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Eaton Analysis of Face Seal Contacts

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Analysis of Face Seal Contacts

Team 20:

Seal Team Fix

Final Design Report

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Abstract

Eaton Corporation has tasked Seal Team Fix with the challenge of obtaining the material properties of the carbon compounds used in their face seals and creating a service life prediction model of their seals based on this material property data. Eaton is a worldwide power management company with a multidisciplinary business portfolio. This project pertains to Eaton's Aerospace division, and in particular the carbon face seals in gas turbine engines and gearboxes. This preliminary design report demonstrates the research, design and analysis leading to a final conceptual decision as to how a carbon face seal life prediction model will be created. This model would allow for the justification of Eaton to purchase the more cost-effective product between three manufacturer's supplying similar carbon grades.

Once a clear problem definition of the project had been established, each member of Seal Team Fix developed 30 different design concepts in accordance with the Capstone Design Project requirements. While a small number of these original design concepts would play into our final proposed design, there were still important pieces to our necessary analysis which were overlooked. With the help of our Technical Adviser Dr. D.M.L. Meyer, we were able to conclude our final engineering approach.

Our final engineering approach consists of a three part process, each of which contains multiple studies. This three part process involves a failure mode study, characterization of materials, and finally the prediction model. The failure mode study consists of stress analyses, and pin on flat testing while measuring the roughness values of the carbon materials incrementally. The characterization of materials will consist of hardness testing of the material as well as obtaining the coefficients of friction and wear rates from tribometer testing. The prediction model will consist of calculating the leakage rate of the seals as a function of their roughness values as well as the radius of the seals and using the data gathered through experimentation to create a final prediction model in Microsoft Excel.

Contents

List of Acronyms

QFD	Quality Function Deployment
2D	Two-Dimensional
3D	Three-Dimensional
DIC	Digital Image Correlation
psi	Pounds per Square Inch

Nomenclature

β	Thermal Expansion Coefficient ($^{\circ}F^{-1}$)
ϵ_θ	Strain in Angular-Direction (dimensionless)
ϵ_r	Strain in Radial-Direction (dimensionless)
ϵ_x	Strain in X-Direction (dimensionless)
ϵ_y	Strain in Y-Direction (dimensionless)
ϵ_z	Strain in Z-Direction (dimensionless)
η	Absolute Viscosity of the Lubricant ($\frac{lb_f s}{in^2}$)
$\frac{dp}{dt}$	Change in Pressure Over Width of Seal ($\frac{lb_f}{in^3}$)
γ_{xy}	Shear Strain in XY-Plane (dimensionless)
γ_{yz}	Shear Strain in Axisymmetric Plane (dimensionless)
μ	Coefficient of Kinetic Friction (dimensionless)
ν	Poisson's Ratio (dimensionless)
π_n	Pi Group Number n (dimensionless)
ρ	Density ($\frac{lb}{ft^3}$)
σ_x	Principal Stress in x-direction ($\frac{lb}{in^2}$)
σ_y	Principal Stress in y-direction ($\frac{lb}{in^2}$)
σ_θ	Normal Stress in Angular-direction ($\frac{lb_f}{in^2}$)
σ_r	Normal Stress in Radial-direction ($\frac{lb_f}{in^2}$)
σ_x	Normal Stress in x-direction ($\frac{lb_f}{in^2}$)
σ_y	Normal Stress in x-direction ($\frac{lb_f}{in^2}$)
σ_z	Normal Stress in x-direction ($\frac{lb_f}{in^2}$)
τ_{xy}	Shear Stress Along xy Plane ($\frac{lb}{in^2}$)
τ_{xy}	Shear Stress in XY-Plane ($\frac{lb_f}{in^2}$)

τ_{yz}	Shear Stress in Axisymmetric Plane ($\frac{lb_f}{in^2}$)
a	Contact Half-Width (in)
A_c	Contact Area (in^2)
d	Sliding Distance (ft)
E	Elastic Modulus ($\frac{lb_f}{in^2}$)
f	Load (lb_f)
H	Material Hardness($\frac{lb}{in^2}$)
K	Proportionality Constant (dimensionless)
L	Sliding Distance (ft)
p	Contact Pressure ($\frac{lb_f}{in^2}$)
Q	Leakage Rate ($\frac{in^3}{hr}$)
r_m	Radius of Seal (in)
Ra	Average Surface Roughness (μin)
T	Temperature ($^\circ F$)
t	Time of Operation (hr)
U	Velocity ($\frac{ft}{s}$)
V	Wear Volume (in^3)
W	Load (lb_f)

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1 Introduction

Eaton Corporation is a worldwide power management company employing more than 95,000 people with customers in over 175 countries [2]. Eaton's business groups are divided into five different segments. These segments include Electrical Products, Electrical Systems & Services, Hydraulics, Aerospace, and Vehicle [3]. As part of their Aerospace division, Eaton operates a facility in Rumford, Rhode Island where they design, test, and manufacture mechanical carbon face seals to serve the Aerospace industry. These seals are used to isolate oils which serve to lubricate critical rotating components in gas turbine engines and gearboxes from separate internal components which do not rely on lubrication for their function.

Stringent regulations and higher operational costs are causing airlines to demand more from the companies who manufacture their airplanes. With the ever evolving nature of the aerospace industry, the life cycle of airplanes is expected to evolve alongside it. This includes the gas turbine engines and other power train systems which are the heart of every airplane. Companies like Eaton must push to develop the new technologies and innovations necessary to meet these demands. In order to do so, however, Eaton has to develop a better understanding of their existing product line.

Since power train systems for the aerospace industry are expected to have longer service lives in the coming years, Eaton's seals must withstand these long overhaul periods. At the moment however, Eaton has no way of predicting the service life of their seals. This is mainly due to the fact that there is very little material property information regarding the carbon compounds used in their seals. Eaton's Rumford facility purchases carbon compounds from three main suppliers for their seals. Unfortunately, much of the material property information on the carbon compounds is either proprietary information or is very vaguely described in the material data sheets supplied by the three manufacturers. To make matters more difficult, pricing variations between the three manufacturers for a similar carbon compound can be on the order of twice that of their competitors. For this reason, Eaton has challenged Seal Team Fix to create a solution for this dilemma.

The problem that Eaton has proposed to Seal Team Fix is to create a service life prediction model of their carbon face seals. Eaton has requested that the inputs and equations used for the prediction model be developed in a Microsoft Excel spreadsheet for a familiar user interface. In order to produce this prediction model, it is necessary to understand how the carbon seals fail and what it is that causes the seals to fail. Understanding the failure mode of these seals involves stress analyses of the carbon face seal contacts as well as a study of the material properties of the carbon compounds to better characterize these materials. As previously mentioned, very little material property information is available on the carbon compounds and Eaton would like to gain a better understanding of the materials used in their seals.

The acquisition of an accurate service life prediction model would yield various benefits for Eaton. The company would have a better understanding of whether or not their existing seals can meet the demanding requirements of the industry. If it is determined that the existing seals can meet the requirements for increased service life of power train systems in the industry, then the prediction model can also aid in the development of more accurate warranty periods. If it is determined that the existing seals will not be able to meet the requirements, then the prediction model will serve as proof that Eaton must continue its technological innovation in developing new products to serve the industry in the future.

The service life prediction model would also serve as an economic ally for Eaton. Since the development of the prediction model entails gathering accurate material properties of the carbon compounds used, the material property data gathered during experimentation can be used during purchasing. As mentioned earlier, pricing of similar carbon compounds between suppliers can vary greatly. If the prediction model verifies that choosing the most cost-effective supplier will still yield an acceptable service life, then Eaton can continuously cut costs.

While the prediction model will have a direct benefit for Eaton, the model will in turn benefit the aerospace industry as a whole. If Eaton can verify that their seals will endure longer service periods then the maintenance and overhaul periods for airlines will inherently decrease. A decrease in maintenance and overhaul periods means less downtime for airplanes within an airline and more flight time. Less downtime for the airplanes means lower costs for the airlines who drive the price of flight costs. This could lead to lower ticket prices for travel.

2 Project Planning

The scheduling of this project has been based off of the six-step design process introduced in the first lecture of the Capstone Design class. This design process consists of the stages of defining, conceiving, proving, building, testing, and redesigning the solution to the proposed problem. Since this is a very general approach to solving any real world design problem, the team has taken the basic idea of each stage and adapted different techniques to solving the specific problem. The problem that Seal Team Fix has been proposed does not involve actually creating a physical product. The end result will instead be an analytical service life prediction model. For this reason the design process has been reformed for the necessity of the project.

2.1 Define

The project began with a preliminary meeting with the team sponsor Drew Bangs from Eaton Corporation. During this initial meeting the problem that Eaton proposed to Seal Team Fix was introduced and discussed with some detail. While this initial meeting defined the problem which the team is currently challenged with, it would take a number of meetings before all of the necessary information for the design specifications were established. In the mean time, a preliminary project plan was established which would help guide the team in the right direction. The original tasks of the project plan can still be seen in Figure 1 but the complete project plan consists of Figures 1 and 2. Following the creation of the project plan, the team began to research information on carbon face seals as well as existing service life prediction models.

Research began with a patent search in an attempt to find more information on carbon compounds, carbon seals, and existing seal life prediction models. The team was unable to find patents on seal life prediction models specifically, however a number of patents regarding dynamic carbon seals were found. While these carbon seal patents were useful in understanding more about the design of sealing systems, more information was necessary about Eaton's own seals in order to advance with the team's design specifications.

As previously mentioned, a number of meetings were necessary to completely define the design specifications of this Capstone project. The team met on a weekly basis with the project sponsor, either in person or via a Webex conference call, in order to establish the criteria. With more specific design specifications established the team began brainstorming possible solutions.

2.2 Conceive

With a clear definition of the problem proposed and a firm direction as to where the project needed to go, the team began to develop design concepts. Each member of the team was required to conceptualize 30 different design solutions which could help solve the problem. While a number of these solutions proposed designing a test rig for the carbon face seals, the majority of the solutions involved running experiments. Although some of the original design concepts were later deemed as pertinent to the solution, these concepts were still not all that was needed.

The conceptual stage of this project was key to the future direction of the team. The team was assigned Professor Meyer as a Technical Advisor during this stage and, with her guidance, was able to establish some extra design concepts which are absolutely essential to the solution. These concepts include stress analyses of the carbon face seals, tribometer testing, and leakage rate calculations. With all of the design concepts established, the team began a quality function deployment (QFD) analysis in order to narrow down the design approach.

Throughout the QFD analysis the team looked at the most important factors that would satisfy Eaton's requirements. It was concluded that the most important drivers involved in this project are developing accurate material properties, replicating product environment during testing, and minimizing error in the service life prediction model. Using these driving factors the team was able to narrow the design concepts down into three different approaches which were proposed to the Capstone Design class during the team's Critical Design Review presentation. These approaches were the mechanical approach, the materials science approach, and the failure modeling approach. Each of these approaches consisted of a three stage process. The process consisted of a failure mode study, material characterization, and the development of a prediction model.

2.3 Prove

Following the Critical Design Review of the project, the team began narrowing down the design approaches to establish a final engineering approach. It was decided that the final approach would consist of a combination of the original three design approaches proposed in the Critical Design Review. The failure mode study portion of the final approach involves Two-Dimensional (2D) and Three-Dimensional (3D) stress analyses, as well as tribometer testing while measuring roughness values incrementally. The material characterization portion of the final approach consists of hardness testing at simulated temperatures and the calculation of coefficients of friction and wear volume using a tribometer. Finally, the prediction model portion of the final engineering approach involves calculating the leakage rate of the seals as a function of the roughness of the seal material and the seal radius and compiling all of the aforementioned data to create a prediction model.

Up to this point in time the team has performed the 2D and 3D stress analyses on the carbon face seal contacts. Leakage rates for brand new seals covering a range of roughness values and pressure drops have also been established. These data were presented to the Capstone Design class in a presentation of the team's Proof of Concept. All work following the prove stage will be conducted as part of the Spring semester.

2.4 Build

The Build section of the project will hopefully begin in the month of January, 2017. The team has placed orders for samples of four different types of carbon to perform future experiments with. The team also needs to order 440C stainless steel samples for the experiments. Once the samples arrive the team can begin assembling Professor Meyer's tribometer in order to perform the necessary experiments for the project.

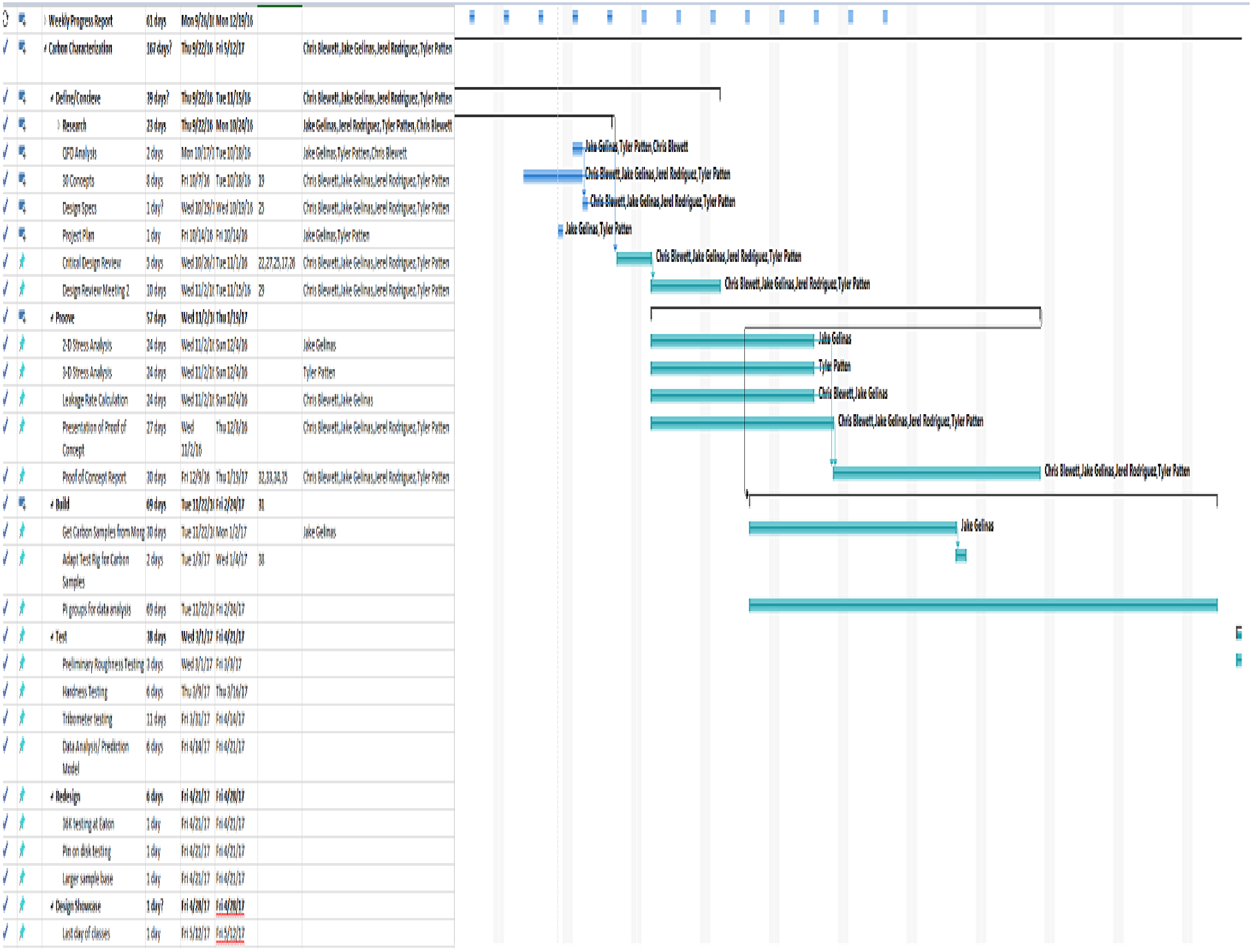
2.5 Test

The Test section of the project will directly correspond to the Build section. As soon as the tribometer is properly assembled the team will begin testing. The team is hoping to complete the tribometer experiments before the beginning of the Spring semester of 2017. It is also necessary to complete the testing of the hardness of the carbon materials. The team is also hoping to complete these hardness tests during the month of January and before the start of the Spring semester of 2017. It will be possible to run the tribometer experiments and the hardness tests simultaneously since only two members are needed to run each experiment.

Once the experimental portion of the project has been completed, the team will need to assess the data gathered. This stage will involve the majority of the service life prediction model's development. The team will begin to analyze the data and make mathematical correlations between the results. These correlations will then be input into an Excel spreadsheet where a user will be able to predict the service life of a seal given certain parameters.

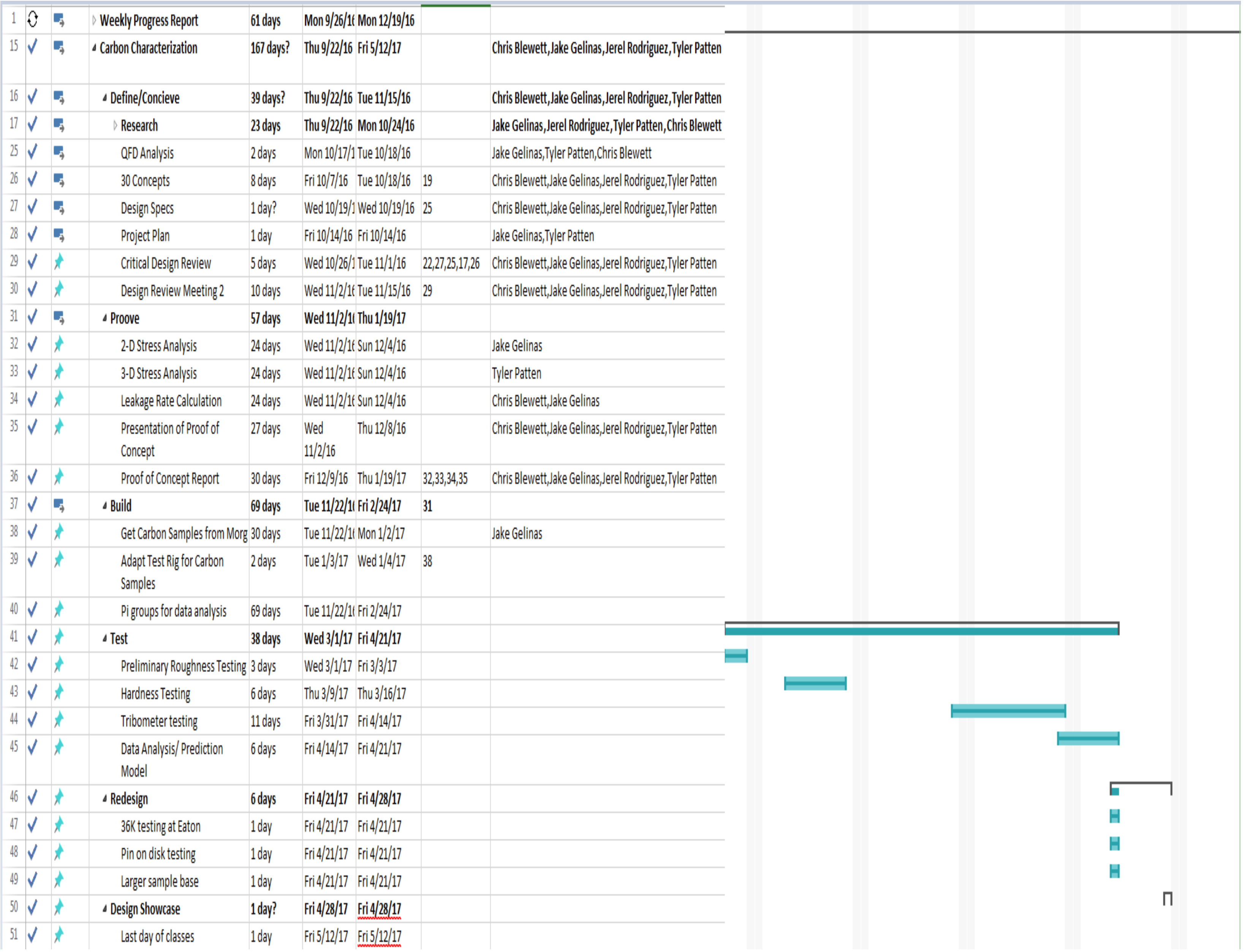
2.6 Redesign

The Redesign portion of the project will differ from what a normal redesign process would be like. Rather than redesigning a physical product, the team will be challenged with reviewing all of data that has been correlated in the prediction model. The team will be tasked with studying the user-interface of the prediction model, the error of the model, as well as the sustainability of the model. These factors will be investigated thoroughly and adapted accordingly to create the best possible solution to Eaton's problem.



	Weekly Progress Report	61 days	Mon 9/26/1	Mon 12/19/16		
✓	Carbon Characterization	167 days?	Thu 9/22/16	Fri 5/12/17		Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Define/Concieve	39 days?	Thu 9/22/16	Tue 11/15/16		Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Research	23 days	Thu 9/22/16	Mon 10/24/16		Jake Gelinas,Jerel Rodriguez,Tyler Patten,Chris Blewett
✓	QFD Analysis	2 days	Mon 10/17/1	Tue 10/18/16		Jake Gelinas,Tyler Patten,Chris Blewett
✓	30 Concepts	8 days	Fri 10/7/16	Tue 10/18/16	19	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Design Specs	1 day?	Wed 10/19/1	Wed 10/19/16	23	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Project Plan	1 day	Fri 10/14/16	Fri 10/14/16		Jake Gelinas,Tyler Patten
✓	Critical Design Review	5 days	Wed 10/26/1	Tue 11/1/16	22,27,25,17,26	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Design Review Meeting 2	10 days	Wed 11/2/1	Tue 11/15/16	23	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Proove	57 days	Wed 11/2/1	Thu 1/19/17		
✓	2-D Stress Analysis	24 days	Wed 11/2/1	Sun 12/4/16		Jake Gelinas
✓	3-D Stress Analysis	24 days	Wed 11/2/1	Sun 12/4/16		Tyler Patten
✓	Leakage Rate Calculation	24 days	Wed 11/2/1	Sun 12/4/16		Chris Blewett,Jake Gelinas
✓	Presentation of Proof of Concept	27 days	Wed 11/2/16	Thu 12/8/16		Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Proof of Concept Report	30 days	Fri 12/9/16	Thu 1/19/17	32,33,34,35	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
✓	Build	69 days	Tue 11/22/1	Fri 2/24/17	31	
✓	Get Carbon Samples from Morg	30 days	Tue 11/22/1	Mon 1/2/17		Jake Gelinas
✓	Adapt Test Rig for Carbon Samples	2 days	Tue 1/3/17	Wed 1/4/17	38	
✓	Pi groups for data analysis	69 days	Tue 11/22/1	Fri 2/24/17		
✓	Test	38 days	Wed 3/1/17	Fri 4/21/17		
✓	Preliminary Roughness Testing	3 days	Wed 3/1/17	Fri 3/3/17		
✓	Hardness Testing	6 days	Thu 3/9/17	Thu 3/16/17		
✓	Tribometer testing	11 days	Fri 3/31/17	Fri 4/14/17		
✓	Data Analysis/ Prediction Model	6 days	Fri 4/14/17	Fri 4/21/17		
✓	Redesign	6 days	Fri 4/21/17	Fri 4/28/17		
✓	36K testing at Eaton	1 day	Fri 4/21/17	Fri 4/21/17		
✓	Pin on disk testing	1 day	Fri 4/21/17	Fri 4/21/17		
✓	Larger sample base	1 day	Fri 4/21/17	Fri 4/21/17		
✓	Design Showcase	1 day?	Fri 4/28/17	Fri 4/28/17		
✓	Last day of classes	1 day	Fri 5/12/17	Fri 5/12/17		

Figure 1: **PROJECT PLAN PAGE 1**



1	↻		▹ **Weekly Progress Report**	**61 days**	**Mon 9/26/1(**	**Mon 12/19/16**		
15	✓		◢ Carbon Characterization	167 days?	Thu 9/22/16	Fri 5/12/17		Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
16	✓		◢ **Define/Concieve**	**39 days?**	**Thu 9/22/16**	**Tue 11/15/16**		**Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten**
17	✓		▹ **Research**	**23 days**	**Thu 9/22/16**	**Mon 10/24/16**		**Jake Gelinas,Jerel Rodriguez,Tyler Patten,Chris Blewett**
25	✓		QFD Analysis	2 days	Mon 10/17/1	Tue 10/18/16		Jake Gelinas,Tyler Patten,Chris Blewett
26	✓		30 Concepts	8 days	Fri 10/7/16	Tue 10/18/16	19	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
27	✓		Design Specs	1 day?	Wed 10/19/1	Wed 10/19/16	25	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
28	✓		Project Plan	1 day	Fri 10/14/16	Fri 10/14/16		Jake Gelinas,Tyler Patten
29	✓		Critical Design Review	5 days	Wed 10/26/1	Tue 11/1/16	22,27,25,17,26	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
30	✓		Design Review Meeting 2	10 days	Wed 11/2/1(	Tue 11/15/16	29	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
31	✓		◢ **Proove**	**57 days**	**Wed 11/2/1(**	**Thu 1/19/17**		
32	✓		2-D Stress Analysis	24 days	Wed 11/2/1(	Sun 12/4/16		Jake Gelinas
33	✓		3-D Stress Analysis	24 days	Wed 11/2/1(	Sun 12/4/16		Tyler Patten
34	✓		Leakage Rate Calculation	24 days	Wed 11/2/1(	Sun 12/4/16		Chris Blewett,Jake Gelinas
35	✓		Presentation of Proof of Concept	27 days	Wed 11/2/16	Thu 12/8/16		Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
36	✓		Proof of Concept Report	30 days	Fri 12/9/16	Thu 1/19/17	32,33,34,35	Chris Blewett,Jake Gelinas,Jerel Rodriguez,Tyler Patten
37	✓		◢ **Build**	**69 days**	**Tue 11/22/1(**	**Fri 2/24/17**	**31**	
38	✓		Get Carbon Samples from Morg	30 days	Tue 11/22/1(	Mon 1/2/17		Jake Gelinas
39	✓		Adapt Test Rig for Carbon Samples	2 days	Tue 1/3/17	Wed 1/4/17	38	
40	✓		Pi groups for data analysis	69 days	Tue 11/22/1(	Fri 2/24/17		
41	✓		◢ **Test**	**38 days**	**Wed 3/1/17**	**Fri 4/21/17**		
42	✓		Preliminary Roughness Testing	3 days	Wed 3/1/17	Fri 3/3/17		
43	✓		Hardness Testing	6 days	Thu 3/9/17	Thu 3/16/17		
44	✓		Tribometer testing	11 days	Fri 3/31/17	Fri 4/14/17		
45	✓		Data Analysis/ Prediction Model	6 days	Fri 4/14/17	Fri 4/21/17		
46	✓		◢ **Redesign**	**6 days**	**Fri 4/21/17**	**Fri 4/28/17**		
47	✓		36K testing at Eaton	1 day	Fri 4/21/17	Fri 4/21/17		
48	✓		Pin on disk testing	1 day	Fri 4/21/17	Fri 4/21/17		
49	✓		Larger sample base	1 day	Fri 4/21/17	Fri 4/21/17		
50	✓		◢ **Design Showcase**	**1 day?**	**Fri 4/28/17**	**Fri 4/28/17**		
51	✓		Last day of classes	1 day	Fri 5/12/17	Fri 5/12/17		

Figure 2: **PROJECT PLAN PAGE 2**

3 Financial Analysis

3.1 Projected Project Budget

Eaton Corporation provided Seal Team Fix with a budget of $3,500 for the duration of the project. During the fall semester, the team discussed what the budget would be spent on. The team came to a conclusion that the budget will be spent on acquiring materials for the spring semester instead of being spent on modifying test equipment to fit the needs of the experimentation portion of the project.

As of December 18, 2016 the budget stands at $3,500. The current expected cost is approximately $1,350. The only fixed cost at this point in time that the team will have to budget for is the cost of the 440c sheet steel. As will be explained later in section 3.2, the expected cost for the sheet steel is $350.

3.2 Testing Costs

The various types of carbon that were chosen to be tested were determined by the highest order quantity according to Eaton. The four most commonly used types of carbon according to Eaton are known as CNFJ, CTI-76, P-4229, and P-5007 carbon compounds. The carbon that will be tested will be provided by the carbon manufacturer known as Morgan. Morgan has informed the team that if the results gathered from the experimentation are disclosed to Morgan at the end of the project then the carbon samples will be free of charge. However,if the team does not disclose the experimental data with Morgan, they will have to charge the team a total of $250 per lot of samples. Since there are four types of carbon being tested, the total amount for these samples would be $1000.

The experiments that will be conducted during this project will only require a single type of steel. The most common mating surface for a carbon seal is 440c stainless steel. According to the wear plate drawing in Appendix A, the minimum required area of 440c sheet steel is 3.125 square feet. The team decided that 4 square feet will allow enough additional material for spacing between the plates. The extra material will also provide enough material to make an extra plate in case there is a deformity during the machining process. Sheet steel is normally sold in mill quantities so ordering the ideal 4 square feet of material is not possible. From the research that the team has conducted on purchasing 440c stainless steel from various distributors, the best possible price is $350 for a 16 square foot section of sheet steel.

The actual tests will be conducted at either Eaton or at the University of Rhode Island. There will be no costs associated with using the testing equipment located at either Eaton or the University of Rhode Island.

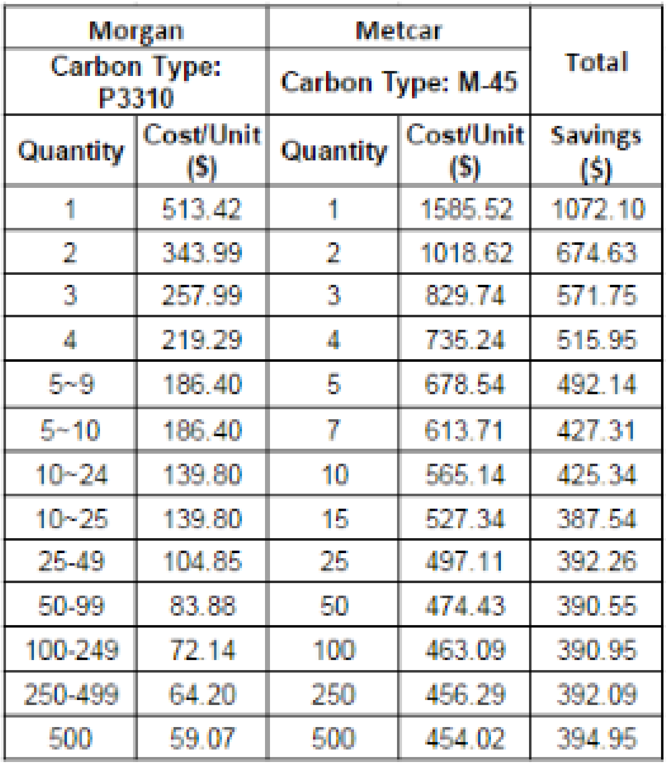
3.3 Potential Cost Savings

Every project that is presented at or by a company must keep the costs and potential savings in mind. Whether the savings will be immediate or over the course of several years the company will save money. In the case of Eaton's project, the cost savings will be a case by case basis and can not be determined at this point in time.

The project proposed by Eaton is a technical bench strength test. A technical bench strength test will allow Eaton to predict the service life of a seal based on its material properties and the tested results. This project will allow Eaton to compare similar grades of carbon from different manufactures to determine which one is more cost effective for the situation. The costs of a similar grade of carbon from two manufactures, Morgan and Metacar, can be viewed in Table 1.

In Table 1, the potential cost savings of a similar grade of carbon from two separate companies is compared at a rate of cost per unit. The left most column contains the data from carbon P-3310 manufactured by Morgan. P-3310 carbon cost varies from approximately $500 for a single seal to $60 per seal when purchased in a quantity of 500 seals. The center column displays the carbon type M-45 that is produced by Metacar. The M-45 carbon can vary in price ranging from approximately $1,600 per single seal purchased to $460 per seal for 500 seals. The potential savings is displayed in the right most column. If the results from the service life prediction model shows that the service life of the cheaper carbon, the P-3310, is similar to the service life of the more expensive carbon, the M-45, then the potential cost savings will range from $394.95 to $1072.10 per seal.

Table 1: **POTENTIAL COST SAVINGS**



Morgan		Metcar		Total
Carbon Type: P3310		Carbon Type: M-45		
Quantity	Cost/Unit ($)	Quantity	Cost/Unit ($)	Savings ($)
1	513.42	1	1585.52	1072.10
2	343.99	2	1018.62	674.63
3	257.99	3	829.74	571.75
4	219.29	4	735.24	515.95
5~9	186.40	5	678.54	492.14
5~10	186.40	7	613.71	427.31
10~24	139.80	10	565.14	425.34
10~25	139.80	15	527.34	387.54
25-49	104.85	25	497.11	392.26
50-99	83.88	50	474.43	390.55
100-249	72.14	100	463.09	390.95
250-499	64.20	250	456.29	392.09
500	59.07	500	454.02	394.95

3.4 Actual Project Cost

As stated earlier, for every project or product that a company is involved with, they must keep the costs and savings in mind throughout the duration of the project or product. That is exactly what our group did during the process of analyzing the carbon samples, as well as obtaining the materials and equipment to do so.

The total budget that Eaton provided remained at \$3,500 during the course of the project and did not change. What did change, however, was the money that was actually spent. As of now, the only part of the project that we were charged for was the 440c stainless steel that we used. These stainless steel plates were flattened, heat treated, and used as the mating surface for the carbon samples while conducting the tribometer experiments. This steel was originally going to cost us \$350 but we found it a little bit cheaper for \$258 from a different manufacturer. As a part of our build process, our group had to create a clamp that would fit in the tribomter, and also be able to hold onto our carbon samples, which were larger in diameter than the original pin that the tribometer had came with. The material used for that could have costed our group some money from our overall budget from Eaton, but it did not. We were able to use scrap aluminum from the machine shop on campus, and machined the clamp ourselves, making the total cost for setting up the tribometer zero dollars.

As for our carbon samples, they provided a lot more room for cost savings than any other aspect of the project. Each lot of carbon was going to originally cost the group \$250 each, and with a total of four carbon grades being used for experiments, that would have cost \$1000. The suppliers for the carbon, however, are willing to not charge us for the carbon they had previously provided for us. This is in exchange for the empirical data that we obtained from our testing. With the carbon samples being provided for free, the clamp being made from scap metal, and the 440c stainless steel being purchased from a cheaper manufacturer, the overall cost of the project would be \$258, a lot less expensive than the \$3,500 budget had in mind.

4 Patent Search

The project that the team is tasked with from Eaton is an analytical prediction model of the service life of carbon based seals in aerospace applications. In order to begin the planning and design phase of the project, a patent search was required to determine if a prediction model for carbon based seals exists. The reason for conducting a patent search for this project was to protect the team and Eaton from possible legal action if a competing company already has a similar prediction model on the market. In doing a patent search, it not only protects the team from legal action, it will also provide ideas on which to base the final product. The competitor's ideas act as a base upon which the team can improve for the final product. The most significant patents from the search are listed below along with a brief description.

Name: Carbon Composite Material for Tribological Applications

Number: 5,538,649
Date: 23 July 1996
Company/Assignee: John Crane Inc.
Inventors: Joseph F. Demendi, PhilippeR. Malle, Yannick A. Le Neve, Xin Chen and William R. Clemens
Description: This patent focuses on the composition of carbon based mechanical face seals. These seals are typically used with a harder tribological pair mating service. The seals can be comprised of various carbons such as amorphous carbon or natural or synthetic graphitic carbon with an impregnation of assorted fluorides or resins not exceeding 30.00 percent weight. The patent also discusses a method at which the carbon is to be mixed and formed into the final seal form. This Patent provided no relevant information toward creating a prediction model for a carbon based seal. This patent did provide an idea as to what the carbon seals can be made of. This information will eventually help in characterizing the carbons that will be tested.

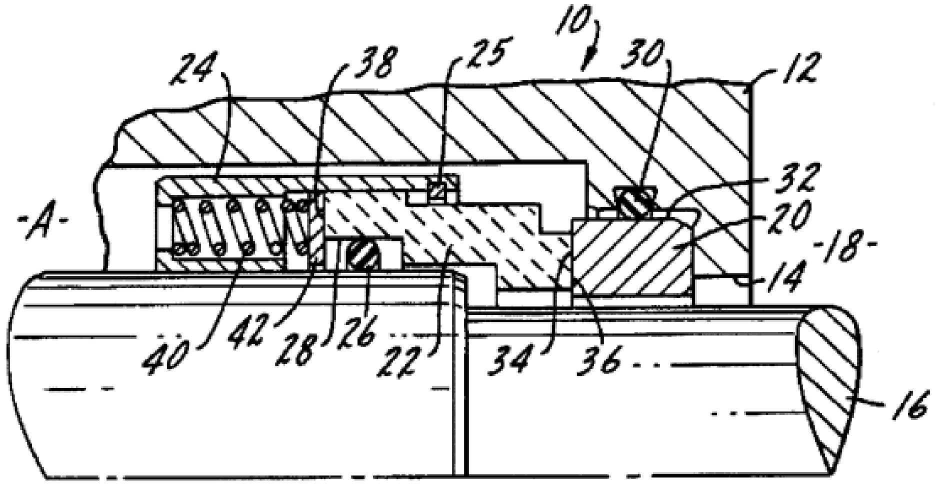


Figure 3: **SEAL APPLICATION DIAGRAM FROM PATENT 5,538,649**

Name: Process for Deposition of Amorphous Carbon
Number: 8222189 B2
Date: 17 July 2012
Company/Assignee: United Technologies Corporation
Inventor: Clark V. Cooper and Michael F. Mullen
Description: The goal of this patent, the process of deposition of amorphous carbon, is to extend the amount of time that a helicopter pilot has to safely land when there is a bleed out of oil in the main drive shaft. This patent describes the process at which a bearing is coated with a hydrocarbon using a process of sputter cleaning. The patent aims to achieve that goal by taking current ball bearings and other main bearings with a hydrocarbon with a low atomic mole percentage of hydrogen. Having a lower percentage of hydrogen in the seal will allow the seal to have an increased longevity and have a low frictional resistance and a low wear rate. The previous patent does not provide any relevant information as to how to generate a service life prediction model, but it does provide the team with a source to look at for possible coatings of the seals.

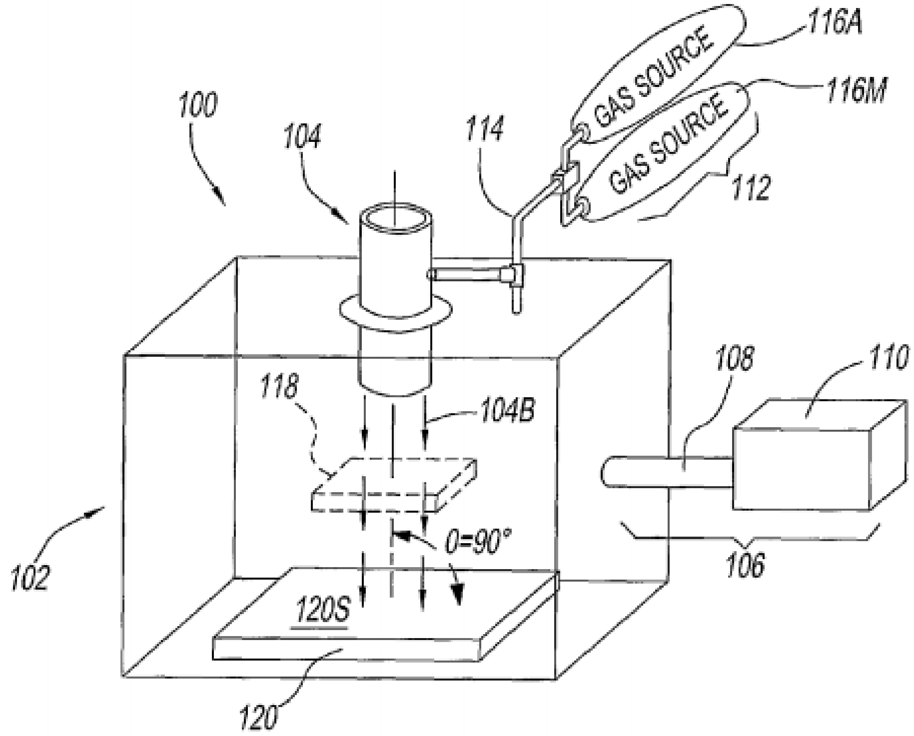


Figure 4: **PROCESS OF DEPOSITION OF AMORPHOUS CARBON**

As of October of 2016, there are no patents on file that pertain to the creation of an analytical model for the service life of carbon seals. One reason that this is the case is because competing companies do not want to allow their competitors to have an insight as to how the carbon is tested. If an analytical prediction model does exist, then it is most likely treated as proprietary information. In order to find a possible starting point for the project, the team conducted a literature search to see if any research relating to either the wear rate or the leakage rate of carbon has been conducted.

4.1 Literature Search

In addition to the patent search, the team conducted a literature search at the suggestion of project and technical advisors. The main two resources that the team used were the Tribology textbook used in Professor Meyers Tribology class [4] and Dr. Sadds textbook on the Theory of Elasticity [7]. From the information gathered through the Tribology textbook, the team concluded that the best course of action was to use the Archard Wear Equation to determine how long a seal would remain viable for use under operating conditions. The Archard Wear Equation takes into account several factors such as the hardness of the softer material and the coefficient of friction that exist between a tribological pair. In order to gain an understanding of the subsurface stresses, Professor Meyer suggested that the team read a section from Dr. Sadds textbook about half body wear and subsurface stresses. From the information gathered from Elasticity: Theory, Applications, and Numerics, the team was able to determine the stress distribution under the contact points of the seal. Upon further research, it was decided that the leakage rate would play a large role in whether or not the seal will fail. The team was provided a leakage rate equation by Dr. Meyer as well as a paper that backed up the equation that was provided [5].

5 Evaluation of the Competition

The evaluation of the competition of Seal Team Fix varied from the average Capstone Design Project. Since the aerospace industry is a very competitive market, many companies tend to keep their information proprietary so as to hold an advantage over their competition. The team researched service life prediction models for various seal materials and designs and very little information was found. After consulting the project sponsor, the team was informed that very few companies will publicly disclose informational studies performed for the benefit of the company and that many companies rely on the material property information provided by their suppliers as being accurate enough. With this knowledge the team instead had to evaluate internal competition.

Since very little information could be found regarding carbon face seal service life prediction models from other manufacturers, the team began to evaluate its own design concepts. The design concepts described later in Section 7 of this report were analyzed and competitively compared with one another to find which design concepts would arguably lead to the most accurate service life prediction model. The choices were narrowed down and, with the help of the team's technical adviser Dr. Meyer, the best design concepts were finalized into three main approaches. Each of these approaches consisted of three stages as will be described later in the Detailed Product Design section. The three main approaches later became known as the Mechanical Approach, the Materials Science Approach, and the Failure Modeling Approach.

5.1 Mechanical Approach

The mechanical approach proposed studying the effect of spalling in relation to the failure of carbon face seals. Spalling is a cyclic phenomena which occurs when wear debris from one material in contact with another material builds up and begins to form a film between the two surfaces. This film can actually begin to lower the coefficient of friction of the materials in contact and therefore lead to a reduction in wear volume. The film is then ”wiped” away and the cycle repeats itself. The purpose of the study of this mode of failure is to understand how spalling affects the service life of carbon face seals.

The second part of the mechanical approach was to perform tensile and compression tests on carbon samples at operating temperature and analyze these tests using Digital Image Correlation (DIC). The images captured using the DIC technique can be uploaded into a software package which analyzes the deformation of the materials throughout testing. This analysis can be used to find the elastic modulus as well as the Poisson's ratio of the material being tested. The purpose of this test method is to find important material properties of the carbon compounds in order to use in the prediction model.

The third part of the mechanical approach is measuring the roughness values of the carbon materials intermittently throughout tribometer experiments using a profilometer. The roughness measurements can be used to calculate a leakage rate of the carbon face seals. The purpose of measuring the roughness's intermittently throughout experimentation is to calculate the leakage rates of each material intermittently and use that data to create a service life prediction model.

5.2 Materials Science Approach

The materials science approach involves running an inclined plane experiment to measure the coefficients of friction between the carbon samples and the mating surface. An inclined plane experiment consists of placing a sample of the carbon material with a pre-determined mass on an inclined length of the mating material. The carbon material would be left to slide down the incline of the mating material. A smaller mass would be connected to the rear of the mass of carbon with a string and left to hang freely in the vertical direction at the top of the incline. The coefficient of kinetic friction between the two materials can be determined when the carbon material slides down the inclined plane at a constant speed. The purpose of this experiment is to establish a value for the coefficient of kinetic friction between the carbon material and the mating material.

The second step of the materials science approach is to test the hardness of the two materials in contact. The hardness of the carbon compounds as well as their mating material need to be determined. In order to accurately characterize the hardness of the mating materials in the environment in which they operate, the materials need to be hardness tested at a simulated operating temperature. The purpose of hardness testing the material is to use the data obtained in order to calculate the wear volume of the material as described later in Section 11. These calculations can then be used to develop a service life prediction model.

The third step of the materials science approach is to use the testing apparatus at Eaton's Rumford facility to simulate an exact environment in which the carbon seals operate. The team can test the seals on Eaton's test rig at simulated operating speeds, temperatures, and pressures and measure the wear volume of the materials after intermittent service periods.

The purpose of this experiment is to obtain the most accurate wear volume results as possible since the team would be able to simulate a nearly exact environment to a real life application.

5.3 Failure Modeling Approach

The failure modeling approach includes pin on flat testing in order to simulate the contact between the carbon material and the mating surface that the material contacts. This process is described later in Section 11.1. The pin on flat testing is a study of the failure mode of the carbon materials since the wear volume of the material can be measured throughout the tests.

The second part of the failure modeling approach involves compression tests of the carbon materials in order to calculate the Young's modulus of the material. The tests can be performed on the Instron compression testing machines at the University of Rhode Island. The data obtained from the equipment can then be collected and analyzed using a Microsoft Excel spreadsheet. The purpose of this experimental process is to characterize the Young's moduli of the different carbon materials. This material property is helpful in determining different wear properties of the carbon materials in question.

The third phase of the failure modeling approach involves calculating the leakage rate of the carbon face seals. This phase will utilize the dimensional analysis in Section 10.1 as well as the leakage rate formula (Equation 18),both described later in this report. Essentially the goal is to calculate the leakage rate of the carbon face seals as a function of the roughness of the seals as well as the seal radius. The purpose of these calculations are to compile these results into a final service life prediction model.

5.4 Comparison of Engineering Approaches

The three aforementioned engineering approaches were then weighed against each other by their expected performance in certain categories. These categories are probability of completion before the end of the spring semester, the ease of experimentation, the access the team would have to the testing equipment, and the overall predicted cost of each experiment. As Table 2 will show, there is no approach that has a distinct advantage over another. This is the reason why the three approaches were combined, taking the best parts from each, as discussed in the Detailed Product Design Section.

Table 2: **Evaluation of 3 Engineering Approaches**

Scale: 1-3, 1 being worst, 3 being best			
	Mechanical Approach	Materials Science Approach	Failure Modeling Approach
Probability of Completion by April 2017	2	3	3
Access to Necessary Equipment	2	2	3
Ease of Experimentation	1	2	1
Cost (3 cheapest, 1 most expensive)	3	2	3

6 Specifications Definition

The specifications for the final engineering approach were derived from customer demands and product specifications obtained through meetings with the sponsor from Eaton Corporation as well as team brainstorming and meetings with the technical adviser of this project. The group of technical parameters pertaining to the simulation of the service environment of the seals were provided by Eaton Corporation and could be directly assigned as mechanical specifications. The specifications pertaining to mathematical modeling and experimentation of the carbon were obtained through consulting the technical adviser about the given parameters and expected outcomes of the project.

The product requirements were categorized into three fields; experimental requirements, environmental replication requirements, and economic requirements.

The experimental requirements for the carbon seal life cycle prediction model dictated the constraints that had a direct impact on the experimental design of this project. The most stringent of these constraints was the amount of time the team has to perform the experiments next semester. Eaton Corporation wanted a functional mathematical model that can accurately predict the life cycle of a given carbon seal geometry for different types of carbon by early May of 2017.

6.1 Experimental requirements

After consulting the technical adviser for this project, it was noted that the number of required experiments would increase exponentially for each metallic mating surface tested. It was also determined that the carbon, being the softer of the two materials in contact, was to be the main focus of this project. Therefore, the most common mating surface material, 440C Stainless Steel, was selected to be the only metal tested against the different carbon grades. Eaton had made it clear that they wanted the team to test only the most popular carbon grades.

After receiving a list of approximately 35 different carbon grades and consulting the project sponsor, it was determined that Eaton desired to test four carbon grades from Morgan: P-5007, P42299, CNFJ, and CTI-76. These four grades were selected because their material properties and resulting life cycle prediction will be directly compared to that of similar but more expensive carbon grades from Metacar. It was then determined that for each grade of carbon, at least 3 tribometer experiments needed to be performed to obtain accurate data, while keeping in mind the amount of time required to perform these experiments as well. Therefore, 5 samples of each of the 4 grades of carbon were ordered to account for errors in experimentation. Furthermore, after the tribometer experiments are preformed, the remaining material of each specimen will be tested for Vicker's hardness at operating temperature. The 440C metal plates to be used in the tribometer experiments can be used twice. So, in the event of any failed experiments, 9 plates will be made to allow for 18 experiments total, despite the minimum requirement of 12.

6.2 Environmental Replication Requirements

The environmental replication requirements for the carbon seal life cycle prediction model dictated what conditions that the carbon seal experimentation and evaluation had to simulate in order to obtain accurate results. It was made clear by the project sponsor that the environmental requirements would simulate the most prevalent value of a given parameter in the dynamic carbon face seal. If a range were given for a parameter, the average of that range would be taken and used in testing. As there are currently no standards for carbon dynamic seals in the aerospace industry, the following parameters were determined utilizing confidential information provided to the team by the project sponsor. Research on behalf of the team was not entirely possible here as this information was not readily available to the public.

Eaton Corporation first provided the team with a very large window of seal and shaft sizes, with the diameter of the seals ranging from 1-21 inches. As it would be impossible under the scope of this project to run tests to simulate every size within this range, the team and the project sponsor decided to only test the most prevalent seal size. After much deliberation regarding overall sales and production of different seal sizes and designs, a seal with an outer diameter of 2.355 in and thickness of 0.065 in was selected as the geometry to simulate.

After consulting the project sponsor, the pressure at the seal and mating surface interface was an important factor to simulate as it would have a direct impact on the seal service life. The seal contact was loaded from $5 - 15$ psi depending on seal sizes and loading springs for different applications. For the purposes of experimentation it was decided that one pressure would need to be simulated, so the average of the range was taken to be 10 psi. This was done to keep the number of experiments to a minimum as there is a major time constraint present, as mentioned above.

The pressure drop across the seal drives the leakage rate of the oil and consequently the service life of the seal. The range of values provided to us by Eaton Corporation was $0-20$ psi. After consulting the technical adviser of this project, it was decided that a conservative estimate of the seal life was desired at first, which would then be altered over time to more accurately reflect the true service life of each carbon dynamic seal in question. In order to achieve the initial conservative estimate of the seal life the worst environmental conditions, in terms of seal leakage, had to be chosen. Therefore the highest pressure drop of 20 psi was chosen, as the pressure drop is directly correlated to the seal leakage rate.

Surface roughness values pertaining to the surface finishes of the carbon seal and the 440c stainless steel mating surface were provided by the project sponsor. The surface roughnesses of both the seal and the mating surface fell within a range of $R_a = 4-8\mu in$. The differences in leakage rates in this range compared to the roughness that approaches the leakage rate ceiling are negligible. Therefore, it was decided that the initial surface roughnesses of both the carbon samples being tested and the metallic contact surface had to fall within this range of surface roughness values.

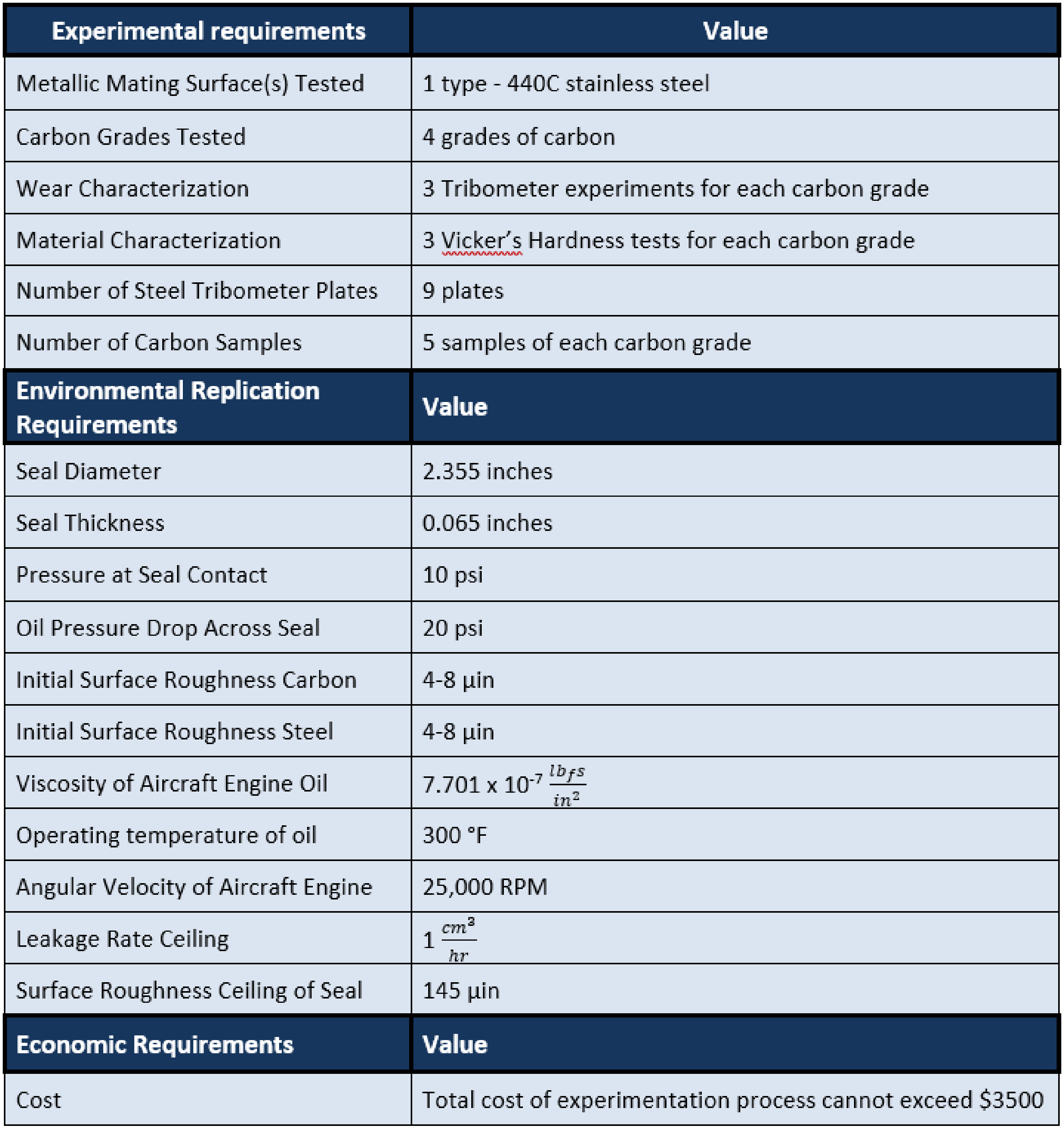
The main applications of the dynamic carbon face seals of interest are to contain aircraft engine oil within a gearbox or bearing housing on the main shaft of a turbine engine. This oil is heated and provides lubrication to the seal. Both the temperature and viscosity of this oil was critical to simulate as it has a direct impact on the service life and leakage rate of the seal. The viscosity of the standard aircraft engine oil is $7.701 * 10^{-7} \frac{lb_f * s}{in^2}$, at a temperature of 300°F. The average angular velocity of an aircraft engine main shaft was given to the team by Eaton as well. The angular velocity of 25,000 rpm will have to be taken into account when the sliding distances of the seal are converted into operating time.

A theoretical leakage rate was plotted as a function of surface roughness, pressure drop across the carbon face seal, as well as the thickness of the seal as a part of the failure mode study. A leakage rate ceiling of $1cm^3/hr$ was provided to the team by Eaton. Using the given dimensions of the seal, viscosity of the oil and maximum pressure drop across the seal, a surface roughness of $145\mu in$ was established to be the surface roughness of a failed seal.

6.3 Economic Requirements

Finally, a budget of $3500 was given to the team from Eaton Corporation. This has not affected any spending as the carbon samples will be free of charge if the results of the project are shared with Morgan. However, the total cost of the experimentation cannot exceed this price limit.

Table 3: **DESIGN SPECIFICATIONS**



Experimental requirements	Value
Metallic Mating Surface(s) Tested	1 type - 440C stainless steel
Carbon Grades Tested	4 grades of carbon
Wear Characterization	3 Tribometer experiments for each carbon grade
Material Characterization	3 Vicker's Hardness tests for each carbon grade
Number of Steel Tribometer Plates	9 plates
Number of Carbon Samples	5 samples of each carbon grade
Environmental Replication Requirements	**Value**
Seal Diameter	2.355 inches
Seal Thickness	0.065 inches
Pressure at Seal Contact	10 psi
Oil Pressure Drop Across Seal	20 psi
Initial Surface Roughness Carbon	4-8 µin
Initial Surface Roughness Steel	4-8 µin
Viscosity of Aircraft Engine Oil	7.701 x 10^{-7} $\frac{lb_f s}{in^2}$
Operating temperature of oil	300 °F
Angular Velocity of Aircraft Engine	25,000 RPM
Leakage Rate Ceiling	1 $\frac{cm^3}{hr}$
Surface Roughness Ceiling of Seal	145 µin
Economic Requirements	**Value**
Cost	Total cost of experimentation process cannot exceed $3500

7 Conceptual Design

Seal Team Fix was tasked with characterizing various carbons that are used to manufacture mechanical face seals in aerospace applications. In order to properly characterize the various carbons, each team member was tasked to generate thirty original ideas that would aid in the creation of a project solution, leading to a total of 120 ideas. Over the course of the generation, the team came to the conclusion that an analytical prediction model is more effective at determining the service life of carbon seals than just using the material properties.

In order to create a service life prediction model, the team narrowed the ideas into three approaches; the mechanical approach, the material science approach, and the failure modeling. The mechanical approach focuses on the frictional forces between the tribological pair and the roughness of the carbon. The main objective of the material science approach is to generate a wear volume equation based on the Archard Wear Equation. The final approach is the failure modeling approach. The majority of the generated concepts had one topic in common, which is to use dimensional analysis to simplify the governing equations and narrow down how many tests must be run to obtain an appropriate sample size. The teams ideas are grouped into the corresponding engineering approach. Some of the teams ideas were removed because they do not have any affect toward the final engineering solution.

7.1 Concept Designs for the Mechanical Approach

The mechanical approach to this problem is used as a general term for the forces and the influences on the forces at the interface and in the seal itself. The main influence that was discovered during the conceptual design phase was the frictional force between the seal and its metal tribological pair. Frictional force can be found several ways, the main method that the team will use is to derive the force of friction from the results of the tribometer tests. A main contributing factor to friction is the roughness of the carbon. On a microscopic scale, the asperity peaks prevent two surfaces from sliding smoothly over each other creating friction. As the asperity peaks slide over one another they either wear down or break off, creating third body wear particles. In order to calculate the effect that that has on the wear of the material, the roughness must be measured before and after the tribometer tests.

The following list are ideas that correspond to the mechanical approach. All of the duplicate ideas have been removed. The ideas that lead to the generation of the mechanical approach are:

- Use the pin on flat tribometer test to measure and compare the force of friction between the carbon samples
- Use a test machine at Eaton known as the 36kW machine to test the carbon
- Take the roughness before and after testing of the carbon samples
- Drop weight carbon compression test to find the Modulus of Elasticity
- Perform a compression test to find the Modulus of Elasticity
- Measure the thickness of the seal before and after testing to determine wear volume

7.2 Concept Designs for the Material Science Approach

The material science approach and the mechanical approach share some of the same characteristics such as friction. In the material science approach the frictional force is not the required parameter, but the coefficient of friction. The coefficient of friction will be achieved from performing a pin on flat tribometer test. The coefficient of friction is a parameter that is required for solving the wear volume equation known as the Archard Wear Equation.

The Archard Wear Equation requires a second parameter that fall under the material science approach. The parameter is the hardness of the softer material. When the carbon seal is compared to its mating surface, the carbon is the softer of the two materials and therefor will be used to find the wear volume. The equation requires the hardness to be measured on the Vickers scale, but a Rockwell hardness scale can be converted into the Vickers hardness. With both the hardness and the coefficient of friction, the Archard Wear Equation can be solved for.

The following list are ideas that correspond to the material science approach. All of the duplicate ideas have been removed. The ideas that lead to the generation of the material science approach are:

- Use the pin on flat tribometer test to measure and compare the coefficient of friction between the carbon samples
- Find the coefficient of friction using a horizontal drag test
- Use the pin on flat tribometer test to measure the wear volume of the carbon

- Attach a heating element to the carbon sample to achieve the 300°F operating temperature
- Run a sample of carbon on the 36kW machine to obtain the coefficient of friction
- Weigh the carbon sample before and after testing to obtain the amount of material that was worn away
- Find the hardness of the carbon sample at 300F, either using the Vicker's or Rockwell Hardness scale
- Find the Modulus of Elasticity for each of the samples
- Take the roughness before and after testing of the carbon samples
- Graphically correlate the results as functions of hardness, temperature, and wear volume

7.3 Concept Designs for the Failure Modeling Approach

To create a failure model, all of the aspects from the previous approaches must be combined to cover all of the possible parameters. The aim of the failure prediction model is to predict how long a seal will last under certain conditions to determine when a seal will be unable maintain the minimum requirements. This approach is split into two parts; to create a script in MATLAB and Excel and to test the a seal under ideal operating conditions at Eatons facility.

The data from the tests and simulations from both the mechanical and material science approach will be inputted into a script to generate a lifetime service model. The model will be generated in both MATLAB so that the team can easily use and modify it and in Excel for Eaton. To test a seal under ideal operating conditions the 36kW testing machine at Eaton would be required to be used. Performing one round of testing will allow the team to confirm or deny the results that have been obtained through the other stages of testing.

The following list are ideas that correspond to the failure modeling approach. All of the duplicate ideas have been removed. The ideas that lead to the generation of the failure modeling approach are:

- Make a prediction model using MATLAB

- Create a MATLAB script that can calculate the service life of the seal based off of the results from the testing
- Make a prediction model using Excel
- Perform a test using the 36kW machine at Eaton

7.4 Evaluation of Concept Designs

The final engineering approach that the team chose was a combination of all three of the approaches. The reasoning behind the decision is that all of the approaches share overlapping parameters that build on one another. Each one of the approaches that were chosen based on how closely the parameters within them relate to the objective of characterizing various carbons and creating a service life prediction model.

The concepts listed above are not the only concepts that were taken into consideration when creating the aforementioned approaches. The following list are the concepts that have been generated during the design process.

7.5 Jacob Gelinas' Design Concepts

- Use an inclined plane experiment to calculate the coefficient of kinetic friction. Using a measured mass of carbon on an inclined plane made of hardened steel to replicate the interaction of the carbon seal on hardened steel shaft, the coefficient of kinetic friction can be calculated between the two materials. Through simple kinematics equations, the coefficient of kinetic friction is determined when the carbon slides down the inclined plane at constant velocity (Appendix U). **Materials Science Approach**
- Use the horizontal surface method to determine the coefficient of kinetic friction between the two materials. This method uses the same kinematics equations and principles used for Design Concept 1 (Appendix V).
- Utilize a replication of shaft/ seal interface which is driven by a variable speed motor to calculate coefficient of kinetic friction. One can vary the power input to the motor until the shaft begins to spin. At the moment the shaft begins to spin, the power input to the motor can be used to calculate the coefficient of static friction. With the shaft spinning, the power input can be lowered until the shaft almost comes to a stop. From this motor speed and power input, the coefficient of kinetic friction can be calculated.**N/A**

- A pin on flat type test can be utilized to test for coefficient of kinetic friction. The principles are along the same lines as Design Concept 3. The power input necessary to make the carbon pin slide across the surface of a hardened steel specimen can be used to calculate the coefficients of static and kinetic friction.**Materials Science Approach**

- A pin on disk test can be used in the exact same manner as Design Concept 4 (Appendix W).**N/A**

- Machine a hollow area inside the shaft of the test rig where a heating element can be inserted. Use this set-up to replicate high temperatures inside jet engine (Appendix X).**N/A**

- Correlate temperatures generated from Design Concept 6 with wear volume graphically.**N/A**

- Replicate an operational environment using a variable speed motor and shaft/ seal interface and measure heat generation at shaft/ seal interface (Appendix Y).**Failure Modeling Approach**

- Correlate heat generation with the shaft speeds tested with Design Concept 8. Show results graphically.**Failure Modeling Approach**

- Weigh seal before and after heat tests to determine wear volume from Design Concepts 6 and 8.**Failure Modeling Approach**

- Measure thickness of seals before and after heat tests to determine wear volume from Design Concepts 6 and 8.**Failure Modeling Approach**

- Create sealed pressure chamber to simulate pressures at operating conditions (Appendix Z).**N/A**

- Use DIC Technique to measure deformation of seal when placed in housing.**N/A**

- Obtain samples of carbon suitable for the application of a heating element. Hardness test each sample after being heated with the heating element.**Materials Science Approach**

- Heat samples of carbon in an oven and hardness test the samples.**Materials Science Approach**

- Correlate the temperature and wear volume of the seals graphically.**Materials Science and Mechanical Approach**

- Correlate the hardness of the carbon and the wear volume graphically.**Materials Science Approach**
- Utilize dimensional analysis to simplify governing equations.**All Approaches**
- The Archard equation is typically used to calculate wear volume, however this equation does not incorporate the coefficient of friction of the materials and the temperature of the materials. Find a way to incorporate these variables into the equation for wear volume based on data correlations mentioned previously in design concepts.**N/A**
- Simulate spalling due to carbon film build-up and test how the carbon film is wiped away.**Materials Science Approach**
- Measure the coefficient of friction between the seal and shaft with a carbon film built up using one of the design concepts mentioned previously.**Materials Science Approach**
- Measure the heat generated between the seal/ shaft interface with a carbon film built up using one of the aforementioned design concepts.**Mechanical Approach**
- Measure the wear volume generated between the seal/ shaft interface with a carbon film built up using one of the aforementioned design concepts.**Materials Science Approach**
- Make an adaptable plate which holds samples of each seal size so that each size can be tested (Appendix AA).**N/A**
- Use a center-bolted shaft on test fixture so that different shaft sizes can be easily interchanged (Appendix AB).**N/A**
- Cut a hole through the center of the shaft large enough to fit a threaded rod through. A plate on each side of the threaded rod can be used to secure the shaft on with a nut (Appendix AC).**N/A**
- Design the shaft with an adaptable ring which can be interchanged as needed. The ring would contain the seal and be bolted directly to the adapter on the shaft (Appendix AD).**N/A**
- Test surface roughness of seal before and after testing to determine if Archard equation accurately predicts wear.**Materials Science and Mechanical Approach**

- Test hardness of material at a multitude of temperatures and use that data to manipulate Archard equation to predict wear at different speeds (ie. engine start, airport speeds, etc.)**Materials Science Approach**
- Design a spring-type fixture or a threaded rod that can apply different pressures to seal/ shaft interface to replicate typical application pressures.**N/A**

7.6 Chris Blewett's Design Concepts

- Perform a Rockwell Hardness test on a material sample to find the hardness.The hardness will be used in a wear volume formula to determine what the volume of wear is. This test will only produce the hardness at room temperature.**Materials Science Approach**
- Perform a Rockwell Hardness test on a material sample at operating temperature to find.The hardness from this experiment will give the hardness at operating temperature.It is plausible to conduct this experiment with the testing apparatuses that are available at URI.**Materials Science Approach**
- Perform a Vickers hardness test to find the materials hardness on the Vickers hardness scale.This test will only produce the hardness at room temperature on the Vickers scale.**Materials Science Approach**
- Perform a Vickers hardness test at operating temperature to find the materials hardness on the Vickers hardness scale. The hardness from this experiment will give the hardness at operating temperature. It is plausible to conduct this experiment with the testing apparatuses that are available at URI.**Materials Science Approach**
- Perform a compression test using the Instron machine to find the deformation of the material. The deformation might be required in order to solve for the wear because the contact area will change. The force that will be applied is the normal force exerted on the shaft from the seal.**Materials Science and Mechanical Approach**
- Perform a compression test at temperature using the Instron machine to find the deformation of the material.**Materials Science and Mechanical Approach**
- Perform an abrasive wear test on the carbon sample, with the carbon stationary and a sample of steel rotating. This will simulate actual interaction between the carbon and steel in the engine.**N/A**

- Perform a pin on flat tribological test on the carbon sample. The linear results can be converted to rotational results from equations provided by Dr. Meyer.**Materials Science and Mechanical Approach**

- Use the pin on flat test to find the coefficient of friction of friction between the carbon sample and the steel.**Materials Science and Mechanical Approach**

- Perform a wear test between the carbon and a sample of steel. In this test, the a carbon seal will be held stationary while a sample of steel that rotates within the carbon sample. This test will most likely need to be run at Eaton.**Materials Science and Mechanical Approach**

- Calculate the wear based on the amount of material that is worn away per allotted amount of time. This is the wear volume.**Materials Science and Mechanical Approach**

- Compare the abrasive wear tests both the carbon and the steel to determine which material is the softer of the two. It is required to use the Vickers hardness of the softer material to find the wear volume.**N/A**

- Perform all of the wear and hardness tests at temperature, using the furnaces in the materials lab.**Materials Science and Mechanical Approach**

- Use MATLAB as the software to write the prediction model.**Failure Modeling Approach**

- Use Visual Basics as the software to write the prediction model.**N/A**

- Use both Visual Basics and MATLAB in order to write the prediction model. The Guis in Visual Basics can be used to control the inputs for the MATLAB script.**N/A**

- Use the wear tests to determine what the kinetic coefficient of friction is between the carbon sample and the steel. It can be calculated from the force being applied to the sample and the velocity of the tests.**Materials Science Approach**

- Calculate the total amount of heat generation using the coefficient of friction, the rotational velocity, and the normal force exerted on the sample. **N/A**

- Calculate the amount of heat flux across the carbon and steel.**N/A**

- Find what causes the spalling effect between the carbon and the steel.**N/A**

- Find a formula or method to predict when the spalling effect occur.**N/A**
- Find a method to prolong the length of time before spalling effect occurs.**N/A**
- Investigate a way to perform all of the tests at an operating pressure. This might not be plausible to test due to a lack of a large enough enough pressure vessel.**N/A**
- Use MATLAB or another simulation software to simulate the experiments at an operating pressure.**N/A**
- Use MATLAB or another simulation software to simulate the experiments at an operating pressure.**N/A**
- Use a smaller sample of carbon to find the wear on a seal with a larger contact area. The smaller sample will have to be run at higher speeds or higher rpms.**Failure Modeling approach**
- Using the results from the wear tests, calculate how long the seal will last. Compare the wear volume results to the given operable wear values from Eaton.**Failure Modeling approach**
- Vary the speeds or rpms of the wear tests to simulate the conditions at start up of the engine.**N/A**
- Vary the speeds or rpms of the wear tests to simulate the conditions at cool down.**N/A**
- Use the DIC method to determine the amount of deformation in the carbon sample. The amount of deformation might affect the contact area of the seal.**N/A**
- Test the amount of oil leakage between a sample seal and the shaft. It can be accomplished by creating a pressurized oil box on one side of the seal.**N/A**

7.7 Tyler Patten's Design Concepts

- Test rig for carbon ring and metallic surface Contains spinning chuck with clamp attached to motor to attach various metallic specimens. An Arm extends above spinning disc, uses load spring to force carbon block against metallic mating surface. A Laser thermometer measures temperature at carbon-metallic surface. An Enclosure surrounds apparatus to maintain temperature. Opening in enclosure connected to solenoid controlled by PI controller. (Appendix J) **N/A**

- Vickers hardness test for use in modified Archard Hardness Equation. Heat carbon up to 300 F in oven and perform experiment at temp to simulate real-world application. Use standardized test to define hardness of softer material using hardness testing machine. The hardness tester is available at URI, simple, easy test. It would not be easy to keep carbon sample at constant temperature. (Appendix K) **Materials Science Approach**

- Rockwell Hardness test for use in equation. The reasoning behind this method is that Eaton uses Rockwell hardness. Procedure similar to Vickers hardness test except uses spherical indenter instead of diamond indenter. Same pros and cons as the previous concept. (Appendix K) **Materials Science Approach**

- Modulus of Elasticity. The carbon seals are being loaded in compression. Plastics and carbon materials tend to behave differently in compression vs tension. Compress carbon on Instron machine. (Appendix K) **Materials Science Approach**

- Initial surface roughness for seal and mating surface. Measure the surface roughness of the tribological pair. Use surface roughness measurement tool in tribology lab. (Appendix K) **Materials Science and Mechanical Approach**

- Coefficient of friction between tribological pair. Use a force gauge to measure the amount of force required to keep a sample of carbon moving against a relative mating surface. Carbon is loaded with adjustable masses (weights) on the top. (Appendix L) **Materials Science Approach**

- Shear modulus of elasticity of carbon. Use Instron machine to pull fixtures attached to parallel faces of carbon cube. Attached using high-strength epoxy. Use resulting strain data to calculate the shear modulus of elasticity. (Appendix L) **Materials Science Approach**

- Alternative method for determining shear modulus of elasticity. Attach one side of carbon ring to fixed support, attach other side to plate with an arm to apply moment. Fix mass to moment arm. Measure deflection of end of beam to determine G for the carbon ring. (Appendix L) **N/A**

- Dynamic measurement of G. If a measurement of G is desired at a non-quasi-static strain rate, the weight in concept 8 can be dropped from a certain height. An angular deflection gauge can be connected to an oscilloscope to measure the maximum torsional deflection of the carbon. (Appendix M) **N/A**

- Pin on disc with heating element. A standard pin-on-disc test can be performed to characterize the wear of the specific carbon seal relative to its metallic counterpart. To simulate the environment of an engine gear box, a heating element will surround the apparatus and use convection to heat the carbon/metallic surfaces. Pin is metallic and disc is carbon. (Appendix M) **Materials Science Approach**

- Pin on disc modified. Same apparatus as 10, with carbon and metallic elements interchanged. Would make measurement of wear volume easier to measure. (Appendix M and N) **N/A**

- Metallic plate and carbon ring wear apparatus. Similar to pin on disc, but testing actual carbon seal in final production form. Motor spins clamp which holds carbon ring, spring loads ring against metallic surface. (Appendix N) **Failure Modeling Approach**

- Thermal control for ring wear apparatus. Thermocouple attached to metallic plate inside carbon ring area, also attached to PI controller. Temperature controlled by switching on and off of circumferential heating element incorporated into circuit. Would eliminate need for enclosure around apparatus.(Appendix N) **Failure Modeling Approach**

- Alternative control for temperature of ring wear components. Use laser thermometer instead of thermocouple in PI circuit. This concept is easier to implement, more accurate, easier to install.**N/A**

- Different method for determining shear modulus G. Side A slots into side B limiting movement to 1 degree of freedom. Carbon cube fits into pocket and is able to be loaded in shear along center without gluing it to a surface.(Appendix O) **N/A**

- Modified seal on face test rig. Pressurized oil and air to simulate bearing housing. Connected to air supply to maintain 10-15 Psi at seal interface. Oil inlet connector to pump/heated reservoir. Oil collector under drain to measure oil leakage across face of seal. (Appendix O) **Failure Modeling Approach**

- Oil pump/heated reservoir for circulation of oil at 300°F. Metal reservoir for oil with heating element on outside sides. Thermocouple inside to measure temp and send signal back to computer. Oil pump after filter on oil outlet. Entire reservoir placed below rig in the previous concept, so no pump required for oil inlet in reservoir. (Appendix P) **Failure Modeling Approach**

- Motor/shaft configuration. Motor on vertical rollers that do not allow motor housing to rotate with respect to rig. Weight of motor + force of spring to produce desired face pressure on seal. (Appendix P) **Failure Modeling Approach**

- Sleeve to simulate circumferential oil pressure on high-pressure side of seal. Carbon press fit into metal ring, with an inner diameter is slightly smaller than the carbon seals outer diameter. Would eliminate the need for oil/ air pressure. Could eliminate the use of oil altogether. (Appendix Q) **Failure Modeling Approach**

- MATLAB code for temperature controller. Consists of feedback loop and disturbance signal. (Appendix Q) **Failure Modeling Approach**

- Method for measuring wear volume. Use water displacement in a beaker before and after testing to determine the amount of material used. This concept is simple and effective. (Appendix Q) **Material Science Approach**

- Alternative method for determining wear volume of carbon ring. The mass of the seal would be measured before and after testing. Then using the density relation to calculate change in volume. This concept is the most accurate method of measuring wear volume. (Appendix R) **Materials Science Approach**

- Pin-on-flat for determination of wear. This is an alternative method to pi on disc testing. This method is cheaper, more reliable, and available at URI. The only con to this method is that it is harder to determine the distance traveled. (Appendix R) **Materials Science Approach**

- Drop weight carbon compression test. If modulus of elasticity is required for a higher strain rate than quasi-static, may be necessary. This is a simple test to run and it is available at URI. (Appendix R) **Mechanical Approach**

- Modified wear equation. Try to use Archard Wear Equation with a scalar incorporating all relevant material properties. (Appendix S) **N/A**

- Us the Truncation function. Take all material properties, use numerical analysis to create completely original function. (Appendix S) **Failure Modeling Approach**

- Graphical interpretation of the results. Plow wear volume vs each of the material properties. Determine the relationships between W_v and all relevant variables. (Appendix S) **Material Science and Mechanical Approach**

- Heat and mass transfer equations to characterize heat equation. Use thermal cameras to track ambient temperatures around rig to determine heat generation due to friction. (Appendix T) **Material Science and Mechanical Approach**

- Stress evaluation of disc using high-speed imagery and Photoelasticity. Use high speed cameras to capture a still photo of an acrylic ring spinning on a test rig under load, with polarized light. Determine stresses using photoelastic stress theory. (Appendix T) **Mechanical Approach**

- DIC for determination of shear stress in rig. Use DIC technique to determine the principal stresses and maximum shear stresses around the outside of carbon ring under quasi-static loading simulating dynamic frictional forces. (Appendix T) **Mechanical Approach**

7.8 Jerel Rodrigues' Design Concepts

- Weigh carbon seal, test the seal in 36kW machine and let run for X amount of hours to simulate wear and then weigh the carbon seal again to measure for amount of material lost for wear volume. **Failure Modeling Approach**

- Use Pi group theory for the following parameters to find the dimensionless constant to use in Archards equation; Hardness,Surface Roughness, Contact Force, Operating Temperature, Volume, Wear, and Distance Traveled. **All Approaches**

- Use pin on disc test to measure and compare the coefficient of friction on carbon samples from the three different suppliers of Eaton Corporation (Metacar, Morgan, and Schunk). **Materials Science Approach**

- Use pin on disc test to measure and compare the friction force on carbon samples from the three different suppliers of Eaton Corporation (Metacar, Morgan, and Schunk). **Mechanical Approach**

- Use pin on disc test to measure and compare the wear volume on carbon samples from the three different suppliers of Eaton Corporation (Metacar, Morgan, and Schunk). **Materials science Approach**

- Create range of values for the following parameters after the tribological testing is done on samples from the three suppliers; Coefficient of friction, Friction force, and Wear Volume. **Materials Science Approach**

- Use the 36kW machine to measure the torque of the carbon seal to the contact surface of the material under operating temperatures. **Mechanical Approach**
- Run carbon seal on the 36kW machine. Use three different carbon seals (made from different carbon material from each supplier) and test it on the three different contact surface materials that Eaton Corporation uses (8740 Tungsten Carbide Coated, 440C Hardened Steel, Nitrated Steel). Gather data on all available parameters and compare data. **Materials Science Approach**
- Find average life span of seals made from each suppliers material by running a minimum of 10 samples from each supplier on one of the machines available at Eaton. Keep in mind that there are three different possible contact surfaces that a carbon seal may make contact with, so keep the contact surface constant. **Failure Modeling Approach**

8 Quality Function Deployment (QFD)

A quality function deployment analysis was performed for this project in order to determine the most important characteristics of the service life prediction model while also taking Eaton's requirements into consideration. A full QFD chart was created to illustrate these characteristics and requirements. Figure 6 displays the customer demands on the left column, the functional requirements along the top row, and a competitive analysis along the right hand side. As there are no natural competitors for a seal life prediction model, the evaluation of competition was performed for the 3 design concepts, as stated in Section 5.

8.1 Functional Requirements

In the QFD chart, seen in Figure 6, the desired characteristics of the project were listed in the top row. Out of all of the quality characteristics, the team came up with four of the most important features to keep in mind while performing the necessary experiments and developing the prediction model. These four major features, in order from most important to least important are the accuracy of the material properties, the error in the life cycle prediction model, the error in replicating operating environment, and the wear volume measurements.

The carbon material data sheets provided by the manufacturer are either lacking in critical information regarding material properties, or provide a very large range for the value to fall. Most of the data sheets do not contain a measurement of material hardness, or Poisson's ratio. The team will have to perform tests to verify these values before moving forward. This would fall under the material science approach mentioned in Section 7 of the report.

Of the top four functional requirements, the two that would fall under the mechanical approach would be the wear volume measurement and the error in replicating the operating environment. The wear volume measurements will be used to see how material is removed from the carbon seal during operation, thereby changing the surface roughness. A difficult aspect of this mechanical approach will be to ensure all of the experiments are performed under the same conditions. The oil temperature and viscosity, initial surface roughness of the seal and metallic interface, as well as the pressure at the contact will need to be replicated.

The fourth important functional requirement will be the error in the life cycle prediction model. The purpose of this model is to predict when the carbon face seal will ultimately fail. With that being said, if the percent error of the model is too high, then Eaton will not be able to successfully choose between carbon grade and manufacturers. This is not beneficial to the company as they want the most accurate service life prediction model of their seals as possible in order to save the company money as well as guarantee their customers are receiving a high quality product.

8.2 Customer Requirements

From the left column in Figure 6, the quality demand from Eaton was determined based on end goals for this project. Based off of this information from Drew Bangs and Eaton Corporation, the customer demands were determined and ranked in order of importance. The three most important customer requirements that were taken into consideration were to generate an accurate simulation of the wear experienced in service of the seal, to determine a method to correlate the material property data to the mathematical prediction model, and the ability to accurately predict the service life of a carbon face seal in an aircraft engine. By relative weight of importance on the team's QFD, the three customer requirements mentioned above constitute 58.8%.

The main cause of a seal leakage rate increase is the increase in surface roughness of the seal as a result of wear. An understanding of the exact modes of wear present, the rate at which material is removed, and how said material is removed is critical to producing a prediction model that will be useful to Eaton. Therefore, simulating the exact wear parameters that a seal encounters during service is of critical importance.

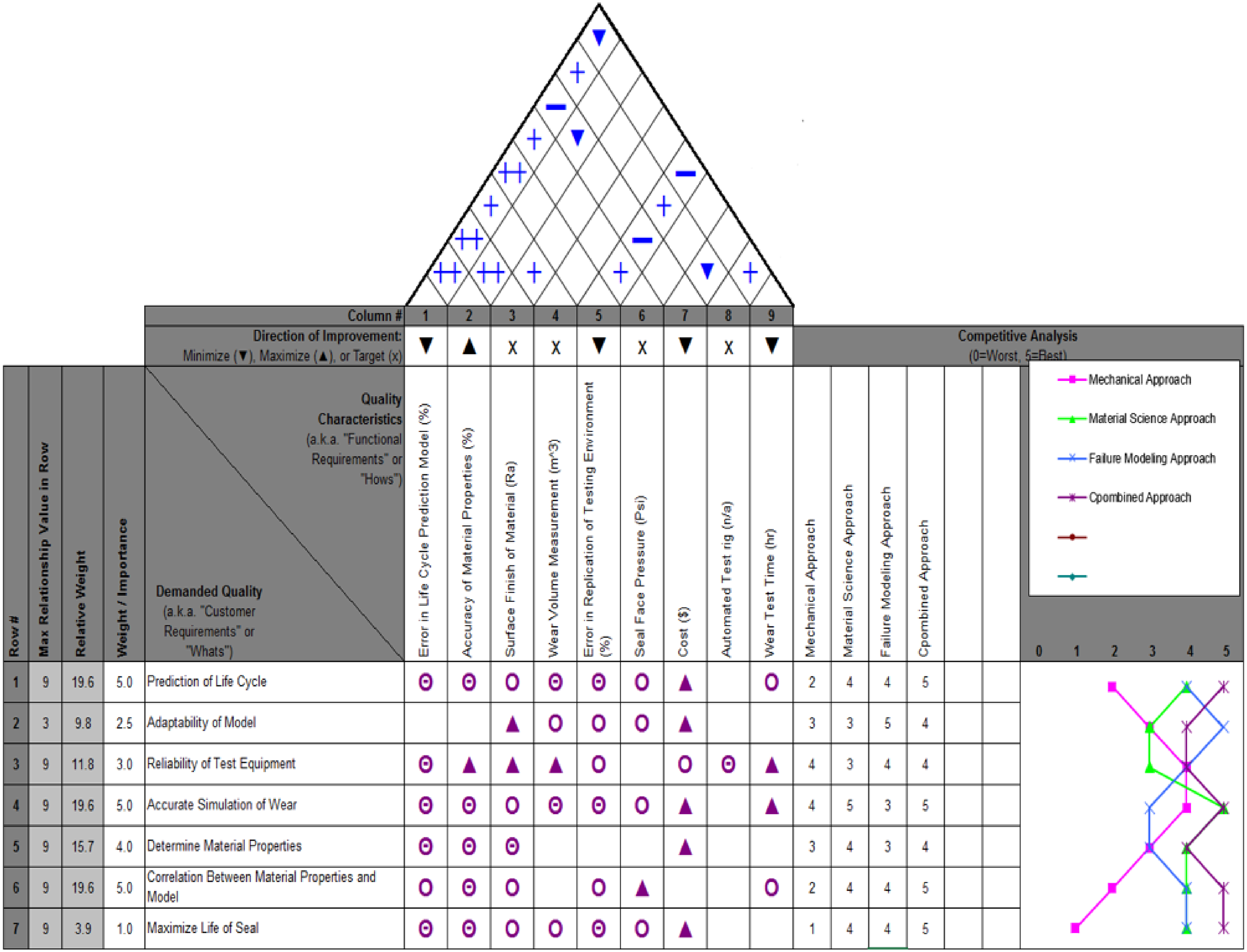
Another customer demand that will impact the accuracy of the prediction model is how the material properties pertaining to the carbon seals are obtained. The carbon is subjected to oil temperatures of 300°F. If the material properties are not obtained at this temperature, they may negatively impact the accuracy of the mathematical prediction model. This initially posed a problem in the conceptual design of the engineering approaches as it is difficult to heat a hardness testing apparatus without damaging it. It was later discovered, after the three engineering approaches were conceived, that heated hardness testing apparatuses would be available in Dr. Ghonem's lab at the University of Rhode Island.

Predicting the service life of the carbon dynamic face seal is the main customer requirement for this project. According to the QFD, the four main functional requirements that the team is focused on have a strong relationship with this customer requirement. Upon generating an accurate service life prediction model, Eaton will be able to choose between different manufacturers' carbon grades and be confident that the chosen grade of carbon will perform as anticipated.

8.3 Combined Approach

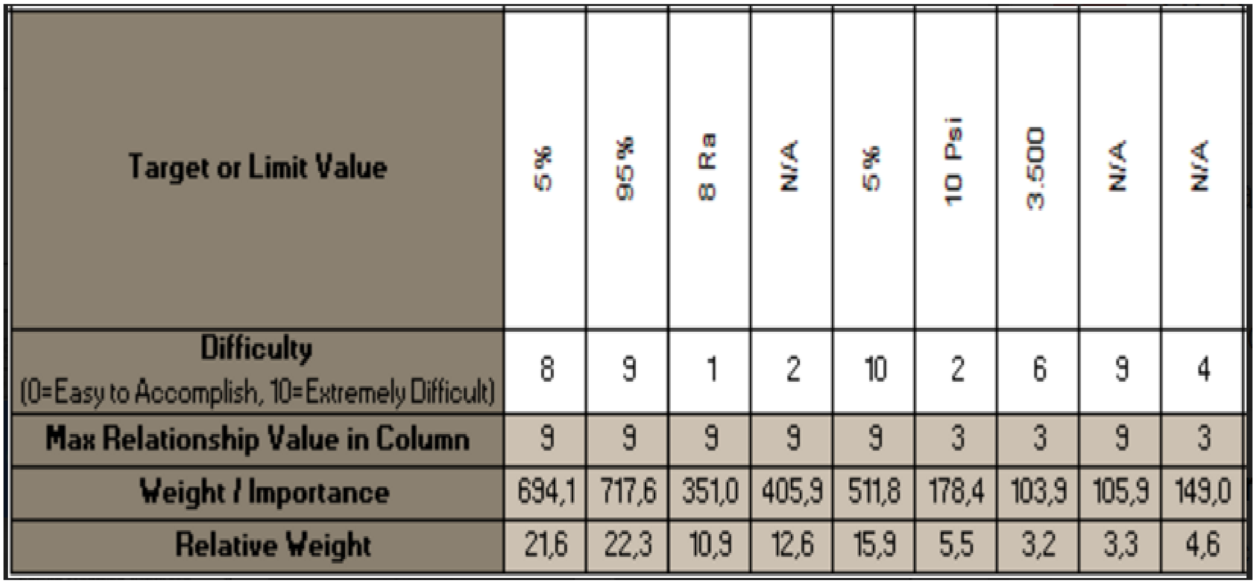
The competitive analysis performed in Section 5 verifies that the final engineering approach best meets the customer demands of the three original concepts. The final approach is evaluated against each of the four most important customer demands below:

- **Determination of Material Properties:** Hardness testing, as well as testing for the modulus of Elasticity will be performed for each carbon grade at the operating temperature of the oil, 300°F. This test will be performed in either a heated Instron machine or heated hardness tester in Dr. Ghonem's lab. This is the most effective and economical method of determining the hardness properties as well as the modulus of elasticity of each of the carbon grade, as it can be accomplished at URI for next to no cost.
- **Simulation of Wear:** The characteristics of the wear of the carbon seal will be replicated by utilizing the tribometer's heating tray to heat the aircraft standard engine oil to 300°F. Samples obtained from the carbon manufacturer as well as steel tribometer plates will be machined to the proper initial surface roughnesses. The pressure at the contact will be adjusted on the tribometer to achieve 10 psi at the contact. Finally, the tribometer will provide the coefficient of friction present during the test. All of the parameters listed above will ensure the near exact simulation of the wear characteristics of the seal environment during operation.
- **Correlation Between Material Properties and Mathematical Model:** Using the procedures listed above in the simulation of wear, the correlation between the material properties and the mathematical prediction of the seal service life will be definitive.
- **Prediction of Life cycle:** The final approach will achieve an accurate prediction of the seal life cycle as it is dependent on other 3 of 4 of the most important customer demands. As the other 3 customer demands will be met, the prediction of the seal life cycle will meet Eaton's expectations.



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Error in Life Cycle Prediction Model (%)	Accuracy of Material Properties (%)	Surface Finish of Material (Ra)	Wear Volume Measurement (m^3)	Error in Replication of Testing Environment (%)	Seal Face Pressure (Psi)	Cost ($)	Automated Test rig (n/a)	Wear Test Time (hr)	Mechanical Approach	Material Science Approach	Failure Modeling Approach	Cpombined Approach
				Column #	1	2	3	4	5	6	7	8	9				
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▲	x	x	▼	x	▼	x	▼				
1	9	19.6	5.0	Prediction of Life Cycle	⊙	⊙	○	⊙	⊙	○	▲		○	2	4	4	5
2	3	9.8	2.5	Adaptability of Model			▲	○	○	○	▲			3	3	5	4
3	9	11.8	3.0	Reliability of Test Equipment	⊙	▲	▲	▲	○		○	⊙	▲	4	3	4	4
4	9	19.6	5.0	Accurate Simulation of Wear	⊙	⊙	○	⊙	⊙	○	▲		▲	4	5	3	5
5	9	15.7	4.0	Determine Material Properties	⊙	⊙	⊙				▲			3	4	3	4
6	9	19.6	5.0	Correlation Between Material Properties and Model	○	⊙	○		○	▲			○	2	4	4	5
7	9	3.9	1.0	Maximize Life of Seal	⊙	⊙	○	○	⊙	○	▲			1	4	4	5

Figure 5: **QFD ANALYSIS: TOP SECTION**



Target or Limit Value	5%	95%	8 Ra	N/A	5%	10 Psi	3.500	N/A	N/A
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	9	1	2	10	2	6	9	4
Max Relationship Value in Column	9	9	9	9	9	3	3	9	3
Weight / Importance	694,1	717,6	351,0	405,9	511,8	178,4	103,9	105,9	149,0
Relative Weight	21,6	22,3	10,9	12,6	15,9	5,5	3,2	3,3	4,6

Figure 6: **QFD ANALYSIS: BOTTOM SECTION**

9 Design for X

9.1 Design for Ease of Use

As part of the customer requirements for this project, it is necessary to design the service life prediction model in such a way that nearly anyone with a basic knowledge of Microsoft Office could use the product. For this reason, the team will be adapting all of the data compiled from their experimentation into an easy-to-use and fully functional Excel spreadsheet. While the original data compilation and calculation will likely be modeled first using MATLAB, this information will later be translated to Microsoft Excel. The sponsor from Eaton has informed the team that Microsoft Excel is one of their most commonly used programs and for this reason the service life prediction model would best serve their company in this format.

9.2 Design for Adaptability

The carbon face seals that Eaton manufactures come in a large range of sizes as well as materials. The diameter of these seals can range anywhere from 2" to over 10" in diameter and can be manufactured from a list of over 20 different carbon compounds from different manufacturers. Since there are so many different options for carbon seals and there will be only one service life prediction model, it is essential that the model is adaptable to predict a wide range of carbon face seals. The team's focus will be on the four most commonly used carbon compounds and a range of seal diameters from 2 to 5 inches. The goal is to create an accurate service life prediction model for this range of seal sizes and materials. The team is hoping that the results from the experimentation throughout this range of seals can also be adapted for larger diameter seals. While the prediction model may not be adaptable for carbon compounds other than the four most commonly used, the model should be adaptable for larger diameter seals as well. Although the total distance traveled along the seal/ shaft interface may be different, this can be adjusted for using the results of the experimentation.

9.3 Design for Sustainability

The end goal of this project is to create a mathematical prediction model in an Excel spreadsheet. The process to obtain this model is designed in such a way that Eaton will be able to integrate it into their engineering processes in the future. The pin on flat testing can easily be altered to accommodate one of Eaton's current testing rigs. The parts used in the tribometer tests can easily me machined in house at Eaton, and the hardness tests can be performed there as well. This engineering approach will lay the groundwork for the analysis of many different triboligical pairs that are outside of the scope of this project.

9.4 Design for Replicability

The environment in which the seal operates will be simulated during the experimentation process of this project. The material properties will be taken at the operating temperature of the oil, in a heated hardness testing machine. The viscosity of the oil will be replicated by using the same oil that the seal encounters. The pressure at the seal interface will be replicated by adjusting the load on the sample in the tribometer to match that of the seal in operation. Finally, the angular velocity of the seal will be simulated on the pin on flat tribometer by linear velocity equivalent equations. The replicability of the seal environment will accurately represent the operational loads and stresses present in a seal.

10 Project Specific Details and Analysis

This product, as stated before, is a service life prediction model of carbon based seals used in aerospace applications. The goal is to determine the service life of the carbon based seals without rigorous testing or in-service monitoring. This would allow Eaton to accurately predict when the companies seals will fail. A prediction model is based off of the material properties such as coefficient of friction between the seal and metallic mating surface and hardness will allow Eaton to choose between different carbon manufactures as long as the material properties are similar.

The data collection for this project is experimentally based and for the large part will be conducted over the course of winter break and spring semester. Some preliminary tests have been conducted. The initial tests that have been conducted are a stress analysis and a leakage rate analysis using MATLAB.

10.1 Dimensional Analysis

In order to analyze the data that will be obtained during the tribometer testing, hardness testing, and the frictional coefficient testing, relationships between important variables had to be established. Dimensional analysis was utilized to perform this task. This dimensional analysis is something very specific to Seal Team Fix's project and plays an essential role in the development of the experimentation necessary to create a service life prediction model. Eighteen variables were selected based on information obtained through a literature search, as well as meetings held with Dr. Meyer and Drew Bangs. Combinations of the resulting Pi groups allow the experimental data to be collapsed down into a line that will summarize the relationships between all relevant variables.

$$\pi_1 = \frac{R_a}{d} \tag{1}$$

$$\pi_2 = \frac{a}{d} \tag{2}$$

$$\pi_3 = \frac{f}{pd^2} \tag{3}$$

$$\pi_4 = \frac{Ud^2}{Q} \tag{4}$$

$$\pi_5 = \frac{f}{pd^2} \tag{5}$$

$$\pi_6 = \frac{A_c}{d^2} \tag{6}$$

$$\pi_7 = \frac{E}{p} \tag{7}$$

$$\pi_8 = \frac{Qt}{d^3} \tag{8}$$

$$\pi_9 = \frac{H}{p} \tag{9}$$

$$\pi_{10} = T * \beta \tag{10}$$

$$\pi_{11} = \mu \tag{11}$$

$$\pi_{12} = \nu \tag{12}$$

$$pi_{13} = \frac{P_c R_a d^2}{tVHT\beta A_c} \tag{13}$$

The resulting Pi groups 1-11 were critical to the determination of experimental parameters such as the number of experiments that needed to be run, the number of grades of carbon and steel to be tested, and which variables were to remain constant and which ones were to be varied. The eleven Pi groups were then combined, with the help of Dr. Meyer, to generate an equation for the leakage rate as a function of the most critical variables. This function can be seen below in Equation 14. This function will characterize how the seals fail and provide a way to analyze the data obtained during experimentation. It was also necessary to generate a Pi group that would allow the experiments to be scaled to replicate the environment in which turbine face seals operate. This pi group, equation 13, and the redesigned pi groups along with how they were used, equations 19 and 20 will be discussed later in both the build and redesign sections.

$$Q = f\left(\frac{\mu a \eta U d^2 T \beta \nu}{ptR_a}\right) \tag{14}$$

11 Detailed Product Design

The final engineering approach chosen for the project became very clear following the QFD analysis. Since the team had to compete between it's own concept ideas as described previously in Section 5, it was necessary that the final concept would best fulfill Eaton's requirements. As described in Section 8.3, the team concluded that a combination of the original three design concepts proposed would be the best solution to fulfill Eaton's requirements and obtain the most accurate prediction model possible. This final engineering approach consists of a three stage process. The process includes a failure mode study, material characterization, and the development of a prediction model.

11.1 Failure Mode Study

The failure mode study consists of 2D and 3D stress analyses as well as roughness measurements of the carbon material. The stress analyses are necessary in order to determine whether or not the stresses that the carbon material of the seal and it's mating material encounter exceed the yield stresses of the materials. This failure mode will be discussed in more detail in Section 12 of this report. The stress analyses are performed analytically using the software program MATLAB as well as computationally using the software program Abaqus.

The roughness of the carbon samples will need to be measured intermittently throughout the experimentation which will be performed for the project. The materials will be tested using a tribometer in Professor Meyer's Tribology Laboratory. The device will consist of a 5/8" diameter pin of the selected carbon material which will be pressurized against a plate of 440C stainless steel to simulate the contact between the carbon face seal and it's mating surface in a real life application. The plate of steel (Appendix A) will remain fixed while the carbon pin is slid back and forth on the plate in a reciprocating motion. The tribometer can be seen in Figure 8. The testing will ensue for a pre-determined amount of time and will be stopped after this allotted time in order to take roughness measurements.

The roughness will be measured using a profilometer as depicted in Figure 7. This process will be repeated until the sample has run for the duration necessary for the experiment. The roughness values measured throughout this process will then be used to calculate the leakage rate as a function of the roughness of the material, which will be described in more detail in Section 11. Since the failure of any seal is determined by the leakage rate of that seal, the roughness measurements of the material will demonstrate a failure mode which directly correlates to the leakage rate of the seal.

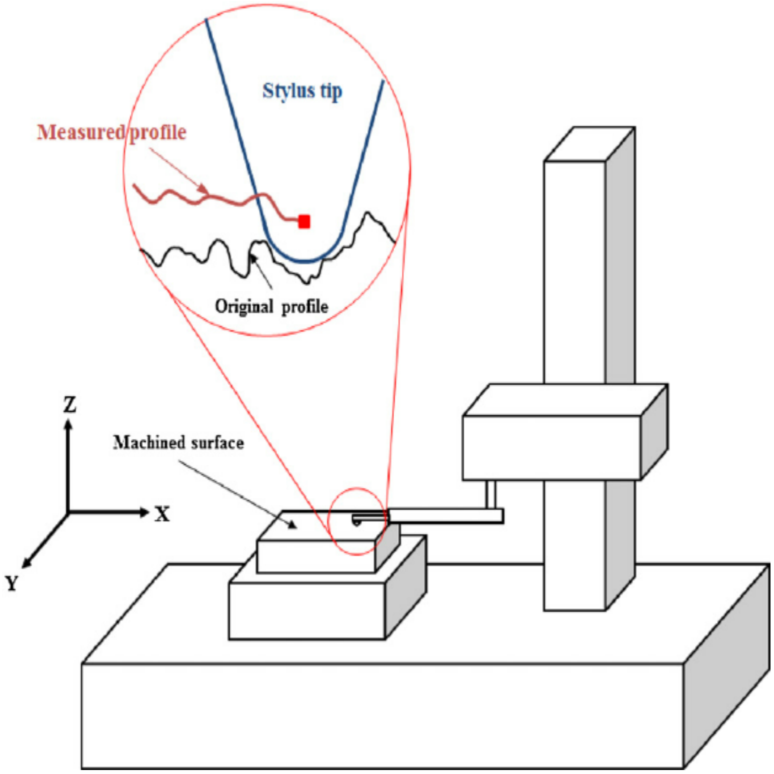


Figure 7: **PROFILOMETER DIAGRAM**

11.2 Material Characterization

The material characterization portion of the final engineering approach consists of hardness testing the carbon material samples and their mating surfaces as well as calculating the coefficients of friction and wear rates between the carbon material samples and their mating surfaces. The hardness of the material is a material property that is directly proportional to the wear volume of the material as demonstrated by the Archard wear volume equation [4]. The equation is as follows:

$$V = \frac{KLW}{H} \tag{15}$$

where K is the proportionality constant, L is the sliding distance, W is the load, and H is the Vickers hardness of the softer surface.

While the Vickers hardness is necessary for the Archard equation, the University of Rhode Island has Rockwell hardness testing equipment, like the one depicted in 9, which can be used for the experimentation. Then the Rockwell hardness values can be converted to the Vickers hardness values. These values will be used in conjunction with the wear volume measurements obtained in the tribometer experiments to calculate the proportionality constant K in the Archard wear equation.

The tribometer depicted in 8 will be used to measure the coefficients of friction as well as the wear volume of the carbon material samples throughout the experimentation. The measured wear volume from the tribometer experiments will act as V in the Archard equation. Once the hardness of the material is known from the hardness testing and the wear volume has been measured, the proportionality constant K can be calculated. This proportionality constant will later be used in the team's prediction model. With the wear volume of the material known, the wear rate of the material can also be calculated as a function of either sliding distance or time. The wear rate of the material will be yet another contributing factor to the final prediction model.

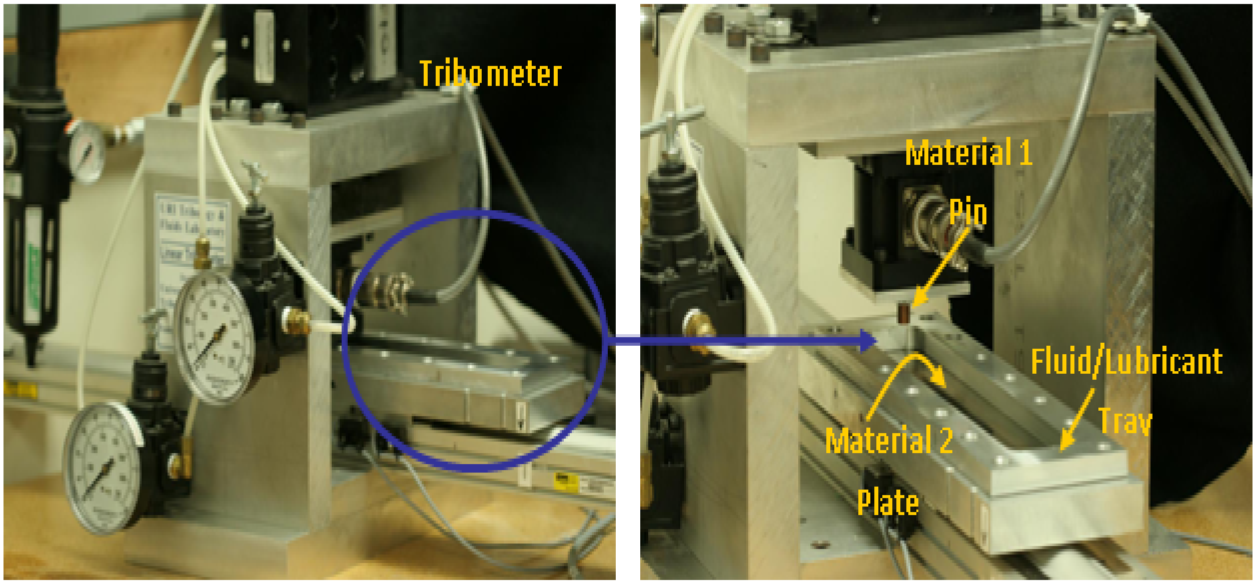


Figure 8: **TRIBOMETER EXPERIMENTAL SETUP**

Figure 9: **HARDNESS TESTER**

11.3 Prediction Model

The prediction model will be the final development of the Capstone Project. This model will tie together all of the data gathered during the failure mode study as well as the material characterization processes. The analysis of all of the data will begin using the formulas developed from the dimensional analysis described in Section 10. The team will begin by utilizing the equations developed throughout the dimensional analysis to calculate the leakage rate of the carbon seals throughout the experimentation. The roughness values obtained incrementally throughout the tribometer experiments will be used in the leakage rate calculations in order to obtain values for each type of carbon at each time interval. The team will analyze this data using MATLAB for preliminary results and will then analyze the data using Microsoft Excel as requested by Eaton. The final prediction model will consist of a correlation of all of the data obtained throughout experimentation and be easily calculated using Microsoft Excel.

12 Engineering Analysis

In order to analyze the seal service life, it was necessary to understand what the subsurface stress contours looked like. These stresses dictate how the seal wears during operation and have an immense impact on the service life of it. The contact stresses and subsurface stresses will contribute to the eventual increase in surface roughness of the seal mating face until the leakage rate reaches the maximum allowable rate. The seal in question as well as the mating surface can be seen in Figure 10. However, despite the complex geometry of the seal/mating surface, it was only necessary to evaluate the contact area and immediate surrounding areas of both the seal and mating surface. Supplementary images of the tribometer plate geometry, seal, metallic mating surface, and seal geometry can be found in Appendices A [6], B, C, and I [1] respectively.

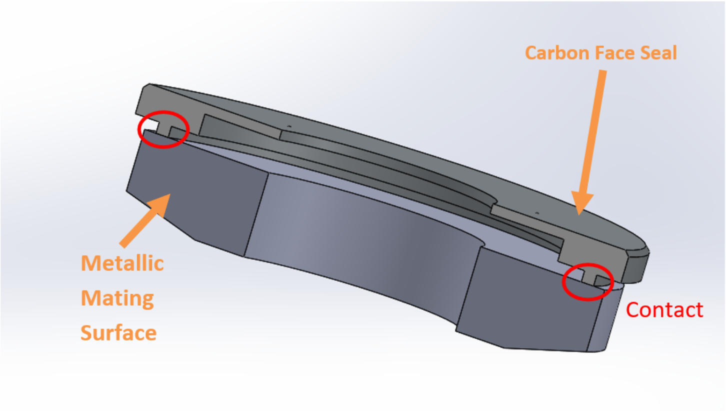
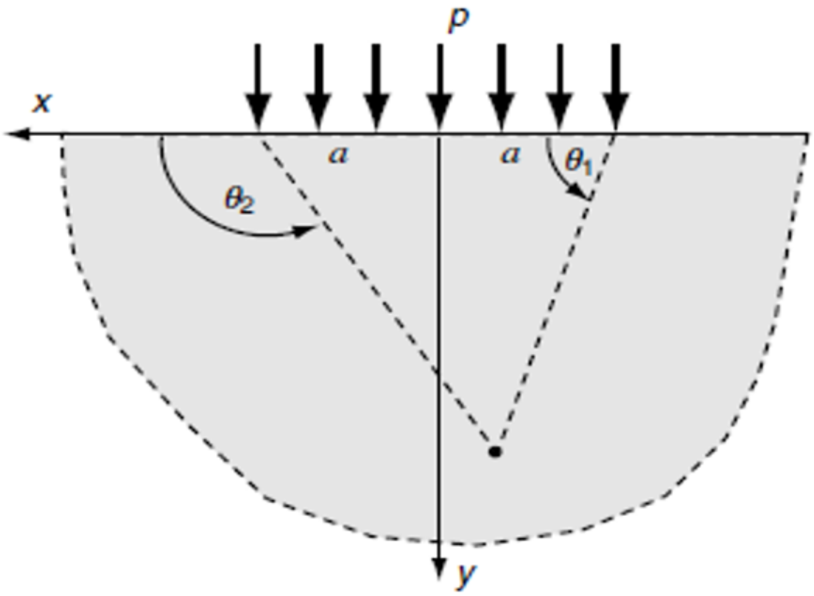


Figure 10: **SECTION VIEW OF SEAL AND METALLIC MATING SURFACE**

12.1 Analytical Evaluation of Seal Contact

Upon conducting initial research related to the sub-surface stresses present in a contact, Dr. Meyer provided the half-space pressure contact model as a starting point for the analytical evaluation of the seal contact. A representative diagram of this contact as well as the governing equations can be seen in Figure 11 [7]. These equations were used to plot the subsurface stresses in the metallic contact surface. The equations were reproduced in a MATLAB script to make the shear stress and y-direction normal stress contour plots in Figures 12 and 13 below. As the highest stresses possible were desired for the forming of a conservative mathematical model,the following parameters were used in the stress analysis of the seal in Table 4.



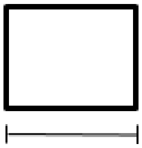
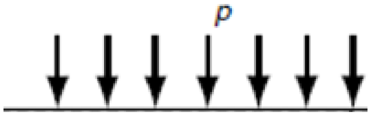
$$\sigma_x = -\frac{2p}{\pi}\int_{\theta_1}^{\theta_2} \cos^2\theta d\theta = -\frac{p}{2\pi}[2(\theta_2-\theta_1)+(\sin 2\theta_2 - \sin 2\theta_1)]$$

$$\sigma_y = -\frac{2p}{\pi}\int_{\theta_1}^{\theta_2} \sin^2\theta d\theta = -\frac{p}{2\pi}[2(\theta_2-\theta_1)-(\sin 2\theta_2 - \sin 2\theta_1)]$$

$$\tau_{xy} = -\frac{2p}{\pi}\int_{\theta_1}^{\theta_2} \sin\theta\cos\theta d\theta = \frac{p}{2\pi}[\cos 2\theta_2 - \cos 2\theta_1]$$

Figure 11: **CONTACT HALF-SPACE AND GOVERNING EQUATIONS**

Table 4: **PARAMETERS FOR ANALYTICAL EVALUATION OF CONTACT**

Seal Width 	**0.065 in**
Pressure at Interface: 	**15 psi**

The top of the analytical shear stress diagrams, Figures 12 and 13, represents the surface where the seal is in contact with the metallic mating surface, with the bottom surface representing a subsurface point within the metallic mating surface that is 0.065 in away from the contact. The contours present in Figures 12 display how the shear stress distributed across the seal contact surface (the top of the graph) are concentrated at the corners of where the seal contacts the mating surface, at 4.5 psi and proceed to go to 0 psi shear stress at the center of the contact. This area in the middle of the contact that is under approximately 0 psi shear stress is about $\frac{1}{2}$ of the total width of the seal. The shear stress concentrations at the corners of where the carbon seal contacts the metallic mating surface could contribute to subsurface cracking of the carbon at the corners of the seal and eventually cause relatively large pieces of carbon to be removed during operation. This is due to the fact that normal stress concentrations propagate into the seal at the corners of the seal due to the shear stress concentrations present in the mating surface beneath where the seal corners contact. This mode of wear is referred to as pitting, as it creates large craters or ”pits” in the surface of a contacting body [4].

The stress contour plots in the y-direction show that the maximum normal stress is present from the contact surface to 0.015 in into the height of the metallic mating surface from the contacting surface. This maximum stress value of 14 psi compressive stress is present from the blue contour line to the contact surface (top surface of the graph). This ”pocket” of maximum normal stress in the center of the seal contact, coupled with the shear stress concentrations at the corners of where the seal contacts the metal could also contribute to the propagation of subsurface cracks within the carbon seal body. The MATLAB scripts used to generate the shear stress and normal stress contours can be found in Appendices F and G respectively.

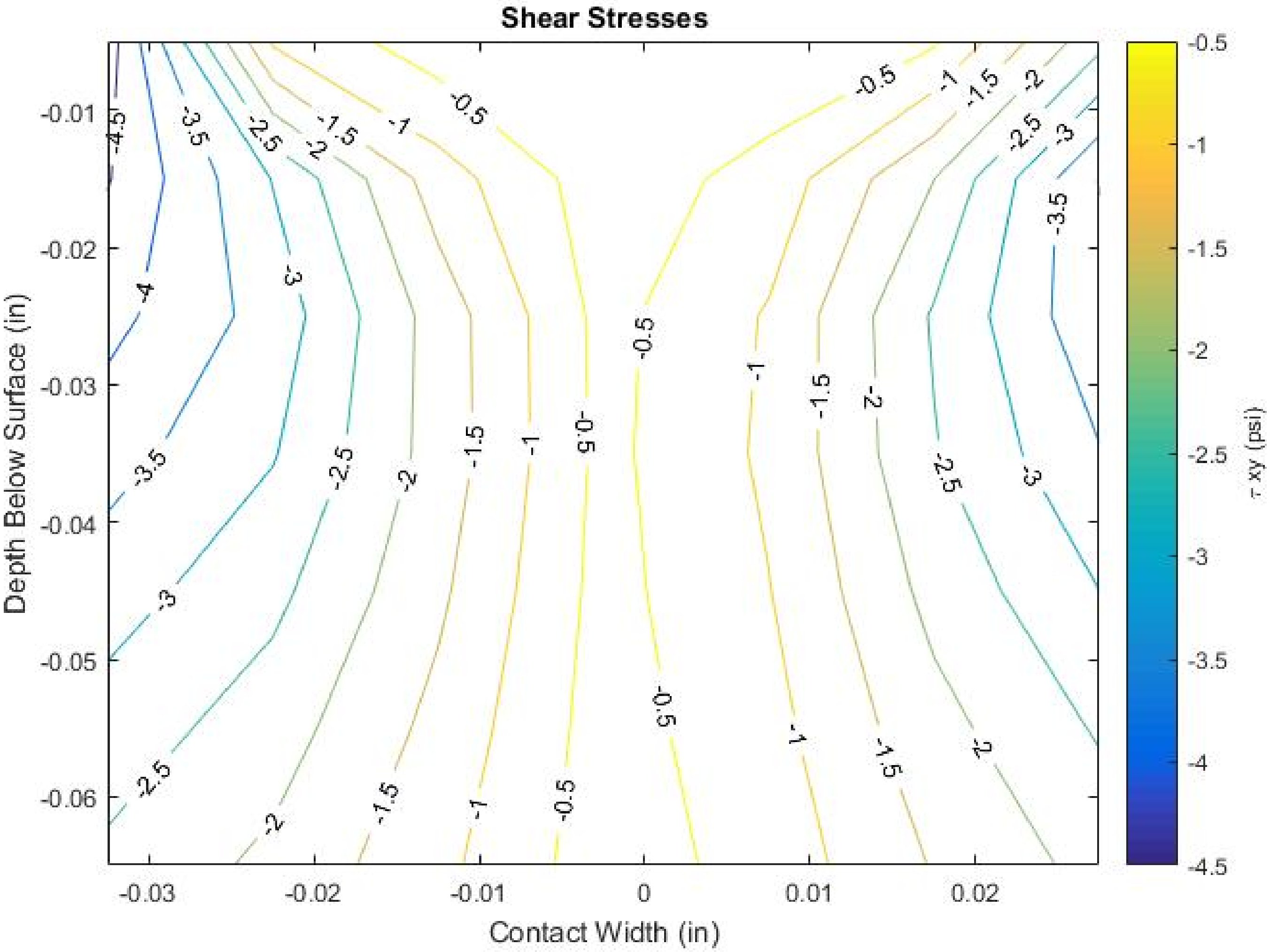


Figure 12: **ANALYTICAL SHEAR STRESS CONTOURS AT CONTACT**

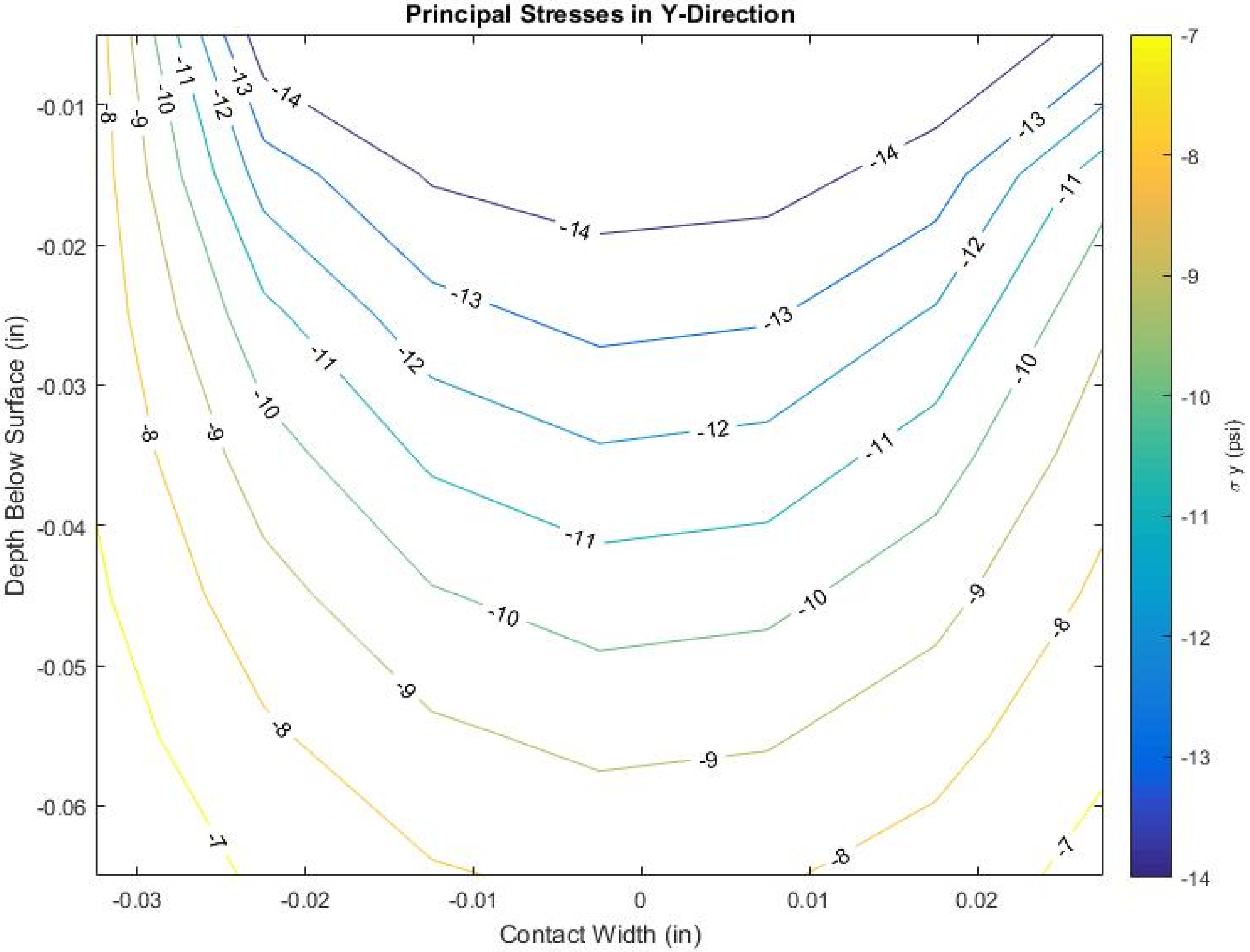
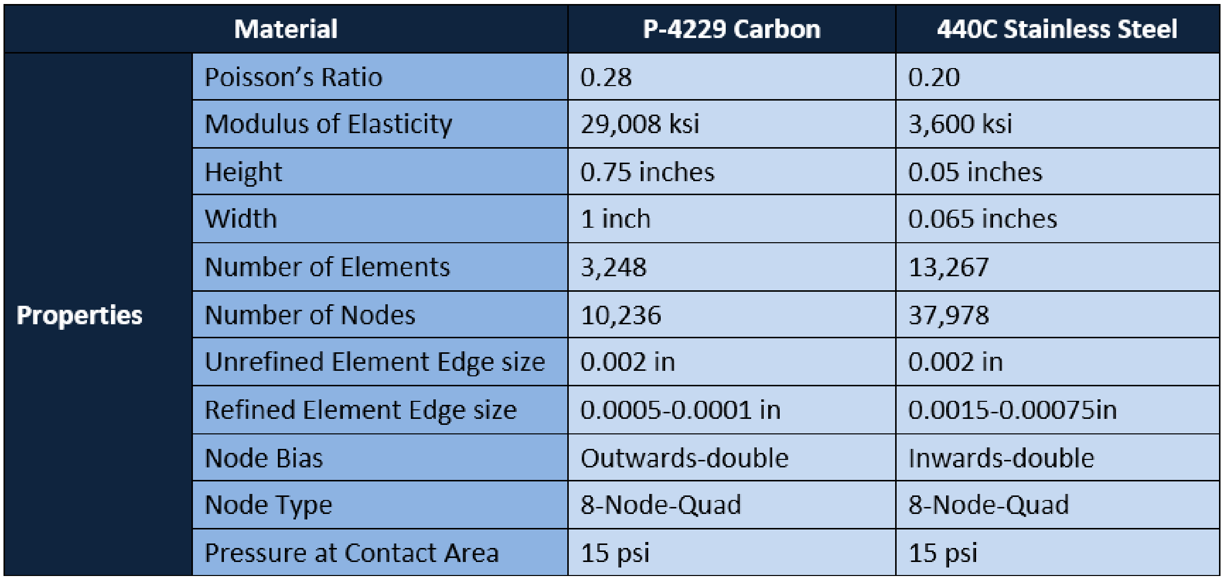


Figure 13: **ANALYTICAL NORMAL STRESS CONTOURS IN THE Y-DIRECTION OF CONTACT**

12.2 FEA Simulations

In order to assess the validity of the analytical solution, an ideal simulation was set up initially in the Finite Element Analysis software, Abaqus. A 2D plane-stress analysis was performed to simulate the ideal loading conditions assumed by the equations and diagram in Figure 11. This ideal simulation used a $1inx0.75in$ piece of 440C stainless steel to represent the half space as it is very large when compared to the overall width and contact area of the seal. One carbon grade, P-4229, was chosen to run the simulation, as the Poisson's Ratio is the same for all carbon grades. The boundary conditions used to simulate the 2d-planar surface contact of the can be seen in Figure 14.The contact area of the seal face is pressurized through an applied pressure load at the top edge of the carbon seal "box". This load propagates through the whole body of the seal and results in a pressure of 15 psi at the contact area of the seal and metallic mating surface. The results of these simulations can be seen in Figures 15 and 16. The material properties and general dimensions of the seal and metallic bodies used in the plane stress simulation can be seen in Table 5. Finally, the plane stress matrix that was solved during the simulations seen be seen below in Equation 16 [8].

Table 5: **PARAMETERS FOR FINITE ELEMENT ANALYSIS OF IDEAL CONTACT**



Material		P-4229 Carbon	440C Stainless Steel
Properties	Poisson’s Ratio	0.28	0.20
	Modulus of Elasticity	29,008 ksi	3,600 ksi
	Height	0.75 inches	0.05 inches
	Width	1 inch	0.065 inches
	Number of Elements	3,248	13,267
	Number of Nodes	10,236	37,978
	Unrefined Element Edge size	0.002 in	0.002 in
	Refined Element Edge size	0.0005-0.0001 in	0.0015-0.00075in
	Node Bias	Outwards-double	Inwards-double
	Node Type	8-Node-Quad	8-Node-Quad
	Pressure at Contact Area	15 psi	15 psi

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{16}$$

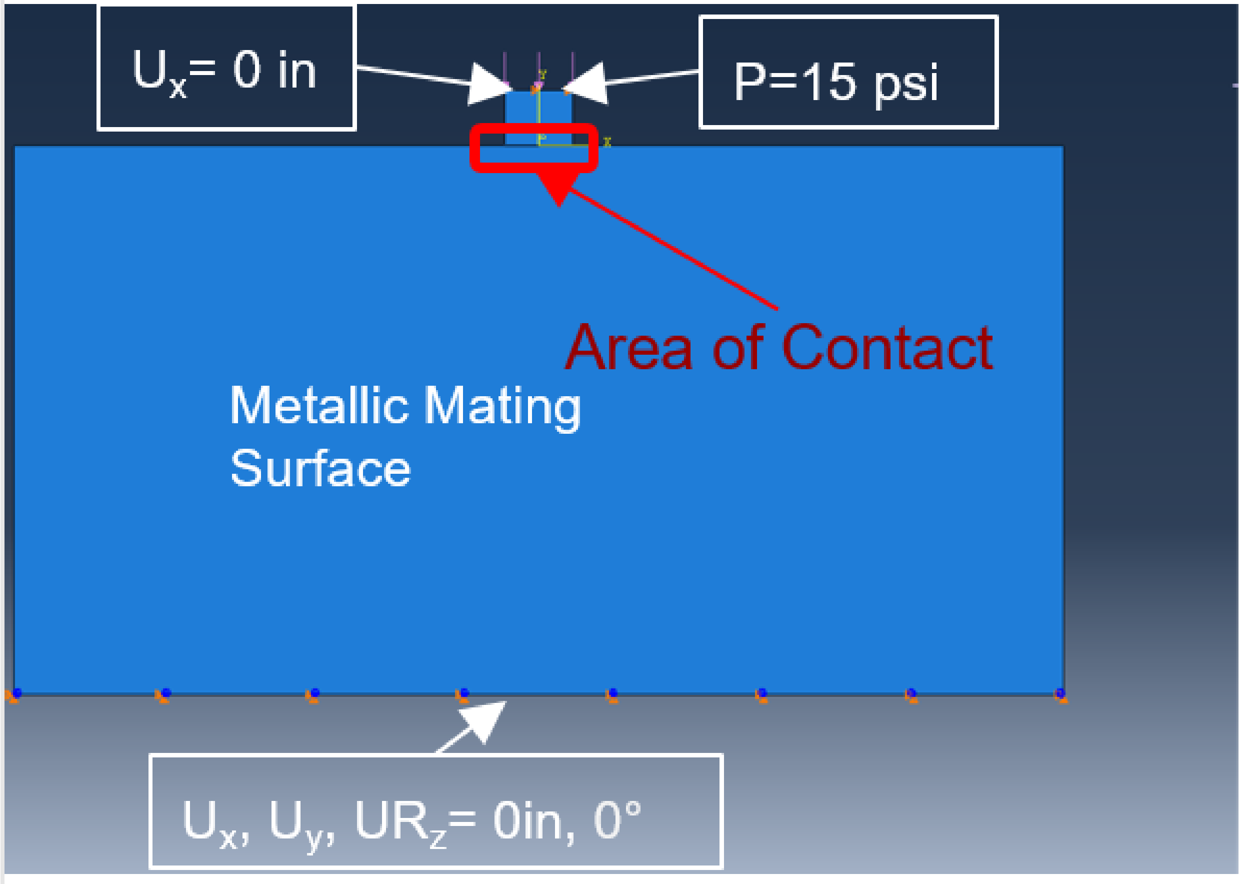


Figure 14: **BOUNDARY CONDITIONS OF IDEAL 2D SIMULATION**

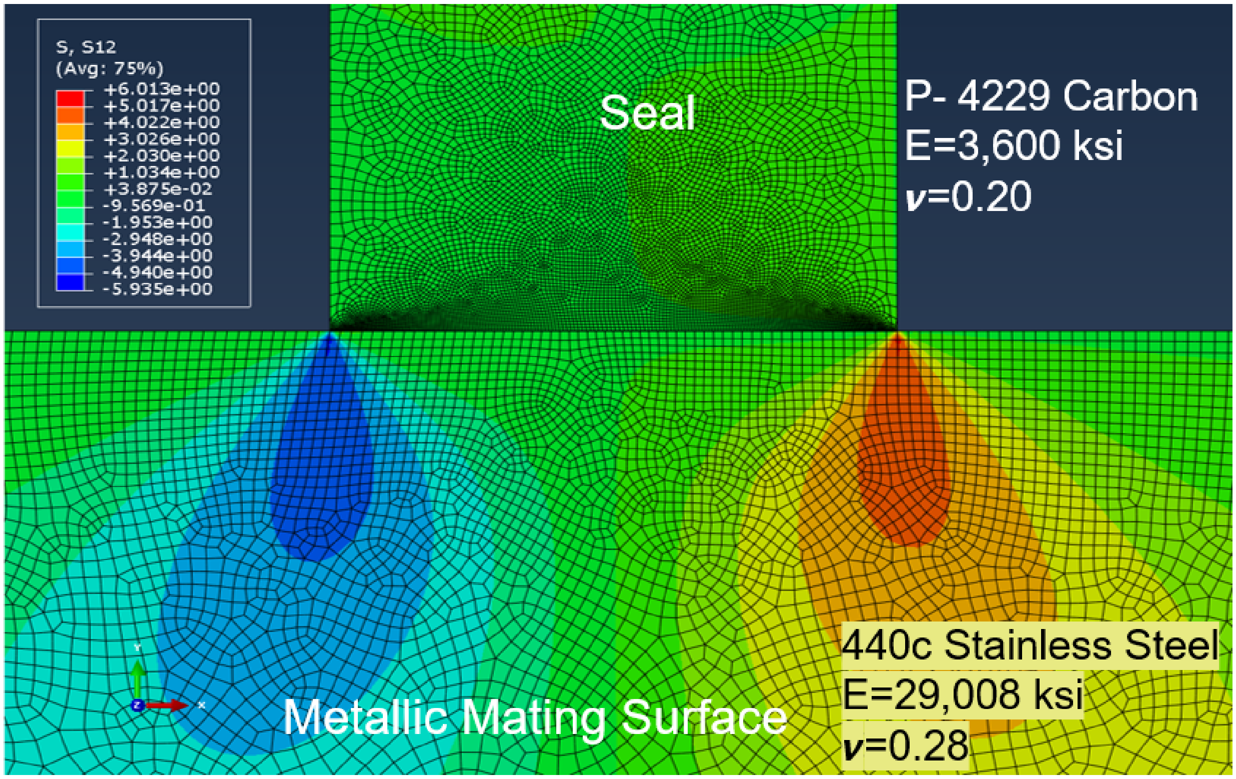


Figure 15: **SHEAR STRESS CONTOUR OF IDEAL 2D SIMULATION**

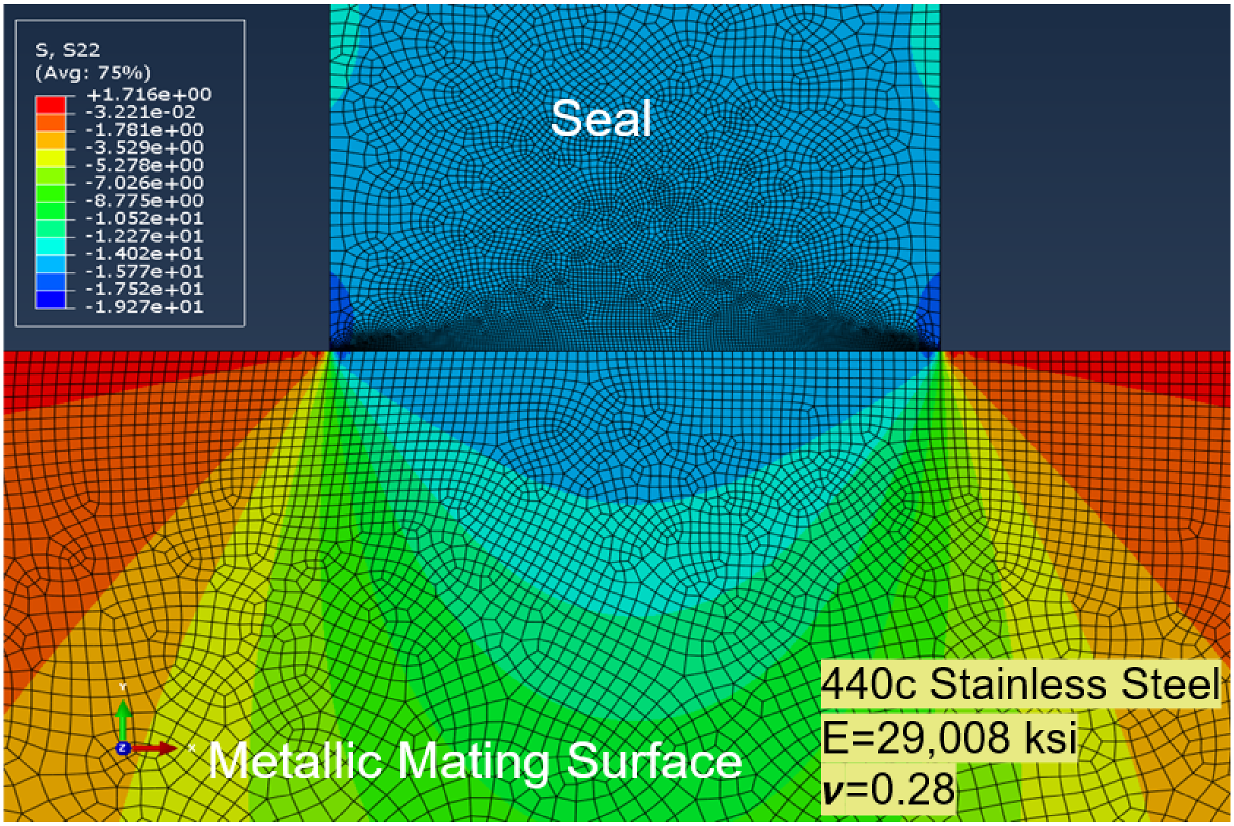


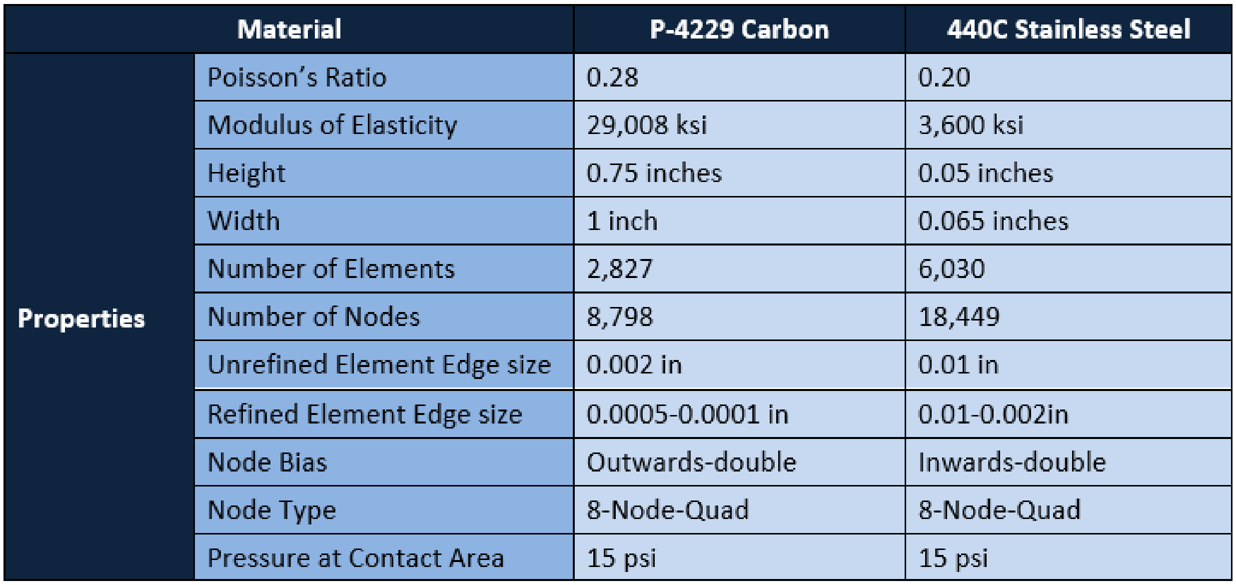
Figure 16: **CONTOURS OF NORMAL STRESSES IN Y-DIRECTION OF IDEAL 2D SIMULATION**

The results of the 2D-planar finite element analysis verify the assumptions made from the results of the analytical stress contours, for both the shear and normal stress contours. The Contours within the metallic mating surface follow those of the analytically derived contours in terms of both shape, size and value. Therefore, as the results pertaining to the stresses within the mating surface were proven to be accurate, the resulting stresses in the carbon seal must be accurate as well. The shear stress concentrations underneath the corners of the carbon seal produce normal stress concentrations in the y-direction at the corners of the seal.

As loading conditions rarely follow an ideal model and the seal and mating surfaces are both axisymmetric objects, the 2D ideal planar model may not have been the most accurate way to describe the stresses present in the tribological pair. These models do represent the basic idea of what the stress profiles within both materials should look like, but the deformation of each part will be different do the non-ideal boundary conditions present in an aircraft engine shaft seal. So, while the analytical model and 2D plane stress model produce similar results, the boundary conditions of both the seal and mating surface are not conducive to obtaining the most accurate result.

An axisymmetric Finite Element Analysis was performed to better represent the stresses and strains within the areas of the carbon seal and metallic mating surfaces immediately surrounding the contact surface. From Figure 17 below, the yellow axis on the left is the axis that the seal (top shape) and the metallic mating surfaces (bottom shape) are rotated around. The radius of the shaft is the distance from the yellow axis to the left side of either the seal or metal. The radius of the edge of the metallic mating surface is 60 thousandths of an inch larger than the outer diameter of the carbon seal. The mating surface that is parallel to the horizontal is fixed along the edge to not move in the y or x direction or rotate about the z axis. The side of the metal that contacts the shaft is fixed in the same manner. The seal is fixed along the left and right sides to not move in the x direction, as well as not rotating about the x or z axes. The pressure applied at the top of the seal is an equivalent pressure to produce 15 psi at the seal contact surface. These boundary conditions can be seen in Figure 17 as well as Table 6. The shear stress and normal stresses in the y-direction contour plots can be seen in Figures 18 and 19. The governing equation being solved for the axisymmetric loading can be represented in Equation 17 [9]. The unloaded meshes for the seal and the mating surface can be found in Appendices D and E respectively.

Table 6: **PARAMETERS FOR FINITE ELEMENT ANALYSIS OF AXISYMMETRIC CONTACT**



Material		P-4229 Carbon	440C Stainless Steel
Properties	Poisson’s Ratio	0.28	0.20
	Modulus of Elasticity	29,008 ksi	3,600 ksi
	Height	0.75 inches	0.05 inches
	Width	1 inch	0.065 inches
	Number of Elements	2,827	6,030
	Number of Nodes	8,798	18,449
	Unrefined Element Edge size	0.002 in	0.01 in
	Refined Element Edge size	0.0005-0.0001 in	0.01-0.002in
	Node Bias	Outwards-double	Inwards-double
	Node Type	8-Node-Quad	8-Node-Quad
	Pressure at Contact Area	15 psi	15 psi

$$\begin{Bmatrix}\sigma_r\\ \sigma_z\\ \sigma_\theta\\ \tau_{rz}\end{Bmatrix} = \left(\frac{E}{(1+\nu)(1-2\nu)}\right)\begin{bmatrix}1-\nu & \nu & \nu & 0\\ \nu & 1-\nu & \nu & 0\\ \nu & \nu & 1-\nu & 0\\ 0 & 0 & 0 & \dfrac{1-2\nu}{2}\end{bmatrix}\begin{Bmatrix}\varepsilon_r\\ \varepsilon_z\\ \varepsilon_\theta\\ \gamma_{rz}\end{Bmatrix} \tag{17}$$

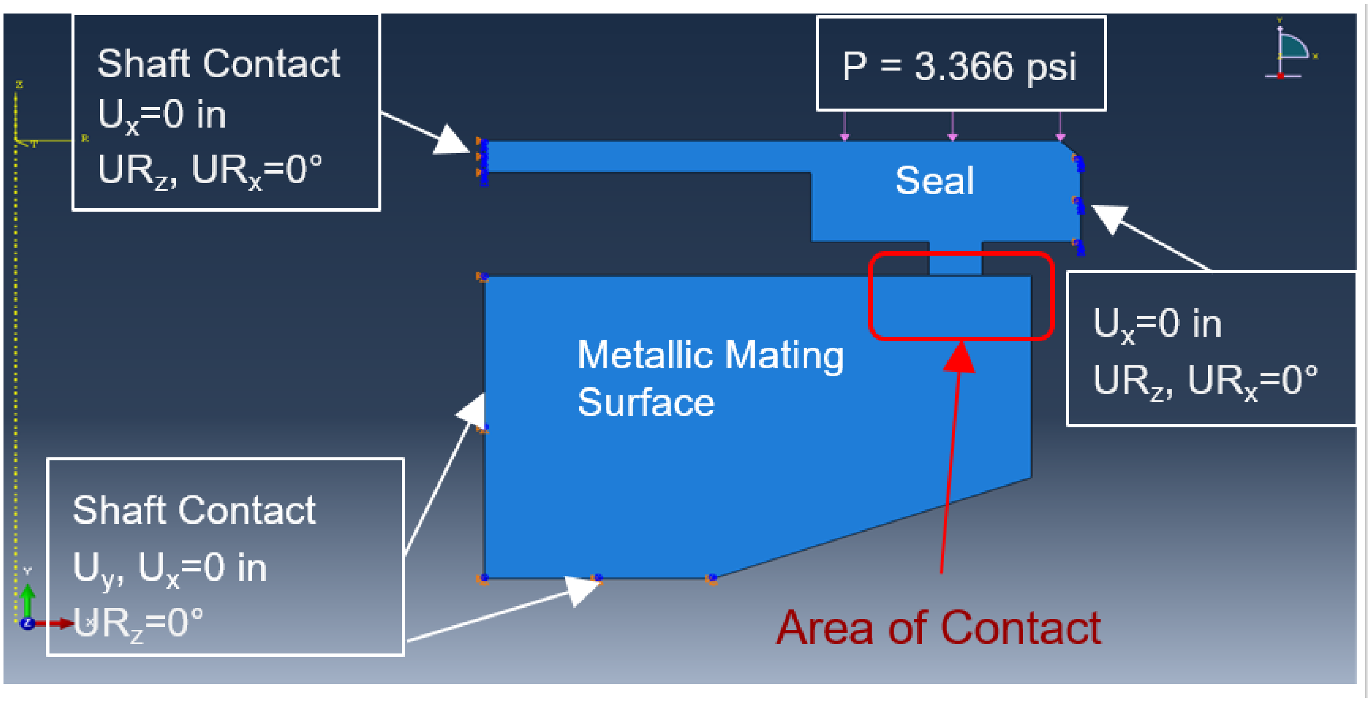


Figure 17: **BOUNDARY CONDITIONS OF AXISYMMETRIC 3D SIMULATION**

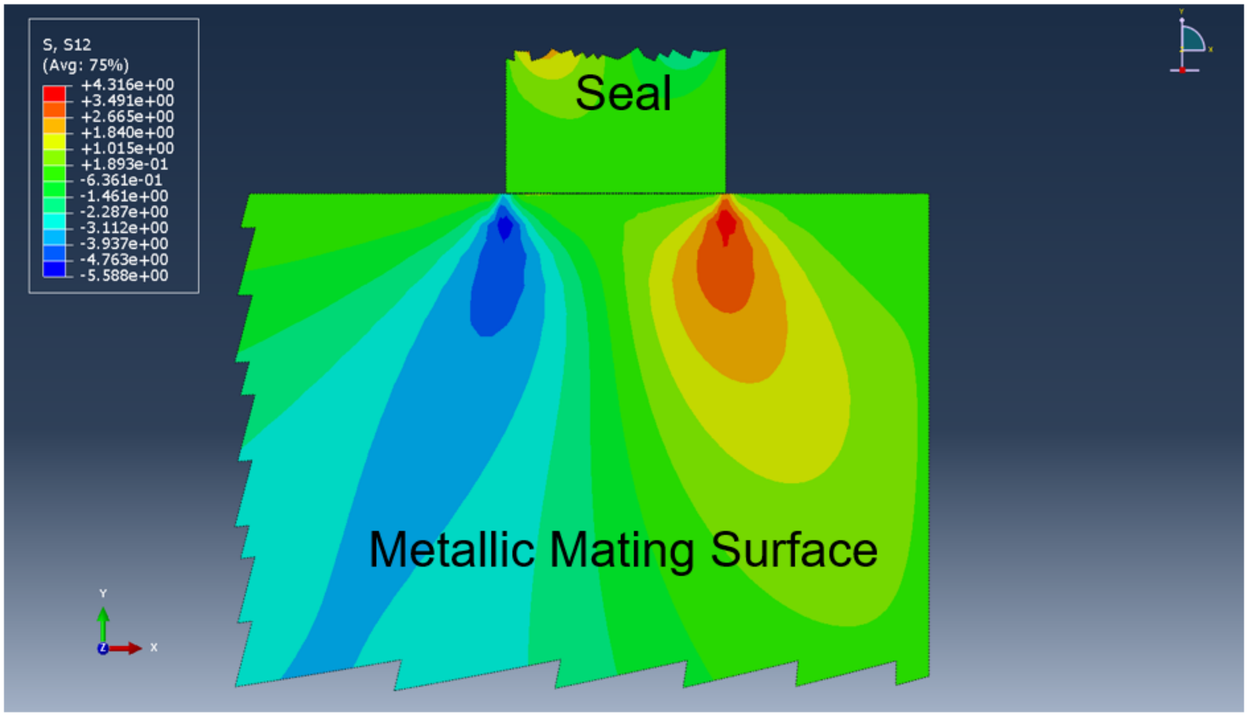


Figure 18: **SHEAR STRESS CONTOURS FOR AXISYMMETRIC 3D SIMULATION**

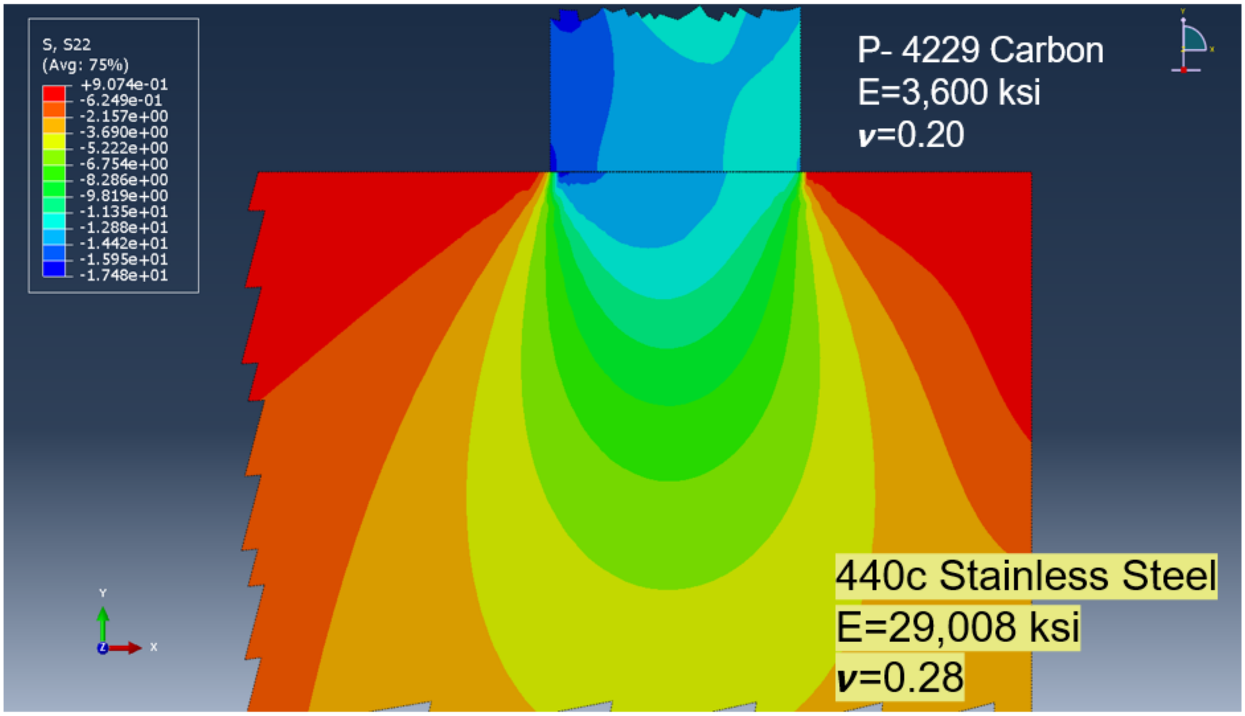


Figure 19: **NORMAL Y-DIRECTION STRESS CONTOURS FOR AXISYMMETRIC 3D SIMULATION**

The results of the axisymmetric analysis followed the same stress contour shapes that the 2D-planar analysis displayed. However, the portion of the metallic mating surface that was unsupported in the axisymmetric simulation deflected and rotated clockwise, causing the left corner of the seal to be loaded more than the right. This caused the normal stress in the y-direction to be 17.4 psi compressive stress at the left corner of the seal and 12.0 psi at the right corner, as seen in Figure 19. This uneven loading also had an effect on the shear stresses present in the metallic mating surface as well. Namely, the shear stress concentration underneath the left corner of the seal had a shear stress value of 5.6 psi and the area underneath right corner had a value of 4.3 psi, as shown in Figure 18.

The end result of the multiple finite element analyses performed is the knowledge of how stress is distributed in both the dynamic carbon face seal and the metallic mating surfaces. The knowledge of how these stresses are distributed within the contacting surfaces will allow for the characterization of the wear of the carbon.

12.3 Leakage Rate Calculation

As previously stated, the leakage rate of a seal is the main determinant of whether a seal has failed. Drew Bangs of Eaton Corporation provided the team with a range of typical initial seal and mating surface roughness values ranging from $R_a = 4 - 8\ \mu in$. An equation describing the leakage rate of a seal as a function of the oil viscosity η, the pressure drop across the seal thickness $\frac{dP}{dt}$, as well as the radius of the seal r_m was given to the team by Dr. Meyer. The dt term represents the seal thickness, rather than a time step. This relation can be seen in Equation 18 [6] [5]. As the oil viscosity and radius of the seal are to be held constant during testing, the leakage rate was plotted as a function of pressure drop from $0 - 20$ psi for each surface roughness value between $R_a = 4 - 8\ \mu in$, with each surface roughness value being assigned its own curve. This can be seen in Figure 20 below.

From the design specifications table, Table 3, the leakage rate ceiling for any seal within an aircraft engine is 1 $\frac{cm^3}{hr}$ which is equivalent to 0.061 $\frac{in^3}{hr}$. As this leakage rate is orders of magnitude larger than any of the leakage rates for a new seal, a surface roughness value that would intersect this ceiling at 20 psi was desired. This surface roughness value would represent the smallest surface roughness value that would approach the ceiling as the leakage rate is directly proportional to the pressure drop. Upon solving Equation 18 for R_a and setting the leakage rate equal to 0.061 $\frac{in^3}{hr}$, a surface roughness value of $R_a = 145\ \mu in$ was obtained. This means that the lowest surface roughness value of the carbon seal at the highest oil pressure that would cause the seal to be considered failed is 145 μin. These results can be seen below in Table 7. The MATLAB script used to generate Figure 20 can be found in Appendix H.

$$leakage\ (in^3 s^{-1}) \propto \frac{R_a^3}{\eta} \frac{dp}{dt_f} \int r_m d\theta \tag{18}$$

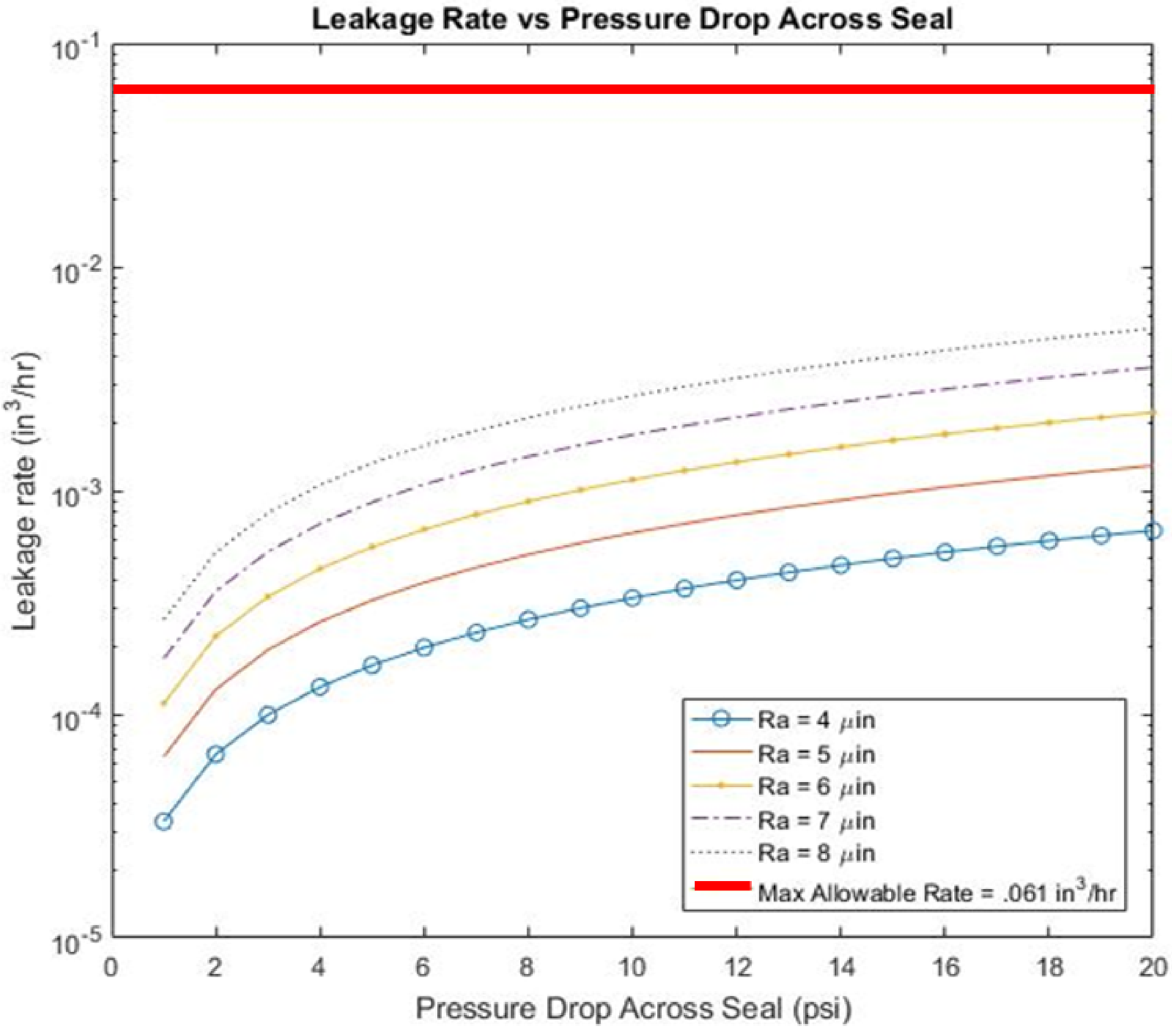


Figure 20: **LEAKAGE RATES FOR VARIOUS SURFACE ROUGHNESSES OF CARBON FACE SEALS PLOTTED AS A FUNCTION OF PRESSURE DROP ACROSS THE SEAL**

The leakage rate data provided a basis with which the team can use to predict the amount of operating time for the seal surface roughness to reach 145 μin. It is also necessary to find the modes of wear that would cause the surface roughness to reach such a value. These considerations will be taken into account when running the tribometer experiments as well as evaluating the data to produce a mathematical service life prediction model.

Table 7: **PARAMETERS FOR LEAKAGE RATE CALCULATIONS OF CONTACT**

Property	Value
Viscosity of Aircraft Engine Oil	$7.701 \times 10^{-7} \frac{lb_f s}{in^2}$
Pressure Drop Across Seal	20 psi
Seal Thickness	0.065 in
Seal Radius	1.145 in
Leakage Rate Ceiling	$0.061 \frac{in^3}{hr}$
Minimum Surface Roughness to Reach Ceiling at Pressure drop of 20 psi	145 µin

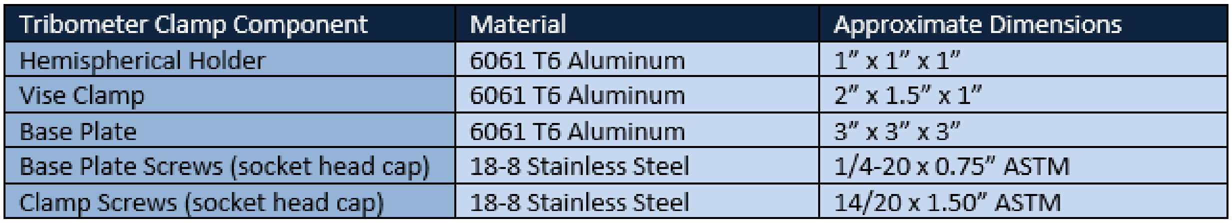
13 Build

As this project is more experimentally oriented, the desired final product was not necessarily a physical object designed to perform a specific task, but rather information characterizing preexisting objects for a given application. Therefore, the bulk of this project did not involve the building of a prototype for mass production. With that being said, there were a few one-off parts that required construction in order to complete the experiments.

13.1 Tribometer Clamp

Upon receiving the aforementioned carbon test specimens from Morgan, it was evident that the carbon pin size that was ordered was too large for the current pin clamp to hold effectively. As simply making new clamping pieces was deemed to be impractical, an entirely new attachment for the tribometer was conceptualized in solidworks, then machined at the URI machine shop. The tribometer assembly as a whole was made out of 6061 T6 aluminum with 18-8 stainless steel hardware, as seen in table 8 below. A Bridgeport was used to do the majority of the milling work for the base plate, vise clamp, and hemispherical holder. The counter-sunk slots in the base plate accommodated the nuts into which the bolts were threaded to hold the clamp vise to the base plate. The hemispherical holder was milled down to a 1"x1"x1" block, in which a 5/8" diameter hole was drilled, and then cut in half with a band saw, forming a gap the width of the blade 1/16". The drawings for the base plate, the clamp vise and the hemispherical holder can be seen in Appendices AE, AF, and AG respectively. The completed assembly can be seen with a carbon pin installed in figure 23.

Table 8: **BILL OF MATERIALS FOR TRIBOMETER CLAMP**



Tribometer Clamp Component	Material	Approximate Dimensions
Hemispherical Holder	6061 T6 Aluminum	1" x 1" x 1"
Vise Clamp	6061 T6 Aluminum	2" x 1.5" x 1"
Base Plate	6061 T6 Aluminum	3" x 3" x 3"
Base Plate Screws (socket head cap)	18-8 Stainless Steel	1/4-20 x 0.75" ASTM
Clamp Screws (socket head cap)	18-8 Stainless Steel	14/20 x 1.50" ASTM

13.2 Test Specimens

The raw materials received for the tribometer wear plates and pins needed to be modified in order to achieve required parameters and to perform preliminary testing. The wear plates were cut to the correct size from the factory, 12.5"x4"x3/16", but required the holes seen in Appendix A to be manually drilled. This was done on a Bridgeport mill in the URI machine shop. The plates also initially had very rough surface scaling, causing the surface roughness to lie well outside the $8\mu in$ acceptable maximum. In order to mitigate these effects, the plates were first milled at Eaton Corporation in to remove the scale, then ground to achieve a surface roughness of $6\mu in$. Finally the plates were not initially heat treated, as seal mating surfaces are composed of 440c Heat treated stainless steel in aircraft engines. In order to attenuate this issue, the plates were heat treated at Eaton Corporation after the desired surface finish was achieved. The plates can be seen in figure 21 below.

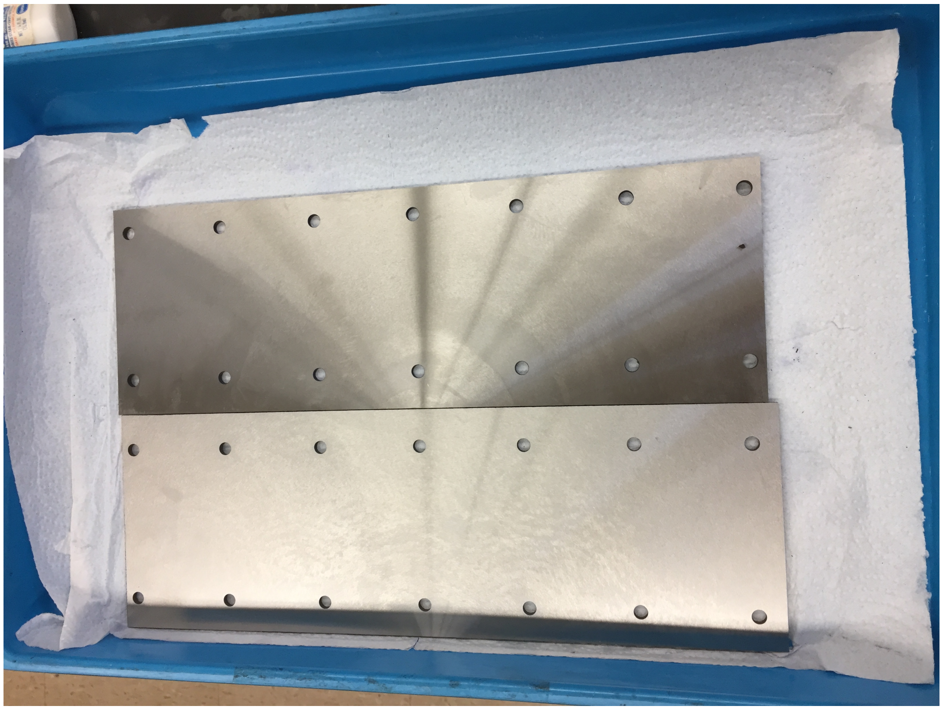


Figure 21: **440C STAINLESS STEEL WEAR PLATES**

Similar to the wear plates, the carbon samples also needed modification before they could have been used for testing. One of these modifications was to add a thermocouple above the sliding surface, within the sample itself. In order to achieve this, Eaton corporation drilled a hole $30 * 10^{-}3$" above the contacting surface of one sample of each grade of carbon. A type-K thermocouple was then epoxied into each of the holes. This was done in order to get an accurate temperature reading at the surface contact, which would then be used to scale the hardness of the carbon to operating temperatures. The image below, figure 22, displays a carbon sample with a thermocouple installed.

As the proper scaling of the carbon hardness data depended on the hardness of the carbon samples, discussed in the testing section, it was obligatory that each grade of carbon be tested at a range of temperatures. As this process destroys the sample in the process, the best course of action was determined to be cutting one sample from each grade of carbon into multiple smaller discs in order to obtain test data. This was done on a slow-speed rotary cutter with a diamond saw blade at the URI machine shop. This achieved a very smooth finish with parallel faces, allowing for accurate hardness data.

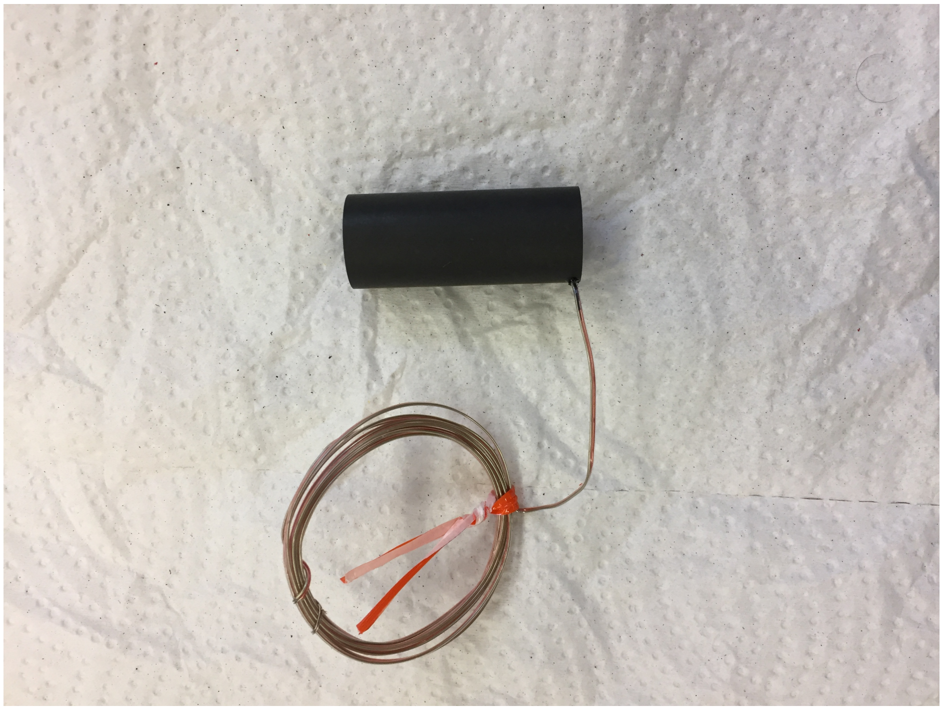


Figure 22: **P-4229 CARBON SAMPLE WITH THERMOCOUPLE**

13.3 Pi Groups

The data pertaining to the tribometer testing was obtained by setting the experimental parameters using a process called similarity. This process involved taking pi group 13, inserting all of the parameters related to the operating conditions of the seal and setting it equal to the same pi group with parameters pertaining to the experimental conditions of the specimens. This can be seen in equation 19, and will be discussed more in the testing and redesign sections to follow.

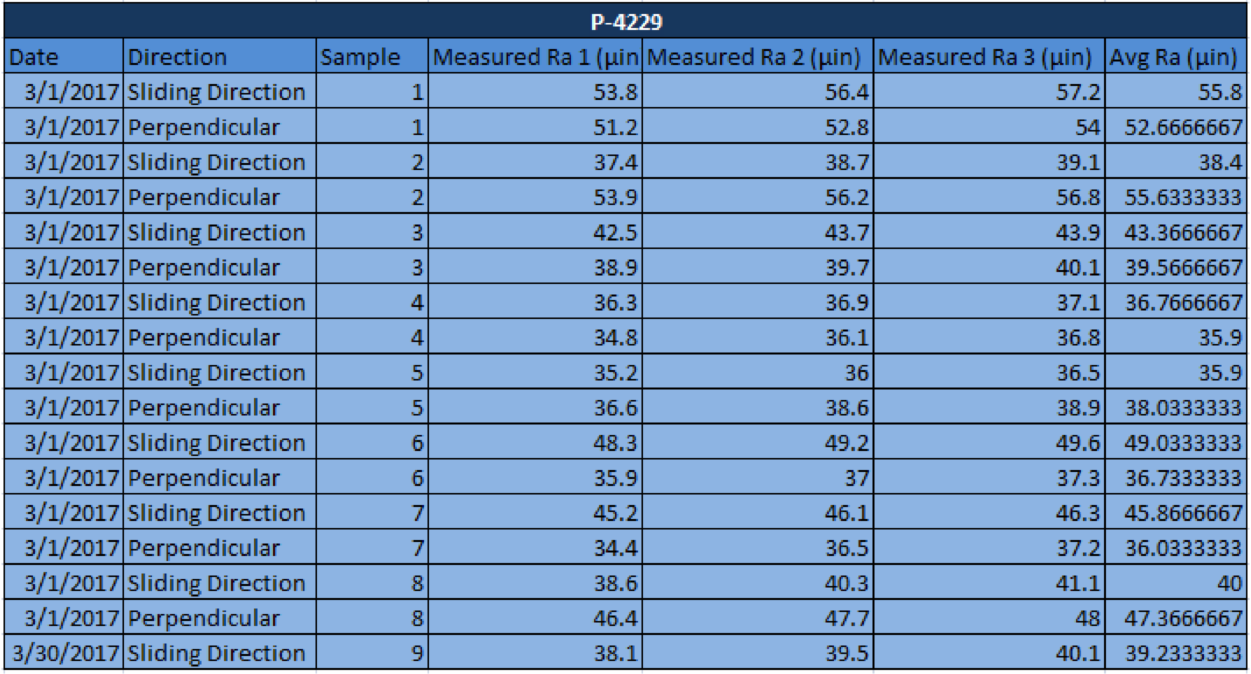
14 Testing

Before even thinking about performing the tests necessary for Seal Team Fix's Capstone Design Project, it was necessary that the team's build be accurate and confirmed. As mentioned in the Build section of this report, all of the team's experimentation was dependent upon the creation and adaptation of various dimensionless Pi groups. Once the final dimensionless equation was created, the necessary testing methodology could be confirmed. From the dimensionless equations created in the build portion of the project, the team confirmed that it was necessary to perform roughness measurements before and throughout our wear testing, hardness measurements throughout a range of temperatures from ambient up to 400°F, and finally wear testing using Professor D.M.L Meyer's tribometer. These experiments will be described in more detail in the following subsections.

14.1 Roughness Measurements

In order to observe how the surface of the carbon in contact with the mating surface (440C Stainless Steel) would change throughout the wear testing, the surface roughness of the carbon would have to be measured before and during the wear testing. The surface roughness of the materials in contact in a seal are directly proportional to the leakage rate of the seal. Therefore, if the surface roughness of the carbon or its mating surface become rougher over time, more oil is likely to leak through the sealing contact. The goal of the team's surface roughness testing was to be able to observe the change in the structure of the mating surface and use the data gathered in order to help in the creation of a service life prediction model. The surface roughness of each and every carbon sample the team had was taken before any wear testing was performed. The results for one particular type of carbon can be seen in Table 9.

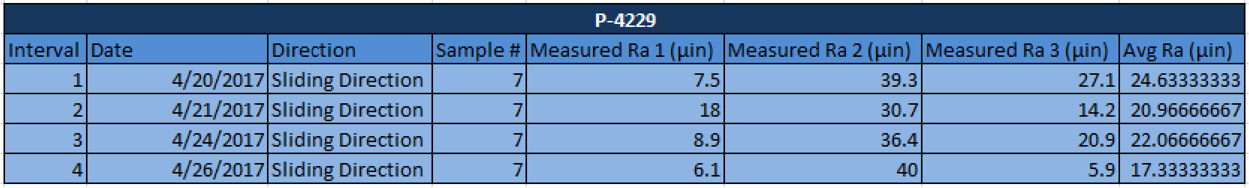
Table 9: **PRELIMINARY ROUGHNESS MEASUREMENTS FOR CARBON TYPE P-4229**



P-4229						
Date	Direction	Sample	Measured Ra 1 (µin	Measured Ra 2 (µin)	Measured Ra 3 (µin)	Avg Ra (µin)
3/1/2017	Sliding Direction	1	53.8	56.4	57.2	55.8
3/1/2017	Perpendicular	1	51.2	52.8	54	52.6666667
3/1/2017	Sliding Direction	2	37.4	38.7	39.1	38.4
3/1/2017	Perpendicular	2	53.9	56.2	56.8	55.6333333
3/1/2017	Sliding Direction	3	42.5	43.7	43.9	43.3666667
3/1/2017	Perpendicular	3	38.9	39.7	40.1	39.5666667
3/1/2017	Sliding Direction	4	36.3	36.9	37.1	36.7666667
3/1/2017	Perpendicular	4	34.8	36.1	36.8	35.9
3/1/2017	Sliding Direction	5	35.2	36	36.5	35.9
3/1/2017	Perpendicular	5	36.6	38.6	38.9	38.0333333
3/1/2017	Sliding Direction	6	48.3	49.2	49.6	49.0333333
3/1/2017	Perpendicular	6	35.9	37	37.3	36.7333333
3/1/2017	Sliding Direction	7	45.2	46.1	46.3	45.8666667
3/1/2017	Perpendicular	7	34.4	36.5	37.2	36.0333333
3/1/2017	Sliding Direction	8	38.6	40.3	41.1	40
3/1/2017	Perpendicular	8	46.4	47.7	48	47.3666667
3/30/2017	Sliding Direction	9	38.1	39.5	40.1	39.2333333

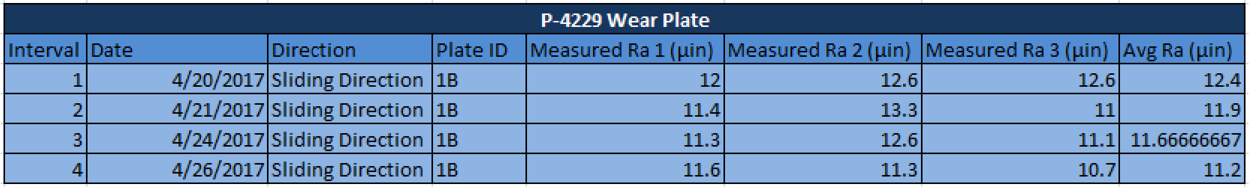
The preliminary roughness measurements shown in Table 9 are for carbon type P-4229 only. The roughness measurements for all four different carbon types were taken prior to wear testing. These preliminary roughness measurements were used in the similarity calculations using the equations described in the Build section. Once these values were input into the similarity calculations, the distance necessary for wear testing could be calculated. The total distance necessary for wear testing was then divided up into four intervals. At each of these four intervals, the carbon test specimen would be taken out of the Tribometer and the surface roughness of the mating interface would be tested again. The surface roughness of the 440C stainless steel wear plate that the carbon pin was tested against would also be measured. An example of the data collected during this process can be seen in Tables 10 and 11.

Table 10: **WEAR TEST INTERVAL ROUGHNESS MEASUREMENTS FOR CARBON TYPE P-4229**



P-4229							
Interval	Date	Direction	Sample #	Measured Ra 1 (µin)	Measured Ra 2 (µin)	Measured Ra 3 (µin)	Avg Ra (µin)
1	4/20/2017	Sliding Direction	7	7.5	39.3	27.1	24.63333333
2	4/21/2017	Sliding Direction	7	18	30.7	14.2	20.96666667
3	4/24/2017	Sliding Direction	7	8.9	36.4	20.9	22.06666667
4	4/26/2017	Sliding Direction	7	6.1	40	5.9	17.33333333

Table 11: **WEAR TEST INTERVAL ROUGHNESS MEASUREMENTS FOR CARBON TYPE P-4229 MATING WEAR PLATE**

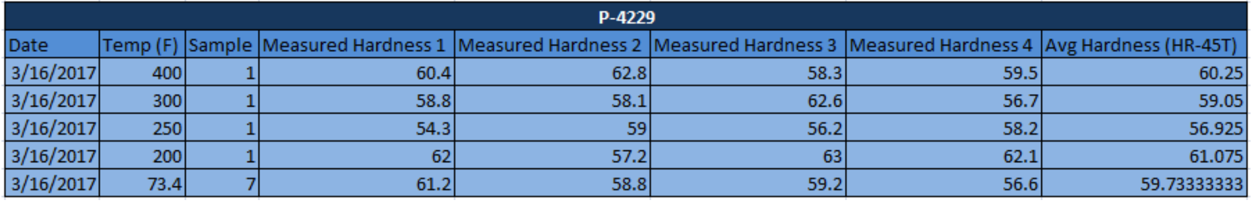


P-4229 Wear Plate							
Interval	Date	Direction	Plate ID	Measured Ra 1 (µin)	Measured Ra 2 (µin)	Measured Ra 3 (µin)	Avg Ra (µin)
1	4/20/2017	Sliding Direction	1B	12	12.6	12.6	12.4
2	4/21/2017	Sliding Direction	1B	11.4	13.3	11	11.9
3	4/24/2017	Sliding Direction	1B	11.3	12.6	11.1	11.66666667
4	4/26/2017	Sliding Direction	1B	11.6	11.3	10.7	11.2

14.2 Hardness Testing

Since the team would not be able to replicate the exact environment that the carbon face seals encounter in an aerospace application given the testing equipment available, the team needed to find material properties that would change under certain conditions in order to scale the experiments accordingly. Seal Team Fix decided that using hardness data would be an accurate means of scaling the experiments accordingly since the hardness of a material typically changes in relation to the material's temperature. The operating environment of Eaton's carbon face seals can reach temperatures of up to 400°F. The team's experiments would have to be run at room temperature, or about $73°F$. Therefore, the team decided to measure the hardness of each of the four different types of carbon at temperatures ranging from room temperature up to $400°F$. An example of the data measured can be seen in Table 12.

Table 12: **MATERIAL HARDNESS VS TEMPERATURE DATA FOR CARBON TYPE P-4229**



P-4229							
Date	Temp (F)	Sample	Measured Hardness 1	Measured Hardness 2	Measured Hardness 3	Measured Hardness 4	Avg Hardness (HR-45T)
3/16/2017	400	1	60.4	62.8	58.3	59.5	60.25
3/16/2017	300	1	58.8	58.1	62.6	56.7	59.05
3/16/2017	250	1	54.3	59	56.2	58.2	56.925
3/16/2017	200	1	62	57.2	63	62.1	61.075
3/16/2017	73.4	7	61.2	58.8	59.2	56.6	59.73333333

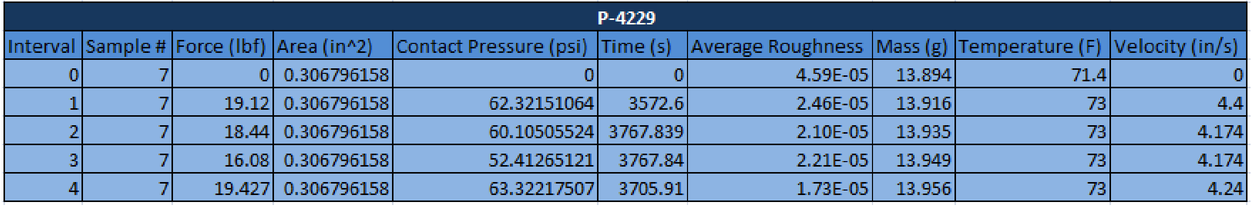
The hardness was measured using a Rockwell Hardness tester. The hardness scale used was the Rockwell 45T scale. These hardness data were then converted to the Vickers hardness scale for ease of use in calculation. The Vickers hardness units can be easily converted to a value in pounds per square inch which was incorporated in the similarity equations necessary for scaling the project.

14.3 Tribometer Testing

The most important experiments performed throughout Seal Team Fix's Capstone Design Project were the wear experiments done on the tribometer. The experiments run on the tribometer incorporated all of the previous experiments performed on the carbon samples and allowed the team to gather the necessary data to create a service life prediction model of Eaton's carbon face seals. The tribometer is a device that allows for a replication of the seal contacting surface through the use of a clamp which holds a sample of the carbon material being tested. The carbon sample can then be pressurized against the mating wear plate made of 440C stainless steel. This replicates a carbon face seal in contact with it's mating surface in a real application. The wear plate then translates back and forth while the carbon sample remains pressurized against it. This action replicates the motion of a shaft which may be found in a real-life aerospace application.

The translating motion of the carbon sample against the 440C stainless steel wear plate creates friction and wear just like in a real application. This wear can be observed by measuring the surface roughness of the carbon sample in contact with the wear plate and the wear plate itself. The wear can also be evaluated by measuring the mass of the sample after each interval of tribometer testing. This is exactly what Seal Team Fix did throughout the tribometer testing. The hardness testing results and preliminary roughness measurements for each sample were input into the similarity equations necessary for testing. Then, the contact force on the carbon sample pin was measured from the pressure transducers on the tribometer and input into the similarity equations as well. The distance necessary for tribometer testing was then calculated using these equations and the total distance was divided over four intervals. At each of these intervals, the tribometer would be stopped and the surface roughness of the carbon sample would be measured as well as the mass of the sample. The sample would then be placed back into the tribometer and run for another interval until the total necessary calculated distance was traveled on the tribometer. A test matrix from the tibometer testing can be seen in Table 13.

Table 13: **TRIBOMETER TEST RESULTS FOR CARBON TYPE P-4229**



P-4229									
Interval	Sample #	Force (lbf)	Area (in^2)	Contact Pressure (psi)	Time (s)	Average Roughness	Mass (g)	Temperature (F)	Velocity (in/s)
0	7	0	0.306796158	0	0	4.59E-05	13.894	71.4	0
1	7	19.12	0.306796158	62.32151064	3572.6	2.46E-05	13.916	73	4.4
2	7	18.44	0.306796158	60.10505524	3767.839	2.10E-05	13.935	73	4.174
3	7	16.08	0.306796158	52.41265121	3767.84	2.21E-05	13.949	73	4.174
4	7	19.427	0.306796158	63.32217507	3705.91	1.73E-05	13.956	73	4.24

The Tribometer testing performed by Seal Team Fix was scaled to replicate the wear of a carbon face seal during a two hour flight, as requested by Eaton Corporation.

15 Redesign

15.1 Tribometer clamp

The original tribometer was able to hold a sample with a maximum diameter of 0.375 inches. The height of the sample was limited by the distance between the pressure actuator and the wear plate. The sample clamp would compress from both sides, tightening against the sample, and hold the sample in place. The original sample clamp would only apply pressure to the lower eighth of the sample, severely limiting the contact area. The obtained carbon samples had a diameter of 0.625 inches and a height of 2 inches, the original sample holder would not be sufficient to hold the carbon samples.

A new carbon sample clamp had to be designed and manufactured. The new sample holder was designed to hold samples with varying diameters ranging from 0.375 inches to 0.625 inches. The sample would be held in place by a cut cube of aluminum with a length side of 0.5 inches, this increases the contact area with the sample between the sample and the sample holder. The sample would be placed into the center of the cube, which was then placed in a pair of sliding clamps. The clamps were tightened until the sample was fixed in place. The tribometer clamp can still be improved. The sample could be held in place by replacing hemispherical inner pieces with a flat block and a v-shaped insert. That will prevent any possible slippage of the sample on it's vertical axis and could be fitted to accommodate a wider range of diameters. The final assembly with a carbon pin can be seen in figure 23 below.

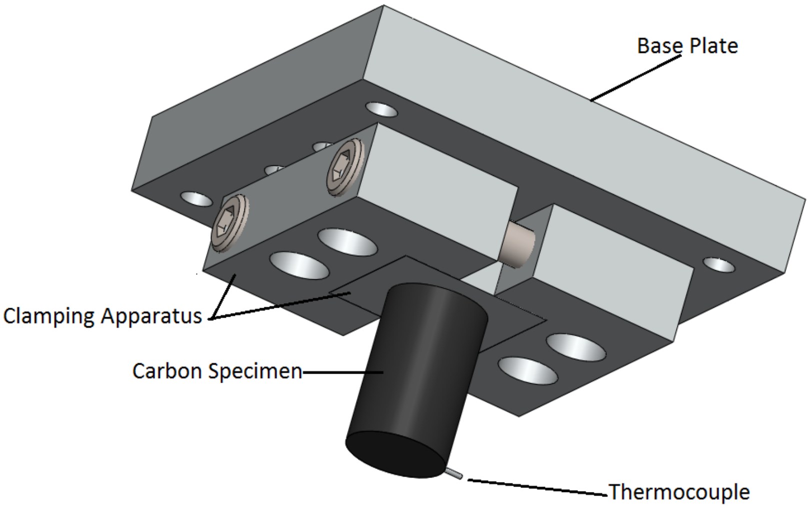


Figure 23: **TRIBOMETER CLAMP ASSEMBLY**

15.2 Pi Groups

Upon further analysis of the non-dimensionalized group in equation 13, the resulting values for experimental test duration and pressure were not achievable. To evaluate for a desired variable, a process called similarity was utilized by setting a group of experimental values equal to the actual values of a seal in a turbine engine environment. This can be seen in equation 19 below.

$$\left(\frac{P_c R_a d^2}{t V H T \beta A_c}\right)_{act} = \left(\frac{P_c R_a d^2}{t V H T \beta A_c}\right)_{exp} \tag{19}$$

The resulting experimental velocities, pressures, and total distances derived from equation 19 laid well outside the limits of the testing equipment and amount of available time to perform said tests. This was due to the fact that Pi group 13 contained co-dependent variables which would affect one another other if a value were to be altered. In order to eliminate this undesired effect, a new Pi group was formulated with no co-dependencies between variables, as seen in equation 20 below.

$$\left(\frac{F_N A_c}{H d R a^3}\right)_{exp} = \left(\frac{F_N A_c}{H d R a^3}\right)_{act} \tag{20}$$

This final pi group not only provided achievable experimental parameters, but the simplification from nine to five variables allowed for only the most critical parameters to be used. This means that any desired parameter that was not included in the final pi group could be derived from the present variables; e.g., the contact pressure, P_c, can be derived from the load, F_N, and the contact area, A_c.

16 Operation

The generated product, data, does not have an operational guide, but the process of data acquisition does. The data was obtained through various methods of testing. The test methods include; hardness testing, surface roughness testing, and pin on flat Tribometer testing. The collected data was to be compared against know wear results from the Eaton

Corporation.

The first test that was conducted on the samples was a series of surface roughness test. The samples were tested in both the sliding direction and perpendicular to the sliding direction. The sliding direction was chosen to be parallel with sliding direction of the Tribometer. Three measurements were taken in both directions and then averaged to determine the surface roughness of both the sliding and perpendicular directions. Surface roughness test were also conducted during the experiments. The surface roughness was taken after the test was conducted, before a new test of the same sample was conducted. The surface of the plates was also taken at the initial starting point and intermittently through out the testing.

Hardness tests were conducted on the samples to determine if the hardness of the carbon samples would change as the temperature increases in the seal contact and in the environment in which the seal is located. One sample from each batch was cut into quarter inch sections using a low speed saw with a diamond edge cutting wheel. A thickness of a quarter of an inch was chosen because that is the minimum thickness that could be used on the Rockwell hardness tester and to minimize used samples. The hardness was calculated by taking the average hardness of the samples that was tested in five locations on the sample's surface.

Tribometer testing was conducted between March 22nd and April 21st. The tribometer testing was conducted using a pin on flat tribometer in Professor Meyer's lab in Morrill Hall. The tribometer was controlled using a computer in the lab and the data was collected using the data acquisition software known as LoggerPro. An Ardunio was attached to the Tribometer so that the cycle time could be calculated to help determine the duration of each test. A stainless steel wear plate was placed on the sliding platform of the tribometer. The lubricant tray was placed over the wear plate, lining up the screw holes, and the lubricant tray and wear plate were tighten to the tribometer. A sample of carbon was placed into the new tribometer clamp and then was attached to the pressure actuator of the tribometer. If the sample that was being tested had a thermocouple, then it was plugged into a voltmeter to display a read out of the temperature. The tray was then filled with 30 ml's of the lubricant and the sample was lowered until it became in contact with the wear plate. A 15 second loggerPro test was run to determine the amount of force that had to be added to simulate operating conditions, the force was manipulated by changing the amount of pressure that was applied to the actuator from an air compressor. The tribometer was run for one cycle to determine the duration of the test. The collected initial data from LoggerPro and Ardunio were input to a similarity file to determine the experimental force and duration as compared to operating conditions.

16.1 Model Maintenance

The maintenance of the service life prediction model will not be the same as your everyday product. This is due to the fact that the project produced a computer model using experimental data, rather than having a physical prototype. The way to maintain the integrity of the model would be to follow the test matrix accordingly. To maintain consistent results, the test methods and test environment needs to be reproduced. This is to avoid unnecessary error and any further uncertainty in the data.

16.2 Test Equipment Maintenance

The maintenance of consistent results had largely to do with test environment replication,but was dependent on the equipment used to conduct the experiments in the as well. Starting with the hardness testing, a Rockwell scale was used. The machine used to measure the carbon samples had to be calibrated correctly before hardness testing could be done. The same goes for the surface roughness machine, which had to use the correct calibration fixture before any roughness values could be attained. After the two machines were calibrated and set up, the other piece of equipment to be maintained was tribometer. As mentioned in the build and test sections, a new clamp had to be created to accommodate the larger diameter of the carbon samples. The tribometer clamp should be briefly examined between test runs to make sure all the pieces are correctly in position. The tribometer gathered data using the computer software Tracer DAQ, and controlled through a computer code. The code is what controlled the amount of cycles that the carbon was dragged over wear plates. The software did not need to be maintained but the tribometer itself did require some attention. The machine should always have an adequate amount of lubricant so there are no dry mating surfaces, which could possibly damage either the clamp or the integrity of results.

17 Additional Considerations

17.1 Oil Saturation

While the initial plan for measuring the wear volume was to record changes in the carbon samples' mass, this was not an accurate method because it was discovered that the carbon samples steadily gained mass as they progress through the tribometer testing. It was determined that the only explanation for this phenomenon was that the resin impregnated in the samples was absorbing the oil that it was coming into contact with during testing.

One way to mitigate the effects of oil absorption would be to saturate the samples in the oil before testing them. In order to do this experiments would have to be conducted by future capstone groups or Eaton staff to find the asymptotic maximum amount of oil that each carbon grade would absorb. Naturally, the oil being present in the binding agent of the carbon seal material might affect material properties such as hardness. So, testing of each grade of carbon both before and after oil saturation would be critical to determining how the performance of each grade of carbon could change in an oil saturated environment.

17.2 Data Accuracy

As only 4 samples were able to be tested during the final semester of this project, the data may not be as reliable as desired. The sample size was initially thought to be limited by time, but as only three of the wear plates were able to be de-scaled, and only four samples with installed thermocouples were received back from Eaton Corporation, sample size was limited to four samples. If a future capstone group were to continue this project, the immediate acquisition of more test-worthy samples would be greatly beneficial.

17.3 Tribometer Pin Holder

Finally, the tribometer pin holder was found to be at fault for the carbon pins initially wearing unevenly. One way to easily and cheaply fix this problem would be to make a new 1"x1"x1" block out of steel and grind the top surface once the dimensions are achieved on the mill. This would ensure that the face that comes into contact with the base plate would be perfectly perpendicular to the 5/8" hole that would be drilled after the grinding process. To further ensure the parallelism of the carbon sample face to the wear plate, the base plate could be ground as well, as this would further improve the tolerances of each part.

18 Conclusions

The objective of Seal Team Fix's Capstone Design Project was to accurately characterize the carbon used in Eaton Corporation's mechanical face seals as well as to create a service life prediction model based on the data obtained during characterization. The team had to meet the requirements requested by Eaton while operating under a very restricted time line and with limited resources. For this reason the team had to limit the experimental requirements in order to complete the project on time. The team also had to scale the experiment to meet the environmental replication requirements. Finally, and perhaps most importantly, the team needed to maintain a certain budget in order to meet the economic requirements of the project.

18.1 Experimental Requirements

In accordance with the design specifications, the team tested Eaton's four most commonly used carbon types with the most commonly used mating surface found in their sealing pairs. These four carbons were Morgan's P-4229, P-5007, CNFJ, and CTI-76. The mating surface used in testing were wear plates made of 440C stainless steel as requested by Eaton. The team was given ten samples of each different type of carbon free of charge by Morgan. The stainless steel however was purchased through Atlantic Stainless in Attleboro, Massachusetts. While the design specifications mention that the team would order nine stainless steel wear plates, it was later decided that the team would limit the number purchased to a total of six wear plates. This brought materials costs down substantially.

While the design specifications mention that the team would test each carbon type on the Tribometer a total of three times, this goal was simply unachievable in the time given. While the preliminary roughnesses of each and every one of the forty carbon samples were measured and the hardnesses of each of the four carbon types were measured throughout a temperature range from ambient to $400°F$, each carbon type was only tested one time on the Tribometer. Unfortunately the team was not able to satisfy the goal of testing each sample three different times on the Tribometer, however the data collected from the one test should leave Eaton with enough information to aid in creating a service life prediction model for their carbon face seals.

18.2 Environmental Replication Requirements

The environmental replication requirements of the design specifications mention a carbon seal with an outer diameter of 2.355 inches and a contact pressure of 15 psi. These are the exact specifications that were modeled in Seal Team Fix's experimentation. While the pressure drop across the seal was not replicated in the team's experimentation, the roughness of the contact surface of the seal was scaled using the team's dimensionless equations in order to satisfy the replication of a real-life application. The aircraft engine oil mentioned in the design specifications was also used in the team's Tribometer experiments in order to replicate a real-life environment as best as possible. While the temperatures of the team's Tribometer testing could not reach those of the operating temperatures of a turbine engine, this environmental condition was compensated for in the teams dimensional analysis. The hardness testing performed throughout the team's project once again aided in scaling the experiments to feasibly be run on the Tribometer.

18.3 Economic Requirements

As mentioned in the design specifications, Eaton offered Seal Team Fix a budget of $3500. The team was able to perform all of the necessary experimentation for the project while maintaining expenses well within the budget proposed by Eaton. The details of this financial information can be seen in the Financial Analysis section of this report. Although not all of Eaton's requests were achieved throughout the course of the project, the majority of the goals were in fact met. Seal Team Fix has supplied Eaton with a vast amount of empirical experimental data that will certainly be of benefit to the company, all while maintaining a budget of about one tenth of that offered by the company. It is safe to say that Seal Team Fix's project was certainly a success from an economic point of view.

19 References

[1] Eaton, 2016.

[2] Eaton. Our company: About us, 2016.

[3] Eaton. Our company: About us: Business groups, 2016.

[4] Andrew Bachelor Gwidon W. Stachowiak. *Engineering Tribology, 3rd Edition.* Elsevier Academic Press, 2005.

[5] L. Wei X. Feng J.J. Sun, X.Y. He. Failure analysis and seal life prediction for contacting mechanical seals. 2008.

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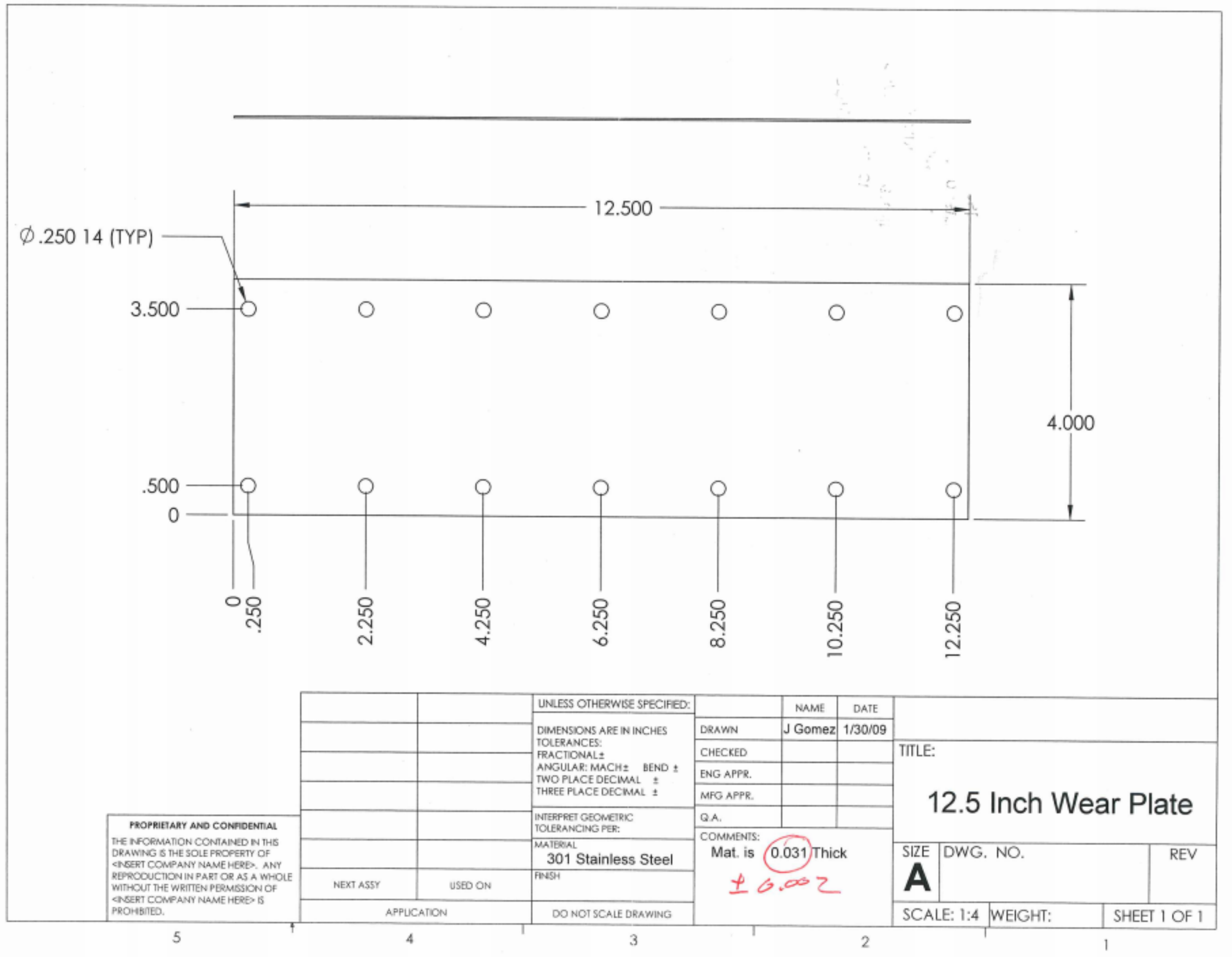
[8] Dr. David Taggart. Chapter 6: Plane stress/strain elements, 2016.

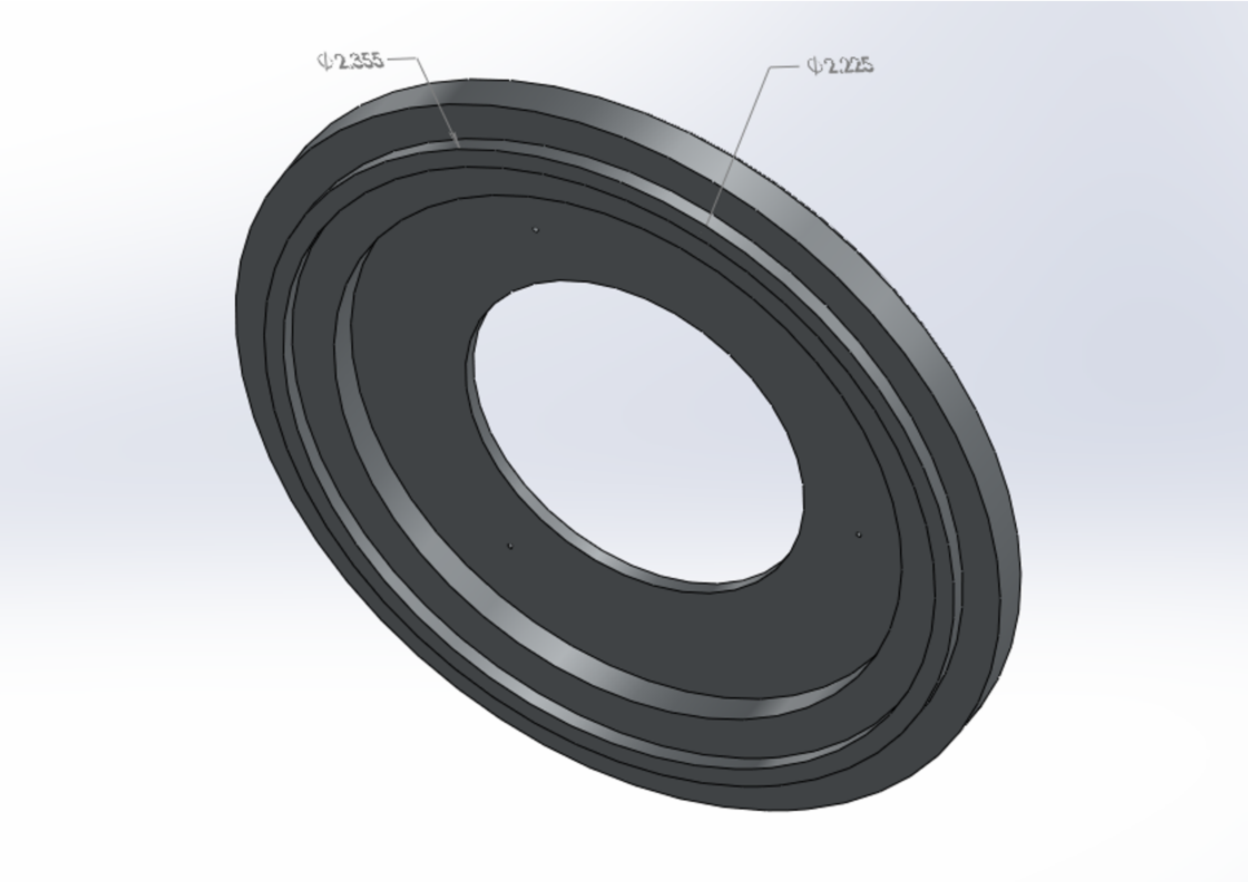
[9] Dr. David Taggart. Chapter 9: Axisymmetric elements, 2016.

20 Appendix

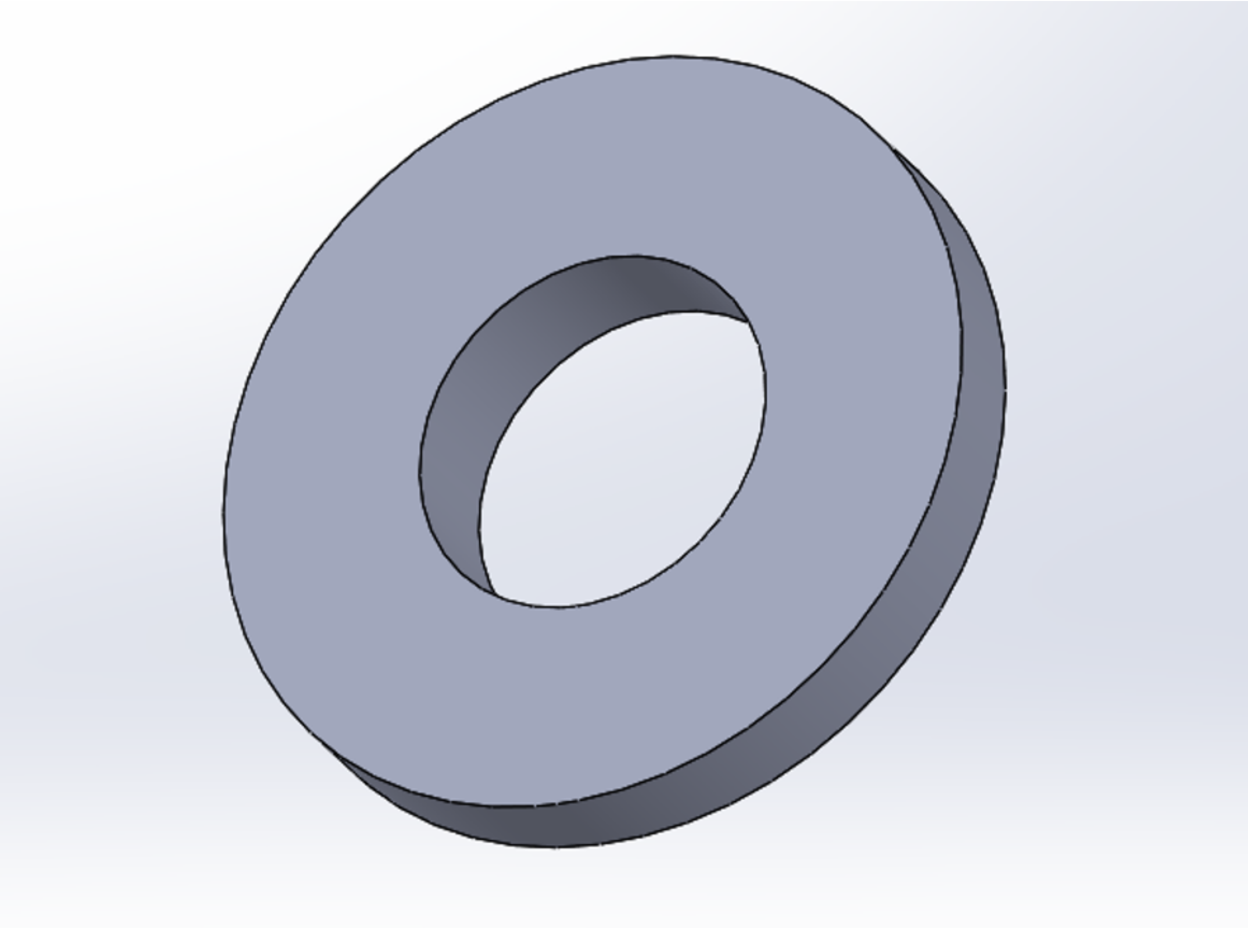
20.1 Appendix A



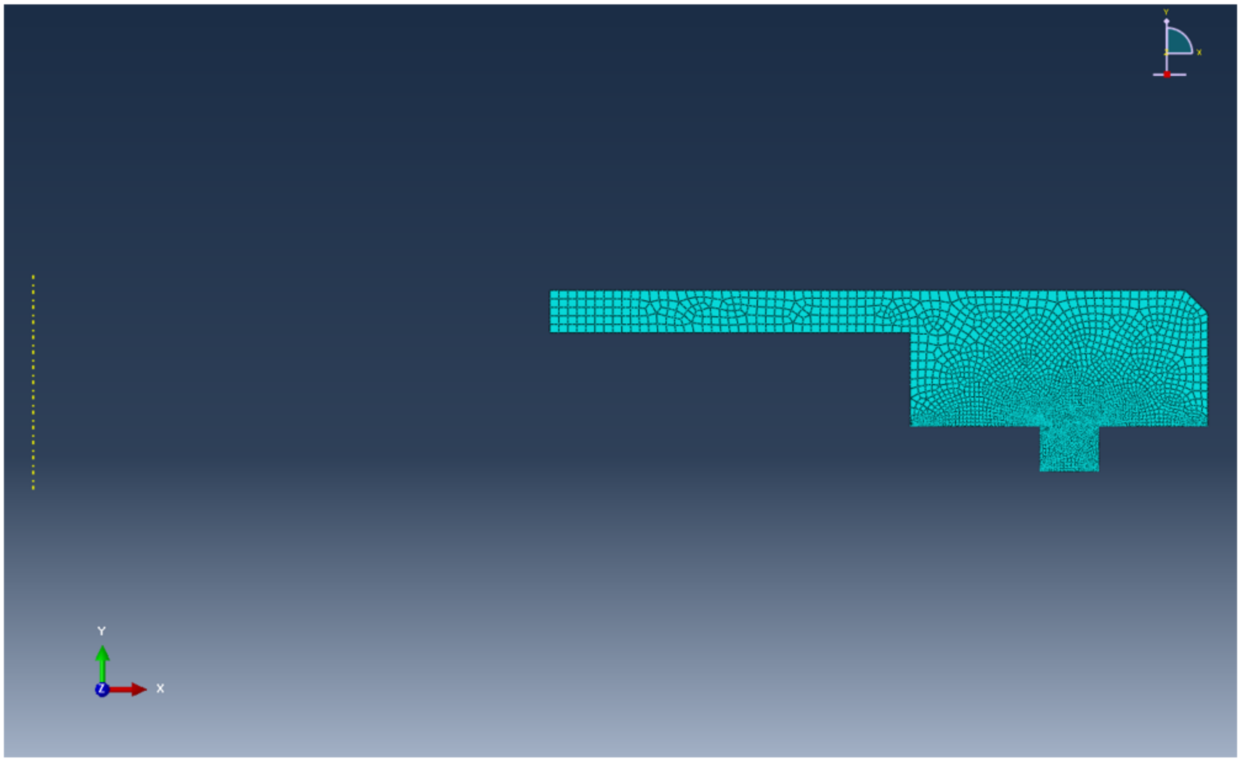
20.2 Appendix B



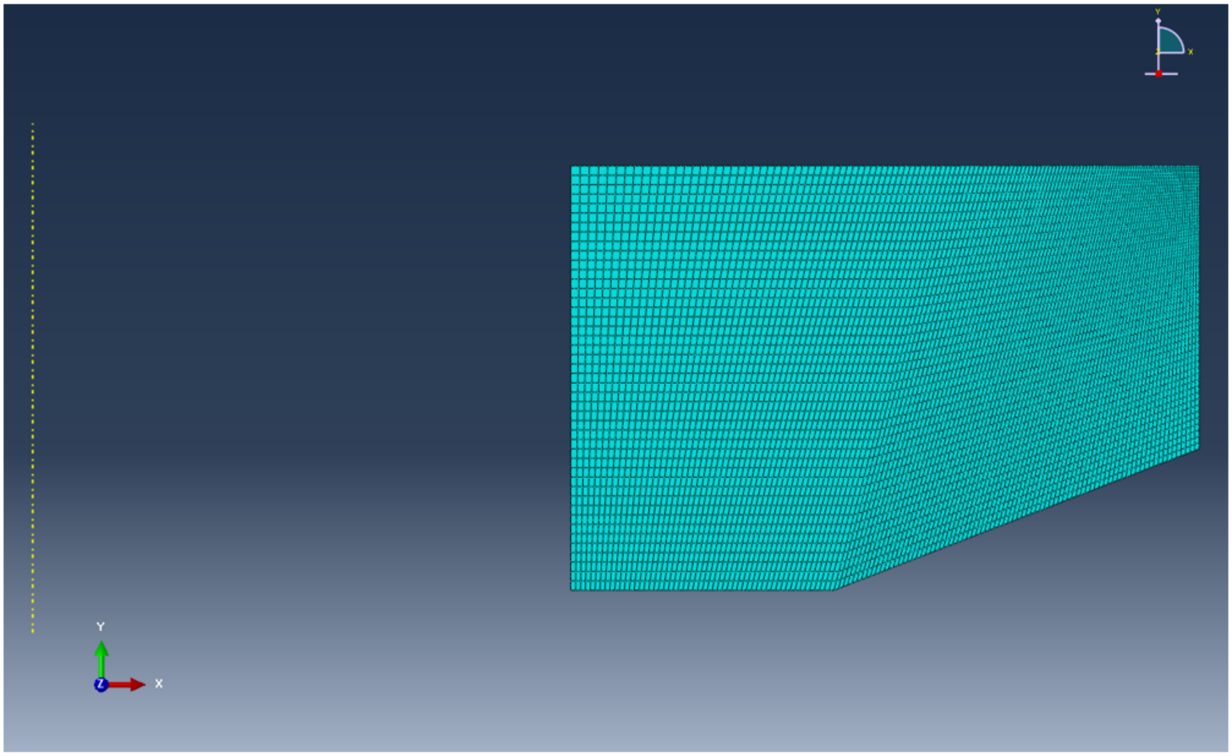
20.3 Appendix C



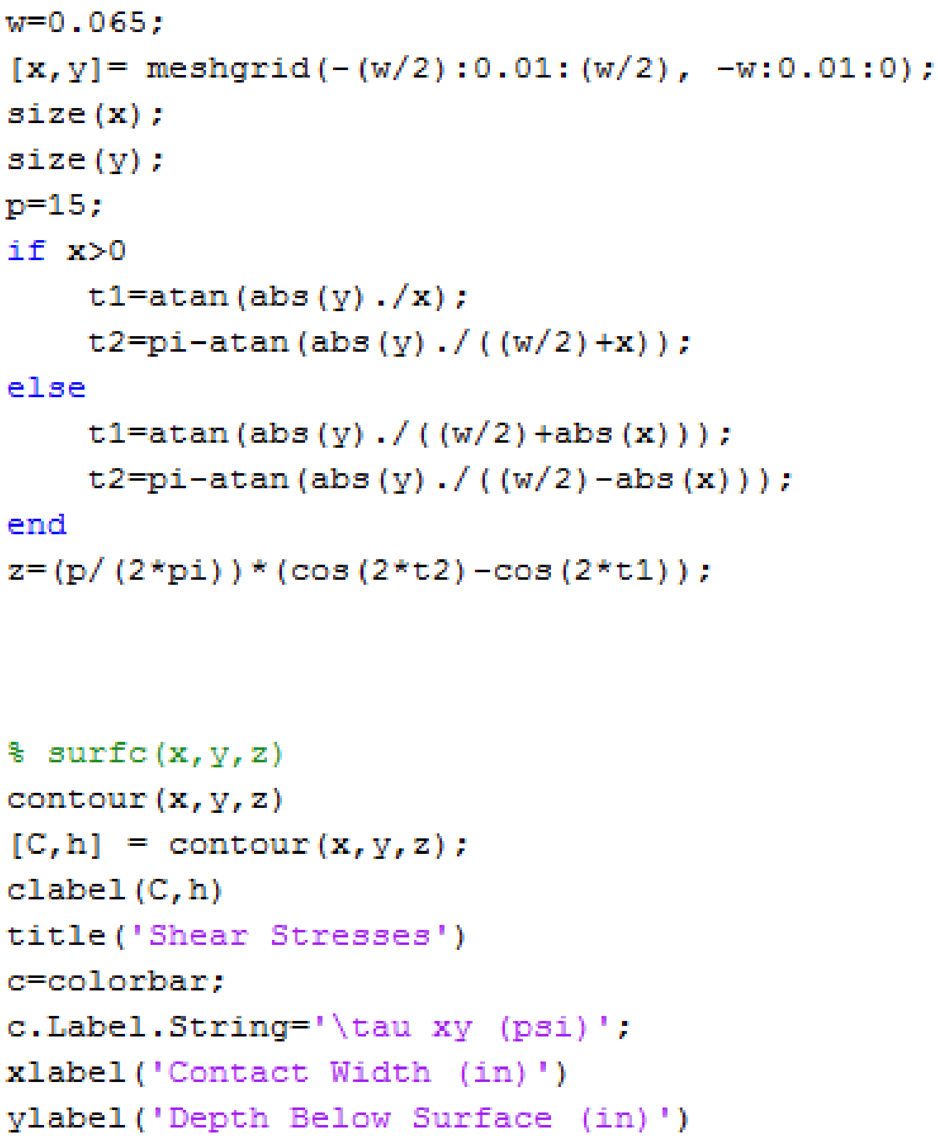
20.4 Appendix D



20.5 Appendix E

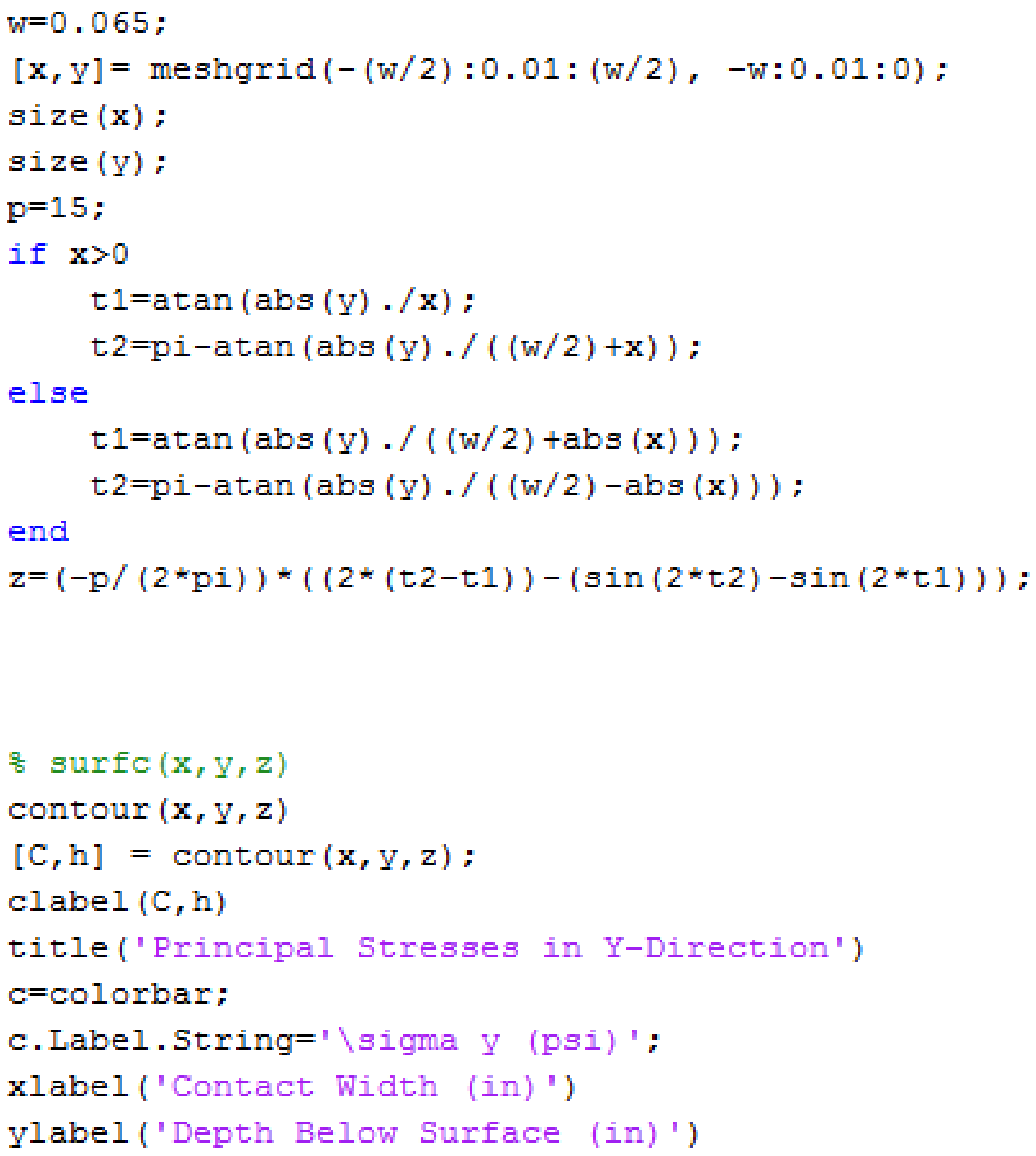


20.6 Appendix F



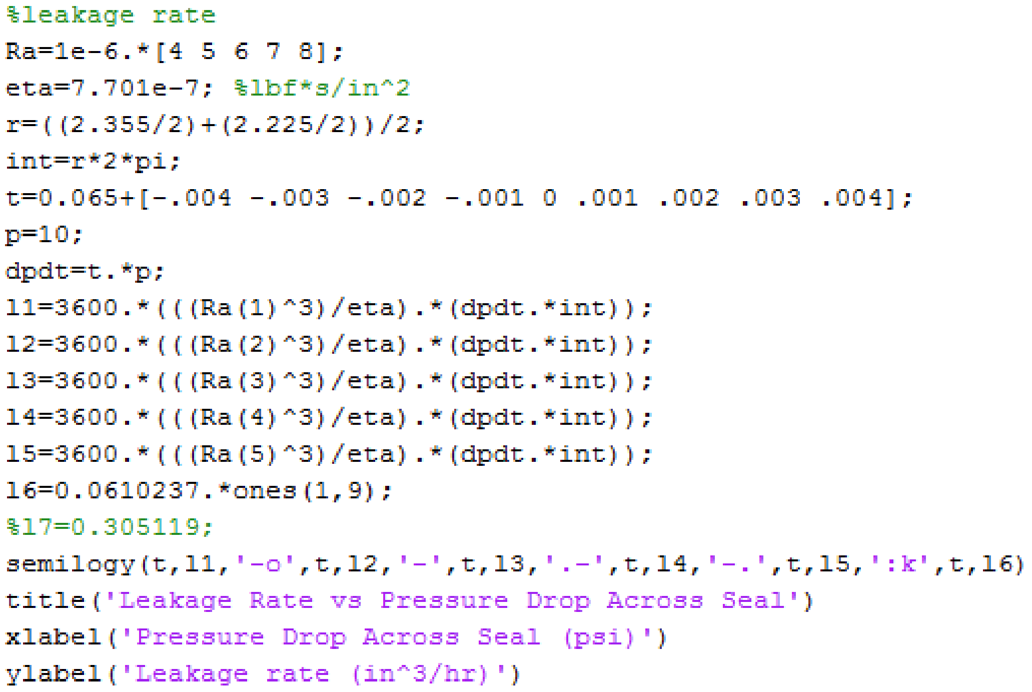
```
w=0.065;
[x,y]= meshgrid(-(w/2):0.01:(w/2), -w:0.01:0);
size(x);
size(y);
p=15;
if x>0
    t1=atan(abs(y)./x);
    t2=pi-atan(abs(y)./((w/2)+x));
else
    t1=atan(abs(y)./((w/2)+abs(x)));
    t2=pi-atan(abs(y)./((w/2)-abs(x)));
end
z=(p/(2*pi))*(cos(2*t2)-cos(2*t1));



% surfc(x,y,z)
contour(x,y,z)
[C,h] = contour(x,y,z);
clabel(C,h)
title('Shear Stresses')
c=colorbar;
c.Label.String='\tau xy (psi)';
xlabel('Contact Width (in)')
ylabel('Depth Below Surface (in)')
```

20.7 Appendix G



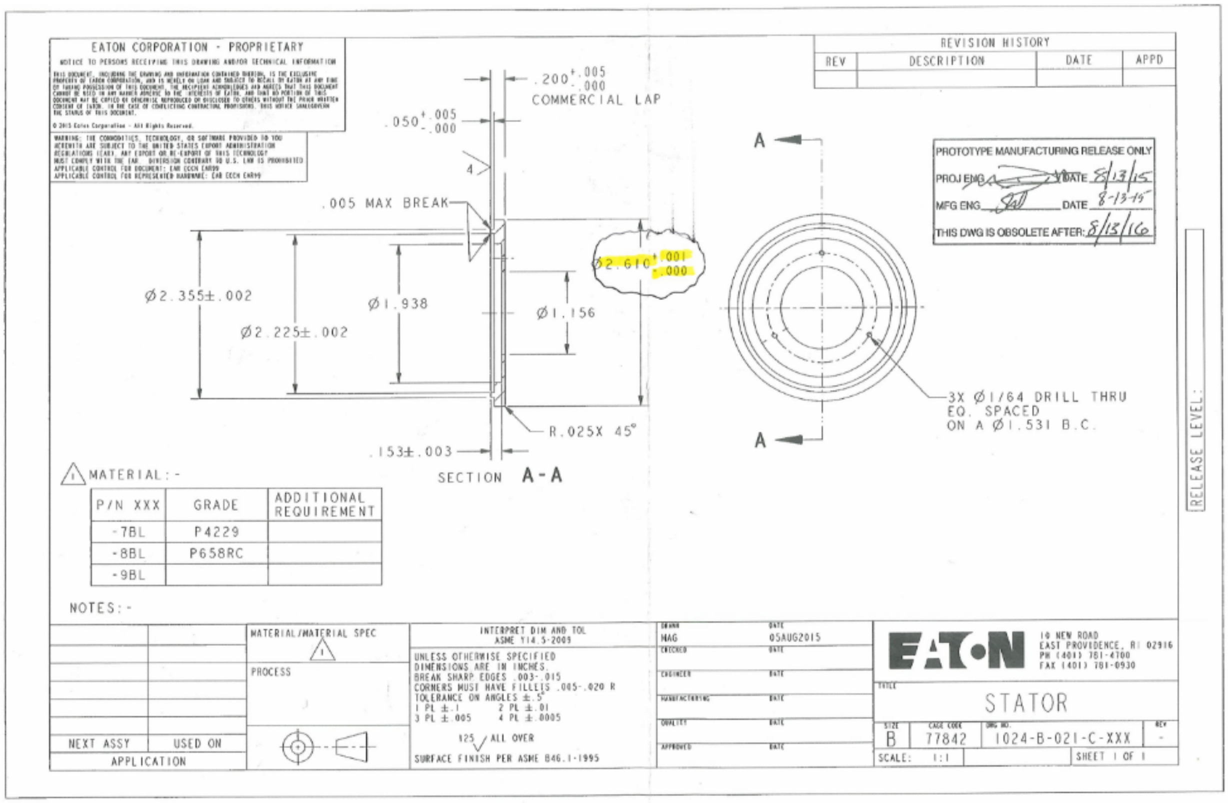
```
w=0.065;
[x,y]= meshgrid(-(w/2):0.01:(w/2), -w:0.01:0);
size(x);
size(y);
p=15;
if x>0
    t1=atan(abs(y)./x);
    t2=pi-atan(abs(y)./((w/2)+x));
else
    t1=atan(abs(y)./((w/2)+abs(x)));
    t2=pi-atan(abs(y)./((w/2)-abs(x)));
end
z=(-p/(2*pi))*((2*(t2-t1))-(sin(2*t2)-sin(2*t1)));



% surfc(x,y,z)
contour(x,y,z)
[C,h] = contour(x,y,z);
clabel(C,h)
title('Principal Stresses in Y-Direction')
c=colorbar;
c.Label.String='\sigma y (psi)';
xlabel('Contact Width (in)')
ylabel('Depth Below Surface (in)')
```

20.8 Appendix H



```
%leakage rate
Ra=1e-6.*[4 5 6 7 8];
eta=7.701e-7; %lbf*s/in^2
r=((2.355/2)+(2.225/2))/2;
int=r*2*pi;
t=0.065+[-.004 -.003 -.002 -.001 0 .001 .002 .003 .004];
p=10;
dpdt=t.*p;
l1=3600.*(((Ra(1)^3)/eta).*(dpdt.*int));
l2=3600.*(((Ra(2)^3)/eta).*(dpdt.*int));
l3=3600.*(((Ra(3)^3)/eta).*(dpdt.*int));
l4=3600.*(((Ra(4)^3)/eta).*(dpdt.*int));
l5=3600.*(((Ra(5)^3)/eta).*(dpdt.*int));
l6=0.0610237.*ones(1,9);
%l7=0.305119;
semilogy(t,l1,'-o',t,l2,'-',t,l3,'.-',t,l4,'-.',t,l5,':k',t,l6)
title('Leakage Rate vs Pressure Drop Across Seal')
xlabel('Pressure Drop Across Seal (psi)')
ylabel('Leakage rate (in^3/hr)')
```

20.9 Appendix I



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REV	DESCRIPTION	DATE	APPD

PROTOTYPE MANUFACTURING RELEASE ONLY
PROJ ENG ____ DATE 8/13/15
MFG ENG ____ DATE 8-13-15
THIS DWG IS OBSOLETE AFTER: 8/13/16

⚠ MATERIAL:-

P/N XXX	GRADE	ADDITIONAL REQUIREMENT
-7BL	P4229	
-8BL	P658RC	
-9BL		

NOTES:-

NEXT ASSY	USED ON
APPLICATION	

MATERIAL/MATERIAL SPEC ⚠
PROCESS

INTERPRET DIM AND TOL
ASME Y14.5-2009

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES.
BREAK SHARP EDGES .003-.015
CORNERS MUST HAVE FILLETS .005-.020 R
TOLERANCE ON ANGLES ±.5°
1 PL ±.1 2 PL ±.01
3 PL ±.005 4 PL ±.0005
125 ✓ ALL OVER
SURFACE FINISH PER ASME B46.1-1995

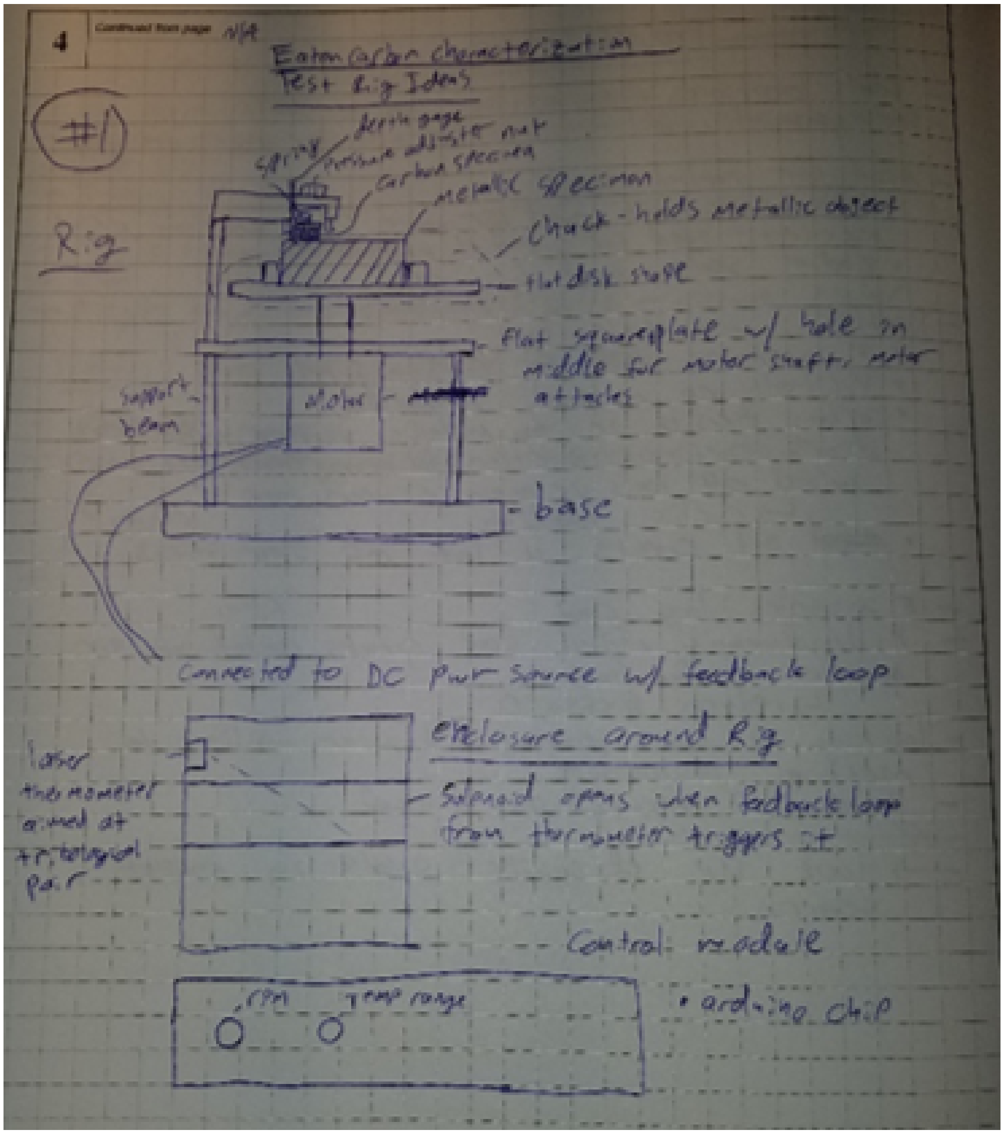
DRAWN MAG DATE 05AUG2015
CHECKED DATE
ENGINEER DATE
MANUFACTURING DATE
QUALITY DATE
APPROVED DATE

EATON
10 NEW ROAD
EAST PROVIDENCE, RI 02916
PH (401) 781-4700
FAX (401) 781-0930

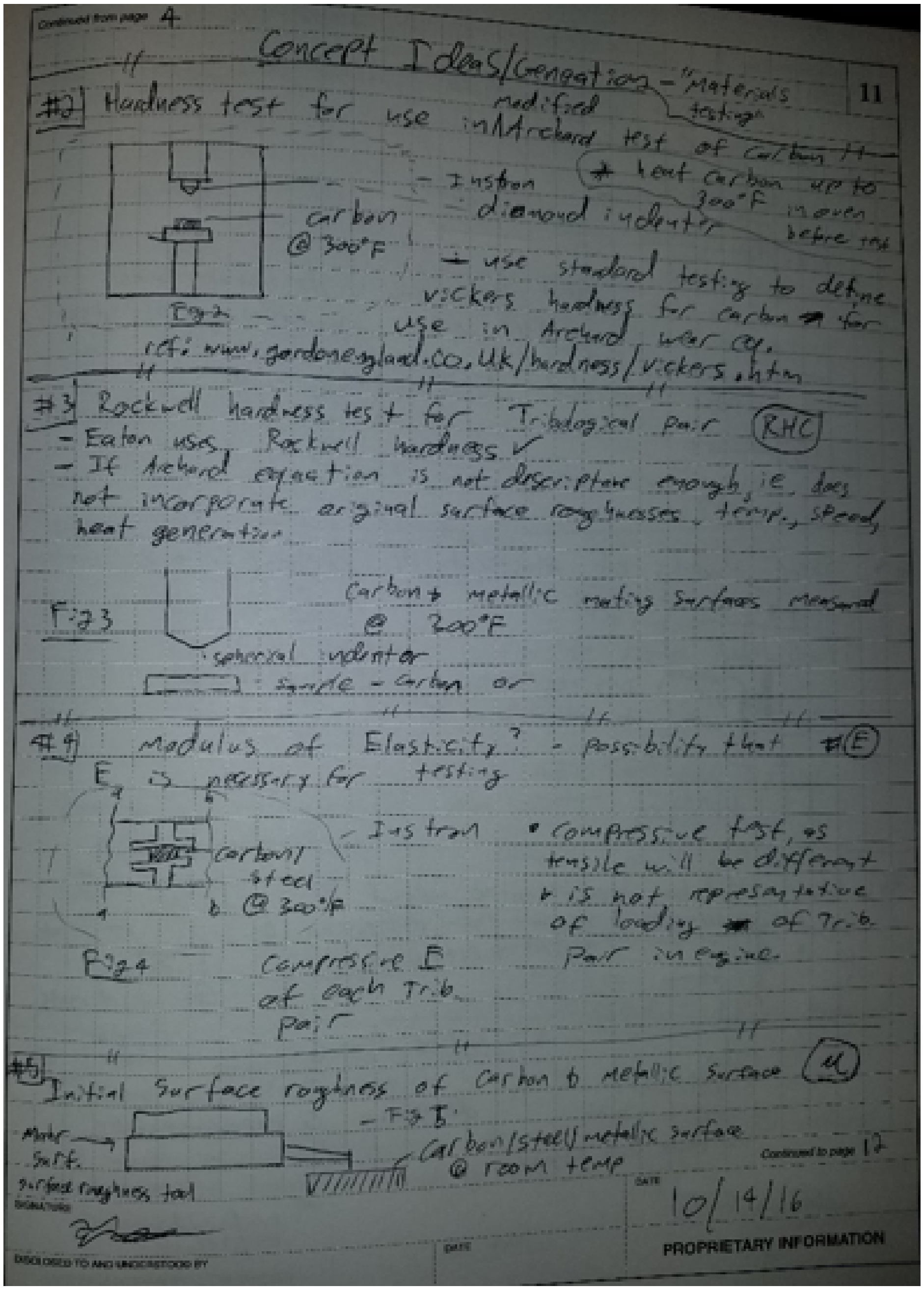
TITLE STATOR

SIZE B CAGE CODE 77842 DWG NO. 1024-B-021-C-XXX REV -
SCALE: 1:1 SHEET 1 OF 1

20.10 Appendix J



20.11 Appendix K



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Concept Ideas/Generation - "Materials testing"

11

#2 Hardness test for use in modified Archard test of carbon

- Instron
- diamond indenter

carbon @ 300°F

* heat carbon up to 300°F in oven before test

- use standard testing to define vickers hardness for carbon for use in Archard wear eq.

Fig 2

ref: www.gordonengland.co.uk/hardness/vickers.htm

#3 Rockwell hardness test for Tribological pair (RHC)

- Eaton uses Rockwell hardness ✓
- If Archard equation is not descriptive enough, ie. does not incorporate original surface roughnesses, temp., speed, heat generation

Fig 3

Carbon + metallic mating surfaces measured @ 300°F

spherical indenter

sample - carbon or

#4 Modulus of Elasticity? - possibility that E is necessary for testing (E)

- Instron

carbon/steel @ 300°F

• compressive test, as tensile will be different & is not representative of loading of Trib pair in engine.

Fig 4

compressive E of each Trib pair

#5 Initial surface roughness of carbon & metallic surface (μ)

- Fig 5

Mater surf.

Carbon/steel/metallic surface @ room temp

surface roughness tool

Continued to page 12

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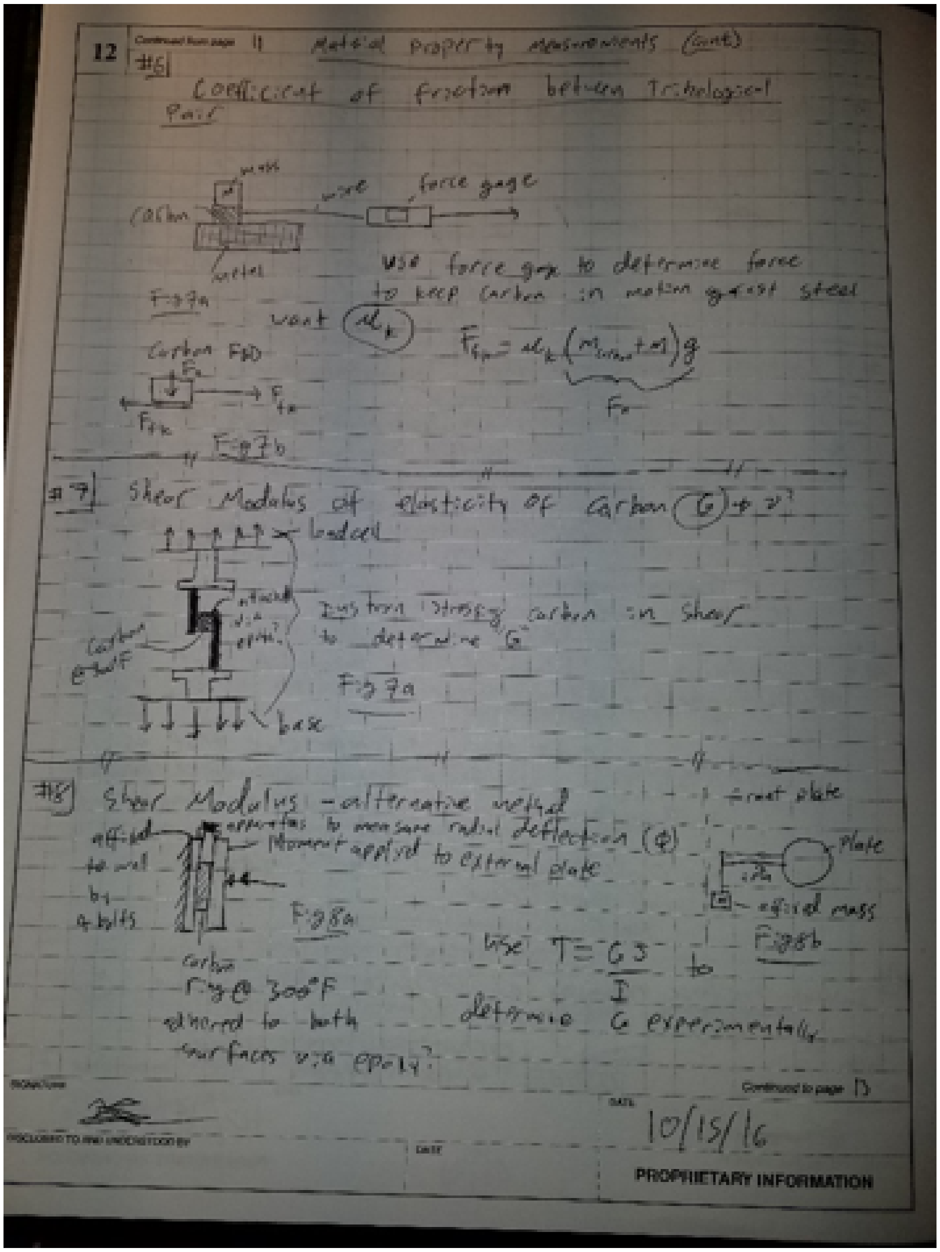
20.12 Appendix L



12 Continued from page 11

Material Property Measurements (cont)

#6] Coefficient of friction between Tribological Pair

mass
carbon
wire
force gage
steel

Fig 7a

use force gage to determine force to keep carbon in motion against steel

want $\boxed{\mu_k}$

Carbon FBD

F_N
F_{fk}
F_{fk}

$$F_{fk} = \mu_k \underbrace{(m_{carbon} + m)g}_{F_N}$$

Fig 7b

#7] Shear Modulus of elasticity of Carbon $\boxed{G}$ + ν?

loadcell
attached via epoxy?
Carbon @ 300F
base

Instron stressing carbon in shear to determine "G"

Fig 7a

#8] Shear Modulus - alternative method

affixed to wall by 4 bolts
apparatus to measure radial deflection (φ)
Moment applied to external plate

Fig 8a

carbon ring @ 300°F adhered to both surfaces via epoxy?

front plate
plate
rigid mass

Fig 8b

use $T = \frac{GJ}{I}$ to determine G experimentally

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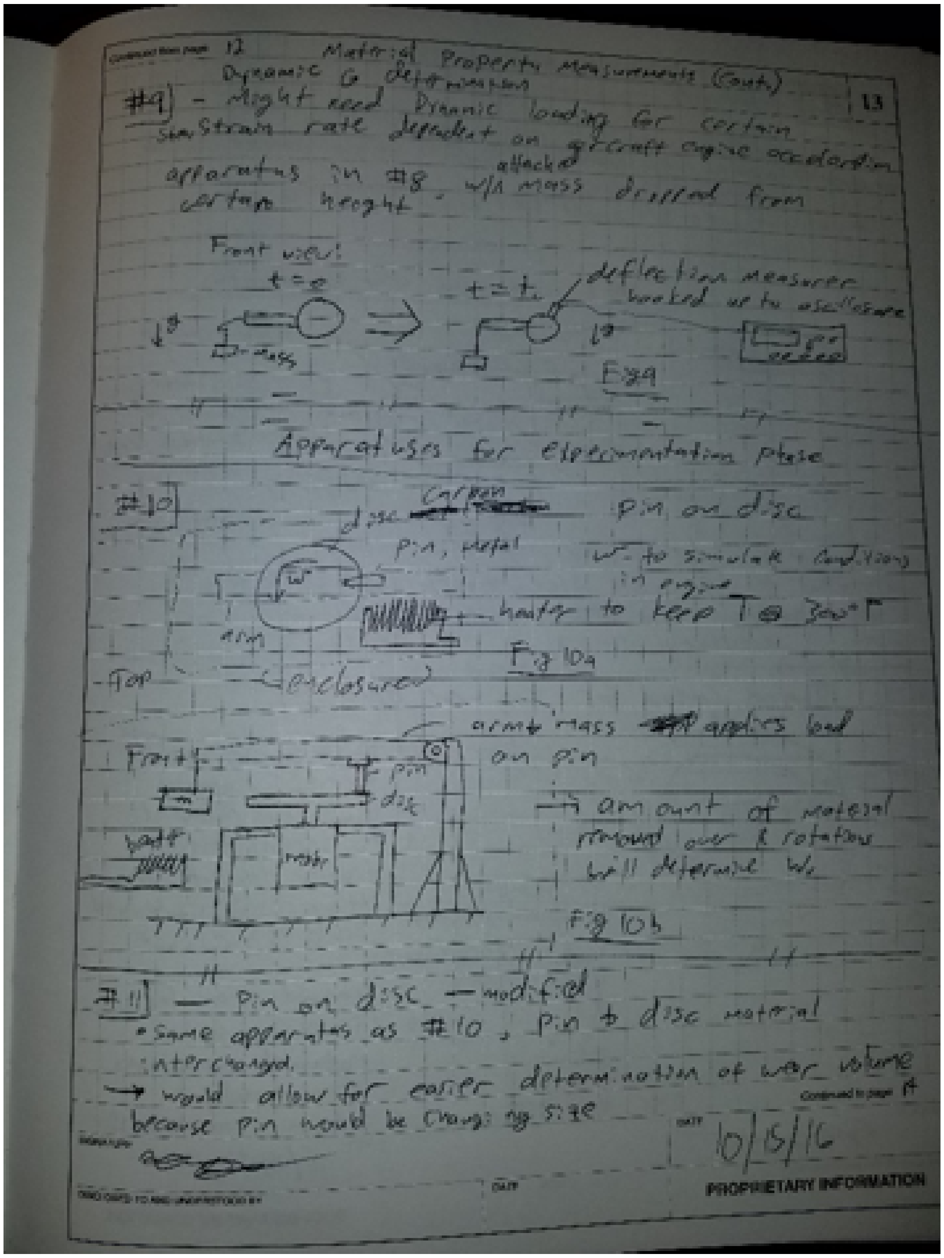
20.13 Appendix M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Material Property Measurements (Cont.)

Dynamic G determination

13

#9) – Might need Dynamic loading for certain Sh Strain rate dependent on aircraft engine acceleration

apparatus in #8, w/ attached mass dropped from certain height.

Apparatuses for experimentation phase

#10 pin on disc

ω to simulate conditions in engine

→ amount of material removed over X rotations will determine W_v

#11 — Pin on disc — modified

- Same apparatus as #10, pin & disc material interchanged.

→ would allow for easier determination of wear volume because pin would be changing size

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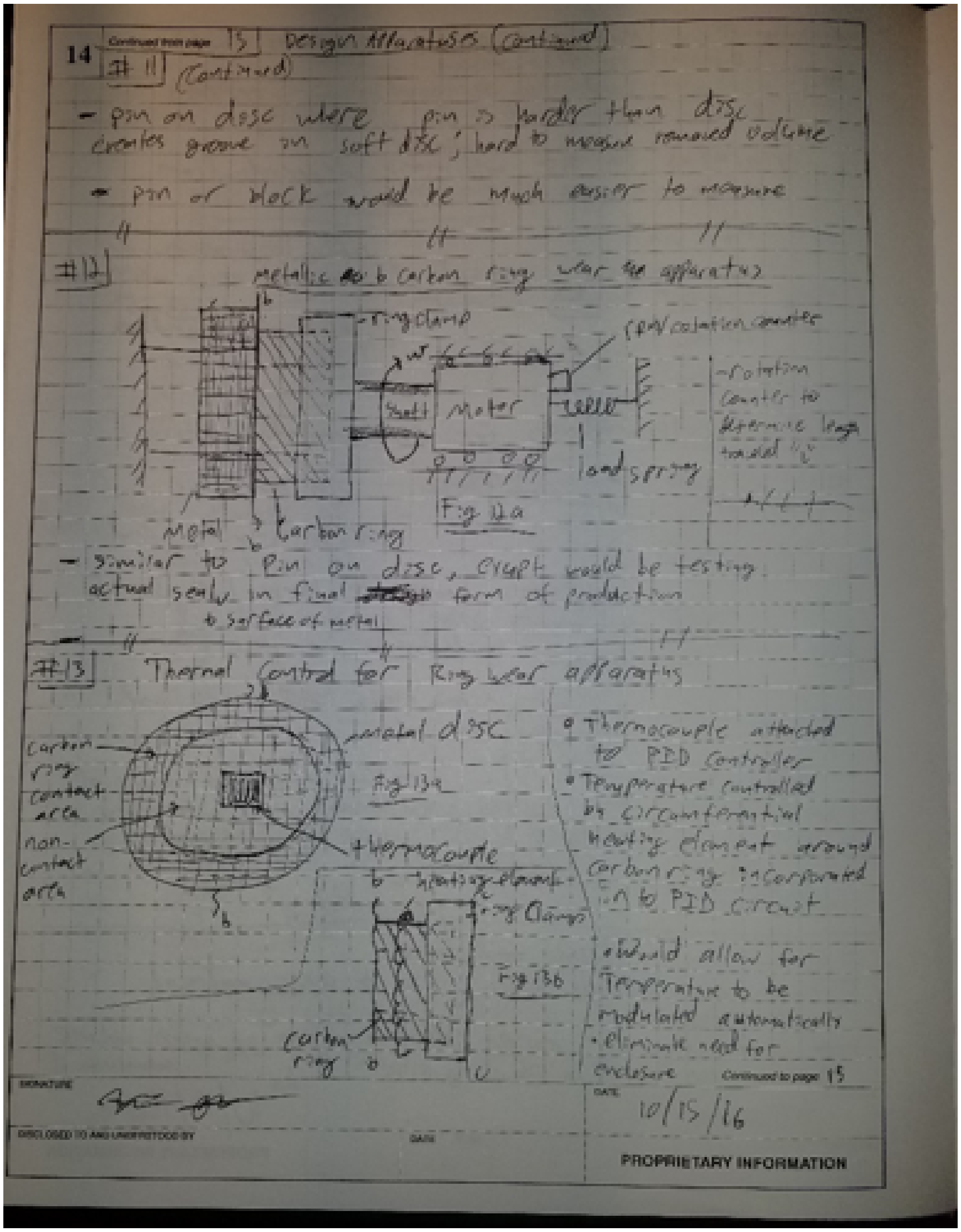
20.14 Appendix N



14 Continued from page 13 Design Apparatuses (Continued)

#11 (Continued)

- pin on disc where pin is harder than disc creates groove in soft disc; hard to measure removed volume
- pin or block would be much easier to measure

#12 metallic to carbon ring wear apparatus

- similar to pin on disc, except would be testing actual seals in final form of production
  to surface of metal

#13 Thermal Control for Ring wear apparatus

- Thermocouple attached to PID controller
- Temperature controlled by circumferential heating element around carbon ring incorporated into PID circuit
- Would allow for Temperature to be modulated automatically
- eliminate need for enclosure

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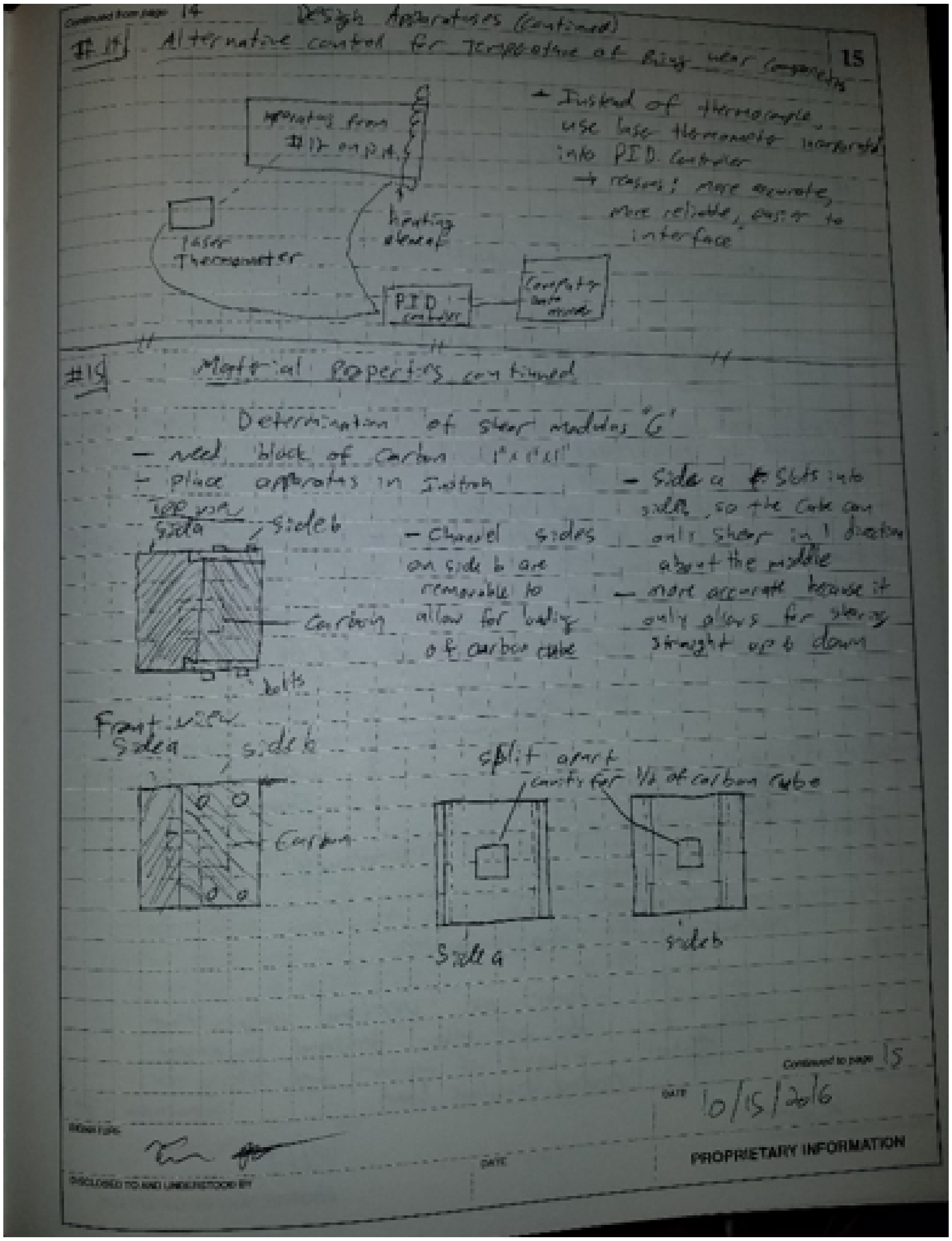
20.15 Appendix O



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Design Apparatuses (Continued)

#15 Alternative control for Temperature of Ring wear components

15

- Instead of thermocouple, use laser thermometer incorporated into PID controller
  → reasons: more accurate, more reliable, easier to interface

#15 Material Properties continued

Determination of shear modulus 'G'

- need block of carbon 1"x1"x1"
- place apparatus in Instron

- Channel sides on side b are removable to allow for loading of carbon cube
- Side a ~~#~~ slots into side b, so the cube can only shear in 1 direction about the middle
- more accurate because it only allows for shearing straight up & down

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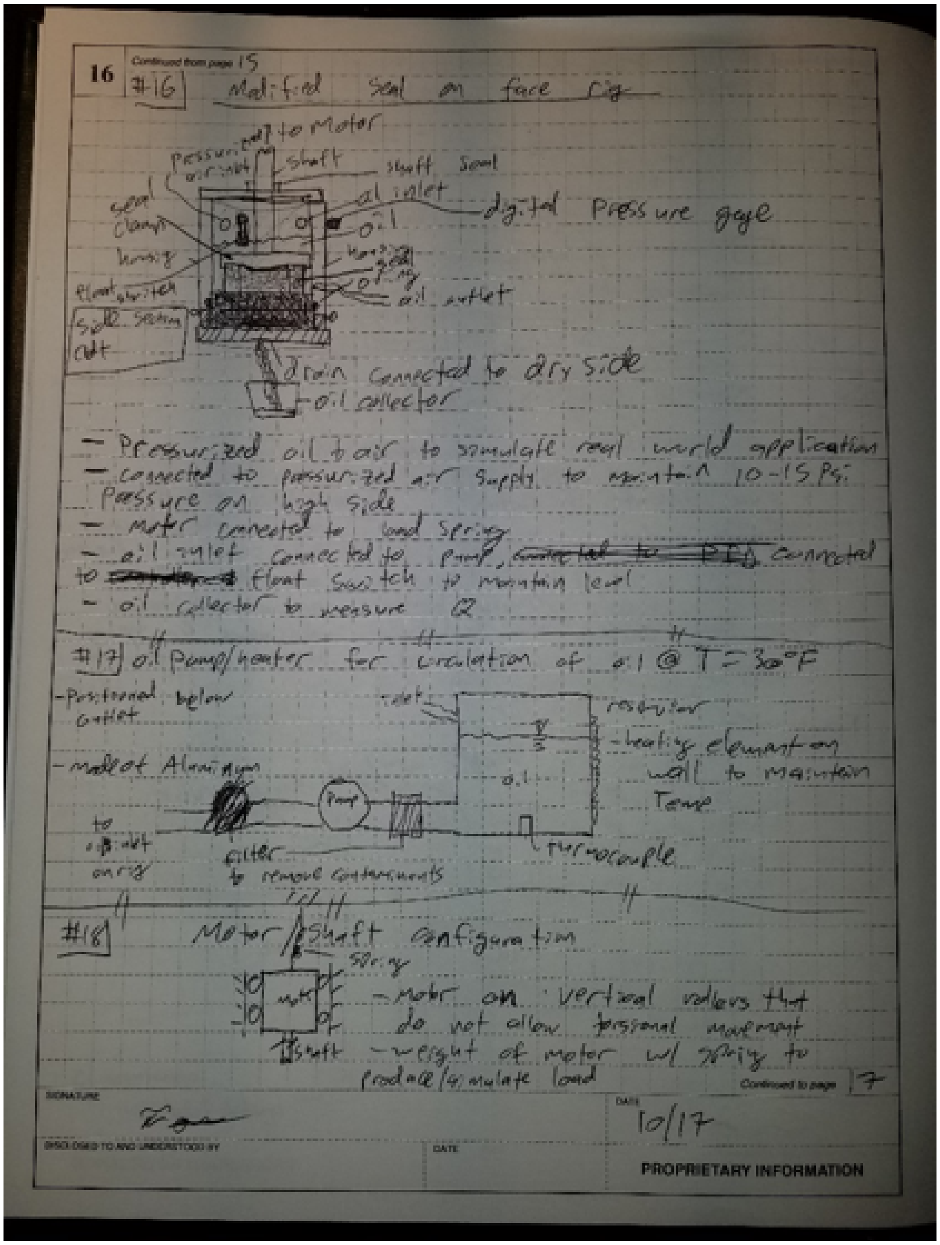
20.16 Appendix P



16 Continued from page 15

#16 Modified Seal on face rig

- Pressurized oil & air to simulate real world application
- connected to pressurized air supply to maintain 10-15 Psi Pressure on high side
- motor connected to load Spring
- oil inlet connected to pump, ~~connected to PID~~ connected to ~~[illegible]~~ float switch to maintain level
- oil collector to measure Q

#17 oil pump/heater for circulation of oil @ T = 30°F

- Positioned below outlet
- made of Aluminum

#18 Motor/Shaft configuration

- motor on vertical rollers that do not allow torsional movement
- weight of motor w/ spring to produce/simulate load

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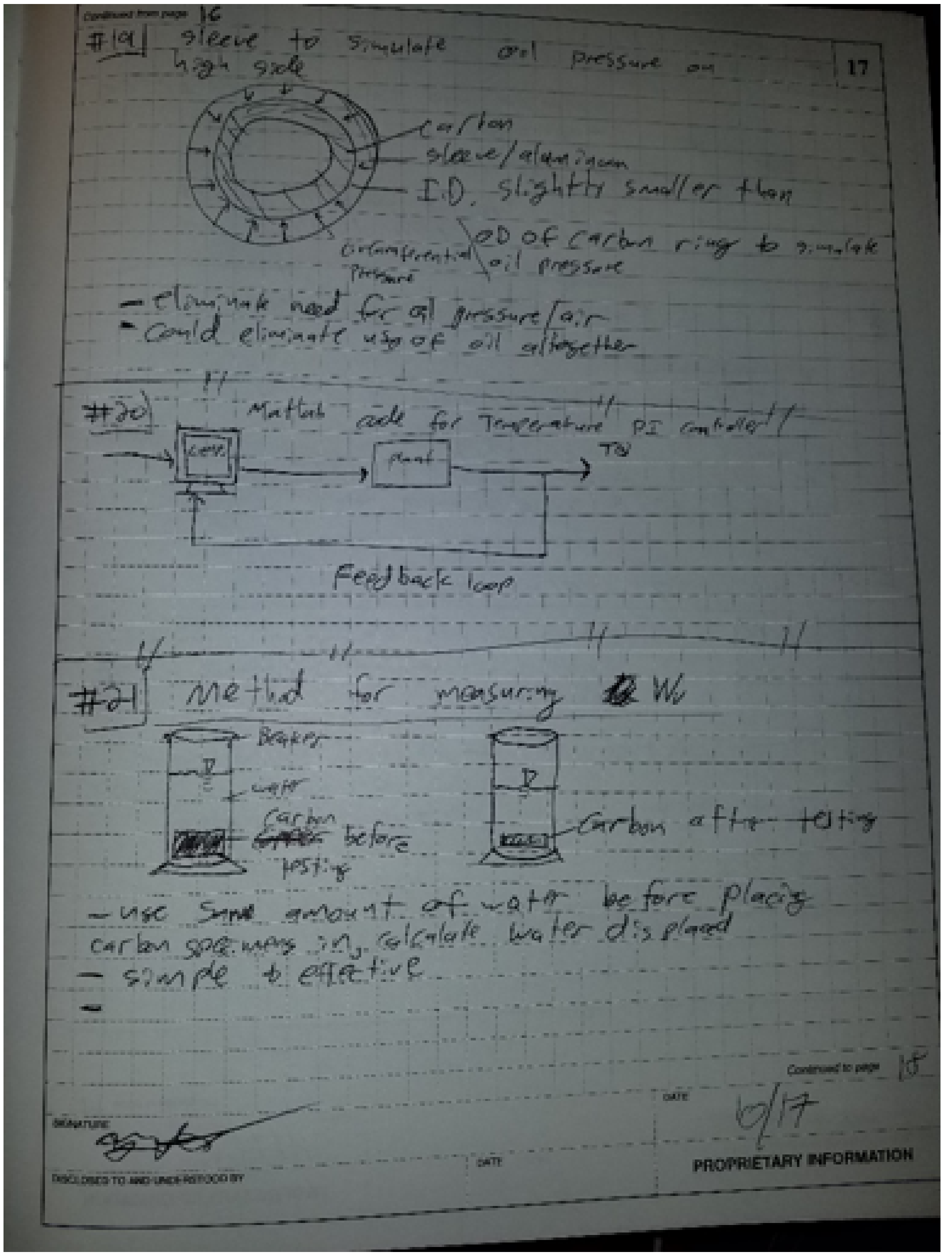
20.17 Appendix Q



Continued from page 16

17

#19 sleeve to simulate oil pressure on high side

carbon

sleeve/aluminum

I.D. slightly smaller than OD of carbon ring to simulate oil pressure

circumferential pressure

- eliminate need for oil pressure/air
- could eliminate use of oil altogether

#20 Matlab code for Temperature PI controller

cont.

plant

T

Feedback loop

#21 Method for measuring W

Beaker

water

carbon before testing

carbon after testing

- use same amount of water before placing carbon specimens in, calculate water displaced
- simple & effective
-

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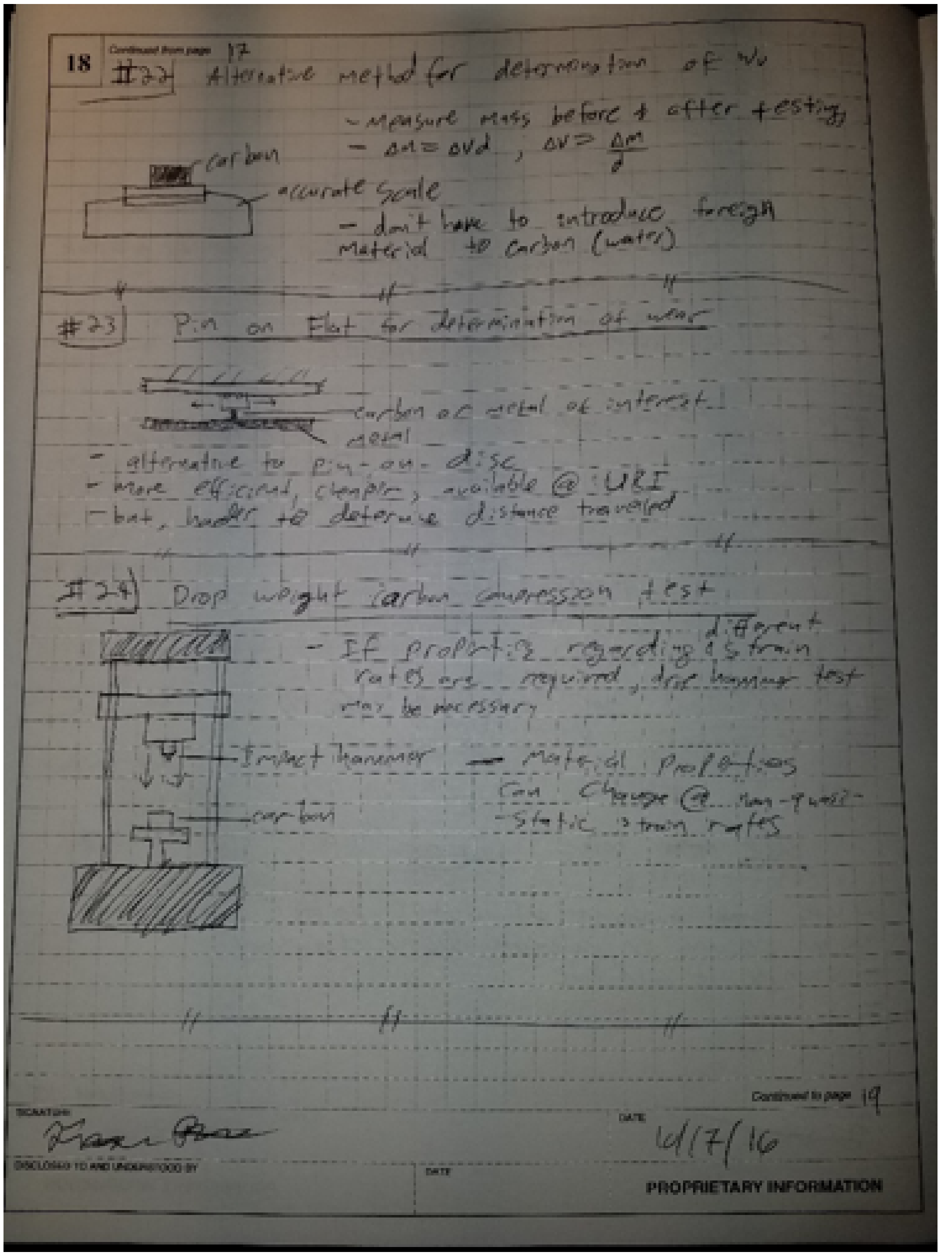
20.18 Appendix R



18 Continued from page 17

#22 Alternative method for determination of W_v

- Measure mass before & after testing
- $\Delta m = \Delta V d$, $\Delta V = \frac{\Delta m}{d}$

carbon

accurate scale

- don't have to introduce foreign material to carbon (water)

#23 Pin on Flat for determination of wear

carbon or metal of interest

metal

- alternative to pin-on-disc
- more efficient, cheaper, available @ URI
- but, harder to determine distance traveled

#24 Drop weight carbon compression test

- If properties regarding different strain rates are required, drop hammer test may be necessary

Impact hammer

carbon

- Material properties can change @ non-quasi-static strain rates

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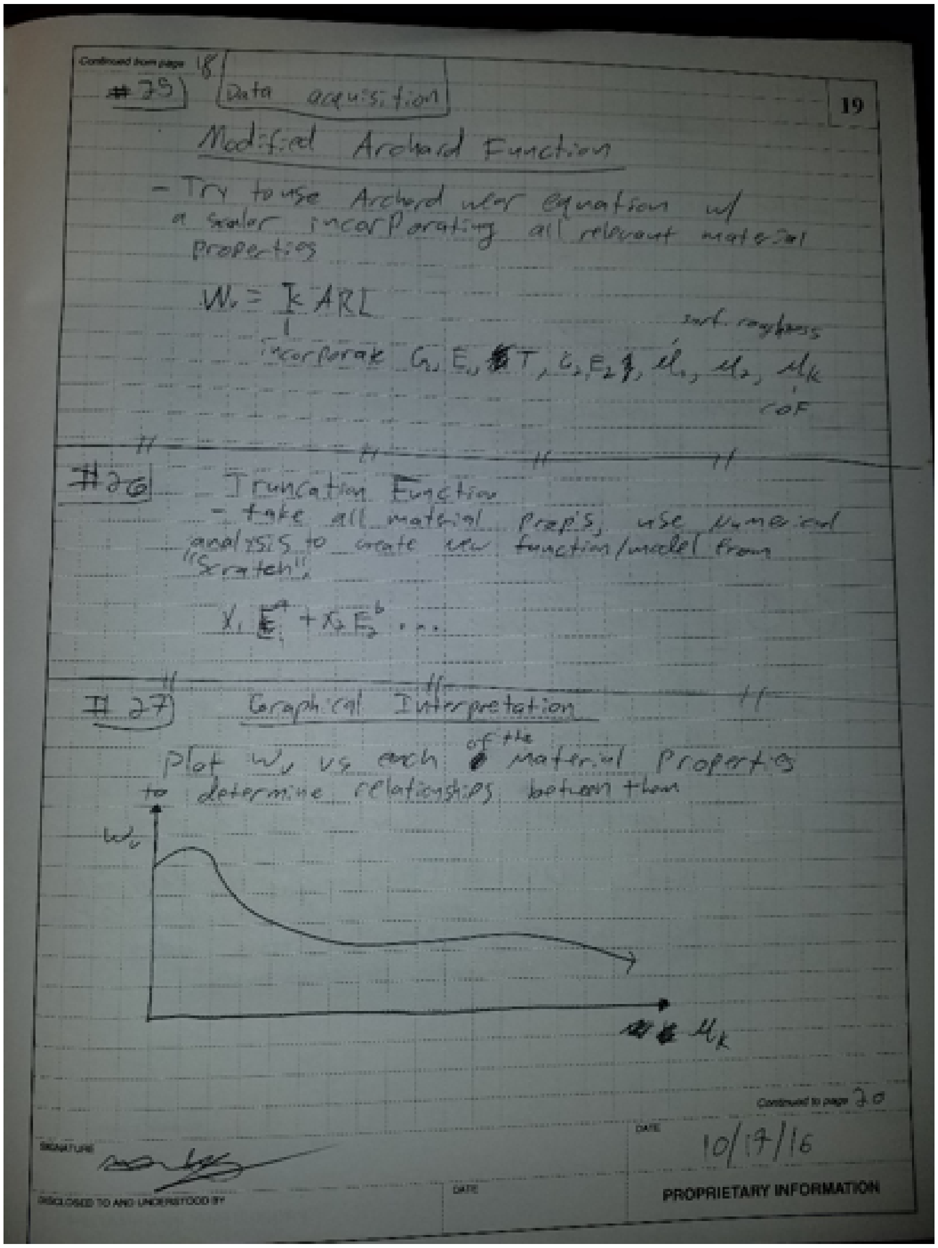
20.19 Appendix S



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19

#25) Data acquisition

Modified Archard Function

- Try to use Archard wear equation w/ a scalar incorporating all relevant material properties

$W_v = \underset{\uparrow}{k} A R L$

incorporate G_1, E_1, T, G_2, E_2, μ_1, μ_2, μ_k

surf. roughness

COF

#26 Truncation Function

- take all material prop's, use numerical analysis to create new function/model from "Scratch".

$x_1 E_1^a + x_2 E_2^b \ldots$

#27) Graphical Interpretation

Plot W_v vs each of the material properties to determine relationships between them

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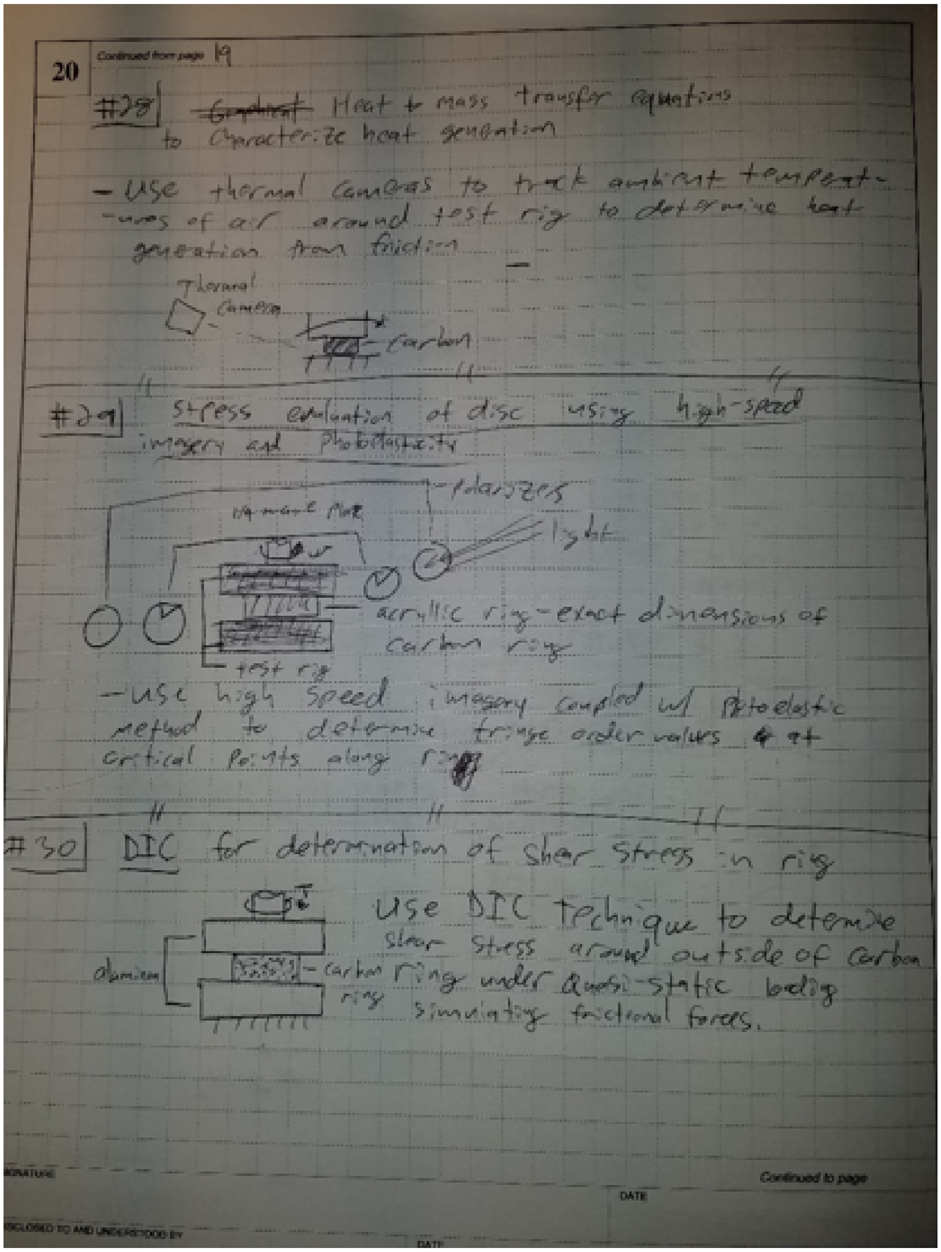
20.20 Appendix T



20 Continued from page 19

#28 ~~Graphical~~ Heat + mass transfer equations to characterize heat generation

- Use thermal cameras to track ambient temperatures of air around test rig to determine heat generation from friction

#29 Stress evaluation of disc using high-speed imagery and photoelasticity

- Use high speed imagery coupled w/ photoelastic method to determine fringe order values at critical points along ring

#30 DIC for determination of shear stress in ring

Use DIC technique to determine shear stress around outside of carbon ring under quasi-static loading simulating frictional forces.

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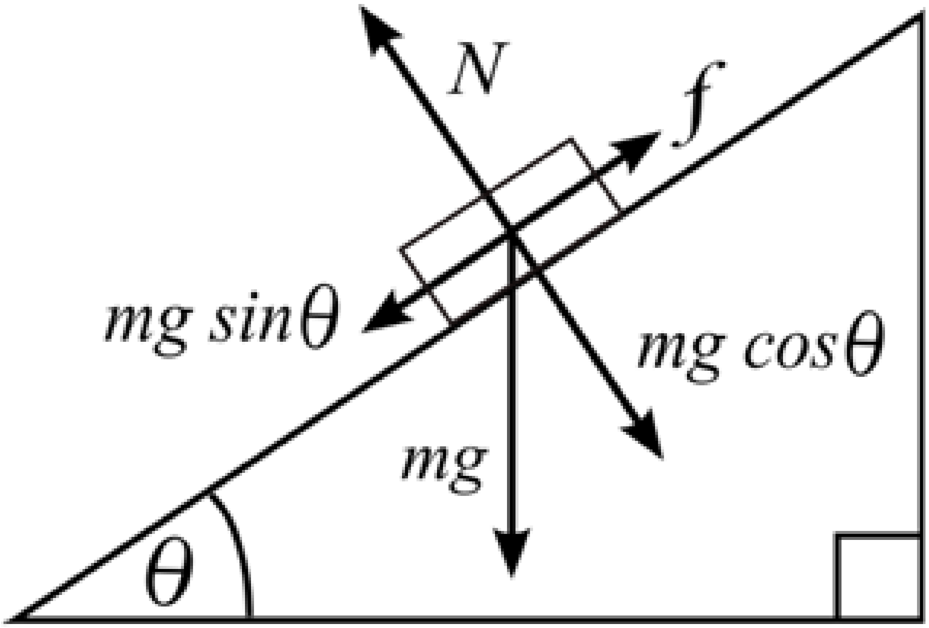
20.21 Appendix U



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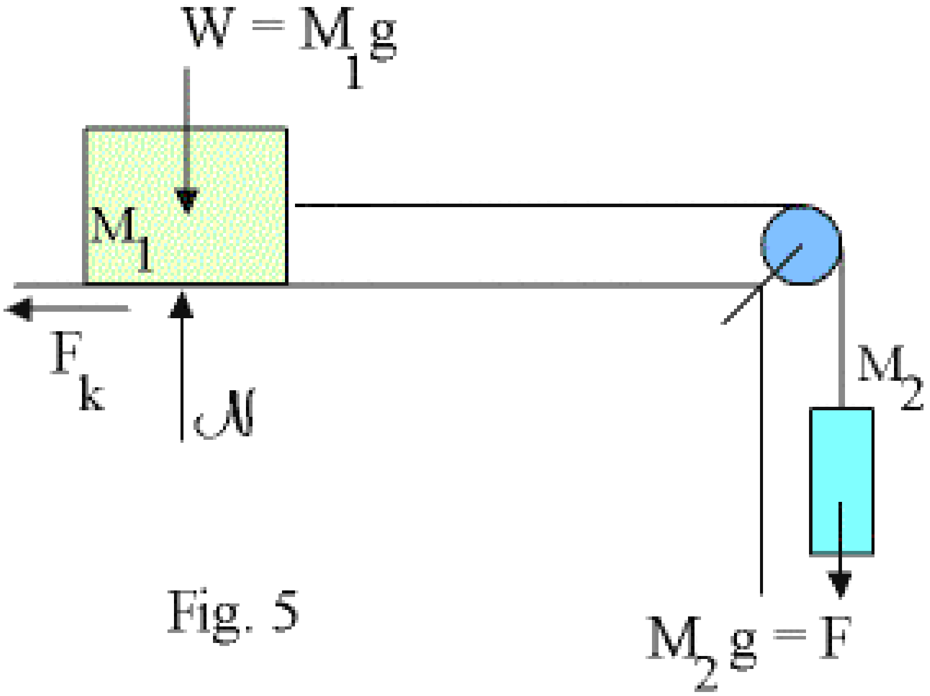
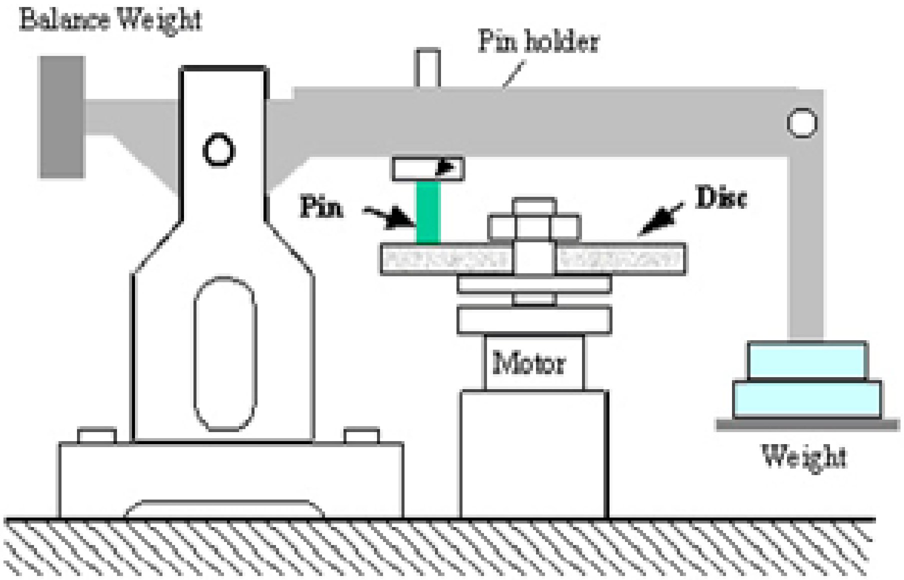


Fig. 5

20.23 Appendix W



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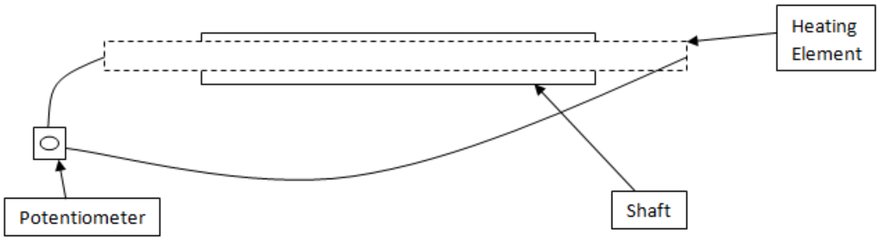

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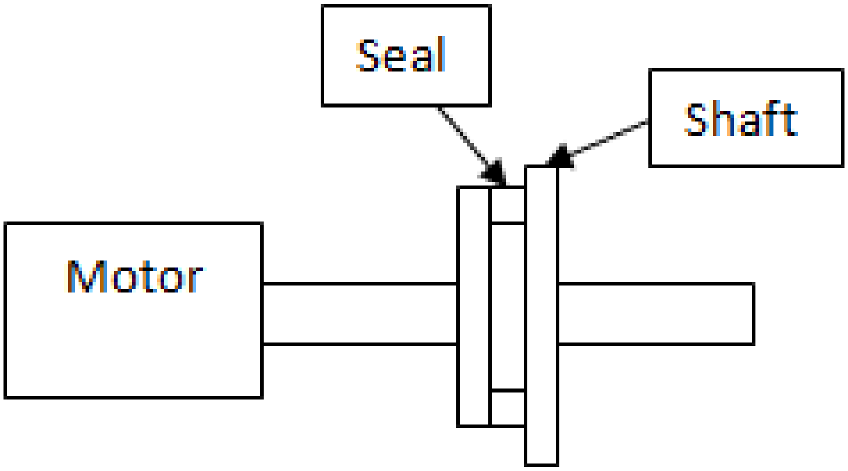
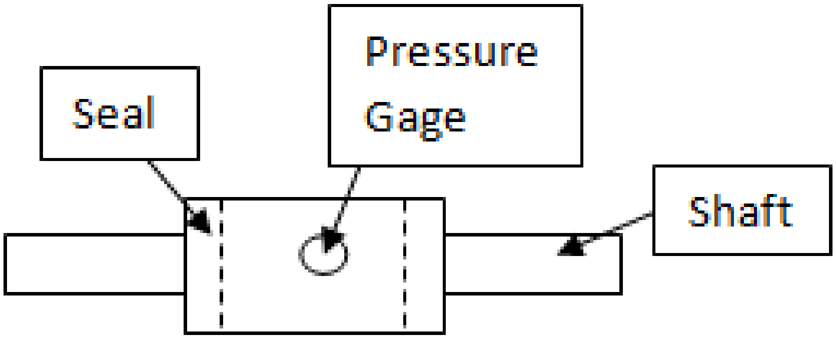
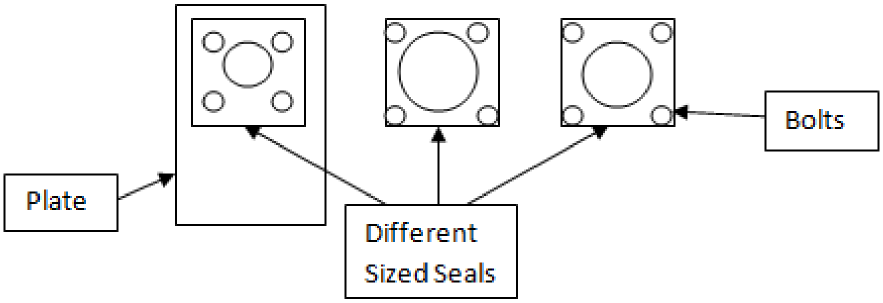


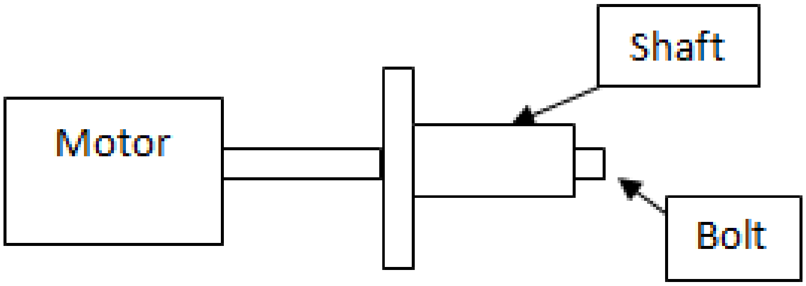
20.26 Appendix Z



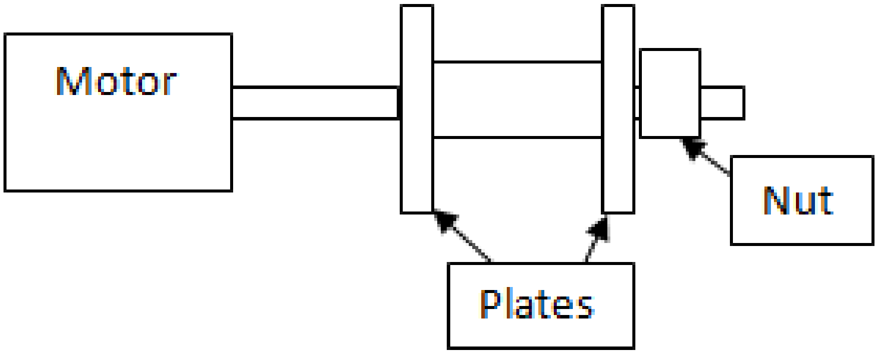
20.27 Appendix AA



20.28 Appendix AB



20.29 Appendix AC



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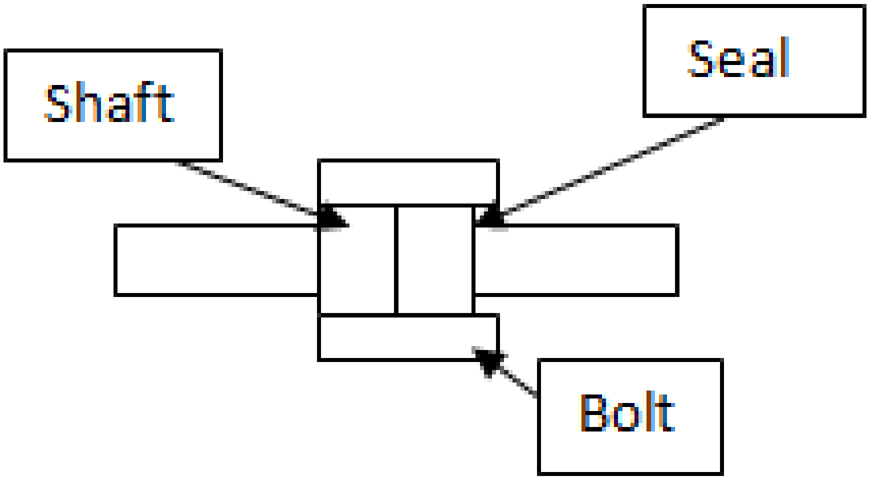
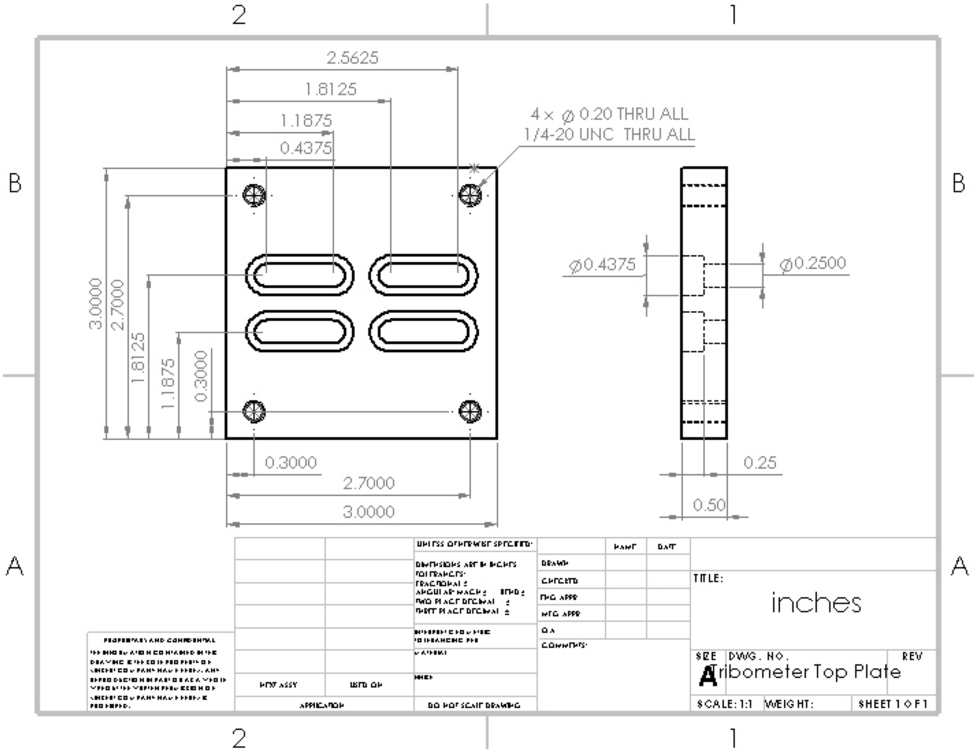
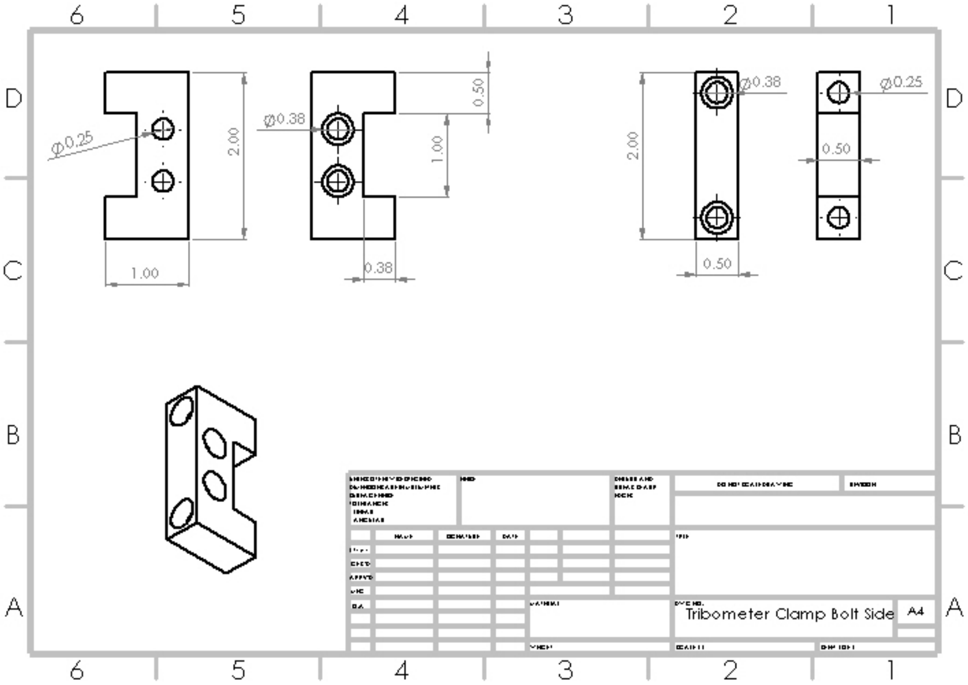


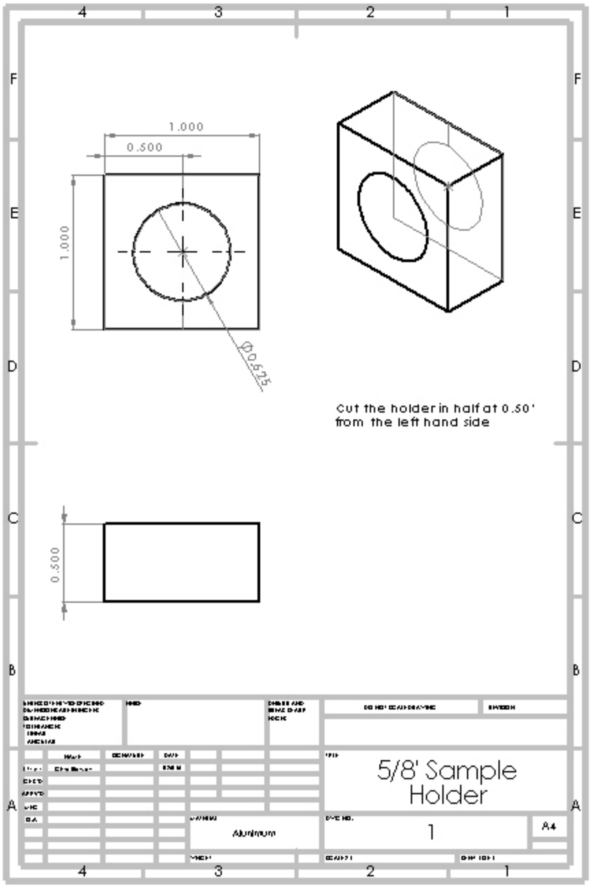
20.31 Appendix AE



20.32 Appendix AF



20.33 Appendix AG



Cut the holder in half at 0.50'
from the left hand side