S.E.A.L.S.

SYSTEM FOR THE ENVIRONMENTAL ANALYSIS OF LUNAR SEALS

By

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System for the Environmental Analysis of Lunar Seals (S.E.A.L.S.)

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Abstract

The following report will outline the processes carried out and results achieved during the design and manufacture of an apparatus to test the effectiveness of lunar dust seals. The report discusses all steps the team took to develop a design that meets the specifications given by Paragon Space Development Corporation. The construction of this design required the team to machine custom parts and is discussed in full in the following report. The team composed and carried out a method to validate and verify that all functional requirements and constraints were met by the prototype. The apparatus designed and constructed by the team is able to test five rotary shaft seals simultaneously in a simulated lunar environment.

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1. Introduction

This project was undertaken to satisfy the needs of Paragon, NASA, and other space development companies by creating an instrument to qualify and quantify the effectiveness of lunar dust seals. It is important to improve the quality of lunar dust seals because this will lengthen the life of instruments used in a lunar environment. The dust in question is highly deleterious and can cause significant damage to mechanical parts on machines such as lunar rovers. This project included the simulation of the conditions on the moon caused by mechanical disturbances in order to effectively test the seals.

The completed system could be implemented in the future as a standard for testing rotary shaft seals designed specifically for lunar applications. One of the advantages of this apparatus is that it was built with a budget that is a fraction of comparable products' prices, which are in the range of $150,000. In addition, previous products could only test one shaft at a time and did not allow for linear or angular offset of the shafts. Most importantly, similar machines have the purpose of testing rotary shaft seals for the automotive and other similar industries. Paragon desired an apparatus that was specifically related to testing seals to be used on the moon. It was necessary that this application take place in a vacuum, but no previous systems allowed for such a test. The product the team developed can test multiple seals at once, allows for angular and linear offset, and is capable of stirring dust similar to dust found on the moon, all while under vacuum. In summary, the customer needed a realistic, cost-effective apparatus to reliably test numerous rotary shaft seals simultaneously under lunar conditions.

The following report enumerates all the steps the team took that led to the production of the final prototype. The report will lay out the requirements and constraints set forth by the sponsor (Paragon) and will discuss the three preliminary designs and how the team evaluated these. Next, the final design will be discussed in depth, as well as its implementation and the changes that were made to the original concept. Finally, the final testing and results, as well as the team's recommendations, will be reviewed.

2. System Requirements

The top level functional requirements for this project were that the apparatus be able to facilitate ergonomic inspection of the lunar seals, standardize the dust concentration in the chamber. In addition, the apparatus needed to be designed with the ability to set and record both lateral and angular offsets of the rotary shafts. This was necessary for complete seal testing because either type of offset could cause a seal to fail. No competitors have systems with adjustable offset. Each of the requirements was weighted based on input from the customer regarding their relative importance. Table 1 lists the top level functional requirements for the project and is shown below.

Table 1: Top Level Functional Requirements with Customer Importance Rating, Relevant CTQ variable, Target and Tolerance

Top Level Functional Requirement	Customer Importance	CTQ (metric)	Target Value & Tolerance
Standardize Dust Concentration in Test Chamber	5	Relative Measurement	Standard ± experimentally determined deviation
Facilitate Ergonomic Inspection of Seals	5	Relative Measurement	Standard ± experimentally determined deviation
Record Angular Offset	3	Degrees	.025° increments
Record Lateral Offset	3	Inches	.0005" increments

Additionally, the customer required that the apparatus be visually appealing and safe to operate. Also, the apparatus was required to have a simple method of inspecting the seals at the completion of each test and needed to have the ability to mate to multiple surfaces. Table 2 enumerates the constraints of the project.

Table 2: Constraints (Verb-Noun) with Relevant CTQ variable and Target and Tolerance

Constraint	CTQ (metric)	Target Value & Tolerance
Set Angular Offset	Degrees	2°±.25°
Set Lateral Offset	Inches	±5% of shaft diameter
Total RPM	Revolutions per minute	3000 – 5000 total rpm
RPM Increments	Revolutions per minute	200 ± 5 rpm
Number Of Seals Tested	Quantity	Minimum 5, requested 10
Chamber Pressure	Torr	High Vacuum ($\leq 10^{-3}$)
Seal Size Variability	Inches	.125” – 1”
Cost	Dollars	≤ $3000
Total revolutions	Revolutions	≥ 150,000

3. Design Concepts and Analysis

3.1 Preliminary Designs

The team developed three preliminary design concepts during the early stages of design. The following table lists the main design variables and the suggested design parameters for each. Table 3 is based on the three preliminary design concepts that were presented in the preliminary design review.

Table 3: Design Parameters for Preliminary Designs

Design Variable	Design 1 (cheap)	Design 2	Design 3 (ideal/expensive)
Interface between clean and dirty chambers	Slotted Plate	O-ring Clamped Plate	Air-lock Mechanism
Chamber Material	Aluminum	Steel	Stainless Steel
Chamber Shape	Cylinder	Box	Cylinder
Dust Agitation System	Flippers	"Mouse-wheel"	Rotating belt
Dust Detection	LED lighting	Reflectivity measurement	laser intensity detection
Dust Introduction	Trap Door	Trap Door	Dust cartridge
Motor-Shaft Interface	Drill Chuck	Spider coupling	Bellows Coupling
Chamber Orientation	Vertical	Horizontal	Horizontal
Readout	Analog	Analog	Digitial
Seal Application	Clamped/bolted seal	Clamped/bolted seal	Clamped/bolted seal
System Control (Method to induce offset)	Manual Knob (screw)	Manual Knob (screw)	Actuator
Valve for Vacuum	Manual valve shutoff (1.5")	Manual valve shutoff (1.5")	Electronic control valve (1.5")
Shaft Angle Measurement	Screw	Plunger	Laser Distance Measurement
Shaft RPM Measurement	Magnetic	Magnetic	Magnetic
Motor	Pneumatic Gearmotors	AC Variable Voltage	DC plus AC adapter
Drive Train	Planetary gear train	Linear gear train	Belt drive

3.2 Decision Matrix

A Pugh Analysis was performed for each of the design parameters in Table 4 in order to help determine which should be selected for the final design. Although other criteria, such as the wishes of the sponsor, were considered, the Pugh Analysis was the driving force behind the selection of design parameters for the final design. The Pugh Analysis for the dust agitation system is shown below. Similar analysis was completed for each other main component and can be found in Appendix A.

Table 4: Pugh Analysis for Dust Agitation System

Dust Agitation System		Design Parameter		
	Weight	Flippers	"Mouse-wheel"	Rotating belt
Risk of failure (5 is lowest risk)	2	1	3	2
Cost (5 is lowest cost)	3	4	3	2
Performance (5 is best performance)	5	1	3	5
Reliability (5 is most reliable)	5	4	5	3
Total (out of 75)		**39**	**55**	**50**

From Table 4, it was clear to the team that the mouse-wheel design for dust agitation was the design parameter that should be employed. The team's contacts at Paragon agreed and it was implemented in the final design.

Other factors that were taken into account to determine the final design included the preference of the team's contacts at Paragon Space Development Corporation. In addition, in some cases, decisions were made based on practicality. In some cases, even if one idea seemed like it would have the best performance, the impracticality of implementing it caused the team to go in another direction. The life of the proposed design parameters were also taken into consideration. It was imperative that the team select parts that could withstand the highly deleterious dust environment present in the chamber during tests.

3.3 Final Design

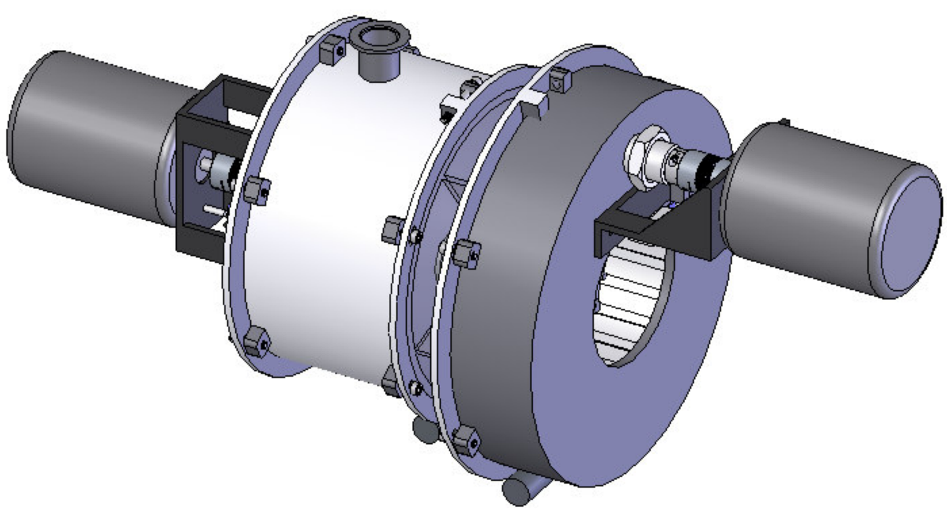

Figure 1: Final Design Concept

The final design, shown in Fig. 1, consisted of three horizontal, steel cylindrical chamber sections. These included a test section to house the dust spinning wheel that the team selected as the dust agitation system, all of the lunar dust stimulant, and the rotary shaft seals that the apparatus tested. The intermediate section, the seal chamber, was intended to contain the dust after it leaked through the seals. The drive section housed the drive train that transferred motion into the testing shafts. The concept included the plan to use one motor to run all five of the testing shafts and another to drive the mousewheel. The shafts were designed to run lengthwise through all sections, and spider coupling was selected because it helps accommodate misalignments and vibrations. It was determined that o-rings should be used to seal the sections together in order to ensure the apparatus stayed at vacuum pressure. In addition, bolts were decided on as the method to hold the chambers together. The team determined that a slotted plate at the interface of the seal and dust chambers would be the best way to create the linear and angular offset of the shafts. Reflectivity measurement was selected as the method to ensure that the dust was standardized in each test.

The team's proposed design was considered a viable solution to all of the functional requirements and constraints put forth by the sponsor, as can be seen in the Design Parameter Determination table in Appendix B. The system was designed to regulate the dust concentration in the chamber by varying wheel rpm, and measuring the dustiness. Dust leak was to be determined both by allowing viewing into the intermediate section during testing and also by containing the dust for inspection after the test has stopped. Angular and lateral offsets were varied by a mechanism, and recorded with very precise linear potentiometers (+- .00005") to meet the tolerance specified of .0005". The team could obtain near lunar pressures by creating a vacuum environment with a vacuum pump, provided by Paragon. The system was designed to be leak tight so as to hold below 1mT of pressure. 5 seals were contained in this design, thus the minimum number of seals was met. RPM was variable by the AC motor speed controllers, and RPM was to be known via the step function created by proximity sensors. The controller was infinitely adjustable; therefore RPM increments were to be easily set. Variable seal size was accounted for by having a set of bushings to adapt the apparatus to each seal size. All components of the system were specified to have a much higher maximum rpm than the apparatus was to be pushed to. The $3000 budget was also met. Overall, the proposed design met all requirements and constraints imposed by Paragon and was also approved by the team's contacts at Paragon.

3.3.1 Concept Analysis

Failure Mode Effects Analysis (FMEA) was performed for the final design to ensure that all possibilities of failure were understood. The possible causes for failure forced the team to reconsider some aspects of the design, such as the material of the gears in the drive train. The entire FMEA is shown below in Table 5.

Table 5: Failure Modes Effects Analysis

Component	Function	Failure Mode	Consequence	Cause	Mitigation
Motors	Drive main shaft	No output	Shafts don't rotate	Electric input interfered with	Ensure correct installation
				Contaminated with dust	Isolate from deliterious substances
	Drive "mouse-wheel"	No output	Dust fails to get stirred	Electric input interfered with	Ensure correct installation
				Contaminated with dust	Isolate from deliterious substances

Coupling	Transmits rotation from gear to rotary shafts	Shafts slip out	Shafts collide	Installed improperly	Provide instructions for proper shaft installation
			Shafts don't rotate		
		Erodes	Loses fitting precision	Dust infiltration	Isolate from deliterious substances
			Decreases coupling lifetime		
			Ergonomics drop		
Gear Train	Transmits motion from main shaft to gears	Teeth break off	Motion interrupted	Too much force on gear	Use gears made of strong material
			Unwanted mechanical vibrations		
		Tooth erosion	Unwanted mechanical vibrations	Dust infiltration	Isolate from deliterious substances
Main Chamber	Keeps dust in controlled environment	Dust escapes	Safety is compromised	O-Ring seal leaks	Implement reliable O-Ring
	Protects mechanical components	Dust infiltration	Lifespan of moving parts shortened	Backup seals fail	Periodically check backup seals
					Clean chamber thoroughly after each test
	Boundary between air and vacuum	Chamber buckles	Cannot achieve vacuum	Material not strong enough	Use strong material (steel)
		Leaks at interfaces	Vacuum lost	Seal not adequate	Properly install seals
					Use reliable seals
Outer Chamber	Provide extra barrier for dust	Dust Leaks through	Safety is compromised	Welds leak	Test welds
				Seal on chamber access leaks	Implement reliable seal
			Lab is subject to contamination	Welds leak	Test welds
				Seal on chamber access leaks	Implement reliable seal
Back Scatter Light Detection	Detects concentration of dust in chamber	Light intensity too low	No reading	Not enough light	Higher-powered laser
		Doesn't detect backscatter	No reading	Not enough dust	Use more dust
		Reflection from light sink	Too much stray light	Light sink fails to absorb all light	Purchase reliable light sink
"Mouse-wheel"	Agitates dust in chamber	Does not stir dust uniformly	Lunar environment not simulated	No fluid to carry dust	Determine optimal speed for even distribution
				Preferential dust distribution	Alternate direction of rotation
		Mouse-wheel falls off axis	Does not spin correctly	Bearings come out of track	Clean chamber thoroughly after each test
Seal/Wall Interface	Holds seal in place	Bolts come out	Vacuum lost	Vibrations	Damping
		Clamps fail	Vacuum lost	Stress	Perform stress analysis
Valve	Keep air out of chamber	Leaks	Vacuum lost	Installed improperly	Ensure proper installation
	Equalize pressure in chamber at test completion	Fails to open	Cannot determine seal effectiveness	Valve sticks	Backup pressure equalization method
Offset Adjustment Knob	Adjust angular and linear offset of shafts	Inaccurate adjustment	Invalid test results	Improperly calibrated	Calibrate correctly and verify calibration
Silicon Detectors	Measure angular and linear offset	Give inaccurate readings	Invalid test results	Reading interference	Ensure no interference
	Measure RPM				
Readout	Displays angular and lateral offset	Fails to give readout	No verification of test conditions	Electical failure	Verify readout correspondence with actual
	displays RPM			Display failure	

In addition, it was assumed that vibrations in the system might occur during testing. Depending on the amount of vibrations, the apparatus could "hop" around and/or incur some damages while in operation. Vibrations would be caused by the rotations of the shafts. Most vibrations, however, would be due to the lateral offset of the shafts. This would cause a rotational unbalance in the system, which would transmit a force to the base. If this force were greater than the weight of the apparatus, then the entire apparatus would "hop" around.

First, the force due to the imbalance was calculated using: $F_o = me\omega^2$, where *m* was the mass, *e* was the offset of the shafts, and ω was the rotational speed of the shafts in radians per second. Using superposition, this force was multiplied by the number of shafts to find the maximum force. Next, the maximum amplitude of these vibrations was determined using:

$$X = \frac{me\omega^2}{[(k - M\omega^2)^2 + \omega^2 c^2]^{\frac{1}{2}}} \approx 0.012in$$

where *M* was the mass of the entire apparatus, *k* is the "stiffness" of the seals, and *c* is the damping coefficient of the seals. Note that the maximum amplitude was found to be about a tenth of an inch. This was the most that could be expected for the apparatus to move up and down.

The amplitude was fairly minimal. However, there was something else concerning the vibrations that required consideration: the frequency ratio. This value was the ratio of the operating frequency to the natural frequency. The natural frequency was found by:

$$\omega_N = \sqrt{k/m}$$

where m was the mass of the entire system. As seen in Fig.2 below, there was infinite vibration amplification at $\omega=\omega_N$ with no damping. This was undesirable as the vibrations would not be able to be isolated. Thus, it was determined that as long as there was some damping on the system, the vibrations would be under control. In short, something like a rubber pad mounted to the bottom of the apparatus base would be sufficient.

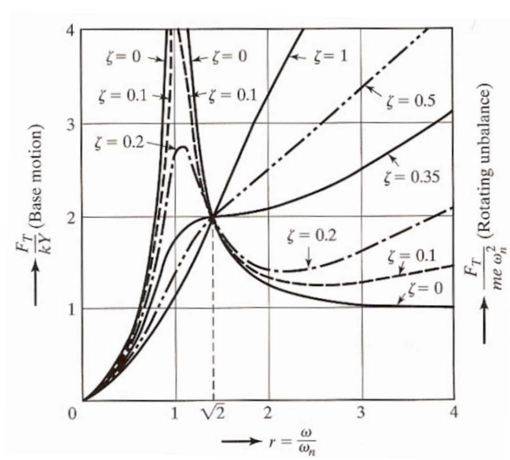

Figure 2: Base Motion vs. Operating Frequency Ratio

4. Design

4.1 Functional Decomposition

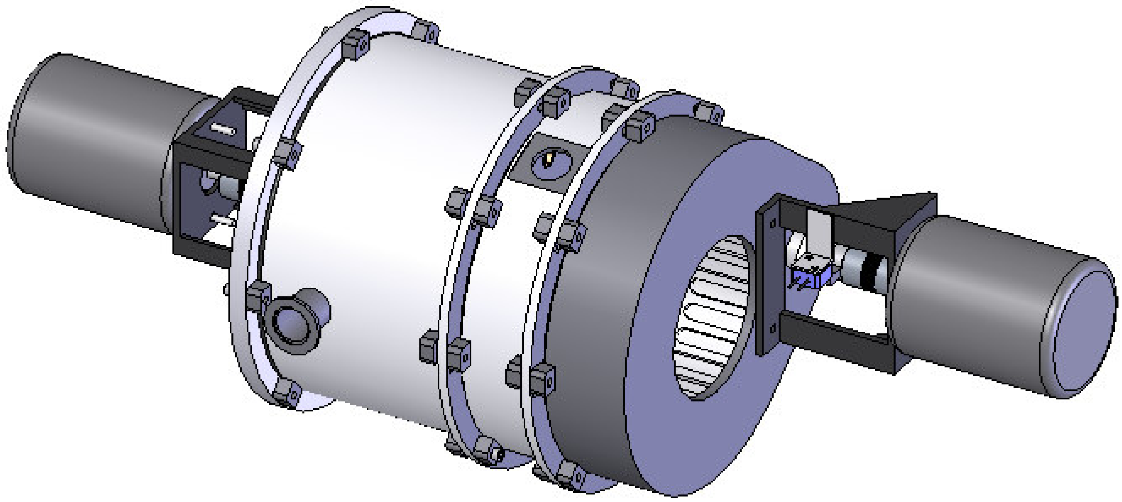

Figure 3: Implemented Final Design

4.2 Units and Subsystems

The test chamber, shown in Fig. 3, consisted of three different subsystems, each working along with the others to provide a test atmosphere that would allow for the reliable testing of the lunar seals. These subsystems were divided into the drive chamber, the seal chamber, and the dust chamber. In addition, a frame was designed to house the electronics and to support and house the entire apparatus. The drive chamber represented the part of the mechanism that was responsible for providing the mechanical movement for the shafts holding the test seals. This was accomplished by using a planetary gear train in which the motion of one motor was transferred into motion of the five rotating shafts that were inserted into the test seals. The seal chamber followed and housed the test seals along with the optical detection equipment (which allowed for qualitative analysis of the dust concentration in the test chamber). This chamber was where the linear and angular offset was introduced to the seals, and also where the performance (pass/fail) of the seals was tested. Finally, the dust chamber, where the dust was stirred by a mechanical “mousewheel” device, competed the apparatus. The mousewheel allowed for the mechanized movement of dust around the seals. Investigation of whether or not the seals allowed for dust to pass into the seal chamber was carried out by removing the dust chamber from the apparatus.

A sealed environment for the testing was maintained while allowing for the reliable movement of dust around the seals, along with the movement of the seals themselves, by keeping the individual subsystems separate. Also, by producing each of the systems together, the team was able to ensure that they would fit together in a fashion that would allow for proper vacuum sealing, accomplished with o-ring seals at each of the interfaces between the individual subsystems. The separation of systems into individual parts ensured that the tests performed were reliable in terms of keeping the dust where it was supposed to be (especially away from the motors and moving parts).

4.2.1 Drive Chamber

The final design included an AC motor mounted on one end of the drive chamber, as shown in Fig. 4. The motor speed was controlled with a motor controller dial. This motor was connected to a ferrofluidic coupling with a helical coupling. The ferrofluidic coupling contained an o-ring to seal it to the end plate, which it mounted to through a 1 inch hole. Inside the chamber, a 2.4” gear was mounted on the shaft of the coupling. Around this gear were 5 smaller 1.6” gears, each of which was mounted to a 3/8” shaft with a 3/32” keyway. These shafts were mounted on each end with ball bearings which rested in the bearing plates. The original concept was for one bearing plate to be bolted to the end plate, and for the other to be bolted to the first bearing plate with hex standoffs. With the use of a CNC machine, the team was able to adjust the design to include the bearings in the end plate itself. The code used for the CNC machine can be found in Appendix C. Each shaft extended through the second bearing plate, where a spider coupling hub was clamped on. Another hub was connected to the testing shafts. These two sets of hubs were designed to simply slip together into the spider, which was an elastomeric material that allowed for the angular misalignment of the shafts. This section bolted to the intermediate section through 8 square nuts welded to both the drive chamber and the endplate of the intermediate section. A 1/8” o-ring was utilized at the interface of these two sections to provide a vacuum seal between the two sections.

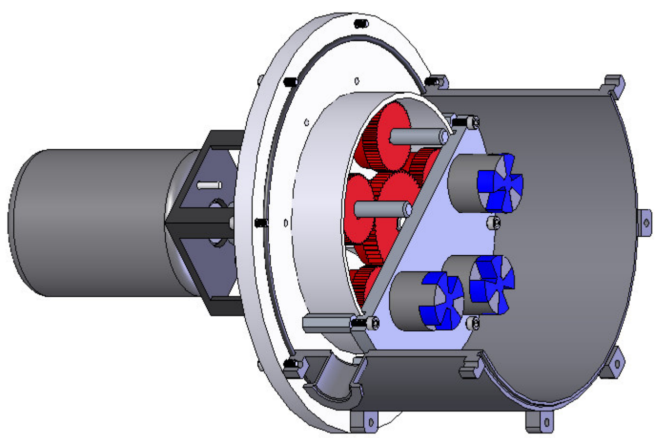

Figure 4: Exploded Side View of Drive Chamber

4.2.2 Seal Chamber

The middle section of the apparatus, the seal chamber, contained the shafts, the seals, and the plates used for the lateral and angular offset of the shafts. As discussed above, this chamber included an end plate to protect the gear chamber from any dust that passed out of the dust chamber in the event of seal failure. This plate was constructed so that five shafts held by the spider coupling and driven by the planetary gear train could pass through. The holes for the shafts were sealed with a set seals and bushings designed to allow the end plate to accommodate for the various size seals. The only purpose of these seals was to protect the gear train; these were not the seals that were under investigation. The plate on the other end of the seal chamber was also built to allow the different size shafts to pass through. The seals on this plate were the seals being tested, and the outside of this plate was the section that was exposed to the simulated lunar environment. In order to adjust the plate to different shaft and seal sizes, a set of 10 1.25" bushings was constructed for each seal size (from 1/8" to 1" in 1/8" increments). Both end plates of the seal chamber were sealed with 1/8" o-rings to insure that the chamber would not leak. The original concept was for this cylinder to be constructed out of a glass cylinder, but the team decided to use a steel cylinder with viewports built in. This change, though it required more time to construct, reduced the overall cost of this section and also increased its strength. It was also determined that it would not be feasible to separate the chamber into five sections, one around each seal. Each of the end plates was constructed with eight slots of 5 degree radius near the edge. These slots allow the user to adjust the offset of the shafts. To create the offset, the user simply needed to unscrew each of the eight screws passing through the slots, rotate the plate, and tighten the screws. The seal chamber is shown in Fig. 5.

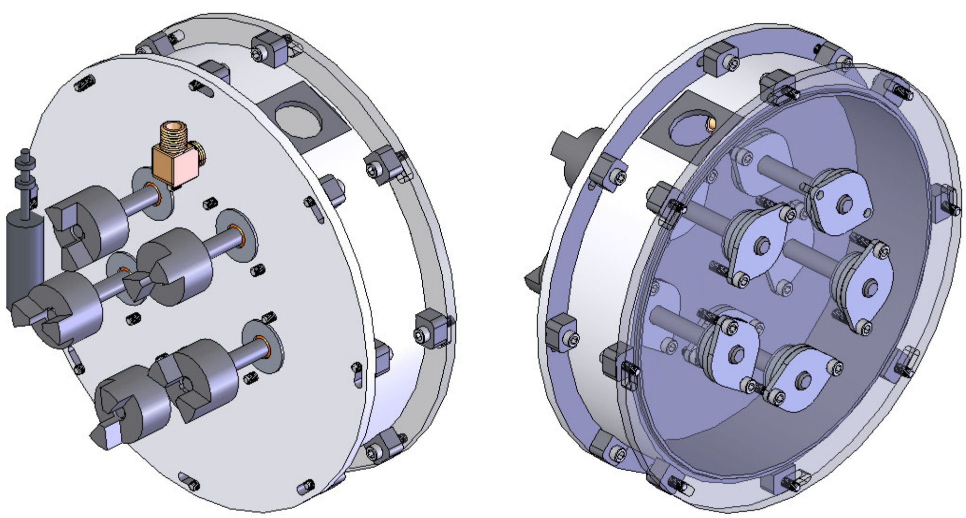

Figure 5: Exploded Intermediate Section of Final Concept

4.2.3 Dust Chamber

The next section of the final design was the test section shown in Fig. 6. This section had an AC motor mounted to it. This motor used the same ferrofluidic coupling, helical coupling, and rpm measurement as the drive section motor. The motor speed was controlled with the motor controller dial. A pulley was mounted on the end of the ferrofluidic feedthrough on the vacuum side. A flat belt ran around this pulley and the dust agitation wheel. The wheel was mounted by four cam followers, which were screwed into the end plate. The concept was designed so that dust could be introduced into the wheel by the tester. The laser diode mounted in the vacuum chamber, inside the mouse wheel, and was expected to shine across the diameter of the chamber. A glass disk was mounted in the end plate to allow the detector to look at the laser diode beam in various locations throughout. All measurements of rpm, offset, and pressure were fed into LabView, and an interlock program was written to automate the test after initial setup by the tester.

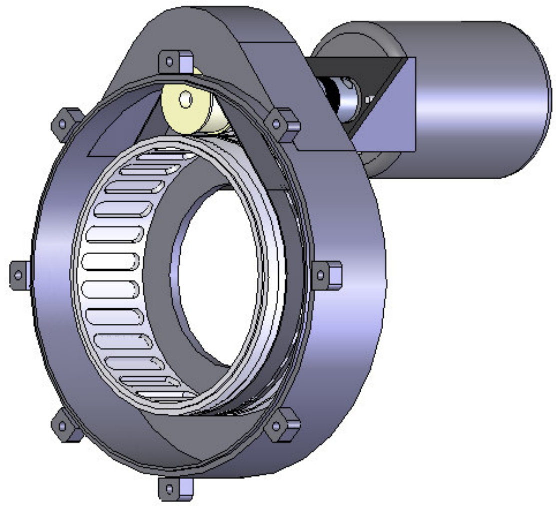

Figure 6: Test Chamber of Final Design Concept

4.2.4 Frame

The frame was designed to serve three main functions. The first was to dampen the vibrations caused by the offset shafts. This was done by using neoprene damping pads and vibration dampening feet. The second was to contain the chamber with a see-through dust barrier. This was accomplished by making a frame that had acrylic sheets bolted to it. The acrylic was mounted close to the body of the chamber so the system could still be monitored visually. The third was to house the electrical components. This was done by building a box into the bottom of the frame. The box housed a power strip for power distribution, a 25A contactor with a 24V coil for remote motor starting, two motor speed controllers, a 24V power supply for the vacuum gauge, a 5V power supply for the laser diode, and a potentiometer for laser diode intensity adjustment. The Electrical Schematic can be found in Appendix D.

4.3 Budget

The budget for the final design of the prototype is shown in Table 6 below.

Table 6: Budget

Description	Source	Part Number	Extended Price
Ferrofluidic Feedthrough	AN Corp	FTRF-038-BP	$960
Motor and Accessories	McMaster Carr	Various	$370
Guages / Sensors	Omega	Various	$800
Gears	McMaster Carr	Various	$225
Hardware & O-Rings	McMaster Carr	Various	$40
Stock Material	McMaster Carr	Various	$450
Labview, DAC Box	Labview	N/A	Provided, NC
Total:			**$2845**

The full Bill of Materials is located in Appendix E of this report. This gives a detailed description of each of the parts used for each of the above categories and includes part numbers and cost.

4.4 Analysis of Design

Measures were taken to ensure that the final design concept would satisfy concerns regarding stress on the chambers. During operation, the inside of the chamber was under vacuum. Thus, a pressure differential between the outside of the chamber and the inside would exist (pressure of the atmosphere on the outside, and approximately zero for the inside). In order to prevent the chamber from buckling under this pressure, an appropriate chamber wall thickness was selected.

Figure 7 below is a free body diagram of the expected forces that would be acting on the cylinder.

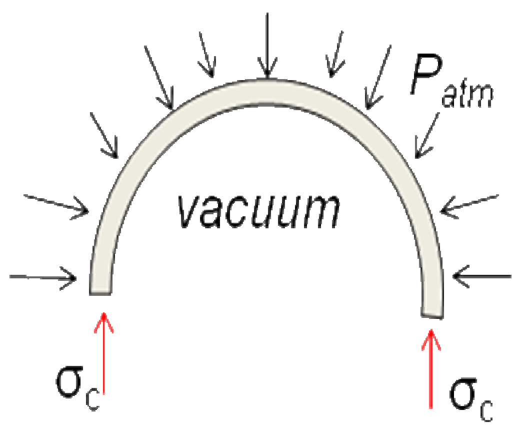

Figure 7: Free Body Diagram

Figure 8 is a SolidWorks rendition of the pressure distribution on the chamber.

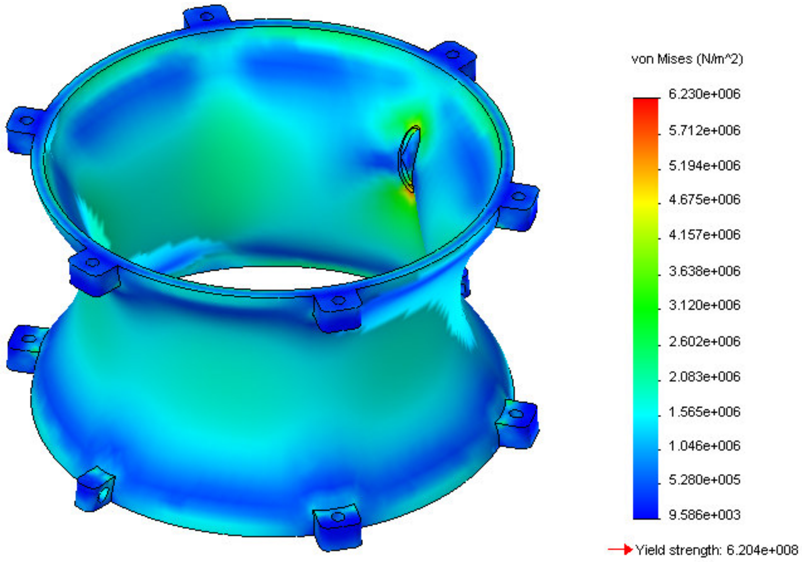

Figure 8: Pressure Distribution

Logically, the team suspected that the highest stresses would be in the middle of the cylinder; the SolidWorks model in Figure 8 confirmed these suspicions.
The force acting on the cylinder was found using

$$F = PD_oL$$

Once the force was determined the tangential stress was calculated using the following equation.

$$\sigma_T = \frac{(F/2)}{(t \times L)}$$

From this equation, the thickness of the chamber wall was varied to produce a stress that would be less than the yield stress of the chamber material (in this case, steel was used). In general, by using this analysis, it was determined that a fairly thin steel cylinder could be used. Ultimately, it was decided that a thickness of 3/16" would be a good choice. This thickness yielded a safety factor of 101. Though this safety factor may have seemed like overkill, this thickness was chosen because of its practicality. If the thickness were too small, an o-ring of that size would not seal the chamber sections properly. Using a larger o-ring would cause the o-ring to squeeze outside of the sealing surface. Therefore, the choice for 3/16" thickness was practical, and would give a large enough sealing surface for the chamber.

5. System Assembly

5.1 Construction, Debugging, and Testing

The team divided each individual part of the chamber as a separate task in order to machine each subsystem separately, one part at a time. Each subsystem was broken into its individual components and the team produced each of those individual components. By doing this, the small problems associated with each subsystem on a more individual basis. Also, as assembly for each subsystem was undertaken, the team was able to positively ensure that the mechanical movement and alignment of parts worked properly. It could be assumed that that system would work properly in association with the others once it was known that each individual component linked up properly with itself. Also, by taking time in construction of each individual component, the team was reassured that the surfaces at each subsystem interface would mate properly. This was done in the same fashion as producing the systems, in that both of the mating surfaces of two subsystems were produced and tested to ensure that they linked up properly.

In testing each of the subsystems and their individual components, it became clear that the subsystems would indeed link together properly. However, the team had to wait until the entire system was completed to check that the mechanism pumped down properly and maintained vacuum. Once the entire system was finished, vacuum reliability was tested for. After minor adjustments, each of the inside components worked as planned, thanks in part to the vigorous testing along the way. During each test after completion of different parts for the subsystems, the team looked for problems in the mechanical workings of the systems and either eliminated them by remaking the parts, or improvised to fix them, by using the existing parts and making changes to the interactions of the components.

5.2 Integration and Testing

The integration of the subsystems involved creating a vacuum seal between the three chamber sections. This was done with eight screws at each interface that held the chambers together. The screws also served to compress a 1/8" o-ring between adjacent sections. The three sections, now assembled to form one chamber, were bolted down to a frame through vibration damping neoprene pads. The frame sat on adjustable vibration dampening feet for leveling.

Integration of the control system involved providing inputs and outputs from the electrical box to Paragon's LabView setup. The inputs to LabView were one 0-10VDC analog pressure reading, one 0-24VDC digital pressure switch, two 0-83.33Hz 24VDC RPM step functions, one 0-5VDC analog Laser Backscatter Intensity (LBI) measurement, and two 24 bit offset measurements with 20ms cycle time and a 90kHz clock pulse. The output from LabView was one 24VDC digital output that closes the motor contactor. This integration was done by running a bundle of wires from the electrical box into Paragon's LabView setup.

Testing of the vacuum seal was done by pumping down the chamber with a rotary vane pump, closing off the vacuum isolation valve, and measuring the pressure output from the vacuum gauge over an extended time to verify an acceptable leak rate. Testing of the vibration damping and mechanical mounting integrity was done by rotating the shafts at full speed and verifying visually that the system did not "walk" due to vibration.

The control system integration was tested by checking each input and output. The gauge measurement was verified to be the barometric pressure at atmosphere, and the ultimate lowest pressure of the vacuum pump when fully evacuated of air. The pressure switch was verified to connect at a reasonably low level of vacuum, and was verified to disconnect above this level. The rpm measurement was verified to read 0 Hz at no speed and 83.3 Hz at full speed. The LBI measurement was verified to vary within a detectable amount with no dust agitation versus full dust agitation. The two offset measurements were verified to detect accurate offset measurements against the digital readout on each caliper. The 24V output was tested to only be supplied to the contactor when the pressure setpoint was reached, the rpm measurements were within a specified frequency range, the LIB was within a specified voltage range, and the specified test elapsed time was not reached. This testing verified that all subsystems were working correctly, and that the final design met acceptance testing.

6. Design Results

6.1 Verification Testing Results

In order to validate that the functional requirements were met by the final prototype, a test plan was written and carried out by the team. The top level functional requirements included standardizing the amount of dust in the chamber, facilitating the ergonomic inspection of the seals, and allowance for linear and angular offset.

Dust concentration was measured using the optics included in the test chamber over a number of different trial runs. The information gathered from these tests was used to examine the measured dust concentration over all of the trials. These tests were performed using a laser diode and a detector. The laser diode shone a beam of light through the dust in the test chamber, and the detector related how much light from the laser was being scattered on the surrounding dust. In conjunction the diode and detector indicated that the dust concentration level was standard relative to the other trials.

The system needed to be ergonomically satisfied since determination of the seals' effectiveness will be performed by any number of testers. The ergonomics of the completed system were validated through examination of the size of the interior of the apparatus. This was compared to the approximate size of a human's hand in order to validate that inspection of the seals could be easily performed. Each member of the team ran through all of the steps needed to be taken in order to inspect the seals to ensure that the design was ergonomic. These steps included the removal of the dust chamber and the bushings that held the seals in place.

RPM verification was conducted using a magnetic flag coupled with a proximity sensor. The flag was on a collar of the main drive shaft, and the flag's proximity to the sensor was recorded and verified by an oscillating square wave that was the output of the proximity sensor. This output varied from 0 Hz to 83.3 Hz at top speed.

The lateral and angular offsets were measured and verified using digital calipers. It was verified that the readout on these calipers was correct.

6.2 Data and Research Results

Verification that the lower level functional requirements were met was completed based on the steps the team laid out in the validation test plan.

Visual inspection confirmed that one motor was driving the mousewheel and that the other motor was connected to and drove the five rotary shafts. This verified that the planetary gear train was contained and that it was effective. The rotary motion of both motors was confirmed to have been transferred into the vacuum chamber by visual methods as well.

An inspection of the drawing verified that the magnetic flag was correctly mounted to the main drive shaft and a proximity sensor was coupled with this flag to ensure that the RPM was changing.

All the required shaft sizes were connected to the spider coupling and the seals were mounted to each of these shafts. It was verified through visual inspection that the apparatus was able to adapt to each size shaft and that the seals were correctly mounted. Visual inspection also confirmed that the dust had been contained after seal failure. O-ring seals effectively sealed the various sections of the apparatus, as was inspected as per the drawing.

Visual inspection of the manual vacuum gage confirmed that the apparatus was connected to a vacuum pump and the vacuum pressure was displayed. In addition, it was verified that the chamber held vacuum by noting that the steady state pressure in the chamber did not exceed 1 mTorr.

It was confirmed that the laser diode beam in the vacuum chamber worked properly by ensuring that he laser was emitting light. Measurement of the change of laser beam backscatter was verified by checking the output of the optical sensor.

All parts have dimensions commonly found in industry, which confirms that they can be easily replaced. Finally, it was verified that the apparatus was contained in a backup dust containment chamber through visual inspection.

6.3 Functionality of System

The S.E.A.L.S. system is fully functional. The testing we have done shows that it meets all specified functional requirements proposed by Paragon Space Developments Ltd. The system runs safely and autonomously off of 115VAC standard power, with no need for compressed air or water. The system requires that Paragon supplies a vacuum pump and LabView control system. The machine tests five shafts of any size from 1/4” to 1” in 1/8” increments. Five seals are tested at one time, at up to 5000 rpm, while maintaining a constant dust environment. The system requires initial manual setting of vacuum, dust rpm, and shaft rpm, and shuts itself off after completion of the test for the specified elapsed time. Seal effectiveness is verified by visual inspection of the seals at the test chamber interface. The system has been designed so that disassembly of the interface can be done without disturbing evidence of seal performance. The system shall remain fully operational until normal wear and tear and chemical corrosion due to the dust cause the eventual breakdown of moving parts, at which time the system will require minimal maintenance of at least shaft, motor brush, and drive belt replacement and at most cam follower, ferrofluid, and dust agitation wheel replacement.

7. Conclusions and Recommendations

In summary, Paragon stipulated the need for an apparatus accommodating a functional rotary seal testing system. The apparatus needed to accommodate a minimum of five rotary seals and shafts simultaneously, agitate a dust simulant over a range of shaft speeds (3000-5000 rpm), and have the ability to reach 150,000 revolutions in a single test. The system needed to be an approximate simulation of the lunar atmosphere including a practical vacuum level pressure.

A prototype that met the functional requirements and was within the constraints of the system was constructed. The design utilized a unique dust agitation system and multiple chambers to maintain component longevity and ensure reliable data for each seal test run. For the benefit of the sponsor, the manufacture and assembly of the final design was carried out with a "lean process" in mind. This resulted in as many off-the-shelf components as possible being implemented to ease repair and/or replacement.

The team recommends that future versions or alterations to the existing design be completed to both increase the effectiveness of the system and fulfill a more accurate simulation of the lunar atmosphere. These changes could include higher precision calibration gauges. These would be implemented to measure and record angular and linear offset of the shafts. Additionally, a more refined lunar simulation could be easily facilitated. The fluctuation in temperature on the lunar surface is a predominant factor in the durability of many space components, with a temperature range of over 500 degrees F. To allow for this temperature range, the testing portion of the chamber could include a steam/water controlled sub-chamber. Aside from the cooling and heating unit, additional spacing and cooling would need to be provided to the surrounding o-ring seals to maintain the integrity of the vacuum seal.

8. Acknowledgement

The team would like to thank many people for this great opportunity to experience the design of a system and the execution of its production firsthand. We would like to foremost thank the University of Arizona, which ensured the chance for us to be a part of the 498 Engineering Design class. Without having this class as part of the required curriculum to graduate from our individual colleges, most of us would not have had the opportunity to participate in an authentic engineering project of this magnitude. On the same plane as the gratitude we have to the U of A, we are grateful to the Paragon Space Development Corporation for putting forth the project. We are also appreciative for their willingness to help us succeed in the production of this prototype. Without being able to maintain constant contact with the company (mainly Grant Anderson and Christie Iacomini), we would not have known that our system was going to do what it was designed to do, down to the very last detail. Also, without the help of Joe Hartley in the AME machine shop, none of the machining that was necessary for the production of this system would have been completed. Mr. Hartley was paramount in maintaining that we were doing the machining correctly, and in taking time to teach all of us the proper ways to run different machines.

9. References

The team utilized SolidWorks 3D Design Software for all modeling performed for this project. In addition, this was used for a good deal of design analysis, including the stress analysis discussed in Section 4.4. The figures of the preliminary and final designa were all taken from the SolidWorks models.

The equations for the vibration analysis were acquired from *Mechanical Vibrations, 4th Ed.*, by Singiresu Rao and from *Shigley's Mechanical Engineering Design*, by Richard Budynas. The basis for much of the design analysis stemmed from these two texts.

10. Appendices

Appendix A: Pugh Analysis for Each Component

Table 7: Pugh Analysis by Component

Interface between clean and dirty chambers		Design Parameter		
	Weigh t	Slotted Plate	O-ring Clamped Plate	Air-lock Mechanism
Risk of failure (5 is lowest risk)	2	5	5	3
Cost (5 is lowest cost)	3	4	2	1
Performance (5 is best performance)	5	3	4	5
Reliability (5 is most reliable)	5	5	4	3
Total (out of 75)		**62**	**56**	**49**

Chamber Material		Design Parameter		
	Weigh t	Aluminum	Steel	Stainless Steel
Risk of failure (5 is lowest risk)	2	1	4	5
Cost (5 is lowest cost)	3	5	5	1
Performance (5 is best performance)	5	3	4	5
Reliability (5 is most reliable)	5	2	4	5
Total (out of 75)		**42**	**63**	**63**

Chamber Shape		Design Parameter	
	Weigh t	Cylinder	Box
Risk of failure (5 is lowest risk)	2	4	2
Cost (5 is lowest cost)	3	4	3
Performance (5 is best performance)	5	4	4
Reliability (5 is most reliable)	5	4	3
Total (out of 75)		**60**	**48**

Dust Agitation System		Design Parameter		
	Weigh t	Flippers	"Mouse-wheel"	Rotating belt
Risk of failure (5 is lowest risk)	2	1	3	2
Cost (5 is lowest cost)	3	4	3	2
Performance (5 is best performance)	5	1	3	5
Reliability (5 is most reliable)	5	4	5	3
Total (out of 75)		**39**	**55**	**50**

Dust Detection		Design Parameter		
	Weigh t	LED lighting	Reflectivity measurement	Laser intensity detection
Risk of failure (5 is lowest risk)	2	2	5	4
Cost (5 is lowest cost)	3	5	3	3
Performance (5 is best performance)	5	3	5	4
Reliability (5 is most reliable)	5	3	4	4
Total (out of 75)		**49**	**64**	**57**

Dust Introduction		Design Parameter	
	Weigh t	Trap Door	Dust cartridge
Risk of failure (5 is lowest risk)	2	4	2
Cost (5 is lowest cost)	3	4	2
Performance (5 is best performance)	5	3	4
Reliability (5 is most reliable)	5	5	4
Total (out of 75)		**60**	**50**

Motor-Shaft Interface		Design Parameter		
	Weigh t	Drill Chuck	Spider coupling	Bellows Coupling
Risk of failure (5 is lowest risk)	2	1	4	4
Cost (5 is lowest cost)	3	4	3	2
Performance (5 is best performance)	5	4	4	3
Reliability (5 is most reliable)	5	1	3	4
Total (out of 75)		**39**	**52**	**49**

Chamber Orientation		Design Parameter	
	Weigh t	Vertical	Horizontal
Risk of failure (5 is lowest risk)	2	2	4
Cost (5 is lowest cost)	3	5	5
Performance (5 is best performance)	5	2	4
Reliability (5 is most reliable)	5	4	4
Total (out of 75)		**49**	**63**

Readout		Design Parameter	
	Weigh t	Analog	Digitial
Risk of failure (5 is lowest risk)	2	3	4
Cost (5 is lowest cost)	3	4	2
Performance (5 is best performance)	5	3	5
Reliability (5 is most reliable)	5	3	4
Total (out of 75)		**48**	**59**

System Control (Method to induce offset)		Design Parameter	
	Weigh t	Manual Knob (screw)	Actuator
Risk of failure (5 is lowest risk)	2	4	3
Cost (5 is lowest cost)	3	4	2
Performance (5 is best performance)	5	5	5
Reliability (5 is most reliable)	5	4	3
Total (out of 75)		**65**	**52**

Valve for Vacuum		Design Parameter	
	Weigh t	Manual valve shutoff	Electronic control valve
Risk of failure (5 is lowest risk)	2	3	4
Cost (5 is lowest cost)	3	5	3
Performance (5 is best performance)	5	4	4
Reliability (5 is most reliable)	5	5	4
Total (out of 75)		**66**	**57**

Shaft Angle Measurement		Design Parameter		
	Weigh t	String Pot	Capacitive sensor	Laser Distance Measurement
Risk of failure (5 is lowest risk)	2	3	4	2
Cost (5 is lowest cost)	3	5	4	2
Performance (5 is best performance)	5	3	4	5
Reliability (5 is most reliable)	5	4	4	4
Total (out of 75)		**56**	**60**	**55**

Motor		Desgin Parameter		
	Weigh t	Pneumatic Gearmotors	AC Variable Voltage	DC plus AC adapter
Risk of failure (5 is lowest risk)	2	2	5	5
Cost (5 is lowest cost)	3	5	3	4
Performance (5 is best performance)	5	2	4	5
Reliability (5 is most reliable)	5	2	4	4
Total (out of 75)		**39**	**59**	**67**

Drive Train		Design Parameter		
	Weigh t	Planetary gear train	Linear gear train	Belt drive
Risk of failure (5 is lowest risk)	2	4	4	3
Cost (5 is lowest cost)	3	4	4	3
Performance (5 is best performance)	5	5	5	4
Reliability (5 is most reliable)	5	4	4	5
Total (out of 75)		**65**	**65**	**60**

Appendix B: Design Parameter Determination

The team determined the design parameters (listed in Figure 3) by using Acclaro. These parameters were used in production of the design matrix.

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Test Lunar Dust Shields	DP Top level DP's
1	FR Standardize Dust Concentration in Test Chamber	DP Mouse Wheel
1.1	FR Drive Wheel with Motor	DP AC Motor
1.1.1	FR Transfer Rotary Motion Into Vacuum	DP Ferroflouidic Feedthrough
1.1.1.1	FR Connect Motor to Feedthrough	DP Helical Coupling
1.1.2	FR Vary Speed	DP Motor Speed Controller
1.1.3	FR Transfer Motion Into Wheel	DP Flat Belt
1.2	FR Detect Dust Concentration	DP Laser Beam Back-Scatter Measurement
1.2.1	FR Mount Optical Feedthrough	DP Glass Vacuum Viewport
1.2.2	FR Create Laser Beam in Vacuum	DP Laser Diode
1.2.3	FR Measure Laser Beam Back-Scatter	DP Optical Sensor
1.3	FR Recover Fallen Dust	DP Horizontal Chamber
2	FR Determine Dust Leak Through Seal	DP Clamped, O-ring Sealed Plate
2.1	FR Mount Seal	DP Clamped Ring
2.2	FR Contain Dust After Leak	DP Acrylic Dust Containing Sections
2.3	FR See Dust Leak While Testing	DP Glass Cylinder Arround Test Section
3	FR Rotate Shaft	DP AC Motor
3.1	FR Vary Speed	DP Motor Speed Controller
3.2	FR Connect Motor to Shafts	DP Planetary Gear Train
3.2.1	FR Contain Gear Train Geometry	DP Cylindrical Chamber
3.2.2	FR Adapt to Various Shaft Sizes	DP Spider Coupling
3.3	FR Measure Shaft RPM	DP Proximity Sensor
3.4	FR Mount Flag on Shaft for Sensor	DP Modified Shaft Collar
4	FR Hold Vacuum	DP Sealed Chamber
4.1	FR Connect to Vacuum Pump	DP Manual Vacuum Valve
4.2	FR Prevent Air Diffusion	DP Plain Carbon Steel
4.3	FR Seal Various Sections	DP Buna-N O-ring on Each Interface
4.4	FR Display Vacuum Pressure	DP Convectron Gauge
5	FR Record Angular Offset	DP Linear Potentiometer
5.1	FR Display Angle	DP Analog Input to LabView
5.2	FR Set Angular Offset	DP Adjustment Screw
6	FR Record Lateral Offset	DP Linear Potentiometer
6.1	FR Display Distance	DP Analog Input to LabView
6.2	FR Set Lateral Offset	DP Adjustment Screw
7	FR Replace Parts Easily	DP Off the Shelf Components
8	FR Have Backup Dust Containment Chamber	DP Plexiglass Box Around Chamber

Figure 9: Design Parameters Produced Using Acclaro

Appendix C: Computer Numerical Control (CNC) Codes Utilized

The following codes were created by the team in order to create the end plates on the CNC machine.

3661 January 29 "Bearing Plate"

To cut test plate use tool offset with x = + 16.552, y = 7.4034 (use E11)

Center Hole

1) M03 E11 to # S900
2) Xo Yo Zo
3) Xo Yo Z-1 to RO 0.5015 C2 G7 P6 F5 Event type 4
4) F0003 T 4 Event Type 6

   M30 Use T09

   Notes for Ref Z + .5 D .875, D.876

Feb 3 "O-ring Grove and OD Circles

Cut plus mounting (smaller) holes

Feb 4
Presented with "Rev B" of drawing will try to rough out primary features of (bearing) plate.

Features:

1.003 Bore
5 circular pockets 0.87525 and .250 deep
(8) .2 Thru holes on 9.10 BC
(8) .16 X .300 deep blind holes tapped to 10-32
(1) .135" wide grove, @ 0.1125 deep with an OD of 6.005

Tool offset for woodcut
X 16.6374
Y 5.0235 5.0235
Use Fixture offset E08

(O-ring Grove)
Use T03 or T07
N0001 (9) M03 E08 T03 S1000
N0002 (4) Xo Yo Z-3.5 W-0.5 F5 R3.0025 G0 P3 C1
N0003 (9) M30
Programs B, C, D 3 hrs.

Feb 6th 1 hr.
Debug program AME3661- successful

Feb 9th AME 3661 1E
N0001 (9) M03 E08 T07 S1000 $
N0002 (0) Xo Yo Z-2
N0003 (4) Xo Yo Z-2 W-0.5 F5 R3.500 G0 C2
N0004 (9) M30

(OD cut) 2hrs.
E08 should be X = 16.6374
Y = 5.0235
<R = 3.0025> Feb 12th

2/11 CNC Time: 7 hrs.
X = 16.4568
Y = 5.4765
Z = -5.4538
Fix O-ring Program

1 full turn= 110thermometers
Inner Bolt pattern
0.050”
.100”
.150”
.200
.250
.300
.35
.4 25

2/12 Bearing Plate Rev B
Drill # 7 thru on outer bolt circle
- will take 0.050” cuts at low feed rates

.05
.1
.15
.2
.25
.3
.35
.4
.45
.5

O-ring groove
Fixed program radius and tool Description
Took one pass to verify location
2nd pass is light cut of = .005

O-ring groove will take .01” passes to achieve 0.16 depth (shoot for .0155)
.01
.01
.03
.04
.05
.06
.07
.08
.09
.1
.11
.12
.13
.14

.15

Fly cut surface
Starting position
X = 23.75 1 12” cut
Y = 5.5
E1 fixture

Y = 2.25
Y = 9
Y = 5.625
In Theory: R = 3.0025 CC= C2 Tool Diameter = 0.125” =➔ doesn’t work

Feb 20 4 hrs.
2.4375 = r of
6.005/2 = 3.0025
1. drill with X drill again
2. figure out 6.01 or 6.005
3.0025- 2.4375 = .565

Feb 23
Bearing plate 8.5 hrs. O-ring groove
Widened, drill outer 8 holes,
Interpolate OD of plate to 7”

Cut 7” OD for bearing plate

```
N0001 (9)           M03      E08T97  S01750
N0002 (0) Xo Yo Z-0.5
N0003 (4) Xo Yo Z-1 W-.5             R3.500
C1        P1        F4       $
N0064               M30$
```

Feb 26

X = 16.7648
Y = 7.0342

ARC Mill
A= start angle
B= finish angle
R=4.5650
D=0
F= 3
C= 0

X= 16.7648
Y = 6.784

```
0001   M03      E08      T03     S1200   (9)
0002   X 4.565  Yo       Z-2     W-0.5   (0)
0003   A0       B355     R4.565          F3     (2)
0004   Z-1.5    (0)
0005   Xo       Y-4.565  Z-2     W-0.5   (0)
0006   A270     B265     R4.565          F3     (2)
0007   Z-1.5    (0)
```

```
0008	X-4.565	Yo	Z-2	W-0.5	(0)
0009	A180	B175	R4.565		F3	(2)
0010	Z-1.5
0011	Xo	Y+4.565Z-2	W-0.5	(0)
0012	A90	B85	R4.565		F3	(2)
0013	M30	(9)

0001	M03	E08	T03	S1200	(9)
0002	X 3.2560		Y-3.1996		Z-2	W-0.5
0003	A315.5		B310.5		F3
0004	Z-1.5
0005	X-3.1996		Y-3.2560		Z-2	W-0.5
0006	A225.5		B220.5		R4.565		F3
0007	Z-1.5
0008	X-3.2560		Y+3.1996		Z-2	W-0.5
0009	A135.5		B130.5		R4.565
0010	Z-1.5
0011	X 3.1996		Y3.2560Z-2	W-0.5
0012	A45.5	B40.5	R4.565
```

March 2
Cut Out OD

```
0001	M30	E08	T08	S900	(9)
0002	Xo	Yo	Z-.1	(0)
0003	Xo	Yo	Z-1.2	W-0.5	R=4.815(4)
	C1	G0	K .02	F2	P1
0004	M30	(9)

0001	M03	E08	T03	S1750	$
0002	Xo	Yo	Z-2	(0)
0003	X 1.8	(1)
0004	X3.75	Y-.21
0005	A90	B0	R=.2	C2
0006	Y-1.72
0007	A0	B2.70	R.2	C2
0008	X-1.95		Y-1.93		(No Y!)
0009	X-3.75
0010	Y .14
0012	X0	Y0
M30
```

March 4th
Remake Cover Plate

New Offset values
X= 16.35
Y = 6.9

Appendix D: Electrical Schematic

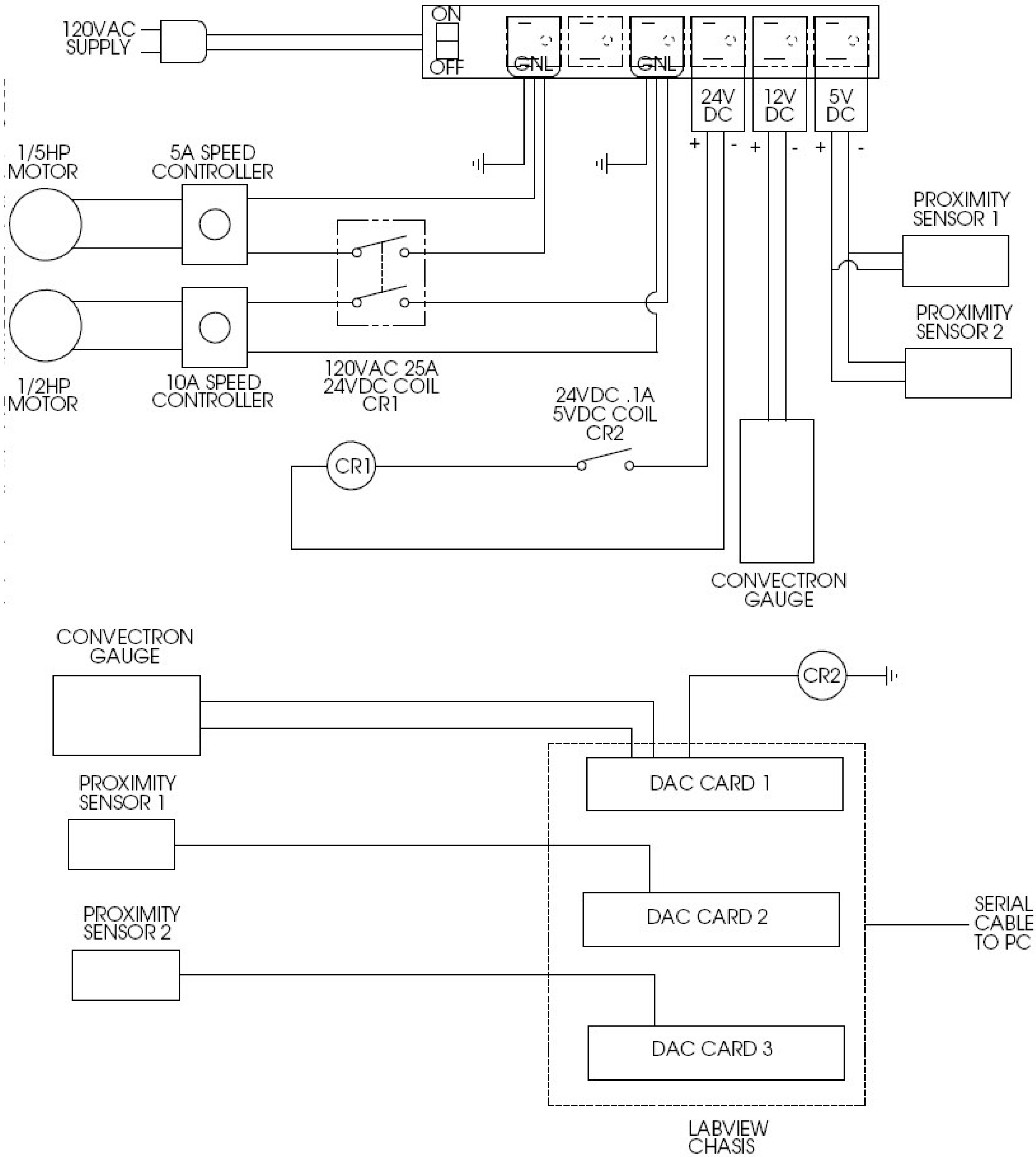

Figure 10: Electrical Schematic

Appendix E: Bill of Materials

Table 8: Bill of Materials

Description	Vendor	Vendor PN	Price	Qty	Ext. Price	Notes
Electric Motor 1/5 hp	Grainger	2M139	$82.45	1	$82.45	
Motor Speed Controller	Grainger	4X796	$37.65	1	$37.65	
Helical Beam Coupling (5/16" to 3/8")	Mcmaster	9861T7	$20.46	2	$40.92	Specify 5/16" to 3/8"
Ball Bearing (3/8" shaft)	Mcmaster	2342K65	$9.30	10	$93.00	
2.4" gear	Mcmaster	6867K36	$43.97	1	$43.97	
1.6" gear	Mcmaster	6867K34	$36.20	5	$181.00	
Hex Standoff	Mcmaster	91780A890	$1.54	5	$7.70	Specify #10-32 Screw
Proximity Sensor	Grainger	5AY33	$36.90	1	$36.90	
Shaft Collar	Mcmaster	9739T2	$7.24	1	$7.24	
10-32 Socket Head Cap Screw (qty 100) .75 lg	Mcmaster	92196A272	$11.46	1	$11.46	
# 10 lock washer 18-8 ss (qty 100)	Mcmaster	98437A108	$3.68	1	$3.68	
Spider Coupling Hub	Mcmaster	6408k12	$3.39	10	$33.90	
Spider Coupling Spider	Mcmaster	6408K73	$2.02	5	$10.10	
18-8 SS keystock (12")	Mcmaster	92530A117	$3.37	1	$3.37	
3/8" Keyed Shaft (24")	Mcmaster	7398K11	$27.27	1	$27.27	
Steel Threaded Rod 10-32 Thread, 1' Lg	Mcmaster	98790A310	$0.69	2	$1.38	
6" Wiper	Mcmaster	9403K45	$11.77	2	$23.54	
8" ID 1/8" O-ring, Pack of 5	Mcmaster	4679T313	$14.82	1	$14.82	
5.75" ID 1/8" O-ring, Pack of 2	Mcmaster	1201T889	$9.51	1	$9.51	
1.125" ID 1/6" O-ring, Pack of 25	Mcmaster	1201T36	$9.13	1	$9.13	
Hex Standoff	Mcmaster	91780A890	$1.54	3	$4.62	Specify #10-32 Screw Size
Belt	Mcmaster	6082K601	$3.29	1	$3.29	
1/4" SS shaft, 36" LG	Mcmaster	88855K212	$10.5	1	$10.50	
3/8" SS shaft 36"LG	Mcmaster	88915K213	$19.54	2	$39.08	
1/2" SS shaft 36"LG	Mcmaster	89535K153	$12.14	1	$12.14	
5/8" SS shaft 36"LG	Mcmaster	89535K113	$16.71	1	$16.71	
3/4" SS shaft 36"LG	Mcmaster	89535K123	$20.34	1	$20.34	
7/8" SS shaft 36"LG	Mcmaster	89535K343	$28.96	1	$28.96	
1" SS shaft 36"LG	Mcmaster	88915K213	$38.62	1	$38.62	
1" Tube O-ring	Mcmaster	4518K67	$20.11	3	$60.33	
1.5" OD borosilicate glass disk, 3/16" thk	Mcmaster	8477K62	$6.85	1	$6.85	
1/32" key stock, 1' lg	Mcmaster	98535A125	$1.5	1	$1.50	
3/32" end mill	Mcmaster	8770A163	$11.87	2	$23.74	
Breather Vent 1/4" NPT Female	Mcmaster	9833K25	$1.6	2	$3.20	
Pipe Fitting 1/4" (M) NPT, Elbow	Mcmaster	50785K123	$2.45	2	$4.90	
Lip Seal 3/8" ID X 5/8" OD X 1/8" Height	Mcmaster	9505K15	$2.61	5	$13.05	

Mobil Oil Vacuum Pump Oil, 32-oz	Mcmaster	2158K71	$9.15	1	$9.15	
Dow Corning Vacuum Grease	Mcmaster	2966K52	$21.67	1	$21.67	
1" vacuum flange	Mcmaster	4518K41	$17.66	1	$17.66	
1.5" vacuum flange	Mcmaster	4518K42	$20	2	$40.00	
1" vacuum o-ring	Mcmaster	4518K63	$7.39	1	$7.39	
1.5" vacuum o-ring	Mcmaster	4518K64	$11.17	1	$11.17	
1" vacuum clamp	Mcmaster	4518K72	$9.38	1	$9.38	
1.5" vacuum clamp	Mcmaster	4518K73	$11.06	1	$11.06	
flat urethane belt	Mcmaster	9485T14	$15.2	1	$15.20	Specify 19" circumference, 1 belt
Light absorbing paper	Mcmaster	9019T1	$13.48	1	$13.48	
Laser Diode	Edmund Scientific	NT59-080	$89	1	$89.00	
Silicon Detector	Edmund Scientific	NT53-372	$19	1	$19.00	
Medium Strength Thread Locker	Mcmaster	1810A315	$13.42	1	$13.42	
4" ID X 3/16" Dia O-ring	Mcmaster	9464K174	$5.34	1	$5.34	
4-1/2" Glass Disk	Mcmaster	8477K76	$14.95	1	$14.95	
24V Power Supply	Mcmaster	70235K84	$18.81	1	$18.81	
#10-32 Sealing SS Screw	Mcmaster	95198A675	$2.38	10	$23.80	
#10-32 1" SS Screw	Mcmaster	92185A992	$7.81	1	$7.81	
1/4"-28 1-1/2" LG Screw	Mcmaster	90128A380	$9.86	1	$9.86	
1/4" Clevis Pin W/ Retaining Ring, 1" Lg	Mcmaster	92735A230	$7.18	2	$14.36	
1/4" SS Tube, .035" Wall, 36" Lg	Mcmaster	89895K125	$11.96	1	$11.96	
1/4" Compression Nut	Mcmaster	5182K554	$2.18	4	$8.72	
1/4" Compression Front Sleeve	Mcmaster	5182K574	$1.24	4	$4.96	
1/4" Compression Rear Sleeve	Mcmaster	5182K584	$1.13	4	$4.52	
25A Contactor	Mcmaster	7678K42	$14.67	1	$14.67	
Aluminum Helical Coupling	Mcmaster	6208K14	$30.40	1	$30.40	Specify 3/8" by 3/8"
Spider Coupling Hub	Mcmaster	6408k12	$3.39	5	$16.95	Specify 3/4" Bore
Replacement Mirror	Mcmaster	1017T311	$2.85	2	$5.70	
1.5" OD borosilicate glass disk, 3/16" thk	Mcmaster	8477K62	$6.85	2	$13.70	
Damping Mounting Pad	Mcmaster	5996K1	$9.32	1	$9.32	
Damping Feet	Mcmaster	2515T16	$4.05	1	$4.05	
Economy Potentiometer	Mcmaster	7436K31	$11.39	1	$11.39	Specify 1 KOhm
Mini Analog Potentiometer dial	Mcmaster	7436K39	$10.26	1	$10.26	
5V power supply	Mcmaster	70235K22	$12.76	1	$12.76	
Proximity Sensor	Mcmaster	14215T22	$39.13	1	$39.13	
10A Motor Speed Controller	Grainger	4X797	$47.95	1	$47.95	
1/2 HP 10000RPM Motor	Grainger	2M145	$189.50	1	$189.50	
Total					**$1,775.27**	