Final Design Report

Team 1

Sealing Ring Testing and Characterization

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Abstract

The purpose of the final product of this project is to reduce the time, effort, and money required to design the sealing components between mating engine parts. These most common type of sealing component is the elastomeric sealing ring which comes in various cross sections, but currently, the performance of irregularly shaped cross sectional seals such as the diamond seal are not known until finite element analysis is applied during the design process of mating components. This process becomes costly due to the need to perform an extensive analysis for each individual potential type of seal to be used, some of which perform better than others. The product of this project serves to provide a starting point for the design process analysis by utilizing parameters of the application known to the designer to give instantaneous approximations of several different types of seals. To accomplish this, tests were performed on several different types of fluoroelastomeric seals including circular, rectangular, and irregular cross sections of varying sizes which were provided by Cummins, Inc. Relationships were defined through data analysis between percent crush and sealing pressure for each type of cross section geometry. This was done with the use of a test fixture specially designed for this application and an MTS machine that was used to apply a compressive force to seal samples at percent crush increments from 5% up to 40% to ensure a wide range of data was collected. A user interface was developed in Microsoft Excel that incorporates the relationships defined using the test data to find approximations of unknown application parameters. The interface can take two out of three possible inputs including cross section geometry, percent crush, and sealing pressure, and output a third parameter within 10% accuracy.

Acknowledgements

Senior Design Team 1 would like to acknowledge and thank Cummins, Inc. for making this project possible, particularly Terry Shaw and Parker Harwood for being our liaisons and providing guidance along the way. We would also like to thank Dr. Alvi and Dr. Oates for acting as faculty advisors and being available to meet and discuss the project whenever the need arose. We would like to thank Danny, a teaching assistant of Dr. Kalu, for volunteering his time to help the team access and use the facilities. Furthermore, the team thanks Dr. Kalu for letting the group use his lab and equipment. Team 1 would additionally like to acknowledge Dr. Gupta and his teaching assistants Sam Botero, Ricardo Aleman, and Yuze Liu (Liam) for all the time and effort put into the Senior Design class. Last but not least Team 1 thanks Dr. Shih, for without whom all this would not be possible.

1. Introduction

Engines have many parts, and in order for engines to operate correctly, their parts must fit together properly. Keeping the pressures, temperatures, and fluids of unique systems separate is particularly crucial, and this is possible only if the joints between the mating parts are leak-free. One way manufacturers accomplish this is by using sealing rings of various shapes and sizes as displayed in Figure 1.

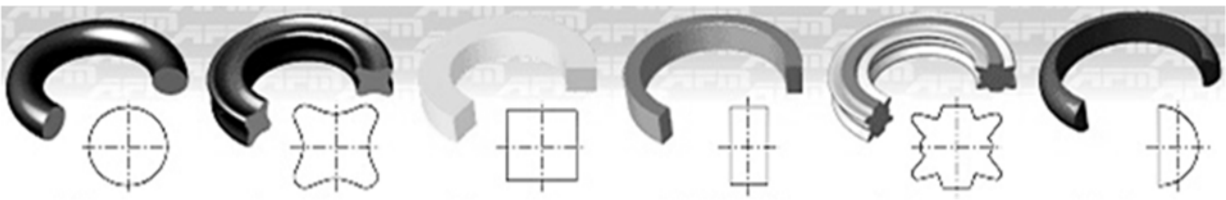

Figure 1: Various Sealing Ring Cross-Section Profiles [1]

The high temperature and high pressure working environments require the best quality elastomeric sealing rings to have the capability to function while exposed to the elements and harsh chemicals. A capable and efficient material that is commonly used is a fluoroelastomeric material referred to as FKM [2].

Cummins, Inc. designs, manufactures, and sells engines. As a corporation that strives to produce marketable and efficient engines, the joints between mating parts must be totally sealed. Determining the proper sealing ring shape for an application such as the one shown in Figure 2 requires a process that currently depends on multiple iterations of finite infinite analysis. This process is both costly and time consuming.

Figure 2: Irregular Sealing Ring in Application [3]

Cummins, Inc. requested Team 1 to examine the behavior of various selected sealing rings as an endeavor to define a relationship between the cross-sectional geometry of a sealing ring, the sealing pressure, and percent crush.

With an allocation of $2000.00 and multiple sealing rings of various cross-sections (circular, rectangular, diamond, and pseudo-diamond), Team 1 implemented compression tests with an MTS machine to record data and analyze the seals. The pressures required to reach certain percent crush intervals were documented with pressure sensitive film. The load was recorded by software connected to the MTS machine, and along with the pressures and cross-sectional profiles, evaluated. The effects of high temperatures, pressures, and harsh chemicals on the material properties of the seals were not taken into consideration. The sealing rings were cut into straight samples with length ten times the diameter of the cross-section to negate the effects of the ends and facilitate test fixture design. In addition, the seal ring samples were assumed to be under no stretch during testing. Ultimately Team 1 inspected a relationship that would minimize the amount of finite element analysis required for the selection of the appropriate sealing ring for an application, saving time and money.

2. Background and Literature Review

Due to its elementary shape, the circular seal ring, or typically called an o-ring, is designed by simply varying the clearance gap between mating parts that would define a percent crush and result in a sealing pressure. Percent crush is the ratio between the compressed height (or radial dimension) under loading and the original height (or radial dimension) times 100, as seen in Equation 1.

$$Percent\ Crush = \frac{Compressed\ Height}{Initial\ Height} \times 100\% \qquad (1)$$

Sealing pressure is the pressure generated between the elastomeric sealing component and the mating parts due to the crush of the sealing component [4]. When the compression force is applied to a sealing ring, it deforms and creates an equal and opposite force. Depending on the load applied and the cross section of the sealing ring, the contact area will grow to match the force. This results in the sealing pressure. The goal of this project was to apply a similar method to measure sealing pressures and understand how varying the cross section affects their performance. In Figure 3, one can see how sealing rings are used between mating parts and how their performance depends on the pressure applied. When a fluid is under high heat and trying to escape, it applies pressure on the sealing ring. If the sealing pressure between the seal and the mating components is not greater than the pressure of the fluid then the sealing ring will fail and the system is compromised.

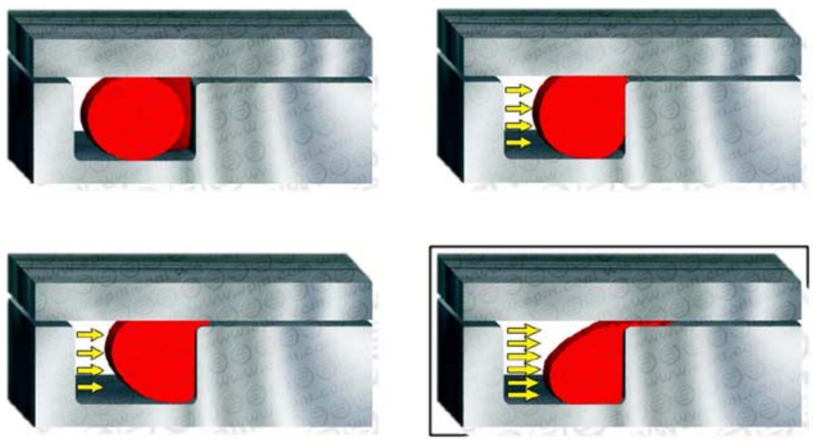

Figure 3: Example of Failure in Application; Installment of O-Ring (top left), Pressure Applied to O-Ring (top right), Extrusion of O-Ring (bottom left), Failure of O-Ring (bottom right) [5]

Presently, there are some existing ASTM standards for testing elastomeric seal rings' performance capabilities. The ASTM D1414-19 - Standard Test Methods for Rubber O-Rings is conducted on rings with contrasting cyclic loads and working temperatures in order to give insight into how the different properties of an O-ring will be affected by age [5]. Although standards for testing sealing rings with a general or typical cross section already exist, standards specific to non-circular or irregular cross sections do not exist. Therefore, testing beyond circular rings currently has no standards.

Another reason deviations from standards were made was because the sponsor requested testing a percent crush of up to 40%, which is beyond the industry standard of 30%. This is beyond standard because structural damage begins to occur in the seal beyond 30% crush due to the limitation of space in a mating groove. To be able to reach 40% crush, the depths of the grooves used in testing had to be decreased from the standard dimensions so that the load piece did not bottom out on the top of the groove plate before reaching 40% crush. The ASTM D395 - Standard Test Methods for Rubber Properties in Compression was also consulted but had to be adapted to testing seals in grooves whereas the standard calls for the test fixture being two parallel flat plates

[6]. During testing, the team dealt with the differences in data with assistance from sponsor and faculty advisors to create the test method used.

3. Concept Generation

There are two parts to this project: sealing ring testing and data analysis. In order to test the sealing rings, a test fixture was created for use in an MTS machine. The final test fixture design was chosen from three initial design concepts. The initial design concepts were created for an MTS machine that would later become unavailable; however, only minor modifications were needed to make the final test fixture design compatible with the MTS machine used for testing. The three design concepts are explained thoroughly in the following paragraphs, followed by the decision matrix used to evaluate the strength of each concept.

The first design was conceived with the concept of simplicity in mind. It consists of static grooves of varying widths and depths machined into a plate. The groove dimensions are calculated using equations based on information found in the Cummins, Inc. Engineering Standard – 98010 [4]. The standard contains a table of common seal sizes, which gives groove height and width based on each seal size. This data was graphed to check for linearity between sizes and because there is a linear correlation, this graph can be used to determine groove dimensions for seal sizes not listed in the table.

The model of this design, which consists of a groove plate and base, is shown in Figure 4. In this preliminary design, nine grooves are machined into a plate. In order to test all cross-sections, three groove plates would need to be machined. On the bottom of the groove plate there is rectangular protrusions of equal dimensions centered under each groove. These protrusions will fit into corresponding notches on the base which will help hold the groove plate in place. With the protrusions being centered under each groove and a notch in the base centered directly under the load cell, a groove loaded with a sample can be centered under the load cell simply by placing it's corresponding protrusion in the center notch. A clamp can be applied to the edge of the plate to ensure the groove plate does not move during testing. Having the base plate the same length as the groove plate will allow the groove plate to be supported under at least half of its length at all positions. The clamping flange is designed to be used with the MTS machine's vice which is adjustable side to side so the base will be able to be centered under the load cell easily. Also, the top of the vice's jaws are flat and already parallel to the load cell so when the base is loaded it will sit on this surface thus making the base and ultimately the groove plate parallel to the load cell which is a paramount feature.

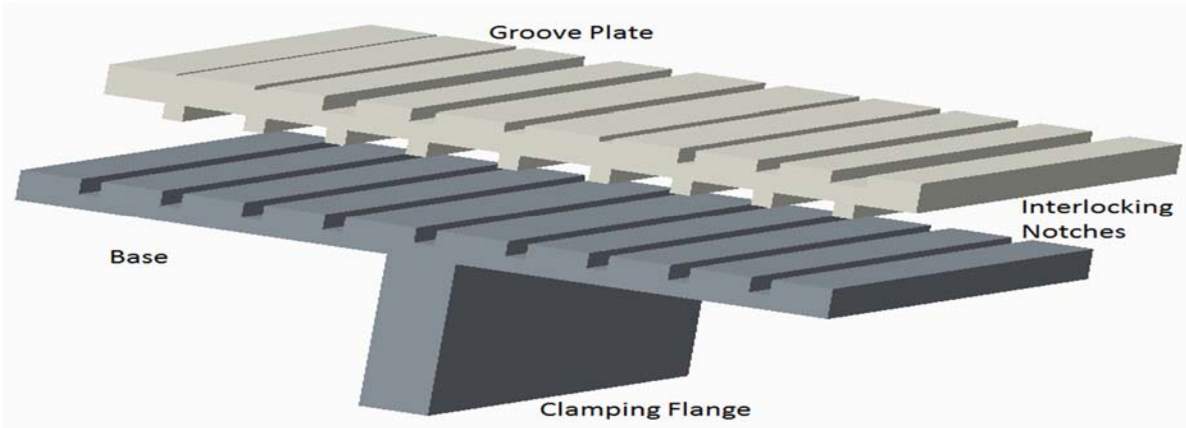

Figure 4: Design 1 - Centered Test Position

The second design was created in order to tackle a large bulk of different cross sections. It consists of three grooves on the base plate that serve as a guiding track for two plates (or adjustable groove walls) that translate from opposite sides as seen in Figure 5. The base has the same clamping flange as design 1. In design 2, the grooves are trapezoidal in order to limit movement to the y-direction and to negate the moment created from an overhang of the adjustable plate over the base. Since we want to test in the same direction as design 1, we need to create these trapezoidal grooves perpendicular to the longitudinal axis of testing.

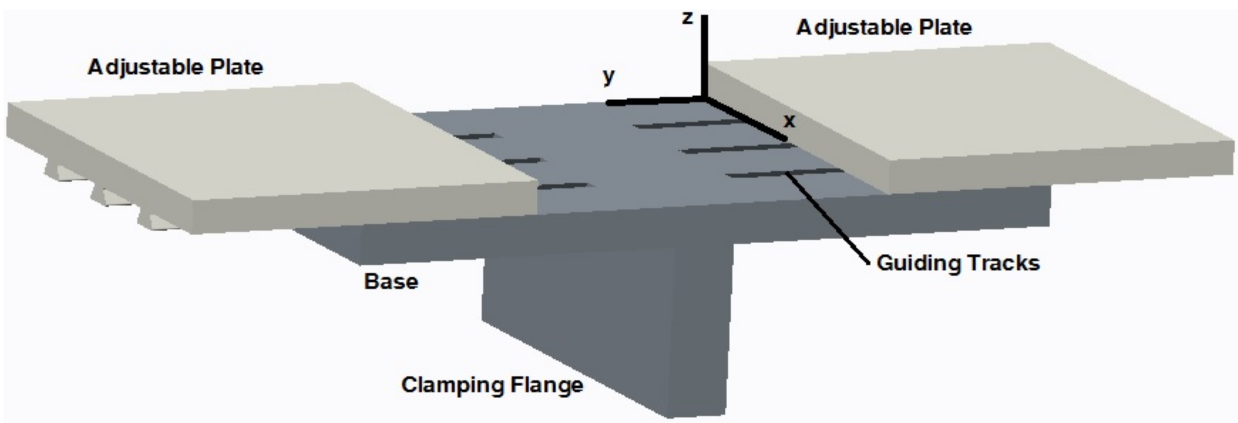

Figure 5: Design 2 - Adjustable Groove Plates

The adjustable plates resting on the base plate will be machined in pairs and will vary in height, to accommodate for the various groove heights. As mentioned earlier, depending on the height of the seal, there is a standard groove height. In order for this design to be effective, the cross sections, although varying in geometry, need to have a small variation in heights. This will make this design feasible, by only having to adjust the width of the groove with the translation of the two upper plates along the track. The bottom of these adjustable plates have a protrusion that matches the base plate in order to guide the plates along the y-direction. During testing the seals will expand in the lateral direction, creating a force that could translate the adjustable plate. Therefore, in order to limit that, a set of clamps must be used during testing to limit the effects of seal expansion. The adjustable plates can accommodate unlimited width dimensions under 12mm, but can vary in force application location since there is no groove mechanism to ensure the centering of the material.

Design 3 features a single base, with smaller, individual plates containing one groove per plate. The base features a rectangular depression on the top surface that will receive the smaller individual groove plates. This design requires an individual plate for every cross-section. These individual plates will lie in the depression of the base and should be easily exchanged between testing of different cross-sections. The groove plates sit slightly above the surface of the base plate to allow for an easier extraction when changing from one cross-section to another. There is a retaining lip on the front and back of the baseplate to help hold the groove plate in place during testing. The retaining lips are recessed below the surface to further ease the testing setup and tear-down times. As shown in Figure 6, the baseplate is much smaller than those of the other design concepts, however the clamping flange will have the same dimensions. The vice on the MTS machine will ensure the base plate is perpendicular to the compression direction. A small clamp is used to reduce the noise that may arise from minor slippage between plates due to the tolerance limits of both the baseplate and the groove plates. The individual groove plates of design 3 will be machined from a thinner block of Aluminum 6061 than designs 2 and 3, which will reduce the financial burden of machining individual plates with a single groove. This design was created with simplicity in mind. The testing procedure using this design will be easier than designs 1 and 2 and allow fewer opportunities for human error to affect testing results.

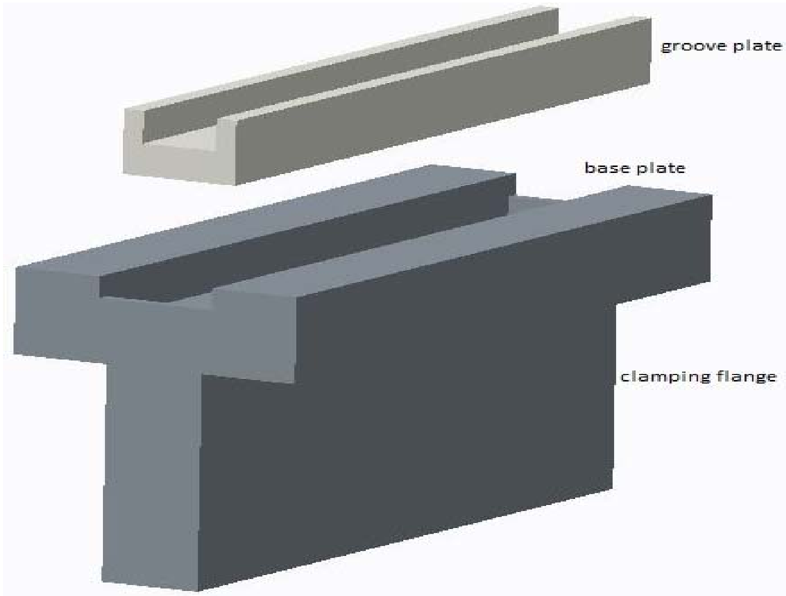

Figure 6: Design 3 - Individual Groove Plates

A decision matrix was used to choose the final design concept. The criteria for the designs were derived from several places like the design specifications, performance specifications, and industry standards. These criteria or design parameters were then weighted upon importance by percentage. The heaviest parameter was "cost", with "rigidity", "setup time", and "stability under load", which all weighed the second most. "Cost" weighed the most because of the budget constraint, but also because one of the main goals of this project was to produce a method that would reduce cost. "Ease of use" was weighed the least important parameter due to the necessity of the method. It was concluded that even if the design was not easy to use, the team was willing to trade ease for data security and accuracy. Also, the team would be capable of writing a proper procedure to simplify use and minimize error as much as possible when using the design.

Table 1: Design Concept Decision Matrix

		Types of Design		
Design Parameters	**Weight (%)**	**Design 1**	**Design 2**	**Design 3**
Rigid	15	6	3	9
Ease of Use	5	9	3	6
Machineability	10	6	3	6
Cost	20	6	6	6
Setup Time	15	6	3	9
Durability	10	6	3	9
Stability under load	15	3	6	9
Safety	10	6	3	9
	Total	**570**	**405**	**795**

Based upon the results of the decision matrix and the deep consideration of each design, Design 3 was chosen to be the final design concept. The individual groove plate design had the highest total in the decision matrix, which shows that it displayed the most promise for meeting the criteria listed. Design 1 also showed possibility, but did not meet the same criteria with the same strength as design 3. Design 2 was an interesting concept, but the complex machining required and the propagation of error throughout the design were too large for design 2 to be considered. Design 3 was chosen to be the final design. This design, however, would need to be slightly altered for use on a different MTS machine.

4. Final Design

The final design of the test fixture kept the three main parts as before which are the load piece, the interchangeable groove plates, and the base that the previous iterations incorporated but was adapted to the new C45.105 MTS machine. The load piece was designed to mount to a receiver attached to the load cell of the machine which measures loads felt by it. The load piece applies a compressive force to a sample of a sealing ring that is mounted in groove that is specifically designed for each different type and size of sealing ring. Each individually designed groove is cut into a groove plate that is supported by the base of the fixture. The base is mounted to the bottom receiver of the MTS machine which remains stationary during testing. While the main components of the fixture remained similar to previous iterations adaptations were made to the mounting features of the fixture to work with a different MTS machine than was originally designed for. The specifications of the MTS machine used can be found in Appendix A. The fixture material remained as aluminum 6061 for its rigidity, machinability, weight, and price.

4.1 Features

The final design of the test fixture features a load piece that is used to apply a compressive load to samples mounted in the base of the fixture. The load piece is essentially a rectangular block that, when mounted in the MTS machine, produces a flat contact surface to the sample that lies parallel to the groove plate mounted in the base. The parallelism between this contact surface and the groove plate, and therefore sample, ensures an evenly distributed load is applied to a sample mounted in the groove plate. Each groove was either cut to specifications called for in the engineering drawings, which was the case for most irregular cross sectional seals, or designed to Cummins standard 98010 Molded Elastomeric Gaskets. Each groove plate fits snuggly into the base of the fixture to ensure minimal deflection occurred in the fixture during testing. An assembly of the test fixture is shown in Figure 7.

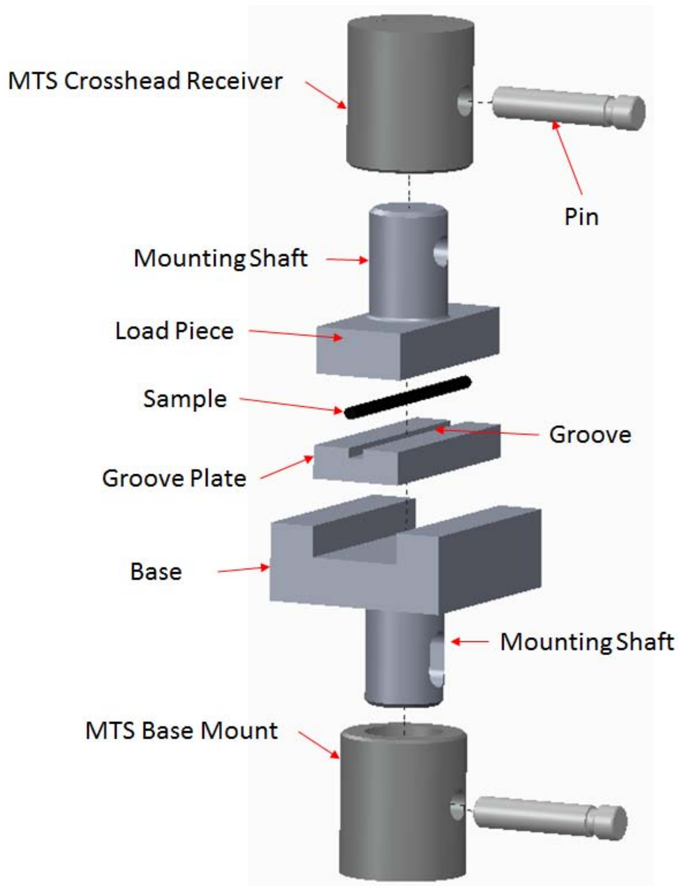

Figure 7: Final Test Fixture Design

Deflection also came into consideration during design of the attachment shafts of the fixture. Minimal deflection was achieved by allowing the base and load piece to rest on the receivers of the MTS machine rather than having the mounting pin or some other some other surface carry the load. These surfaces of the receivers are also what is responsible for keeping the parallelism between the load piece and other parts because the machine maintains the orientation of these receivers through its full range of motion. All groove dimensions, part dimensions and tolerances can be found on the engineering drawings in Appendix B. Another key feature of the testing operation is the use of Fujifilm, which is a type of pressure sensitive film. A slice of Fujifilm was placed between the sample and the load piece so that an impression of the sample would be made on the film. The film would then be scanned and analyzed to find the sealing pressure felt by the film. An example of what the film looks like after use and scanning below in Figure 8. The scale of pink color is read by the scanning device and converted to the color spectrum for differentiation of pressures felt by the sealing ring under compression.

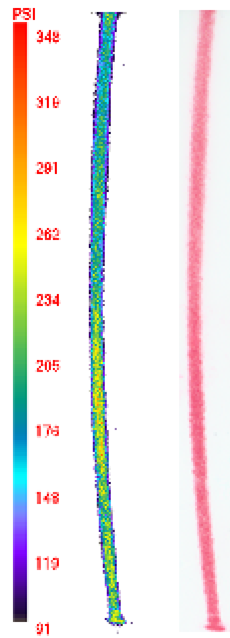

Figure 8: Fujifilm Before Scanning (right) and After Scanning (left)

4.2 Crucial Dimensions

The test fixture was designed to be used with MTS machines that have cylindrical receivers with interior diameters of 1.25 inches. The load piece has a circular shaft with a through hole so it can be mounted with use of a pin in the MTS machine receivers. The critical dimensions for the fixture can be shown in Table 2. Both the load piece and base must have the pin-hole diameter, mounting shaft diameter and length in order to fit into the MTS machine. Also, the MTS machine is capable of closing to a gap between both crossheads of approximately 2 inches, and therefore the overall height must be defined in order to ensure the capability of the full compression of a specimen.

Table 2: Fixture Dimensions

Dimension	Measurement (in.)
Mounting Shaft Diameter	1.24
Mounting Shaft Length	1.75
Pin hole diameter	0.50
Overall Width	3.00
Overall Height	5.72

4.3 Test Fixture Assembly

Assembly of the fixture into the MTS machine and set up of the test required about 10 minutes. The load piece and the base are mounted to the upper and lower receivers of the MTS machine using a pin that is provided with the MTS machine hardware. The sample to be tested is loaded into its corresponding groove plate and a slice of Fujifilm is placed on top of the sample making sure the rough sides of the two pieces of film are facing each other. Once the groove plate is seated in the base of the fixture the test can be performed.

4.4 Design Reliability

Before the test fixture was finalized to be built, FEM was performed. The results of this are shown visually in Figures 9 and 10 which reinforce the decision to use Aluminum 6061. With the material's tensile yield strength around 276 MPa and the fixture only experiencing a load of up to 6 MPa during tests, failure is an unlikely event. Under a high amount of tests, the fixture could possibly fatigue and fail under lower stresses than the tensile yield strength, but Aluminum 6061 has a fatigue strength of 96.5 MPa after five hundred million cycles, so the fixture will not have the chance to fail under the life cycle of its use, at least for the duration of this project.

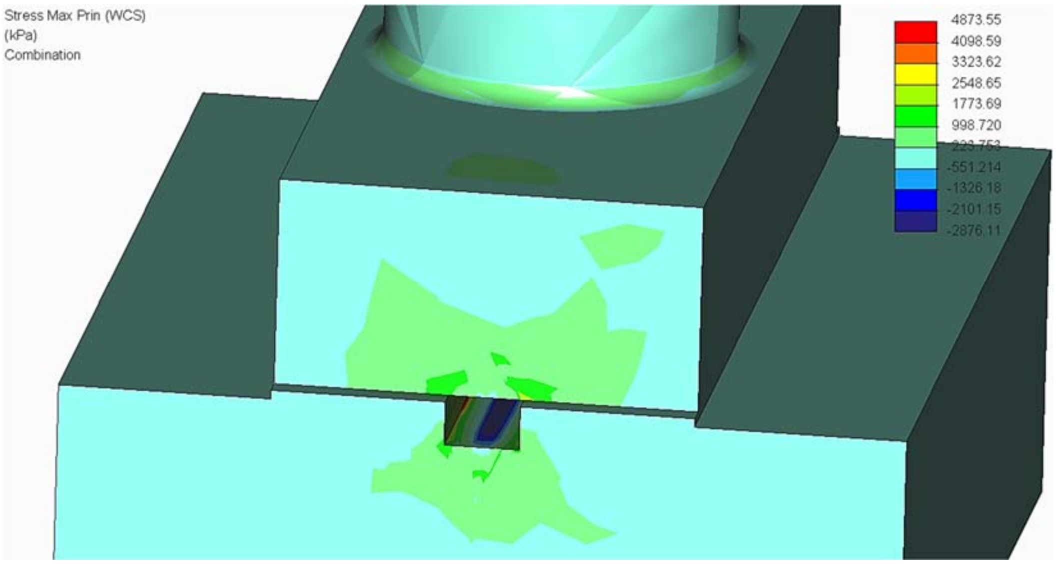

Figure 9: Maximum Principal Stress FEM

In order to produce usable data, the test fixture should not deflect under the loads applied during testing, so plastic deformation is considered failure for this instance. Figure 10 shows the deflection analysis under extreme testing conditions which shows that the fixture will not deflect more than 0.00035 mm which is well under maximum deflection of 0.01 mm that was defined with the advisement of the sponsor liaison.

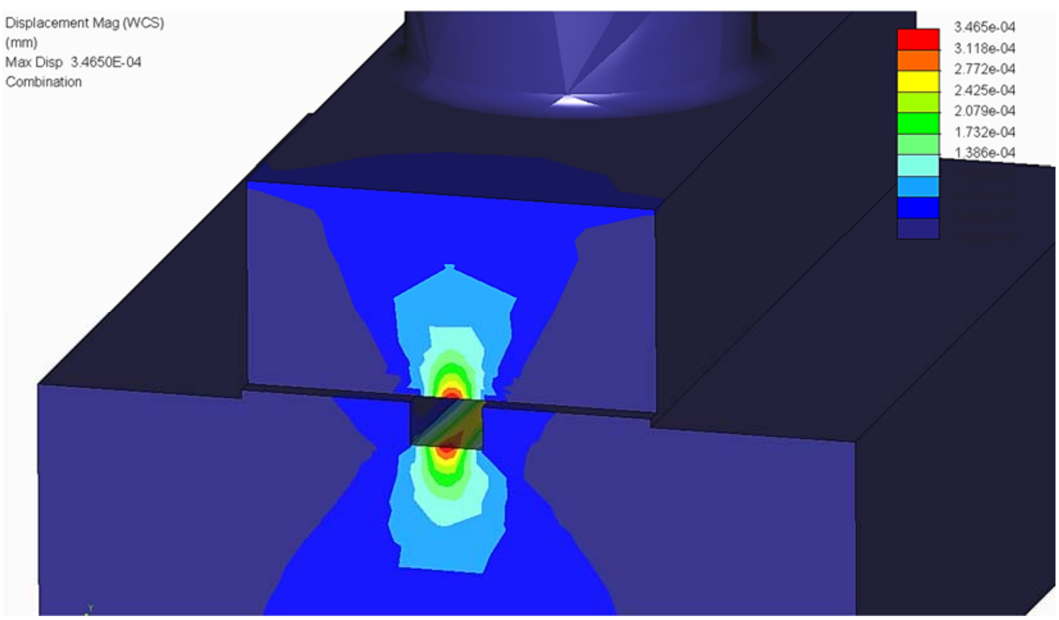

Figure 10: Maximum Deflection FEM

4.5 User Interface

The interface consisted of a Microsoft Excel spreadsheet that was capable of receiving two known parameters of the three required (sealing pressure, percent crush, and cross section geometry), and outputting the unknown parameter within 10% accuracy.

5. Considerations for Environment, Safety, and Ethics

Since the project assigned was more of a research venture rather than a deliverable product or device, the environment was not a critical factor considered during any stages of the project. Safety, on the other hand, was an influential factor during the design of the test fixture and the testing of the sealing rings. When designing the fixture, the stability, durability and rigidity of the fixture was taken into account not only for performance reasons, but also for the safety of the team. The test fixture was designed using Aluminum 6061 in order to prevent any plastic deformation or sudden failure through fatigue. This metal has a tensile and fatigue strength that far exceeded the expected loads of the sealing rings in order to prevent any plastic deformation that could lead to fracture. In addition, finite element analysis (FEA) was done on the test fixture in order to locate the presence of any stress concentrators to minimize their effect on the final design. During testing, precautions were maintained while operating the MTS machine. Fingers and clothing were kept away from moving parts, and the area surrounding the machine was kept uncluttered so as to not create any tripping hazards.

Ethics was also considered when designing the test fixture. Research was done on existing test fixtures for sale and patents before the team began designing. The fixture was not created with the use of an existing patent and all research was cited and referenced in all of the reports throughout the design process.

6. Project Management

6.1 Schedule

A workflow breakdown structure, seen in Figure 11, was created in order to illustrate the main tasks that must be completed in order to complete this project. This project can be broken down into three main tasks: testing, data analysis, and creating the user interface if possible. In order to complete this project in a timely fashion, the original Gantt chart, which can be seen in Appendix C, was created.

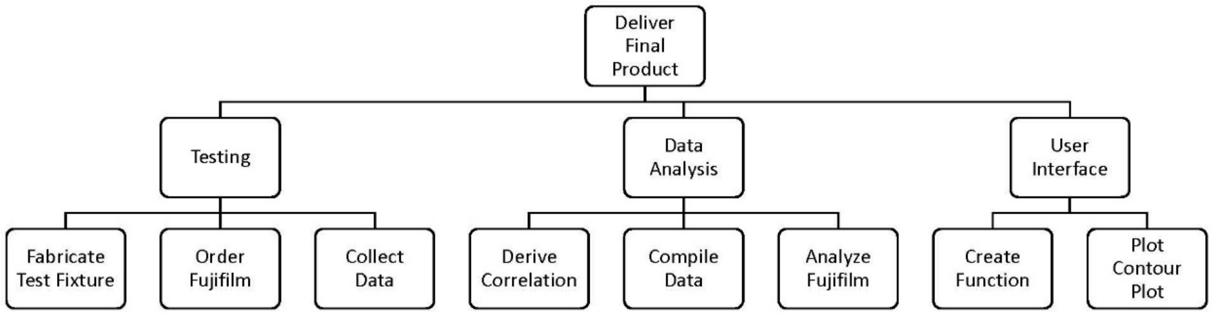

Figure 11: Workflow Breakdown Structure

The first phase of the project was testing. Before beginning, research on testing methods and how they were related to the project had to be done. Once a testing method was found, a test fixture needed to be designed and fabricated in order to run these tests. Several designs for this fixture were created and a final design was selected. In order to finalize the selection, a list of the cross sections most used by Cummins, Inc. needed to be sent in order to calculate the material strength needed by the testing fixture in order to have very minimal deflection. Also, the number of cross sections that were going to be tested was unknown, which made it impossible to calculate how much raw metal material will be needed in order to make the groove plates. The test fixture was scheduled to be fabricated by the end of October. But due to the previous reasons, it was delayed to November. After deciding on the testing procedure, the team needed to decide on the Fujifilm sensitivities needed and the testing procedures. Although that was initially scheduled to be completed in the Fall, it was actually completed in January. In the Spring semester, very few preparations were needed and testing would begin in January. However, it was discovered that our testing location no longer available after the conclusion of the winter break. Finding a new testing location, redesigning a test fixture, creating a template on the new MTS machine software, and working a schedule with Dr. Kalu and his TAs delayed testing by a little over a month. As a result, testing was concluded in March rather than January. Revisions were made to the original Gantt chart, and the Spring version can also be found in Appendix C.

The second phase of the project was the analysis of the data collected from the testing. Once pressure readings were output from the tests, the Fujifilm needed to be sent to Cummins, Inc. and scanned. In the original Gantt chart, data analysis was supposed to be completed over the month of February, but due to our delays it had to be completed quickly in March. This task was expected to be finished in three days, however it was done in a week. The user interface, or third phase of the project, was also allotted a month for completion, but was pushed back due to complications and was unfortunately unable to be completed to expectation. This phase was deemed not as necessary as the first two phases, as for the method devised by the team would require much more information from a greater variety of cross section geometries to be truly viable for industry use.

6.2 Resources

Throughout the year, several resources became available and allowed for the completion of the main aim of this project in a timely manner while still keeping the budget low. Through the cooperation of the College of Engineering, the testing fixture was fabricated in the machine shop and the MTS machine was used for testing free of charge. For fabrication in the machine shop, the team provided descriptive CAD drawings in order to reduce time and effort by the machine shop in creating the fixture. When using the MTS machine, proper precautions were taken in order to add minimal wear and tear to the machine throughout testing. The team spent a day not only training on how to use the machine and its accompanying software, but also how to troubleshoot if any problems arose. Another resource that was provided was all the sealing ring samples that were being used for testing. These were sent by Cummins, Inc. in order to keep the budget low and to provide the team with sealing rings that were a symbolic representation of what they is used in their applications. A representative amount of these sealing rings were tested and correlations were found for these cross sectional geometries.

6.3 Procurement

The project cost a total of $593.87, which is 30% of the $2000 budget provided by Cummins, Inc., as seen in Figure 12. The Fujifilm Prescale pressure sensitive paper cost $380.99, which was 27% of the budget. This paper comes in different pressure sensitivities that work in limited pressure ranges. Prior to the experiment, theoretical data was devised and it was concluded that three

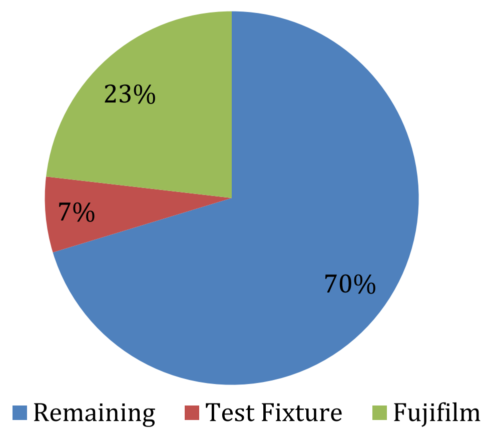

Figure 12: Budget Diagram

sensitivities will be needed to complete these tests. Table 3 shows the selected sensitivities and their range. Each sensitivity cost $123 and its shipment, since it requires a special container, cost $59.99.

The Aluminum 6061 used to build the testing fixture and its accompanying groove plates cost $130.70, which was 7% of the budget. This budget was sufficient, since expenditures were kept low by machining in-house, receiving the sealing rings from the sponsor, and having the Fujifilm analyzed by Cummins, Inc.

Table 3: Fujifilm Sensitivities Bought for Tests

Type of Film	Pressure Sensitivity Range (psi)
Low	350-1400
Super Low	70-350
Ultra Low	28-85

6.4 Communications

The main forms of communication were over GroupMe, a group-texting application, email, and phone calls. The preferred method over the past year for communicating among the senior design group was group texting through GroupMe to facilitate the speed of communication. Communication with the sponsor was done mainly through weekly teleconferences and occasional emails in order for them to see the team's progress through presentations and data sets. An email account was created for the team in order for all team members to be informed about all communication. For file sharing, Google Drive was the main method of transfer.

Members were responsible for checking their emails at least twice a day for important information and updates. Throughout the year when a meeting was needed, the team members were notified of the meeting dates, expected to bring completed work the meeting and agenda of what was expected to be accomplished during the meeting through group text. Meeting with TA's were usually done before a deliverable for any questions or a quick overview on the format of the assignment that was going to be submitted. Due to the TA's busy schedule, email was not the best form of communication so we had to visit their offices for any help. Advisors were very helpful and were punctual with meeting times. There were few times where the team or advisors couldn't meet, but an email was sent beforehand to reschedule or cancel.

When communicating with advisors, there was only one issue when locating an MTS machine for compression testing. When communicating with the advisor during the fall, it was understood that the team will be testing on a machine that is under the advisor's department. Knowing this, a testing fixture was created to fit on the provided MTS machine. When the team returned in the spring the advisor decided, after further deliberation, that the risk of having the team test on his machine along with the limited availability will make testing on his MTS machine difficult. ue to this miscommunication, the test fixture design had to be changed and another MTS machine had to be located. In order to stop any further delays due to miscommunication, when an MTS machine was found, the objectives of the project were clearly discussed and its implementations on the amount of testing needed. Afterwards, the team was able to redesign the fixture and begin testing.

7. Conclusion

Over the course of the academic year, the senior design team defined the scope of the project set forth by the sponsor, researched, designed, and machined a test fixture, and was successful in deriving correlations between cross-section geometry of a sealing ring, sealing pressure, and percent crush. This accomplished by testing sealing ring samples supplied and selected by the sponsor and then analyzing the information provided. The reliability of the testing fixture designed to simplify the procedure was certified for use through the implementation of finite element method (FEM). Research was done to prevent any possible copyright infringement, and the proper safety precautions were put into effect when testing. Obstacles and delays were dealt with and overcome, resources were allocated efficiently, and communications happened in a timely manner. Planning for unforeseen circumstances and time management of the project overall were the only components of the project that could have been improved. With further work and research, the foundation laid by Team 1 and the correlations and relationships examined could greatly reduce the time and money required in selecting the proper sealing ring geometry for an application.

To continue, the next stage for a student team would be to expand the testing pool and increase the database. To do this, a greater variety of cross section geometries that were not tested in the scope of this project should be tested and examined for correlations. Another expansion of the project could be the testing of complete seals in full grooves rather than straight samples. This would require more material, pressure, and time but would provide insight into how the sealing rings behave as complete components. Finally, another possibility is to test sealing components of different materials as well as under application conditions.

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[4] Cummins, Inc. "Seals, Molded Elastomeric." Technical Engineering Standard - 98010. n.d. 10 October 2014.

[5] "ASTM Standard Test Methods for Rubber O-Rings." Technical Standard. n.d. Online. 10 October 2014. <http://www.astm.org/Standards/D1414.htm>.

[6] "ASTM Standard Test Methods for Rubber Properties." Technical Standard. n.d. Online. 10 October 2014. <http://www.astm.org/Standards/D395.htm>.

Biography

Richard Edgerton - Team Leader

Richard is a senior Mechanical Engineering student at Florida State University with a focus in Mechanical systems. He recently interned for Cummins, Inc. as a product validation engineer for the QSK 23L engine family in Seymour, IN but will be working as a Product Development Associate Engineer in the Engineering Rotational Development Program at Caterpillar in Peoria, IL after graduation.

Emilio Kenny - Project Analyst

Emilio is a senior Mechanical Engineering student at Florida State University with a focus in Thermal Fluids. Emilio recently interned for Eli Lilly and Company as an Automation/Process Engineer in the injectables sector in Indianapolis, IN. After graduation, he plans to get a Master's Degree in Thermal Fluids.

Kenneth McCloud - Financial Coordinator, Webmaster

Kenneth is a senior Mechanical Engineering student at Florida State University with a focus on Thermal Fluids. He is interested in working on the research and development of renewable energy sources.

Tawakalt Akintola - Project Support

Tawakalt is an exchange student at Florida Agricultural and Mechanical University from Federal University of Technology Akure, Nigeria. Her main focus is in Materials Engineering. She obtained a Diploma in Metallurgical and Materials engineering and had an industrial training at Tower Aluminum Roofing Company, Nigeria. She plans to get a master's degree in Materials Engineering after graduating with a B.S. in Metallurgy and Materials.

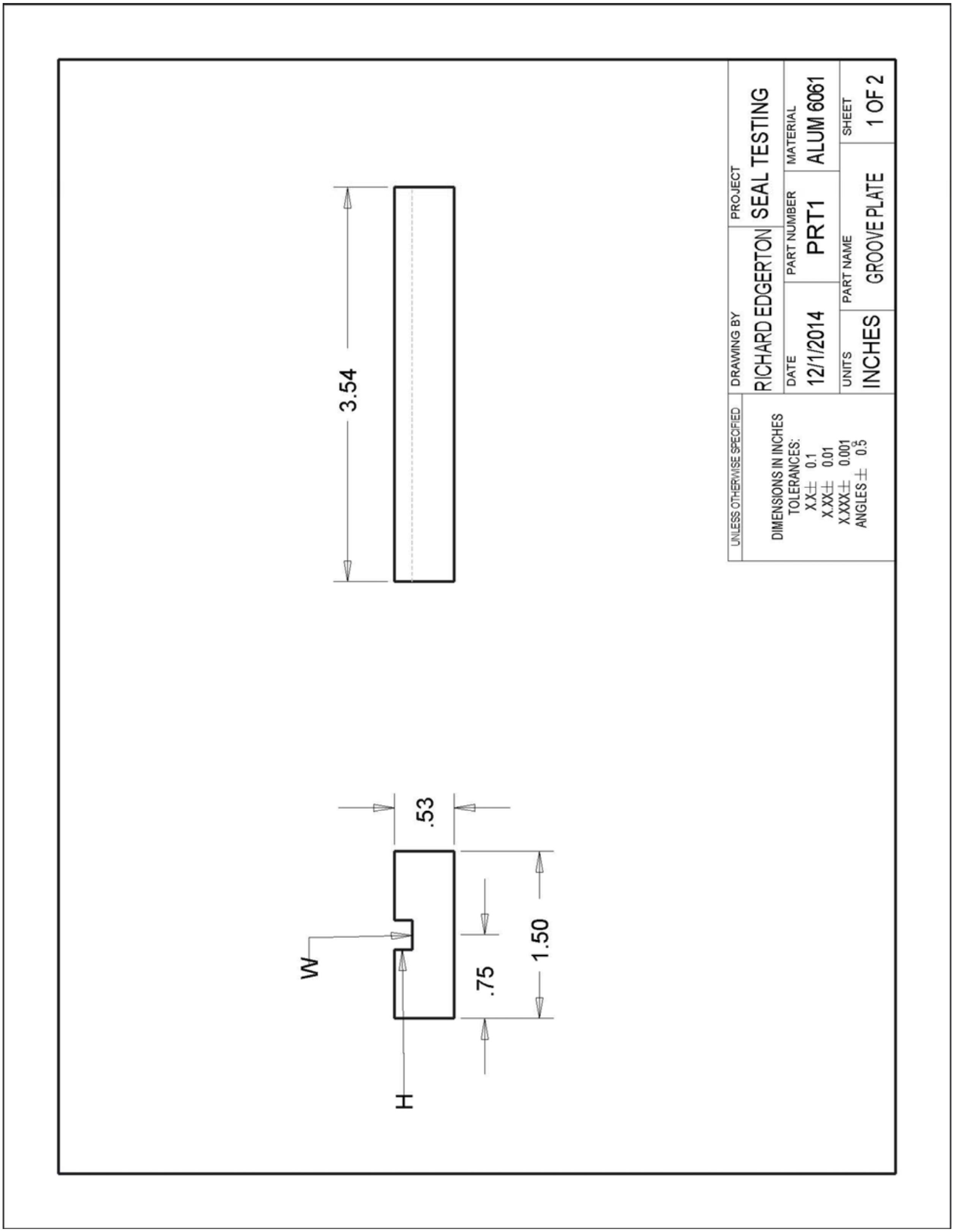
Erin Flagler - Project Planner

Erin is a senior Mechanical Engineering student at the Florida State University with a mixed focus in Energy Systems and Materials. Erin interned for Black and Veatch this past summer as a Mechanical Engineer in the Energy Division in Overland Park, KS. After graduation, Erin plans to pursue an engineering career in the energy sector.

Appendix A: MTS Machine Specifications

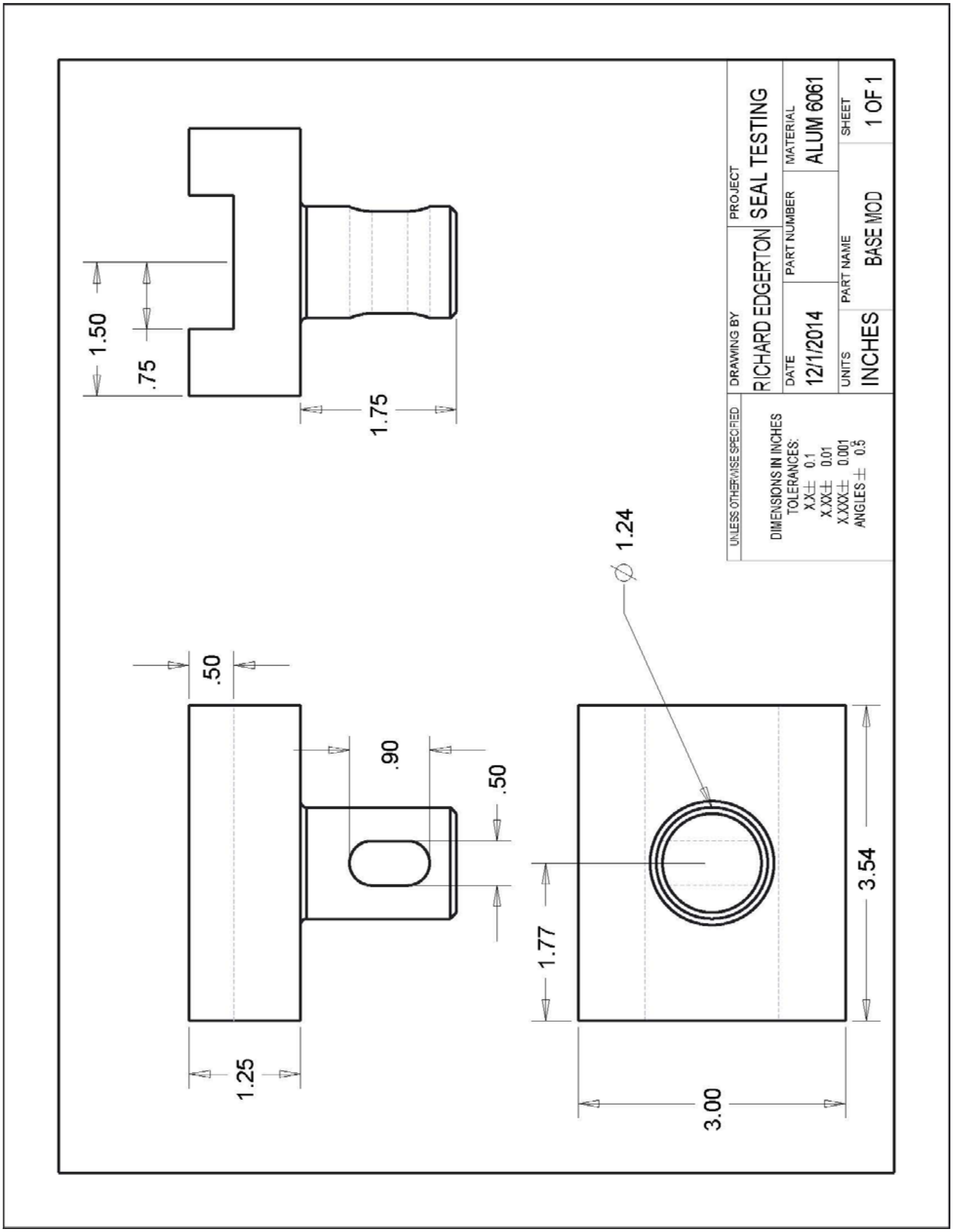
Product Specification	**Value**
Maximum Rated Force Capacity	1 kN, 2.5 kN, 5 kN, 10 kN, 20 kN, 30 kN, 50 kN
Maximum Test Speed	750 mm/min
Minimum Test Speed	0.005 mm/min
Position Resolution	0.000047 mm
Power Requirements	200 – 230 V AC, 22 A, 50/60 Hz, 4400 W, 1-phase
Space Between Columns	600 mm
Vertical Test Space *Standard Length* *Extended Length*	 1200 mm 1520 mm
Crosshead Travel *Standard Length* *Extended Length*	 1000 mm 1300 mm
Frame Height *Standard Length* *Extended Length*	 2269 mm 2569 mm
Frame Width	1315 mm
Frame Depth	957 mm
Frame Weight *Standard Length* *Extended Length*	 1195 mm 1265 mm

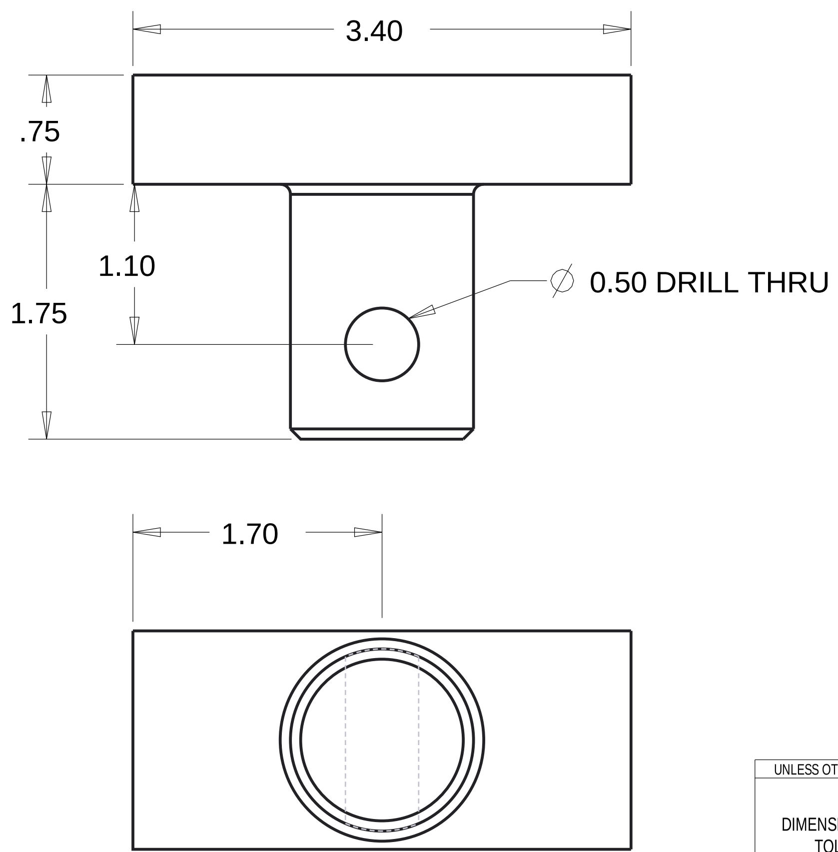
Appendix B: Engineering Drawings



P/N	HEIGHT H	WIDTH W	NOTES
2863702	0.077	0.139	
3082358	0.168	0.291	
3348617	0.100	0.104	
3348618	0.122	0.077	
3638326	0.104	0.182	
3651213			
3683495			
3683495	0.118	0.197	
3685556	0.144	0.098	
3867646	0.052	0.101	
3914095	0.088	0.154	
3915772	0.049	0.096	
3919953	0.207	0.165	
4010636			
4323688	0.206	0.354	
4323985	0.104	0.186	
4325753	0.118	0.079	
4325829	0.169	0.118	
4910519	0.150	0.400	
4962609	0.265	0.265	
4985661			
4995185			
5253501	0.100	0.180	
5267506	0.117	0.119	

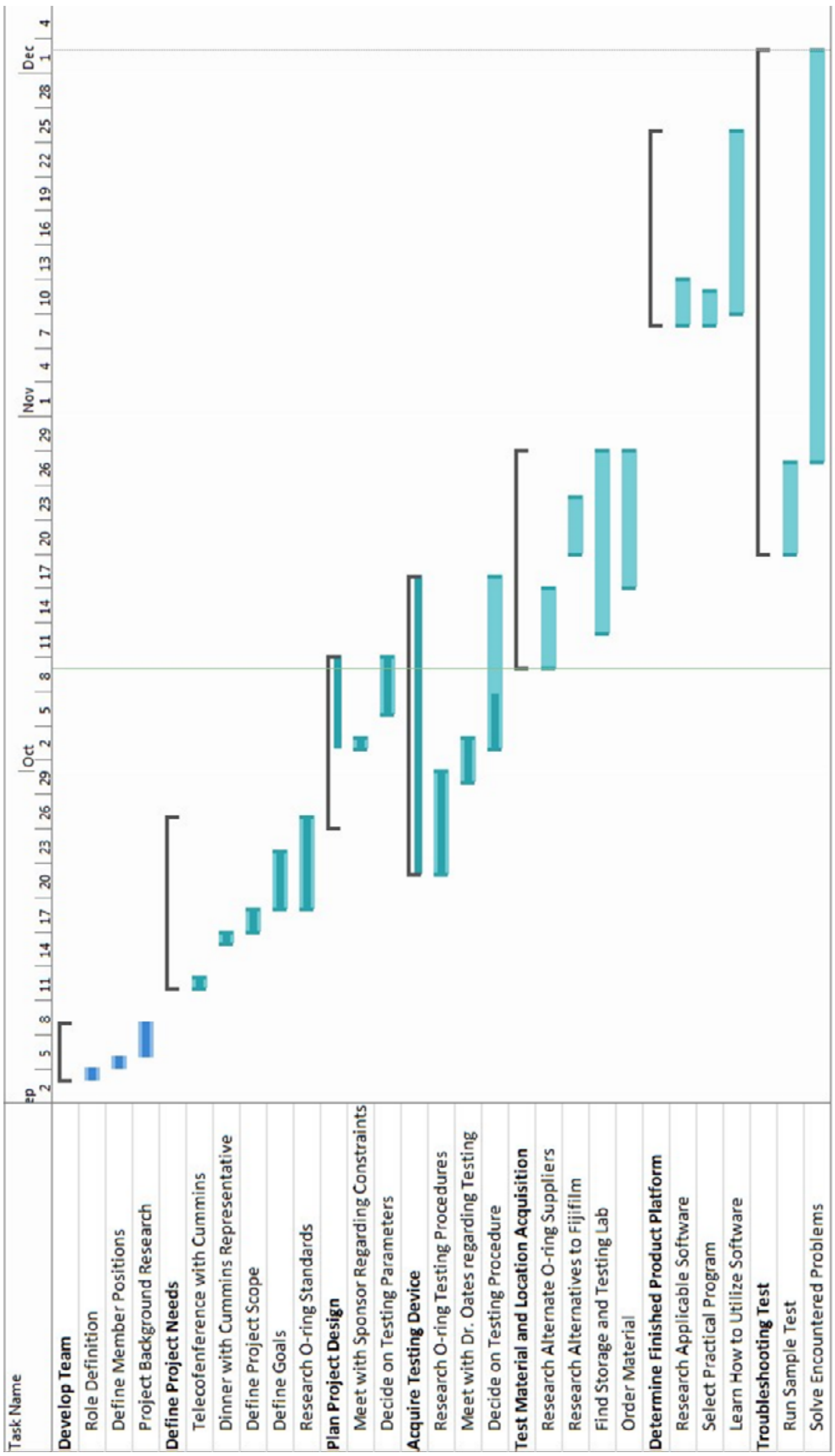
UNLESS OTHERWISE SPECIFIED	DRAWING BY		PROJECT
DIMENSIONS IN INCHES TOLERANCES: X.X± 0.1 X.XX± 0.01 X.XXX± 0.001 ANGLES ± 0.5	RICHARD EDGERTON		SEAL TESTING
	DATE 12/1/2014	PART NUMBER PRT2	MATERIAL ALUM 6061
	UNITS INCHES	PART NAME GROOVE PLATE	SHEET 2 OF 2

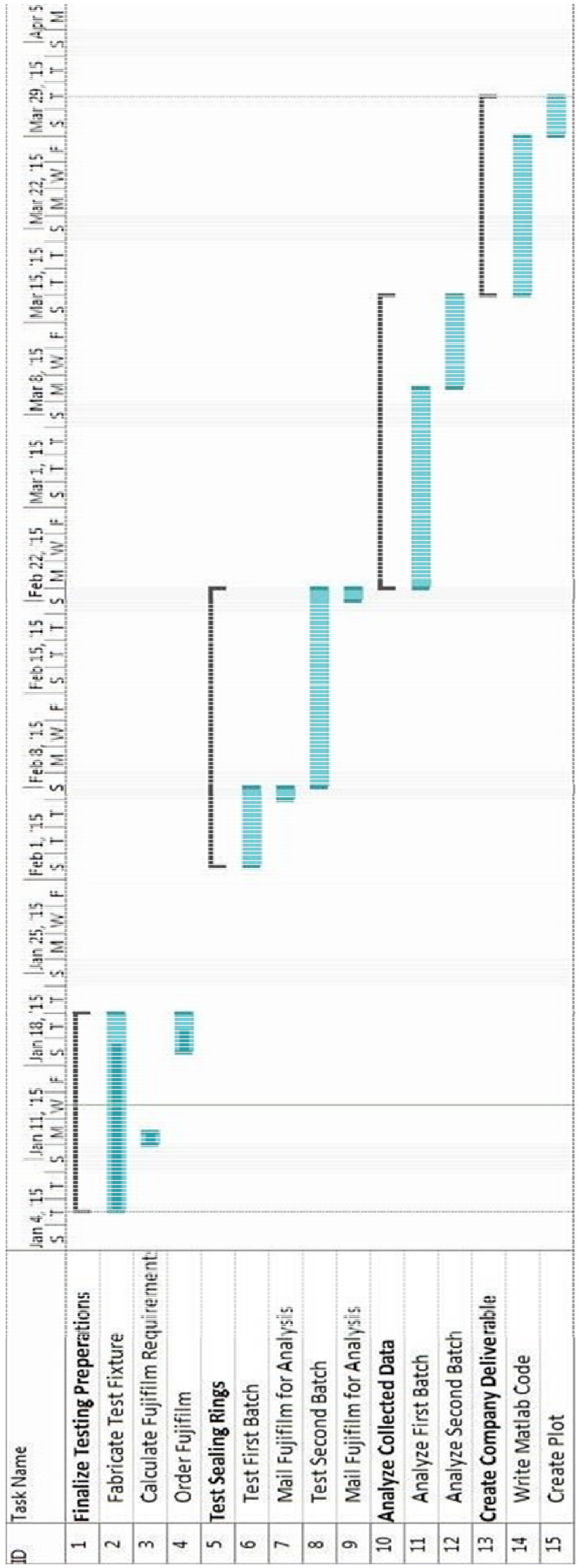

1.50
.75
1.75
.50
.90
.50
1.24
1.77
3.54
1.25
3.00
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
XX± 0.1
X.XX± 0.01
X.XXX± 0.001
ANGLES ± 0.5
DRAWING BY
RICHARD EDGERTON
PROJECT
SEAL TESTING
DATE
12/1/2014
PART NUMBER
MATERIAL
ALUM 6061
UNITS
INCHES
PART NAME
BASE MOD
SHEET
1 OF 1



UNLESS OTHERWISE SPECIFIED	DRAWN BY		PROJECT	
DIMENSIONS IN INCHES TOLERANCES: X.X± 0.1 X.XX± 0.01 X.XXX± 0.001 ANGLES ± 0.5°	EMILIO A. KENNY		SEAL TESTING	
	PART NAME	PART NUMBER	MATERIAL	REV
	LOAD PIECE	PRT-2	AL6061	1
	SCALE	DATE		SHEET
	1.000	1 FEBRUARY, 2015		1 OF 1

Appendix C: Gantt Charts




ID
Task Name
1 Finalize Testing Preperations
2 Fabricate Test Fixture
3 Calculate Fujifilm Requirements
4 Order Fujifilm
5 Test Sealing Rings
6 Test First Batch
7 Mail Fujifilm for Analysis
8 Test Second Batch
9 Mail Fujifilm for Analysis
10 Analyze Collected Data
11 Analyze First Batch
12 Analyze Second Batch
13 Create Company Deliverable
14 Write Matlab Code
15 Create Plot
Jan 4, '15
Jan 11, '15
Jan 18, '15
Jan 25, '15
Feb 1, '15
Feb 8, '15
Feb 15, '15
Feb 22, '15
Mar 1, '15
Mar 8, '15
Mar 15, '15
Mar 22, '15
Mar 29, '15
Apr 5