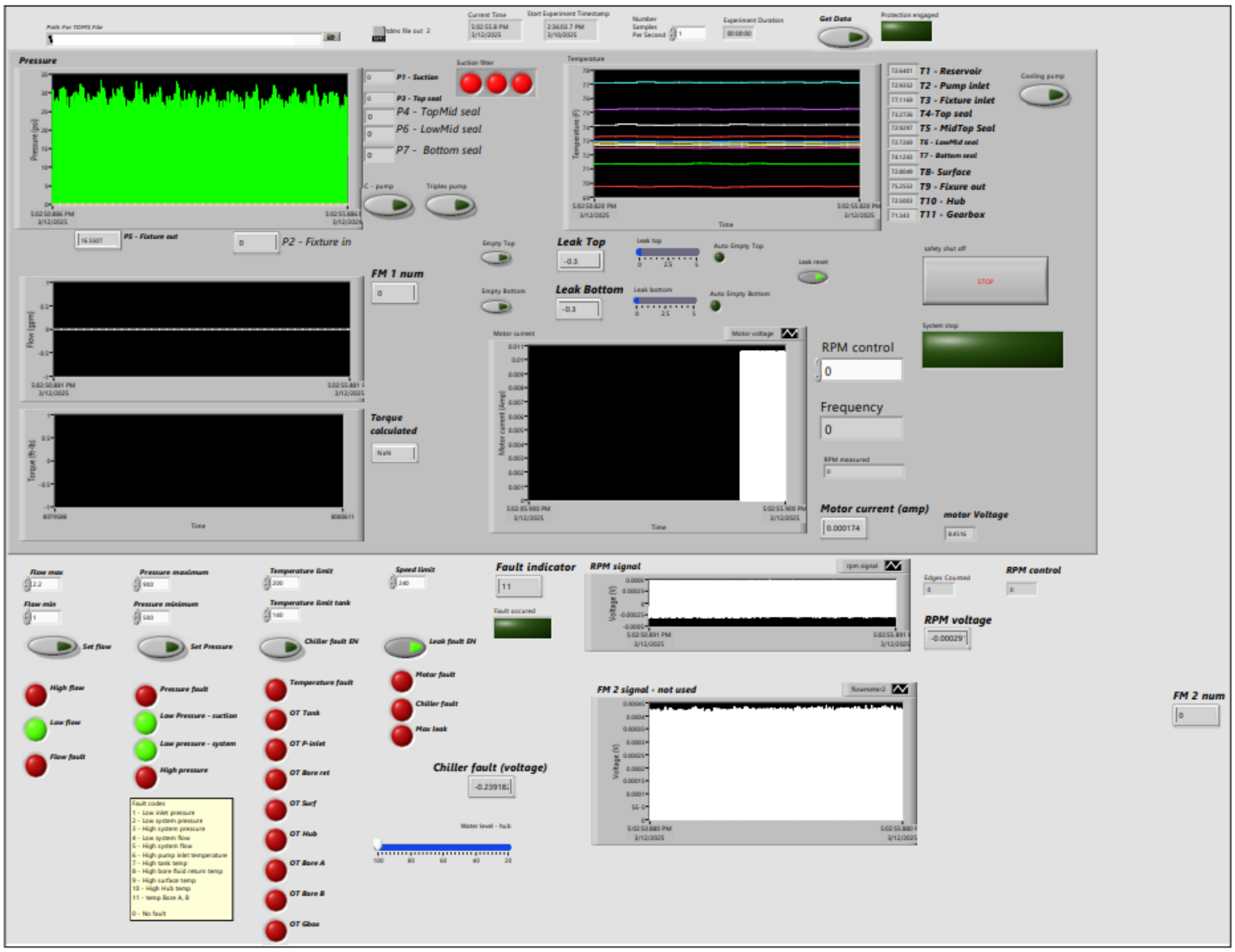

Figure 21: LabView Screen for Test Setup

Figure 21 shows the screen for LabView. The top part of the screen is where the file path is entered to save the data, the button to start recording data, and the duration of the recording. The graph in the top left-hand corner shows the different pressure levels at the inlet of the DUT, the outlet of the DUT, at the inlet of the triplex pump, at the top seal pair, between the top and middle seal pair, between the middle and bottom seal pair, and at the bottom seal pair. The three red dots titled," Suction filter" indicates if the filter for the triplex pump needs to be cleaned out. The two buttons next to the graph turn the centrifugal and triplex pump on or off. The two graphs below the pressure graph show the flow rate of the system and the torque calculated.

On the top right side of figure 21, there is the temperature graph. The temperature graph shows the temperature at the water reservoir, at triplex pump inlet, at the DUT inlet, at the top seal pair, in between the top and middle seal pair, in between the middle and bottom seal pair, at the bottom seal pair, at the surface of the DUT, at the outlet of the DUT, inside the DUT, and at the gearbox. To the left of the graph, there is a button to turn on and off the cooling pump. The leakage data is below the temperature graph. There are two buckets to capture any leakage of the system, the leak top and the leak bottom. Each bucket has a capacity of 4 gallons before it automatically empties itself but can also be controlled by the buttons to the left of the values. To the right of the leakage data is the safety shut off button. If the button is pressed, the whole system turns off immediately. Below the leakage data is the motor current graph. To the right of that is the rpm control, frequency, and motor voltage values, which are all proportional to each other.

Table 5: Fault Code Definitions

Fault Codes	**Definition**
0	No Fault
1	Low Inlet Pressure
2	Low System Pressure
3	High System Pressure

4	Low System Flow
5	High System Flow
6	High Pump Inlet Temperature
7	High Tank Temperature
8	High Bore Fluid Return Temperature
9	High Surface Temperature
10	High Hub Temperature
11	High Temperature at Port A and B

The bottom half of figure 21 shows the safety features and fault warnings implemented into LabView. The maximum and minimum values for the flow rate, pressure level, temperature, and speed can be inputted into this portion and clicking the corresponding buttons enables these limits. If these limits are enabled, the system will automatically shut off if either the maximum or minimum values previously entered are reached. There is also a series of sensors that will give a fault code if any values are unordinary as an extra level of safety monitoring. The definition of each fault code is given at the bottom left-hand corner in figure 21 and also in table 5 for an easier view of each definition.

Table 6: Test Setup Typical Safety Shutoff Values

Condition	**Values**
Flow Maximum	0.1388 L/s
Flow Minimum	0.06309 L/s
Pressure Maximum	6,205 kPa

Pressure Minimum	3,500 kPa
Water Temperature Maximum	93 ℃
Fixture Temperature Maximum	60 ℃

Table 6 shows the typical safety shutoff values entered into the LabView during testing. These values are only enabled after all the pressure and speed increases in the test procedures, since the pressure levels during the test will be below the minimum pressure in table 6. When the minimum pressure is enabled, it will shut off the system if there is a drastic decrease in pressure.

3.2.2.5 The Frame

The frame of the test setup is split into two parts. The first part is built of steel metal sheets to hold the motor, gearbox, the torque sensor, the DUT, the electrical box, hydraulic power unit, the water circulating pump, and a water reservoir. This part of the frame was built to be sturdy but on wheels to accommodate for moving of the fixture. It holds the heaviest components of the setup. This part of the frame was made to hold a water reservoir leveled with the DUT to ensure sufficient flow during operations. The second part of the frame is built from aluminum t-slotted framing rails to hold the centrifugal pump, triplex pump, both radiators, a fan, filters, a water reservoir, and the chiller. This fixture is also on wheels for easy access and movement.

Chapter 4: Testing of Designed Setup

4.1 Testing Procedure

To test the setup, a testing procedure is necessary to clearly outline the operations of the setup. The test procedure is used to evaluate the rotary shaft seals performance with the test setup. The procedure will show all the intermediate steps taken from no speed and pressure to 18 radians per second and 4,800 kilopascals. The duration of the test will last until the seals reach failure.

Table 7: Test Setup Conditioning Testing Procedure

Target Start Time (hh:mm:ss)	**Target Duration (min)**	**Target Speed (rad/s)**	**Target Pressure (kPa)**
00:00:00	2-30	5-11	400-1,000
1:12:00	10-30	0-11	1,000-2,000
1:55:00	1-30	0-18	400-2,000
3:20:00	1-30	0-18	1,000-4,800
4:58:00	2-20	0-18	400-4,800
5:56:00	1-10	5-18	400-3,400
6:20:00	Until Failure	15-18	3,400-4,800

Table 7 lists the conditioning test procedure for evaluating the setup. The conditioning test provides an even initial wear on the sealing lip of the rotary seals which helps prevent any accumulation of heat where the seals and shaft meet. The target speed and pressure are increased in increments to give the test setup time to stabilize. More time is allotted for major increases in speed or pressure as well. This is being done to allow time for the current to stabilize to prevent any overheating or damage to the motor. The test is conducted until the seals fail while being continuously ran at 18 radians per second and 4,800 kilopascals to test the duration of the seals under high speeds and high pressure as well as how the test setup holds up under these extreme testing conditions.

4.2 Testing Results of Conditioning Test

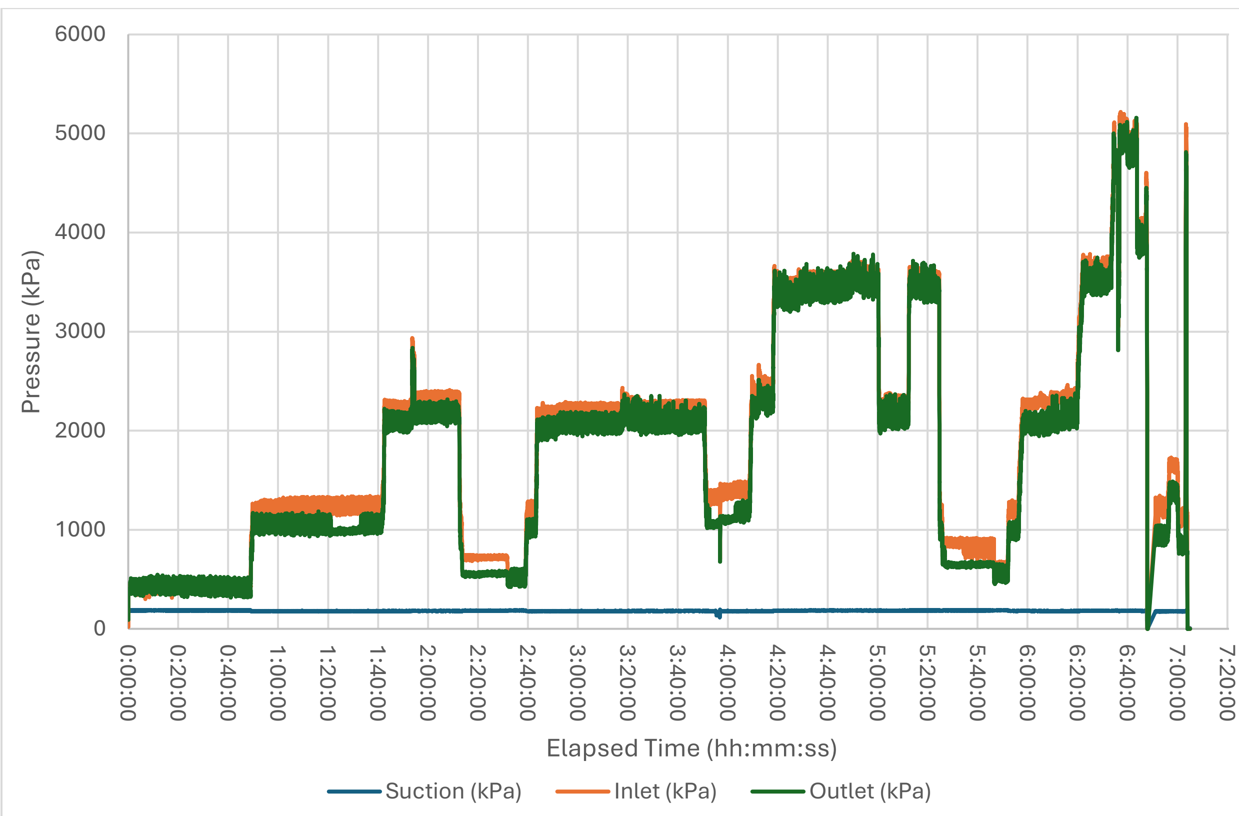

Figure 22: Suction, Inlet, and Outlet Pressure Data for Conditioning Test

Figure 22 shows the pressure levels of the suction of the triplex pump, the inlet pressure of the DUT, and the outlet pressure of the DUT. The suction pressure is constant at about 1,700 kilopascals. This is to ensure that the triplex pump has water to continue operating at high pressure. The inlet pressure and outlet pressure of the DUT are at similar levels throughout the entire conditioning test, showing that the DUT is holding constant pressure. The target pressure is consistent with the test procedure at the beginning of the conditioning test from the elapsed time of 00:00:00 to 1:25:00. It starts deviating as more time is allotted for the current to stabilize. The pressure is then raised to 2,000 kilopascals around the time of 1:45:00. At around 1:50:00, there is a spike in pressure. An increase in the temperature at the hub is seen at the same time shown in figure 23. At approximately 5:25:00, the pressure was dropped back to about 400 kilopascals instead of being increased to 4,800 since the current was not stabilizing and the temperature at the outlet was increasing rapidly. At about 6:30:00, a second attempt was made to raise the pressure to 4,800 kilopascals, however, the current was still unsteady and raised beyond 35 amps, tripping the safety shutoff. The setup was powered back on, and the conditioning test was restarted at about 6:45:00 but stopped when the seals failed shortly after.

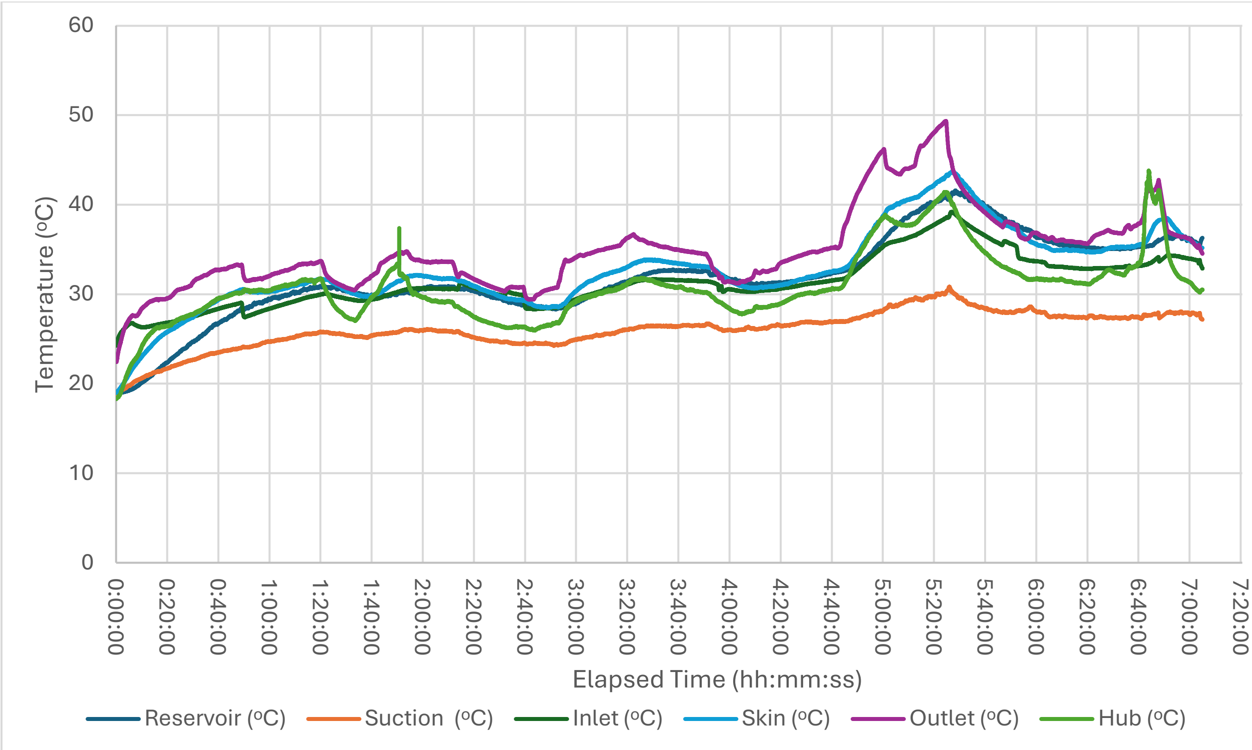

Figure 23: Varying Locations Temperature Data for Conditioning Test

Figure 23 shows the temperature at the reservoir, the suction of the triplex pump, inlet of the DUT, the skin or exterior of the DUT, the outlet of the DUT, and the hub or inside of the DUT. The temperature at each location is similar in value for the majority of the conditioning test with some deviations. For most of the test, the outlet temperature is the highest while the suction temperature is the lowest. This shows that the water circulating out of the DUT is the highest temperature, as expected since the seals are producing heat throughout the test. The suction is furthest from the DUT which also makes sense why its temperature is the lowest. Figure 23 also shows that the temperature is being maintained through the cooling system since the inlet temperature is always lower than the outlet pressure and the temperature of the hub is fairly consistent until late in the test. At approximately 6:45:00, the highest temperature is at the hub. This likely marks when the seals failed in the test.

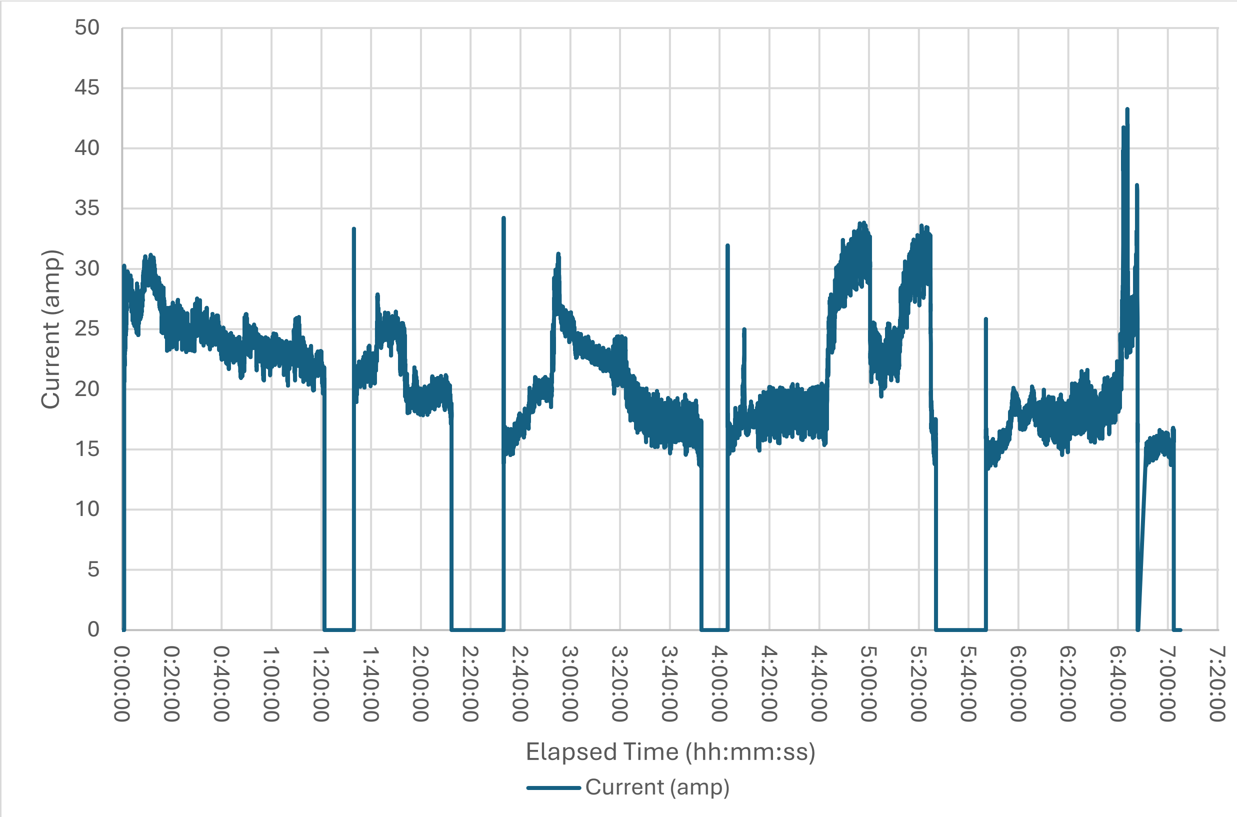

Figure 24: Current for Conditioning Test

When power is initially applied to the motor, there is a high increase in current draw to overcome inertia. This is known as inrush current. This is shown in figure 24 as the current spikes when the speed ramps up from 0 radians per second. Since the motor has a rated current of 46.3 amps, there is a safety shut off to turn off the setup when it reaches 35 amps. At around 6:40:00, figure 24 shows the current jumping from 20 amps to 40 in a short amount of time and the current dropping to 0 amps shortly after, as the safety shut-off was triggered and the test was restarted.

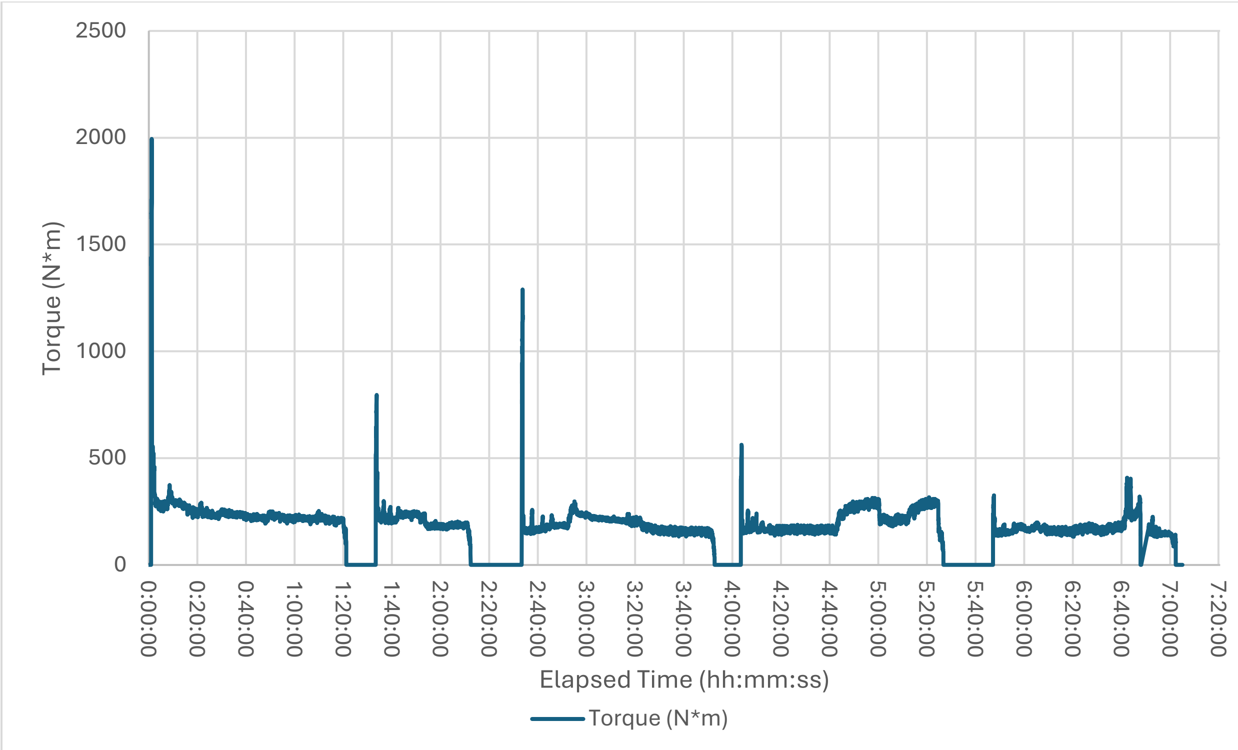

Figure 25: Torque Data for Conditioning Test

The torque data from the test shown in figure 25 is similar in trend with the current, which is expected. This means the torque calculations using equation 2 are consistent, showing the accuracy of LabView's calculation abilities. The torque spikes up as the testing procedures change the target speed and pressure, decreases in a short amount of time, and starts to stabilize around 300 Newton-meters. At about 4:40:00 through 5:20:00, there are some irregular increases in the torque compared to the beginning of the test. This could be due to any buildup in the system, as the torque increase to overcome the buildup. Figure 25 also shows the torque dropping to 0 newton-meters at around 6:45:00, when the conditioning test was restarted.

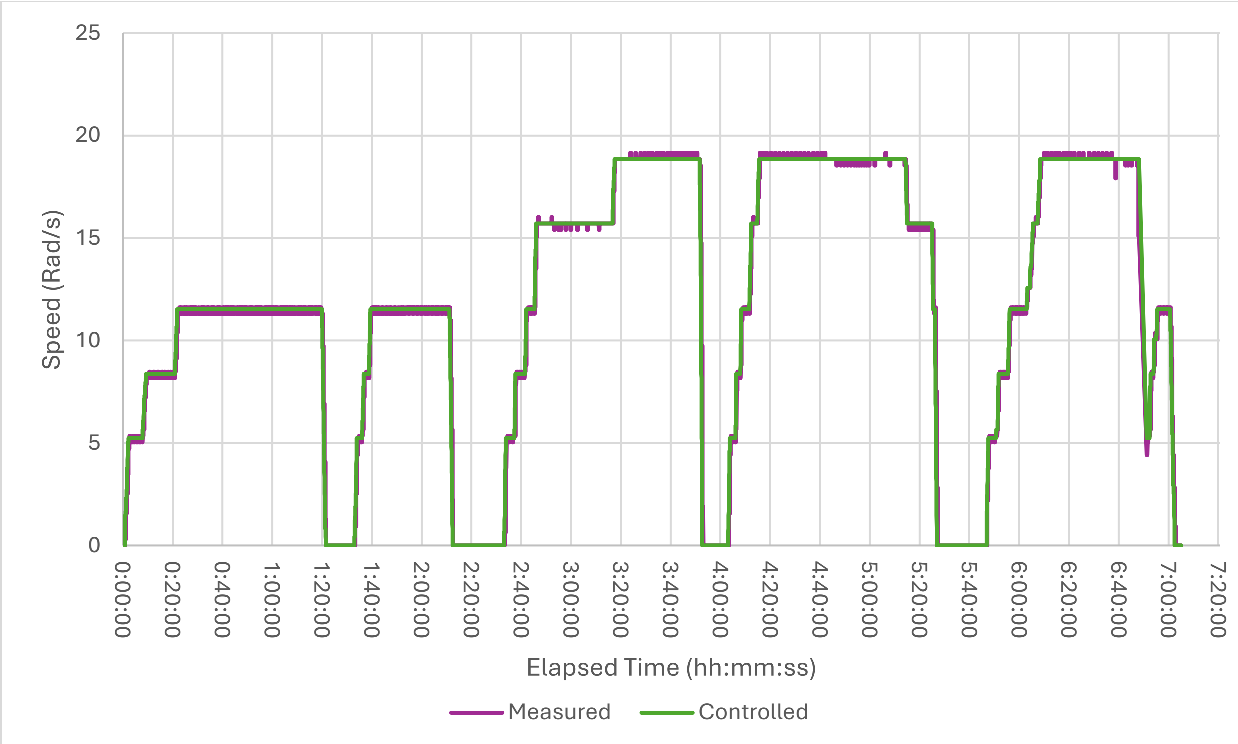

Figure 26: Speed Data for Conditioning Test

Figure 26 shows the speed data for the controlled speed from LabView and the measured speed data. The measured and controlled speed data are very similar in value, showing that the LabView control of the speed is very accurate. There is very minimal deviation from the measure speed versus the controlled speed. The speed data shows the expected values throughout the test which shows the speed control is reliable even as the pressure, temperature, and current waver as the seals fail.

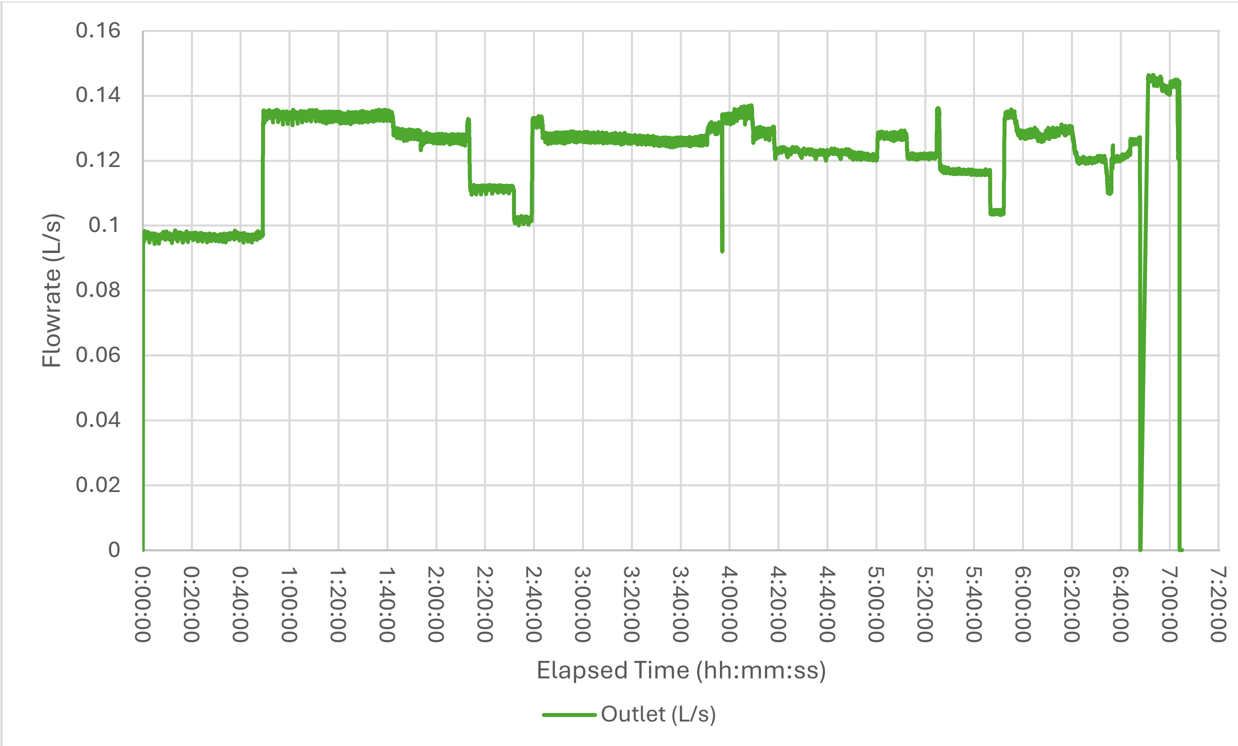

Figure 27: Outlet Flowrate Data for Conditioning Test

The outlet flowrate of the DUT is represented in figure 27. The flowrate trend is similar to the trend of the pressure data, except for the last half hour of the test, where the flowrate increases as the pressure is low. This shows that the seals have failed, causing the higher flowrate. There are also some irregularities in the flowrate from about 4:20:00 to 5:00:00 compared to earlier in the test. This could be due to some buildup in the system causing stalls in the flowrate.

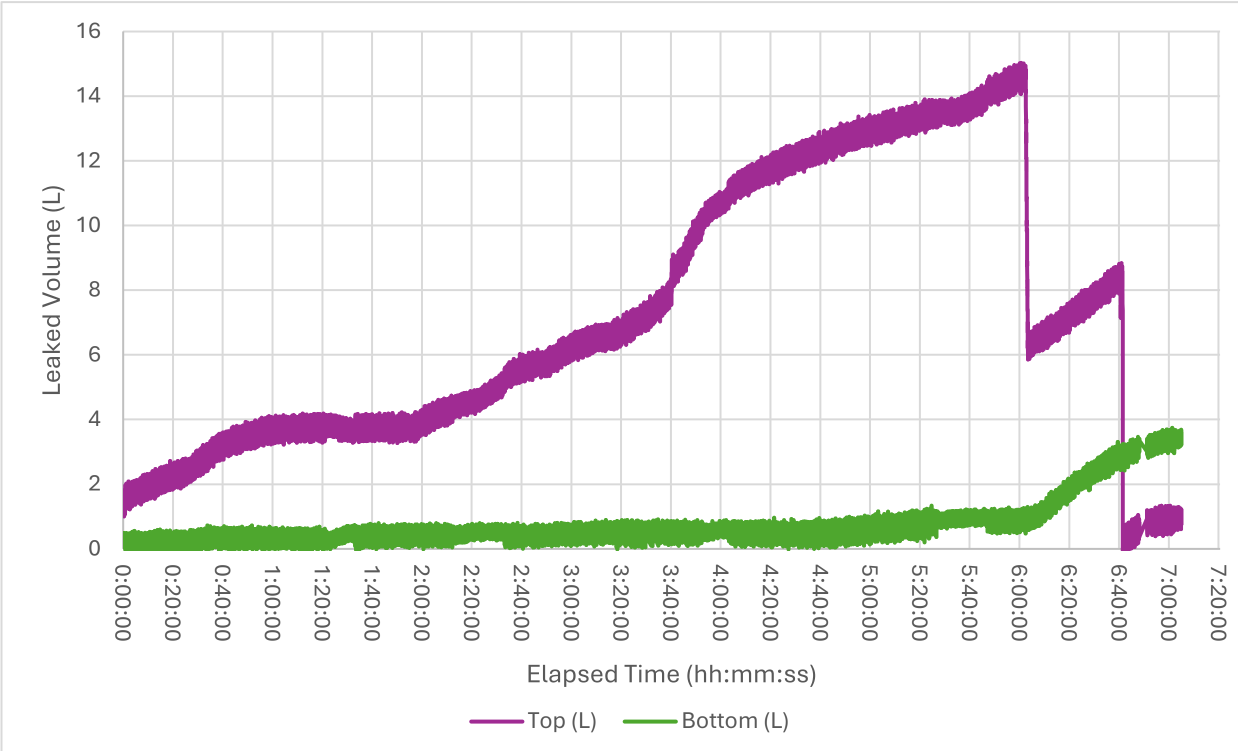

Figure 28: Top and Bottom Leaked Volume for Conditioning Test

Figure 28 shows the leak volume for the top seals and the bottom seals throughout the conditioning test. The top seals continued to leak throughout the duration of the test but increased at a faster rate after around 3:40:00. The bottom seals began to leak at about 5:00:00. After restarting the test at 6:45:00, both top and bottom seals had continued to leak. This is a sign that the seals had reached failure.

Figures 22 to 28 all show a drop in data at approximately 6:45:00, indicating when the seals likely failed. Since both leak volumes in figure 28 continue to increase when the test was restarted, this is another indicator that the seals failed at 6:45:00. This conditioning test shows that the test setup has the capability to test the rotary seals until failure.

4.3 Comparison of Various Tests

The conditioning test showed that the setup was able to conduct a test until the rotary seals failed. To test the full capability of the setup, multiple tests were conducted with different rotary seals in different configurations to verify if the setup was able to test other rotary seals until failure.

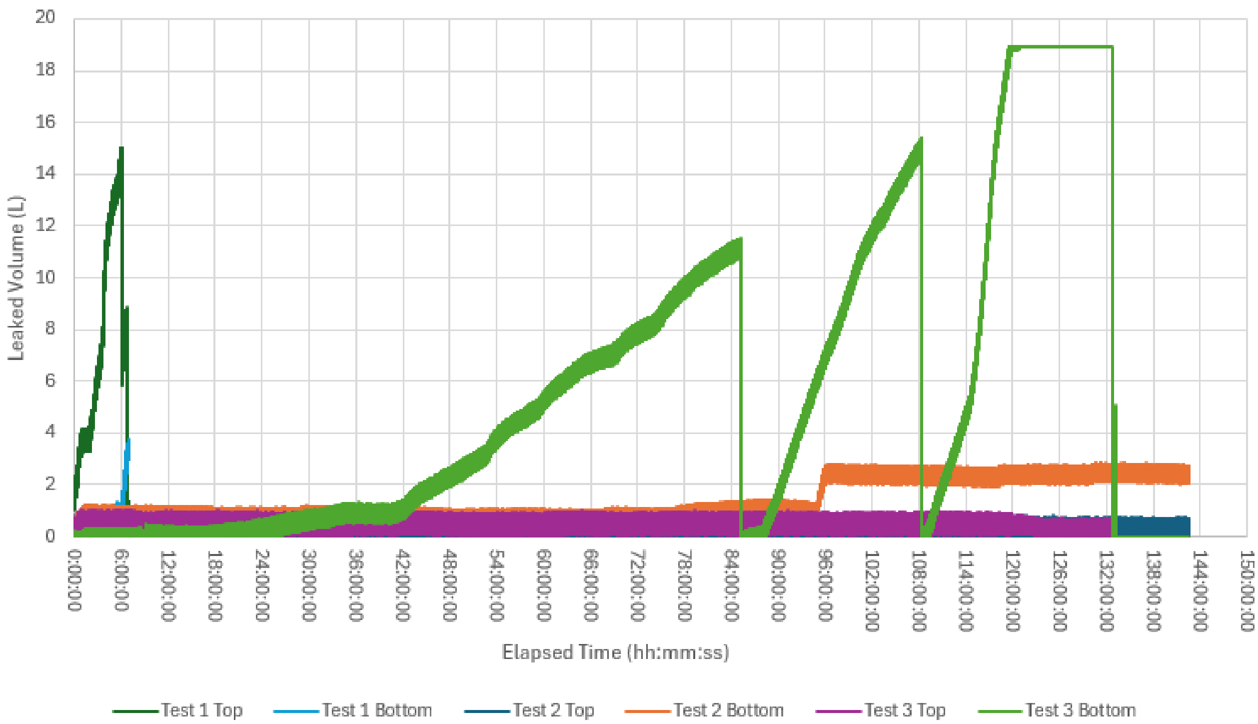

Figure 29: Leaked Volume from Three Rotary Seal Tests

Multiple tests were conducted with various seals requested by the third-party sponsor and each test was conducted with similar testing procedures as the conditioning test. Figure 29 shows the leak volume for the top and bottom of three different tests. Test 1 in the figure, refers to the conditioning test detailed earlier while test 2 and test 3 were test conducted with different seals.

As shown in figure 29, test one failed the earliest of the two tests at approximately 6 hours and 45 minutes while test 2 failed at approximately 142 hours and test 3 failed at about 133 hours. This shows that the setup can confidently test seals until failure whether it is a short-term test or a long-term test. Figure 29 also demonstrates how different seals can vary in leak volume before they fail. The highest leak volume that test 1 experienced was about 15 liters until the rotary seals failed, which is not far from test 3, as the highest leak volume is almost 20 liters. Despite test 2 being the longest lasting test, it had the lowest leak volume of about 3 liters. This shows the different characteristics of the seals that were tested. It also displays the range of performance for rotary shaft seals depending on the geometry of the seal and what material they are made of.

Chapter 5: Concluding Remarks

5.1 Summary

Rotary shaft seals are used in a large number of different industries. They are used as a barrier protecting working liquids and internal components from outside contaminants such as dirt, mud, or dust in machinery. They can be used in extreme conditions at high speeds in conjunction with high temperatures and high levels of pressure. It is valuable to create a test setup to test and evaluate different rotary shaft seals as they are used in very costly machinery and come in a variety of geometries and materials. The objective of the test setup was to be able to test rotary shaft seals until failure while being able to control and monitor pressure levels, speed, and maintain operating temperatures.

Before creating the setup, background research was done to understand the typical operation of rotary shaft seals and how different aspects of the system environment affect each other. The viscosity of lubrication, rotational speed, surface roughness, contact load, and alignment of the shaft to the seals all affect the performance of rotary shaft seals. Therefore, it is important to identify problems that may arise from these aspects to optimize the design of the test setup.

After the background research, the test setup was created using an iterative design process where all the requirements of the test setup were identified first. The requirements of the set up were obtained through identifying typical operations of rotary seals in real world applications. The requirements of the test setup were to hold up to 3 rotary seal pairs, withstand temperatures of up to 93 degrees Celsius, allow for operating speeds of 0 to 200 revolutions per minute, have a pressure range of 0 to 6,895 kilopascals, have a flowrate of 21 liters per second, and be able to test the seals until failure. From there, five modular subsystems were created to meet each requirement. The subsystems were the DUT and drive train, the pressure system, the cooling system, the control and data acquisition system, and the frame. Each system was created modular to easily change or improve the components within each system through out the iterative design process.

After the final design and manufacturing of the test setup were completed, tests were conducted with rotary seals to evaluate if the system met all the requirements. The conditioning test conducted proved the capability of the setup as the speed and pressure were able to be controlled, the cooling system displayed adequate temperature levels, and the seals were able to be tested until failure. After running numerous tests with the setup, it was proven to successfully test multiple sets of seals until failure, showing the capability and reliability of the test setup.

5.2 Limitations

The system utilizes many hoses throughout the test system as the cooling system constantly circulates water through the whole setup when it is in operation. There have been noticeable signs of build-up visible from the clear hoses used in the cooling system. This causes a stall in flow rate and not only affects the hoses but also the connectors and the DUT itself as the DUT is always filled with water and likely accumulates build up similar to that in the hoses. This can be concluded from irregular stalls in the torque, especially since the surface roughness is measured before tests to ensure that each component in the DUT is aligned with the shaft. This creates a limitation because of the need to change out hoses to minimize the effects of the buildup in the hoses to ensure the data being recorded is an accurate representation of the performance of the seals, rather than outside factors.

5.3 Recommendations

The water that is circulated throughout the test system is water from the city of Noman. Water from the city system contains minerals that can cause buildup, corrosion, or rust in the DUT, and overall reduces the quality of the test setup. A recommendation to improve the reliability of the test system is to run it with distilled water or deionized water instead. Since distilled or deionized water is free of minerals that cause corrosion or rust, changing the water in the cooling system will improve the longevity and performance of the system. It will also reduce the hassle of changing hoses due to too much buildup.

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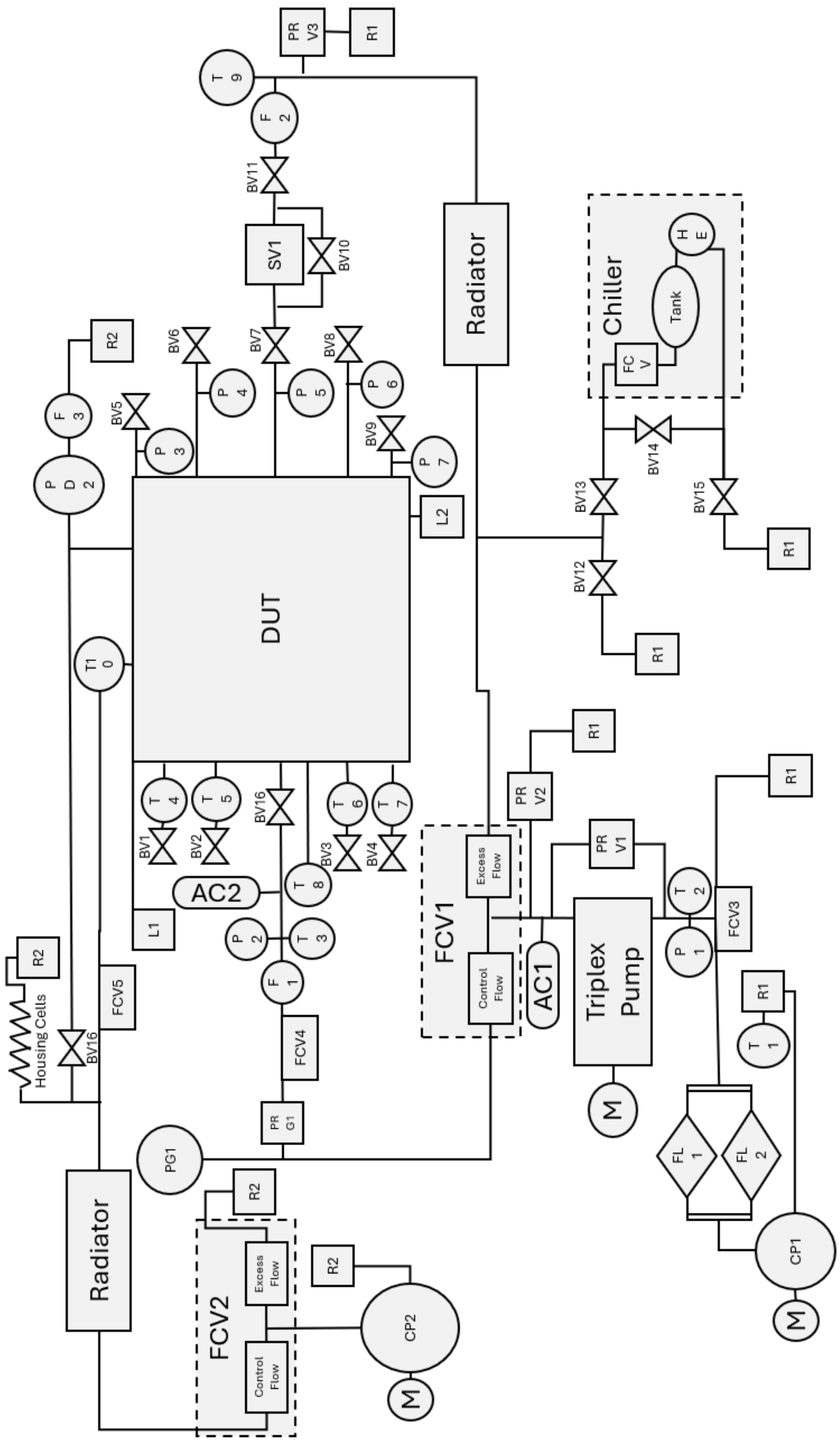
Appendix A


DUT
Radiator
Radiator
Chiller
Tank
FC V
H E
Triplex Pump
FCV1
Excess Flow
Control Flow
FCV2
Excess Flow
Control Flow
AC1
AC2
SV1
CP1
CP2
M
M
M
PG1
PR G1
PR V1
PR V2
PR V3
P D 2
Housing Cells
FCV3
FCV4
FCV5
FL 1
FL 2
L1
L2
R1
R2
BV1
BV2
BV3
BV4
BV5
BV6
BV7
BV8
BV9
BV10
BV11
BV12
BV13
BV14
BV15
BV16
F 1
F 2
F 3
P 1
P 2
P 3
P 4
P 5
P 6
P 7
T 1
T 2
T 3
T 4
T 5
T 6
T 7
T 8
T 9
T1 0