Interim Design Report:

Sealing Ring Testing and Characterization

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TEAM 1 BIOGRAPHY

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Tawakalt is an exchange student of 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 as B.Engr. in Metallurgical and Materials.

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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.

ACKNOWLEDGEMENTS

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ABSTRACT

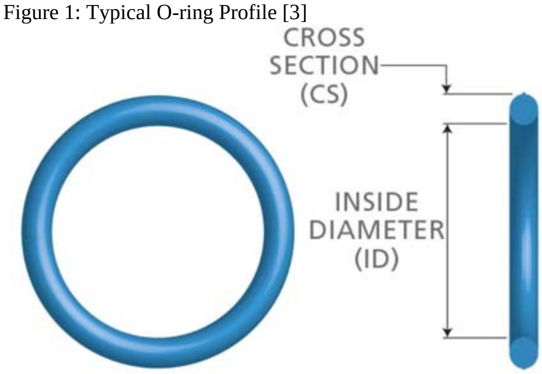
The aim of the Sealing Ring Testing and Characterization project is to create a method in which to approximate which type of sealing-ring to apply in a design, given a mechanical application. The current design process for sealing-ring application requires numerous iterations of finite element analysis, which is lengthy and therefore costly. Team 1 will streamline this long process by testing various sealing-rings under compressive loads at varying crush values. From the data collected from these tests, one can attain a sealing pressure using pressure sensitive film and the force needed to compress the sealing-ring to that pressure. With these values, a geometric shape factor will be devised in order to correlate the cross section of a sealing-ring with a sealing pressure and percent crush. A decision matrix and finite element analysis was conducted to determine which of the test fixture design concepts was most efficient. Material mechanic calculations we were also worked, and in accordance with the decision matrix and fem analysis, the team was able to justify the chosen test fixture design.

I. Project Overview

Cummins' current sealing ring selection process requires extensive analysis for every unique design. The goal of this project is to limit the time needed for selection, thus reducing the cost of analysis in multiple departments throughout the company. Also, if a correlation between sealing ring geometry and sealing pressure is found, the team will attempt to determine a sealing ring cross section that will limit the amount of material needed to form sealing rings that achieve the desired sealing pressures.

A. Background

Figure 1: Typical O-ring Profile [3]



Each and every Cummins (and non-Cummins) engine currently being produced contains a variety of O-rings also called elastomeric seal rings because they are not always circular in cross section. These rings are implemented in order to create leak free joints between engine parts that may contain a range of fluids from coolant and lube oil to compressed air. Many of these fluids are subjected to high pressures with internal parts reaching relatively high temperatures during operation. These high temperature and high-pressure environments require the joint to be designed with the best quality elastomeric seal rings available. Depending on the working environment, the rings must also have the capability to function while exposed to the elements and harsh chemicals. In response to these conditions, seal rings are made from various materials; such as silicon rubber, which is resistant to weathering [1], and fluorocarbon, which can be used in the presence of petroleum based chemicals [2]. In order to produce longer lasting, low maintenance engines, the need for better-designed joints containing elastomeric seal rings is increasing.

A typical elastomeric seal ring is circular in cross section and is referred to as an "O-ring", seen in Fig. 1. Although these will work for most joints, Cummins, Inc. has found that using an elastomeric ring with a non-circular cross section, like the ones shown in Fig. 2, can increase sealing pressure while using less material. However, the current procedure for determining the best type of seal ring for a specific joint requires extensive finite element analysis, which is costly both in time and money. Due to its simplistic shape, the circular seal ring can be quickly and cost effectively designed by using the amount of crush to estimate the sealing pressure created by the mating parts. If a similar process can be applied to rings of different cross sections, the time and cost of designing parts can be greatly reduced.

Figure 2: Elastomeric seal-ring of non-circular cross section [5]

During the design process of elastomeric seal rings, it is important to consider the variables of percent crush and sealing pressure. Percent crush (or crush value) is defined as the percentage of differential between the original sealing component height (or radial dimension) and the compressed height (or radial dimension) under loading. Sealing pressure is defined as the pressure generated between the elastomeric sealing component and the mating parts due to the crush of the sealing component [6].

Another area of testing that will need to be addressed in the future is the effect of fatigue and sidewall effects on these oddly shaped rings. Currently, there are ASTM standards for testing elastomeric seal rings' performance capabilities. The ASTM D1414-19 [4], 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. Although standards for testing sealing-rings with a general cross section already exist, standards specific to non-circular cross sections do not exist. This is important due to the fact that a sealing-ring with a unique cross section will perform differently than a ring with a typical cross section.

B. Need Statement

A method to simplify the sealing ring selection process and allow research into the relationship between sealing ring geometry and sealing pressure will be developed. In order to apply the data to practical use, this method will involve parameters such as the newly developed shape factor, crush value, and sealing pressure. This is a crucial step for the project sponsor, Cummins, Inc., in that costs will be reduced in the form of time saved during the design process and less material being used in the finished parts. This new process could also potentially be used for quality assurance when used with the supplier's products.

"The current design process for sealing-rings requires numerous iterations of finite element analysis which is lengthy and therefore costly."

C. Objectives

The goal of this project is to define a geometric shape factor that correlates the geometry of a sealing ring cross section with the sealing pressure at a given crush value. The values of percent crush, sealing pressure, and the newly developed shape factor will be used to create a 3-D contour plot. The team will decrease the time and cost to analyze sealing-rings by creating an interactive interface that uses the data from the 3-D contour plot to output several sealing-ring options for a given mechanical application.

D. Project Scope and Delimitations

This project was limited to a budget of $2000.00. The MTS machine that will be used to perform the tests is limited to a 1 kN load application and is shown below in Fig. 3. Cummins, Inc. has chosen 23 of their most popular sealing ring cross sections to be tested. These sealing rings are composed of fluoroelastomeric (FKM) material, most commonly used in Cummins, Inc.'s critical applications. The team will be testing each of the designated sealing rings at percent crush values ranging from 0% to 40% and increase by increments of 5%. The percent crush is simply a measure of the displacement in the direction of compression. Software provided by the MTS machine will record the loads at each percent crush interval. For each individual crush value, the sealing pressure will be measured using a pressure-sensitive film placed between the sealing ring and the mating face. These three values will be analyzed in order to identify any correlations that may lead to the development of a geometric shape factor.

There are several delimitations associated with this project that simplify the data collection and analysis processes. The effects of high temperatures and pressures on the material properties will not be taken into consideration. Data collection can be affected by the cut ends of the sealing ring, but these effects will be negated by testing a length of sealing ring that is ten times the diameter of the cross section. The effects of corrosive chemicals on material properties of FKM material will also not be taken in to consideration, as the project does not call for such conditions. Sealing ring properties are slightly affected when the ring is stretched for installation in some designs, however, the group will be testing straight samples that are assumed to be under no stretch.

Figure 3: Picture of MTS machine - taken by Erin Flagler

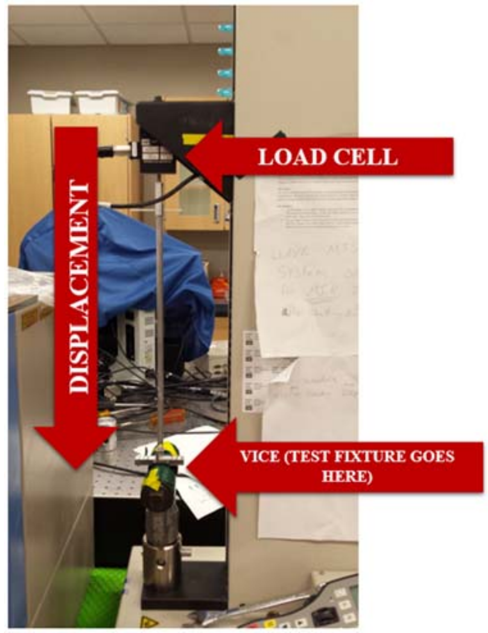
II. Design and Analysis

To accomplish the task set forth by Cummins, Inc., a test procedure was devised to gather data in a controlled, reproducible manner. A test fixture was designed that would receive the seals requested for testing by the sponsor. For expected results from the tests, a data analysis method was formulated that may be used on the data to find the correlation needed.

A. Test Procedure

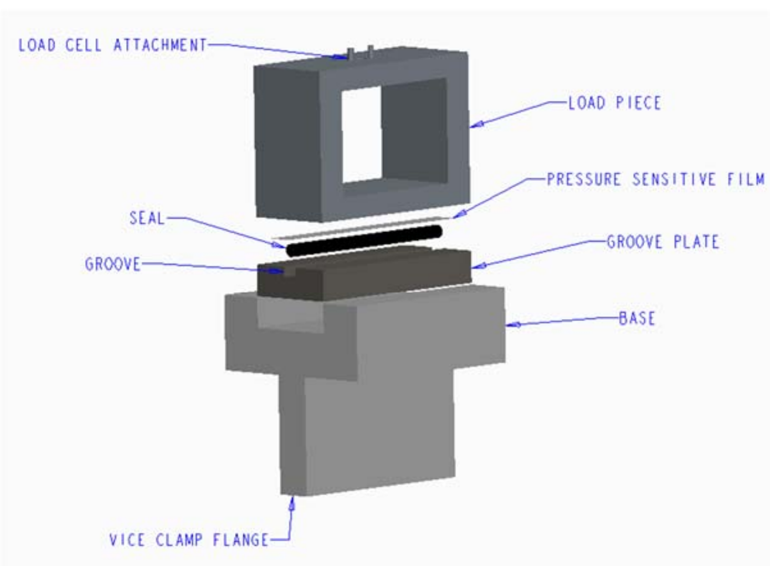
To collect the data necessary for success in defining a correlation between sample cross section and sealing pressure, a uniaxial face compression test will be performed on the 23 different seals. Test samples will be made from the provided seals by cutting them into lengths of at least ten times the diameter, where the diameter is considered is the major dimension of the seals cross section. This is done so that the samples can be tested in a straight line, which simplifies the test fixture design and increases the consistency of the testing procedure. The justification of using lengths of this degree is so that edge effects of the seal under compression are minimized and can be neglected. Each sample will be loaded into a groove plate that is designed specifically for its cross section and size. The groove plate will then be loaded into the test fixture, which would already be mounted in the MTS machine. The base of the test fixture will be clamped in the MTS machine's vice. The vice has been utilized in the design of the test fixture in that the bottom of the base will sit on top of the vice's jaws. The jaws are known to be perpendicular to the translation of the load cell, which will ensure that the base and thus the test sample will also be perpendicular to the load cell. Being perpendicular to the load cells translation means that the test sample will be parallel to the compression piece's contact surface. This is an important feature because it is a necessity to have an evenly distributed load along the test sample. This is only possible if the test sample is parallel to the compression piece surface. A picture of the MTS experimental set up is shown in Fig. 4.

Figure 4: Set-up of MTS machine - taken by Erin Flagler



The MTS machine has the capability of applying up to a 1 kN load which should be sufficient for the size range of seals the team was provided with. For the smaller seals, the 1 kN load cell can be swapped for a 500 N or a 100 N load cell which will increase the resolution of the data recorded from the MTS machine, which will be the load required to compress the sample a certain distance. This distance will correspond to the percent crush of the seal. The tests will begin at 5 percent crush and increase by 5 percent up to 40 percent crush. At each crush increment, the sealing pressure that the sample produced will be recorded using a pressure sensitive film. Once the sample has been crushed to a particular percent crush, the compression piece will be returned to its starting position and the pressure sensitive film exchanged for a fresh piece. Then the load will be reapplied to crush the sample to the next percent crush increment.

Figure 5: Test Fixture

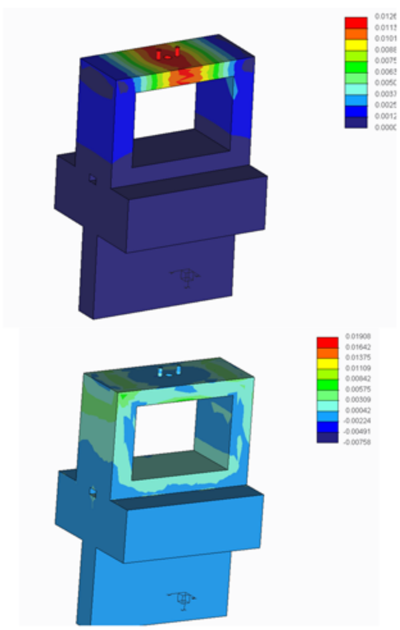


The load will be recorded using the software that also controls the MTS machine. This software records this data as load versus displacement. From the software, an Excel spreadsheet can be exported which will be the standard software for analysis, as the data from the pressure sensitive film will also likely exist in a spreadsheet. This is because the method for analyzing the pressure sensitive film consists of scanning the film then importing the scanned image into software that converts the colors on the film to values of pressure in a spreadsheet.

While this test method was devised with the standard test procedure explained in ASTM D1414 - Standard Test Methods for Rubber O-Rings in mind, changes had to made from the standard procedure to accommodate the requests of the sponsor [ ]. Such requests as crushing the seal to 40 percent crush is beyond the industry standard, which states that damage can occur to the seal beyond 30 percent crush. To be able to reach 40 percent crush, the groove depths had to be decreased from the standard dimensions so that the load piece applying the load did not bottom out on the top of the groove plate before reaching 40 percent 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. There is consideration for testing some samples without grooves, which will follow the ASTM standard more closely, and comparing the results to tests of the same type of seal in a groove to evaluate the effects of the grooves.

B. Test Fixture Design

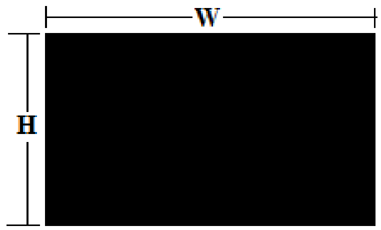
Figure 6: FEA Stress results in Y (top) and X (bottom) directions



The test fixture consists of a base plate, a compression piece and 23 groove plates that insert into the base plate. A schematic of the design can be seen in Fig. 5 above. Every groove plate has the same outer X, Y, and Z dimensions. The inner dimensions differ for every sealing ring cross section in order to achieve the 40% crush for the tests. These groove plates fit in the rectangular depression on the top surface of the base plate. The base's clamping flange and compression piece on the test fixture were designed around the MTS machine used for testing. The MTS machine has a vice on its base that is used to hold specimen during compression tests. The base was designed with a clamping flange that will use the vice to secure the fixture during testing. The compression piece was a pre-existing design used in the lab for previous experiments. It contains two dowels and a hole of ____ centimeters that is used to fasten the compression piece to the load cell with an Allen screw. Its width was altered to _____ in order to fit over the groove plates. All the exact dimensions can be seen in Appendix ___.

Since pressure sensitive paper will be used, the amount of deflection that the fixture can experience is limited to 0.1 millimeters [2]. Deflection of the testing piece above 0.1 millimeters will cause uneven distribution of the pressure applied, adding error to the data. In order to ensure the design can perform under this limitation, the decision was made to make the fixture from Al6061 due to its stiffness and density. Stiffness is an important property that our design must have because the fixture must be able to withstand high loads, and have little strain. Simply selecting a material with the highest stiffness was also not a plausible idea, because if the material is too dense, the compression piece weight will affect the force readings from the machine. FEA analysis was done on the assembly using Creo Simulate and its result can be seen in Fig 6. The maximum displacement the fixture underwent was in a range of ________ millimeters, which is well under our limitation.

Figure 7: Rectangular Cross Section Profile



C. *Data Analysis*

Although all of our testing and analysis will be done in the spring semester, the methods in which analysis of how the area in contact with the applied stress differs with crush value and cross section should be defined. This study is what will be used to correlate the cross section of the sealing rings with the crush value and sealing pressure; thus creating the geometrical shape factor. So in order to understand how this correlation can be defined with the testing outputs and inputs (force applied, sealing pressure, and percent crush), theoretical data was created using the rectangular profile with the given sealing ring dimensions (seen in Table 1 and Fig. 7).

Table 1: Rectangular Cross Section Dimensions

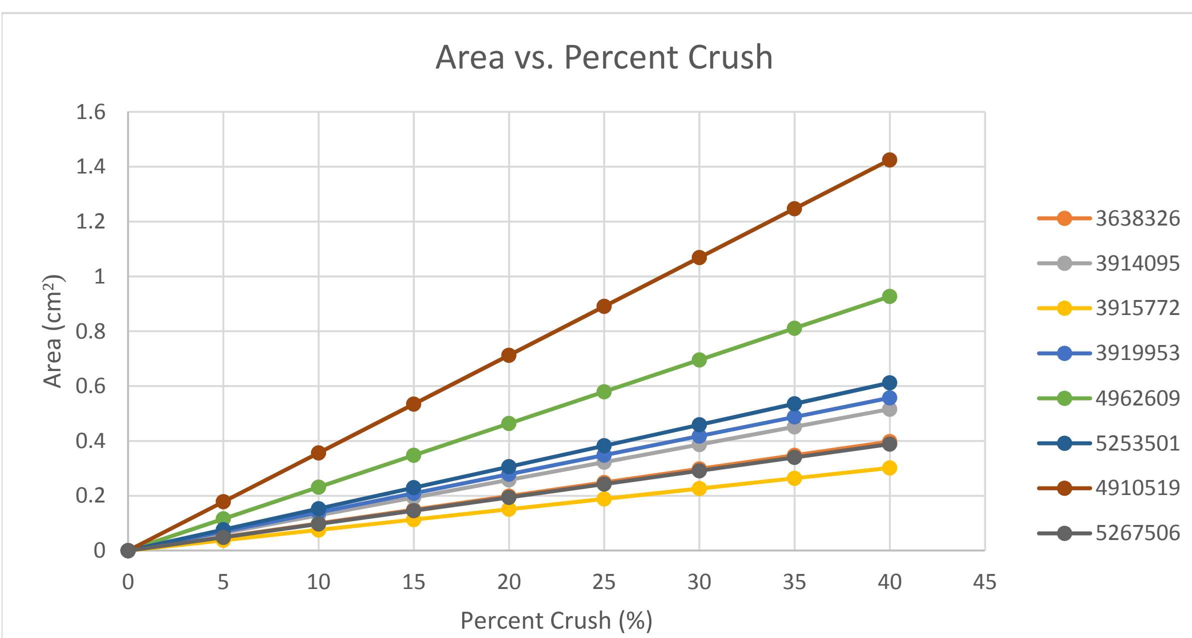
Product Number	H (cm)	W (cm)
3638326	0.353	0.221
3914095	0.300	0.287
3915772	0.168	0.168
3919953	0.704	0.310
4962609	0.899	0.516
5253501	0.340	0.340
4910519	0.508	0.792
5267506	0.399	0.216

As mentioned in the background, FKM is a fluoroelastomers and although it has a nonlinear stress-strain relationship, a linear representation will not add large discrepancies in the theoretical data. The slope or Young's Modulus of this approximation equals 5.9 megapascals. As a material undergoes compression in one direction (transverse direction), expansion in the other two directions occurs (axial direction). The amount of strain in the axial direction can be quantified using the Poisson's ratio (υ) for FKM which is approximately 0.5. Since stretching is not a parameter we are considering, axial expansion is only limited to one direction, and therefore the contact area should have a linear correlation with percent crush. This can be seen by dividing the force outputted by the machine, with the sealing pressure given by the Fujifilm and plotting it against the percent crush. This correlation for the dimensions of all the rectangular sealing rings can be seen in Fig. 8. From this, one can see that the larger the initial cross section area, the higher the rate at which the area varies. Using the approximations specified above, one can approximate the contact area, which is the geometrical shape factor, to equal Eq. 1 below.

$$S = cL_iW_i\upsilon \qquad (1)$$

In this equation c is the percent crush, and L_i and W_i are the initial length and width of the cross section. With

Figure 8: Rectangular Cross Section Plot of Area vs. Percent Crush using Theoretical Data



this correlation, one can approximate the cross section dimensions of a rectangular ring given the sealing pressure and percent crush. The method used, which can be seen in Appendix ____ (Input data analysis matcad), will be used on the other cross sections when data is collected in the spring semester.

III. Risk and Reliability Assessment

A risk associated with the design of the project is called the edge or side-wall effect. This effect occurs when the sealing sample is under compression and comes into contact with the walls of the groove; the direction of pressure within the sample is deflected inward when the groove wall pushes back. This makes the sealing pressure appear higher than it truly would be, inherently skewing the recorded data. Due to the nature of the compression process of sealing rings, the edge effect is unavoidable, and the team designed the grooves in an attempt to minimize it. The risk occurs if the side interference is greater than anticipated when the grooves were designed, as it would produce inaccurate data.

The reliability of this project rests in the testing and data analysis phases. Prior to using the MTS machine to collect actual project data, the team will set the machine displacement to match the height of a known object. Once the machine had assumed the requested position, if the object of known height could be easily removed or even moved then the team is aware that there is a margin of error in the displacement. That margin will then be measured and taken into consideration during the data collection time when the machine is in use. Then, the reliability of the data analysis rests in how the data is worked and the consistency involved. To make the data analysis reliable, all data will undergo the same analysis process, including following the same procedure and organization styles for each sample.

IV. Procurement

The materials needed for the test fixture, groove plates, and compression piece were ordered and have been received. The next step is to finalize the dimensional drawings of all the individual groove plates. The team planning machine all of the fixtures before heading home for Christmas break. This will allow testing to commence immediately upon returning back to school for the spring semester. The design is fairly simple, and a few machining capability constraints have been accounted for and integrated into the design. The team is going to perform sample tests on the largest and smallest sealing rings first in order to find the range of pressures that will determine the necessary sensitivity of pressure-sensitive film before placing any orders.

V. Communications

Throughout the first semester, Team 1 maintained an effective communication system with relative ease. This system not only encompassed the members of the team, but the sponsors and faculty advisors also. Today's technology made communication simple and almost instantaneous, particularly with group text messaging, email, and file sharing programs. Text messaging was the prevailing method of communication within the team, while email was primarily used to discuss items with sponsors and advisors. In addition to using email to converse with the sponsor, the team had a standing weekly teleconference with Cummins, Inc. The teleconference was a way to not only keep the sponsors up to date with the progress of the project, it also made the communication slightly more personal than an email. It also assisted in eliminating possible miscommunications that are a fairly common occurrence with electronic interaction. Team 1 communicated within ease and efficiency this past semester, and that trend is expected to continue.

VI. Project Management

Team 1 was proved with a budget of the initial amount of $2000.00 to purchase resources. After raw Aluminum 6061 was ordered for the creation of the MTS-compatible test fixture and sample testing grooves, the remaining budget was $1869.29. This included the tax and shipping cost of the material. This remaining budget will be put towards the purchase of pressure sensitive film for testing. The other resources utilized for this project, the MTS machine and the sealing ring samples, were obtained without having to reduce the budget.

Gantt chart

VII. Summary or Conclusions

This semester the team conducted research, theoretical calculations, and prepared to begin the sealing ring testing process of the project next semester. The fluoroelastomeric material to be tested was selected, as were the size and cross sectional geometry testing ranges, resulting in 23 unique sealing rings to test. The different sealing rings or testing samples were then ordered and sent directly from Cummins, Inc., along with their specifications in the form of mechanical drawings. The testing method of the samples was selected as a MTS (Measuring, Testing, and Sensing) machine to conduct face compression tests on linear sealing ring sections. The MTS machine was located in the FCAAP wing of the Aeropropulsion, Mechatronics, and Energy (AME) Center. The machine moved in terms of displacement and recorded the load required to reach a desired displacement. Pressure sensitive film was chosen as a method to measure pressure felt by the samples and will be placed between the sample and the test piece. Testing grooves were designed for each individual sample following existing standards to expedite the testing process. Custom test fixture prototype compatible with both the grooves and MTS machine was designed and analyzed. Aluminum 6061 was decided as the raw material for the test fixture and grooves, and has been ordered. Since data analysis requires the testing of the samples, the team attempted some theoretical calculations using predicted data as a method of practice for the real data.

For the spring semester, the team will begin the machining and testing phases of the project. The raw Aluminum will be machined into the texting fixture and various grooves. Those components will then be used with the MTS machine to test the samples one at a time in order to collect data. The data will then be analyzed in order to produce a shape factor. The final stage of the project will involve displaying the shape factor in relation with sealing pressure and percent crush using a simple user interface.

VIII. References

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IX. Appendix

See following sheets for the Appendix.