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Team 501: Tribometer in Space Like Conditions

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Abstract

At the FAMU-FSU College of Engineering’s Aero-propulsion, Mechatronics, and Energy Center (AME), we are doing research to change the way we test materials by using a tool called a tribometer. It measures things such as coefficient of friction, which is how much two surfaces rub against each other. It also measures friction force, which is the force of the rubbing and wear volume, which is how much the surfaces wear down. Our tribometer is made to test materials in a vacuum, which is like the conditions in outer space. Setting up tests in this vacuum takes a lot of time and effort, so our tribometer needs to able to test many materials at once. This is important because it saves time and makes the testing more efficient. When designing this machine, we thought about things like how to handle different temperatures, how to put just the right amount of pressure on the materials, and how to accurately measure how much the materials wear out. We made sure the system would work well, is easy to use, and helps both researchers and people in industry. The final product is a tribometer that tests materials in conditions like outer space. This is a big deal in the world of material testing because it allows us to get more detailed and efficient results. This new system can get useful information faster and more accurately than older ways of testing. This is also important for industries like airplanes or cars, where it is important to know how materials will hold up in tough conditions like space.

Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

- Paragraph 1 thank sponsor!
- Paragraph 2 thank advisors.
- Paragraph 3 thank those that provided you materials and resources.
- Paragraph 4 thank anyone else who helped you.

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1.1 Project Scope

1.1.1 Project Description

The objective of this project is to design, develop, and implement a tribometer that enables the simultaneous testing of multiple samples within a vacuum chamber. . The project aims to supply one single scaled tribometer that has the ability to work jointly with five others. This system aims to increase testing throughput and enhance overall efficiency while maintaining prior accuracy and control.

1.1.2 Key Goals

The primary goal of this project is to enhance and expand the generation of big data concerning the tribology of materials. To achieve this, the tribometer will be designed to concurrently test multiple samples. The testing procedure will involve the precise application and control of a load on each sample to prevent material failure. Furthermore, the tribometer will be responsible for acquiring data related to wear measurements.

In addition to these requirements, the tribometer must also operate under space-like conditions, function in high vacuum environments and withstand extreme temperatures.

1.1.3 Markets

The primary market for this tribometer are researchers who wish to run multiple experiments with varying control and system inputs. That is, researchers who wish to perform tests on free variables such as materials, applied loads, temperatures, and environmental pressures. Some examples of these entities are NASA, Defense Contractors (Boeing, Lockheed Martin, Raytheon), Academic Research Labs, etc.

The secondary market involves the use of the system beyond its initial development. Once the system is operational, the secondary markets for this tool include aerospace companies, automotive industries, low friction coating companies, national laboratories, and any manufacturing and quality control companies. All these companies or industries would be able to benefit from the implementation of the system in their field.

The tertiary market, often referred to as the consumer market, would include individuals or organizations performing independent tribology studies on materials in space-like conditions for recreational purposes. These people or organizations operate downstream from the secondary markets.

1.1.4 Assumptions

Simplifications in the form of assumptions are required to complete the project in the allotted time. To begin, we assume that the materials that will be tested are polymers and coating materials. We assume that the vacuum chamber has preexisting electrical wiring, a cryogenic cooling system, and a means to produce and supply constant pressure and power. Also, we assume that applied loads and temperature settings will not exceed the minimum and maximum range. Furthermore, we assume that testing will be done by individuals who have satisfied the necessary safety training.

1.1.5 Stakeholders

A stakeholder is a group or individual who possesses interest, control, or investment in each project. In Table 1, the left most column displays who the stakeholders are.

Table 1
Stakeholders.

	Investor	**Decision Maker**	**Advisors**	**Receivers**

Sponsor 3M, AME	**X**			**X**
Manager Dr. Krick		**X**	**X**	**X**
Experts Dr. Krick, Dr. Ordonez, Dr. Vanderlaan			**X**	
Operators Graduate researchers, undergraduate students				**X**
General Readers Other educational institutions, materials companies, material hobbyists				**X**

1.2 Customer Needs

During the initial meeting with the project sponsor, Dr. Krick, a variety of customer needs related to the project scope were identified. Dr. Krick, as a professional and expert in mechanical engineering, materials science, and surface physics, plays a significant role in determining the project's focus. We followed up with Dr Krick and his graduate assistants, Kylie Van Meter and Adam Delong, a week later with more questions we thought pertinent to the project. The most crucial questions, answers, and interpretations from the meeting are summarized in Table 2 below.

Table 2
Customer Needs Questions, Responses, and Interpretations.

Questions	Responses	Interpretations
What do you want?	"I want to be able to test multiple samples at once." – Dr. Krick	The system tests multiple samples simultaneously.
What inputs would you like the system to accept?	"Temperature, contact stress, displacement of sample during slide, and number of samples tested." – Kylie Van Meter	The system reads-in and stores inputs.
What would you like the system to determine for you and output?	"Temperature, contact stress, displacement of sample, coefficient of friction, and wear rate." – Kylie Van Meter	The system returns outputs and critical targets from test results.
Do you want a visual display returned along with the parameter outputs?	"A graphical user interface (GUI) developed in MATLAB is expected." – Dr. Krick	The system is compatible with the previous graphical user interface.
Where will this project need to work?	"Ideally, in an ultra-vacuum however, ours will only achieves high vacuum." – Dr. Krick	The system can operate under vacuum conditions.

Do we need to modify the vacuum chamber?	"The conditions in the vacuum chamber are pre-set. The tribometer design needs to fit in the vacuum chamber and work under those conditions." -Dr. Krick	The system works inside a vacuum.
Do the different samples need their own inputs?	"The tribometer has to be able to apply different contact stresses to each sample in order to test the same material at different conditions." – Dr. Krick	The system can apply different inputs to different samples.
What do you consider a success for this project?	"A minimum success would be a single headed prototype that can be expanded in the future. A great success would be a functional model that can test 4-6 samples at once." – Dr. Krick	The system can test at least 1 sample, but ideally 4-6 samples.

From the interpreted customer needs, the most important need of the system is to run multiple tests simultaneously. While the system is running multiple tests simultaneously, the customer also needs the system to accept inputs, give outputs and perform in a vacuum. These are of the utmost importance due to our customers emphasizing them more than three times. In a few of the columns wants were expressed, we will consider these bonuses if successful.

1.3 Functional Decomposition

1.3.1 Introduction

Functional decomposition is the breaking down of larger actions and outcomes from the customer needs into smaller, more manageable and understandable parts or functions. The larger the action or outcome, the broader the overall categorical functionality; thus, further specification is required. The largest of the actions and outcomes posed for our project are inputs, outputs, and testing. To effectively organize our functions by systems, a hierarchy chart was created – Figure 1. To compare each function and determine which are most important a cross reference chart was created – Figure 2. The importance of each function was established by how many systems a particular function could satisfy.

1.3.2 Data Generation

The functions were determined based on both project scope and customer needs. These functions are meant to describe what the project needs to do and become more specific with the constraints outlined in the scope and customer needs. The customer needs were supplied by the primary market, Dr. Krick, Kylie Van Meter, Adam Delong and 3M. Their needs were interpreted into the functions of our system. The hierarchy chart in Figure 1 below shows the relationship of these functions.

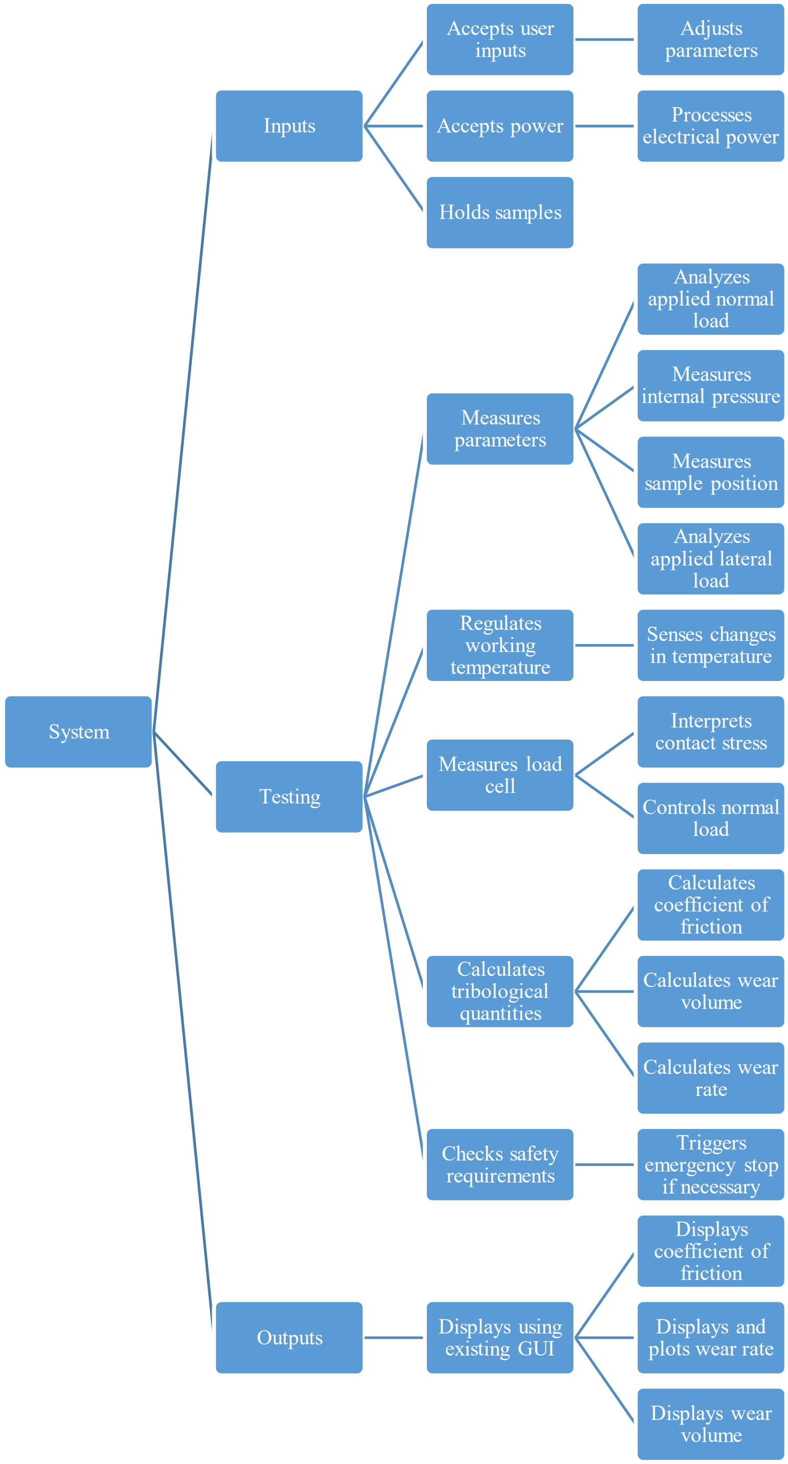


Figure 1. Hierarchy Chart.

1.3.3 Discussion

The objective for this project is to design and implement a system to test multiple samples simultaneously using a tribometer within a vacuum. Looking at our customer needs, we determined that it is necessary for the system to accept user inputs, be able to run tests, and give outputs back to the user. These high-level functions fall under the first level of the design for the system.

The first group selected on our functional hierarchy chart was input. The system will be responsible for accepting user input. This will allow the user to run the tribometer under the specific parameters they wish. The system must also be able to measure parameters such as temperature, load, and pressure as well as displacement and the coefficient of friction of the sample. Temperature must be accounted for because it affects the mechanical properties of the samples which in turn affect friction and wear. The load applied must be accounted for to determine contact force between surfaces, greater contact force leads to greater wear. Pressure distribution can affect the overall wear pattern of the sample and must also be accounted for. Displacement provides information on the wear pattern and deformation of the materials in contact, wear rate is a function of the displacement of the sample and therefore is necessary to control. Lastly, the system will be able to store these inputs for calculations and so the user and future users can review the parameters set for testing and make changes when necessary.

The next high-level function of the system is testing. The testing function pertains to everything the tribometer will do within the vacuum chamber. First, the tribometer will initiate sensor readings. While the system is running within the vacuum it will test applied normal force under the controlled parameters mentioned above for at least one sample. The normal force represents the load applied perpendicular to the sample and surface in contact. It directly impacts the contact force, wear, and deformation of the sample which all can be used to calculate the coefficient of friction of the sample. The system must also test for an applied lateral force under controlled parameters for at least one sample. The lateral force is the resistance to relative motion between the sample and the surface. It is responsible for overcoming the friction between the surfaces. Using the results from the forces applied the system will then be able to calculate the critical targets, coefficient of friction and wear rate. Ideally, the system will be able to perform these tests to multiple samples simultaneously.

The last high-level function for the system is output. Outputs are essential because they serve as the results for testing. The system returns stored inputs to validate the conditions established for the test. The system should use the conditions set by the user to return critical targets based on the test to calculate the desired outputs, coefficient of friction and wear rate. Tribometry is the study of friction and wear, therefore they should be explicitly outputted by the system. The resultant outputs would be used to clarify the mechanical properties of the different samples.

1.3.4 Functional Relationships

Table 3
Functional Cross Reference Table.

	Inputs	Testing	Outputs
Accepts user input.	X	X	
Accepts power.	X	X	
Holds samples.	X	X	
Measures parameters.		X	X
Regulates working temperature.	X	X	X
Measures load cell.		X	X
Calculates tribological quantities.		X	X
Checks safety requirements.	X	X	X
Displays using existing GUI.			X

The functional cross-reference above gives an overview of the priority level for each system based on the number of functions required by each of the final goals of the project. Testing ranks above every function in the system followed by outputs and then inputs. The chart also serves as a reference guide for the function's relationships and the way they interact in the overall system. The overlap between the functions and their respective categories demonstrates how each category helps the next. The input parameters provided by the user set the tribometer up for testing and the test results are then used for calculations which are outputs of the system.

By using the chart, we determined that two subcomponents are critical for our system to function correctly. Regulating working temperature is a function that is first established by the user in the inputs section, then it keeps working through the testing conditions and is displayed in the outputs to calculate the critical targets expected from our system. Also, interpreting contact stress has a similar roll because when establishing a load parameter in the inputs, the system uses the contact area of the sample to interpret a stress in the testing section, and finally displays this stress in the output section to calculate parameters such as wear rate.] Inputs represent the data the system takes in from both the user and sensors. This section is the least important according to the output of the cross-reference table. However, the most important factors to the inputs categories consist of user inputs, active measurements, and storing initial inputs to output later.

The testing feature is where the set inputs create the wanted environment and the system starts its process to determine the desired outputs for the material. During the test, sensor readings must be initiated and then a normal and lateral force will be applied. The sensors will work to keep the environment steady and to gather data for the critical targets.

In this system, the functional relationships among the various components and outputs work together to form the overall system. The system begins by storing the initial inputs related to the sample then it measures the contact stress applied to the sample. It calculates the coefficient of friction and wear rate. Additionally, the system displays the coefficient of friction, wear rate, sample displacement, contact stress, and temperature to convey information to users. Overall, integrated functional relationships are vital for the system.

1.4 Target Summary

After determining the functions for a system that uses a tribometer in spacelike conditions, each function was assigned a target and given metrics. Each function is given at least one metric that defines the function into either a quantitative or qualitative measurement and some functions have multiple metrics to further define its role. A target is given to each metric, so that a goal that the system must attain is defined. The fully developed target catalog is in Appendix C: Target Catalog. The success of this project will be defined by the achievement of these individual targets.

1.4.1 Critical Targets/Metrics

We defined our critical targets and metrics by referencing our objective, customer needs, and functional cross reference chart in Table 3. Based on the objective and customer needs the most important functions are holding the samples and calculation of tribological quantities. From the cross functional reference chart, the most important functions are the regulation of temperature and the safety requirements. These functions are critical because they apply to all the columns in the table and therefore, are active at all times in the system. Additionally, we were able to further validate these critical targets and metrics using our advisor, Dr. Brandon Krick. Our critical targets and metrics are shown below in Table 4.

Table 4
Critical Targets and Metrics.

System	Function	Metric	Target	Unit
Inputs	Holds samples	Number of samples held	4-6	Count
		Types of samples held	2	Count
		Time to load samples	30	Minutes (min.)
Testing	Senses changes in temperature	Resolution of temperature	1	Celsius (°C)
		Ideal error for readjustment	±1	Celsius (°C)
		Marginal error for readjustment	±5	Celsius (°C)
		Readjustment while transient	±10	Celsius (°C)
		Max temperature	200	Celsius (°C)
		Min temperature	-100	Celsius (°C)
Testing	Calculates coefficient of friction	Calculates value	0 - 1	
		Error of calculation	10	Percent (%)
		Ideal resoluble range	0.01 - 0.5	
		Marginal resoluble range	0.05 - 0.4	
Testing	Calculates wear volume	Calculates value	0.05 - 50	Millimeters cubed (mm^3)
		Height loss resolution	5 - 50	Micrometers (μm)
Testing	Calculates wear rate	Calculates value	10^{-4}-10^{-7}	Millimeters cubed per Newton meter (mm^3/Nm)
		Error of calculation	±5	Percent (%)
Testing	Trigger emergency stop	Time to kill	0.3	Seconds (s)

1.4.2 Targets/Metrics Derivation

The function of holding the samples is a critical target because the customer explicitly stated that the goal of this project was to test 4-6 samples simultaneously using a tribometer within vacuum. Therefore, our most important target is the 4-6 samples that the system must be able to test simultaneously. This function also has two other metrics and targets it needs to reach. There are many different types of samples a tribometer can test. After discussions with Adam Delong, the target for our system is to be able to test 2 different kinds of samples. This will add to the versatility and future uses of the system. The last metric for this function is the time it takes to load the samples. The overarching goal for the system is to increase efficiency and work throughput of using a tribometer within a vacuum. The 30-minute target was set benchmarking from prior tests using a tribometer within a vacuum. The target number represents the same efficiency as prior experiments, beating the target represents a higher efficiency than prior experiments.

The testing function of the tribometer is crucial. The tribometer will need to sense the temperature change. This includes the ability to go to a maximum temperature of 200 degrees Celsius, a minimum of -100 degrees Celsius, resolution of temperature, the ideal error for readjustment, marginal error for readjustment, and including readjustment while in transient. This is all incredibly important to providing the best results for sensing the temperature change. Next, the system must calculate the coefficient in friction, which involves calculating the value, then the error of calculation, the ideal resoluble range, and the marginal resoluble range. Testing must also measure wear rate and wear volume, which both involve an error of calculation. Finally, safety is an essential subfunction of the testing function. The device must have the ability to trigger an emergency stop. During the emergency stop, the DC power will need to be diverted. When that happens, the device will stop to protect the device and its user.

Since this project outputs the desired parameters in a graphical user interface designed in MATLAB, most of the outputs are going to be displayed in a plot. The system uses stored inputs and a series of equations written in a MATLAB script to calculate the desired critical targets such as wear volume rate, coefficient of friction and number of cycles done by the testing. The graphical user interface of this project is not going to be made from scratch. An already existing graphical user interface will be connected to our system to test its functionality. However, the MATLAB script that returns our critical targets should be written by our software engineer if time permits to avoid returning values outside the project's scope.

1.4.3 Method of Validation

Validation of the targets is vital to ensure each component of the system is working properly in getting its task done. The critical targets of the system fall into the input and testing functional categories. Breaking this down further and looking at one function of the system at a time, the team will formulate a systematic method of validation for each of the targets deemed critical. These methods will occur after the concept generation and selection when a functional prototype is being fabricated, during validation the team can see which functions are working and which are not to make corrections and improvements for the final design.

Holding samples is the only input considered a critical target, it means that the system can test 4-6 samples and the tests can be run on two different kinds of samples. To clarify, a different kind of sample would be considered the different shapes of a sample such as round or square not the material a sample is made of. To validate that the system meets these specifications the team would have to have the functional prototype run the tests and see that 4-6 samples being tested are working simultaneously and to make sure that it works with two different kinds of samples. To validate that the time it takes to load a sample meets the goal of 30 minutes the team can set up the tests 10 times and use a timer to find how long it takes each time.

These can be averaged together to get an estimate for validation without having to run the prototype.

The temperature regulation is our key parameter to simulate a close space-like environment. For temperature regulation we have two ranges that need to be controlled: high temperature, which has a maximum of 200 degrees Celsius, and sub-zero temperatures, which have a maximum negative range of -100 degrees Celsius. We need a heater able to withstand temperatures greater than the max temperature so we can avoid any overheating problems in the system, and something constructed entirely of low-outgassing materials. This is an important constraint when working in vacuum chambers. Because of the space constraint, we need lightweight heaters that will allow us to apply heat where it is needed, reducing overall operating cost, and the low mass construction should save space. We will be using liquid nitrogen supplied through a plumbing system to create low temperatures. We will need a material with high thermal conductivity so it can decrease thermal resistance and reach the desired temperature by conduction as fast as possible. To validate both high and low temperatures, we will need a sensor to continuously check the temperature in the material. If the temperature remains within ±5 degrees Celsius of the desired temperature, we can affirm our temperature regulation is working properly.

The coefficient of friction is the parameter that governs the force required to move a test sample at a constant speed. This coefficient (μ) is obtained by dividing the frictional force by the applied normal force. There are two primary coefficients of friction: the static coefficient of friction, which quantifies the force required to initiate motion, and the kinetic coefficient of friction, which characterizes the force needed to sustain motion. Our primary focus in this system is on the kinetic coefficient. To validate this calculation, we will utilize the predefined applied load (N) and the measured frictional force (F) to compute the coefficient of friction. The applied load will be manually input and continuously controlled to remain within a ±3% margin of the set load. The frictional force will be a variable that is found utilizing testing equipment. The applied load and frictional force value will be verified using a load cell, which detects and quantifies the applied force. The mechanical stress on the load cell will be transduced into electrical signals by strain gauges. The error in the force calculations will be assessed using the root mean square method, accounting for standard tolerance levels associated with off-the-shelf load cells and strain gauges. To calculate the coefficient of friction, the frictional force (F) will be divided by the normal force (N). The load cell's manufacturer's data sheet will specify the resoluble range and marginal resoluble range, and the signal resolution will be determined in accordance with the load cell manufacturer's data sheet.

The wear volume is the volume loss of the sample during testing worn away by friction. The wear volume (ΔV): $\Delta V = V_i - V_f$ where V_i is the initial volume of the sample and V_f is the final volume of the sample. However, the system will need to calculate real time data for volume loss. This can be achieved by measuring the dimensions of the sample prior to testing and comparing the value to the real time data acquired. The sample volume can be measured during testing using a sensor to track its height loss. The error of calculation is associated with the tools that will be used to measure the wear volume loss.

The wear rate is a direct function of the change in volume of the sample, force on the sample and the distance traveled. The formula for wear rate (K): $K = \frac{\Delta V}{F_n D}$ where ΔV is the change in volume of the sample, F_n is the normal force and D is the displacement. Therefore, to calculate wear rate, these other values must be measured throughout testing. The measurement of the change in wear volume is mentioned above. The normal force can be measured using a load cell. Load cells measure normal forces by detecting changes in electrical resistances from the strain gauges attached to it. The displacement can be measured in many ways, two of the most common are a predefined stroke length of the tribometer and having sensors giving real time feedback of the displacement of the sample. The error of calculation can be measured using uncertainty propagation.

During testing, an emergency stop must be implemented. The tribometer must have the ability to be halted/stopped manually or automatically. The target for the emergency stop is to divert the input of DC power, which is 120 Volts (V). This will add an extra safety measure to protect the tribometer, its samples, and most importantly the users. The samples are highly essential, so, during testing the samples must be protected during events of failure, making the emergency stop even more valuable. To validate this function, switches will be used that will give the ability to stop a single sample without impeding the other samples and this can be tested outside of the vacuum and inside of the vacuum without loaded samples to verify the success of the emergency stop. This will help protect the data collected by other samples in case of failure.

1.5 Concept Generation

The process of generating concepts is most effectively undertaken using tools such as morphological charts, biomimicry, crapshoot, forced analogy, anti-problem, and battle of perspectives. The concepts ideated through these methods are detailed in Appendix D. Highlighted below are the top three high-fidelity and top five medium-fidelity concepts. Predominantly, the anti-problem tool was employed for concept generation.

1.5.1 Concept Generation Tools

The initial challenge addressed was devising a way for the sample to either fall or not be held in place. Potential solutions included removing the normal load, eliminating a mounting point, or suspending the sample with a string. Consequently, we developed a sample holder design that applies a normal load, potentially incorporating a set screw or clamp for securing the sample.

Next, we tackled how to avoid regulating the chamber's temperature. Suggested non-solutions involved leaving the heater or nitrogen supply continuously or excluding temperature control elements. This reverse brainstorming led us to a design that uses heaters and nitrogen to control the temperature range effectively.

The third problem was how to not calculate the coefficient of friction. By considering the elimination of the friction surface, applied load, and translational or rotational forces, we were guided to a solution that involves a frictional surface capable of rotation or translation relative to the test sample's bottom plane.

Lastly, we questioned how to ensure the system remains operational during emergencies. Contrary suggestions included maintaining uninterrupted power, ensuring the vacuum continues, and omitted a kill switch. These discussions brought us to the implementation of a kill switch that can swiftly terminate power in an emergency.

1.5.2 High Fidelity Concepts

Concept 1: Six Mini-Identical Tribometers Side by Side

The tribometer setup will feature six mini-tribometers arranged in two rows, with each row containing three devices positioned back-to-back. We will focus our analysis on a single tribometer unit. This tribometer will employ two slides to exert normal and lateral forces, which will be measured using load cells and strain gauges. It will include a copper slide chosen for its excellent thermal conductivity, paired with a detachable surface that induces friction. To regulate the temperature, Minco space heaters will warm the copper slide to up to 200 degrees Celsius, while a cooling system, anticipated to incorporate Swagelok components, will dissipate excess heat. This will essentially be a combination of the humidity and nitrogen cooled tribometers systems used at the lab. Figure 2 is a rough sketch of the concept.

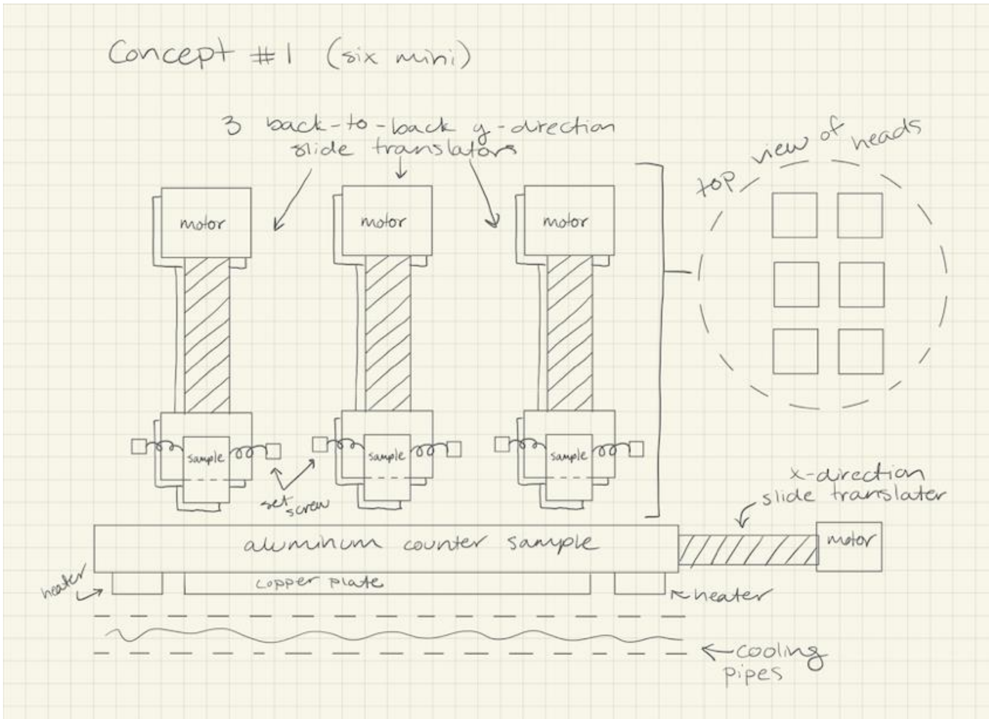


Figure 2. Six Mini-Identical Tribometers Side by Side.

Concept 79: Cross-Headed Sample Holder

This tribometer system works with a cross-headed sample holder in the top where four samples are loaded into the system, and it tests one sample at a time. After finishing the first test, a motor on top of the crosshead sample holder will rotate the head so the next sample will be tested. The parameter conditions applied to each sample are independent from each other. After ending each test, the system accepts the new inputs to regulate the parameters for the next test. The shape of the sample holder ensures there is no cross contamination between tests. The advantage of this system is that four samples can be tested without removing vacuum. Figure 3 is a rough sketch of the concept.

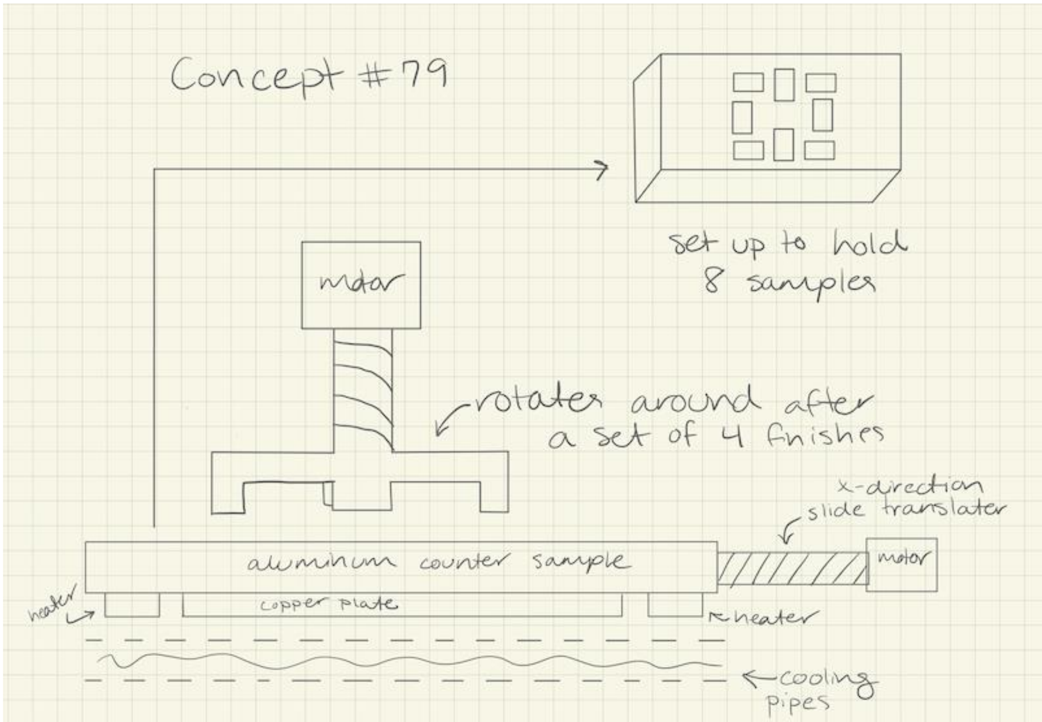


Figure 3. Cross-Headed Sample Holder.

Concept 4: Weights Loaded on Samples to Produce Normal Load

This tribometer system features a series of six hollow tubes, each designed with an end capable of securing a sample via set screws. Upon the placement of a predefined mass into the tube for y-axis translation, ensuring proper contact. Meanwhile, a separate mechanism facilitates x-axis movement to generate friction on the sample's bottom surface. The system incorporates a thermally conductive copper slide with a replaceable friction surface. Temperature control is achieved through Minco space heaters and a Swagelok component-based cooling system. All signal and signal processing hardware will be selected at a later date. Figure 4 is a rough sketch of the concept.

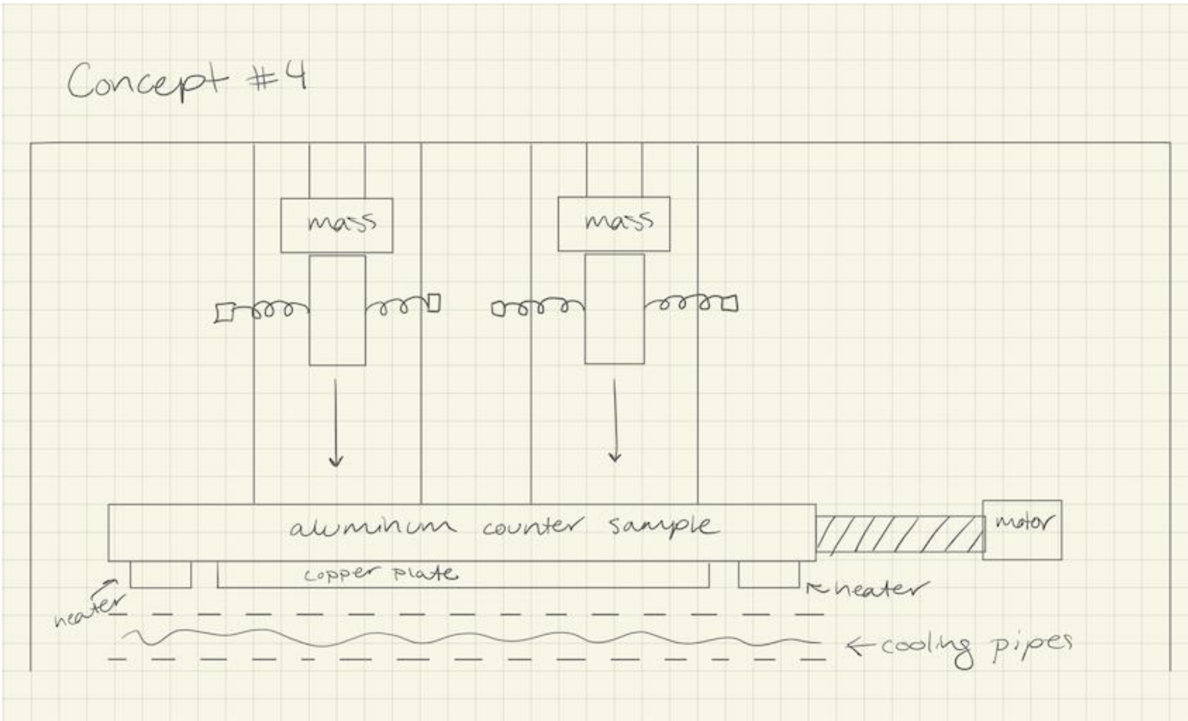


Figure 4. Weights Loaded on Samples to Produce Normal Load.

1.5.3 Medium Fidelity Concepts

Concept 97: Tribological Samples are Nested Together

This concept involves changing the way a traditional tribometer holds test samples. It places progressively smaller specimens within each other, allowing for testing at different scales in a single experiment. Sample preparation will be crucial to prevent errors or inaccuracies when testing. Each sample would still need its own testing parameters. This can be accomplished by testing the outermost sample and working inwards towards the smallest sample. The advantage of this concept is that it will allow comparison of samples side by side, allow testing of different sample sizes and the time that would be saved pressurizing the vacuum chamber. Figure 5 is a rough sketch of the concept.

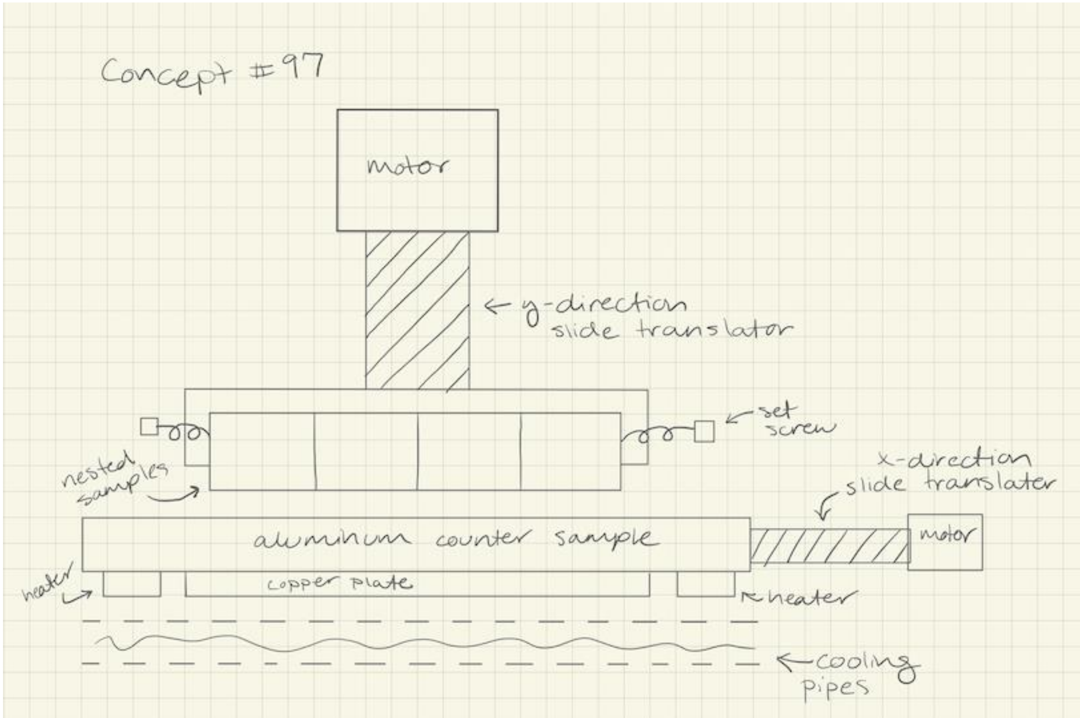


Figure 5. Tribological Samples are Nested Together.

Concept 8: Pin-on-Disk Tribometer with Four Different Samples at Different Radii

This system consists of a variation of the Pin-on-Disk Tribometer where more than one sample is tested using the same contact surface. The samples are going to be held simultaneously at different radiuses on a disk which is going to rotate using the torque generated by a motor. This system will allow the user to test 6 different samples at the same time. The samples are going to share conditions such as temperature and pressure, but parameters such as normal force applied on the sample can vary. The advantage of this concept is the amount of data collected from one test. Figure 6 is a rough sketch of the concept.

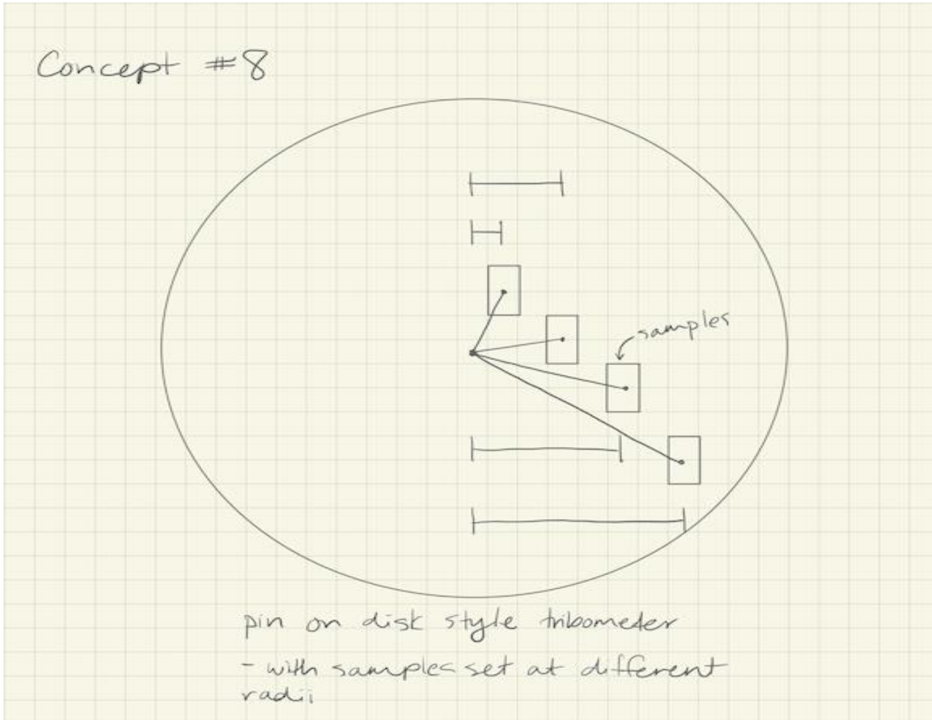


Figure 6. Pin-on-Disk Tribometer with Four Different Samples at Different Radii.

Concept 52: Inverted Existing Tribometer

This concept puts a spin on the traditional tribometer setup. Traditionally, the tribometer head holds a sample flush to a translational stage. In this design the translational stage is between the tribometer head and the sample. This modification enhances the versatility of the tribometer. This new configuration allows for finer control of parameters, improved accessibility of the samples, and reduced contamination from tests. This concept can test multiple samples by using a batch testing method. Multiple samples can be aligned in the testing chamber and texted by the overhead translational stage. Other options for high throughput testing include an automatic sample loader and a rotating lower platform to switch between samples. Figure 7 is a rough sketch of the concept.

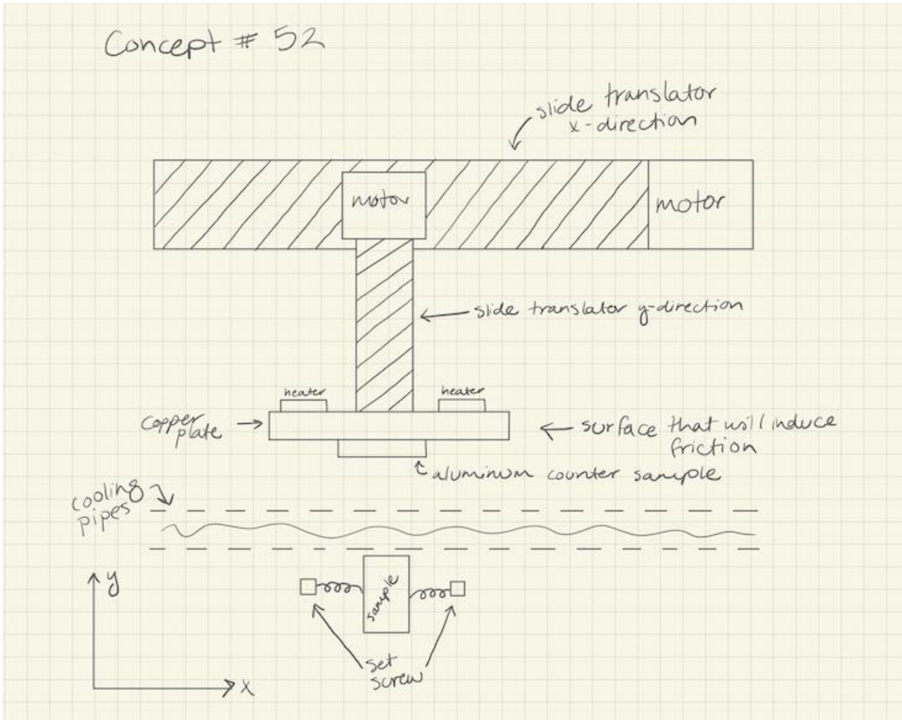


Figure 7. Inverted Existing Tribometer.

Concept 51: Rake Tribometer

This concept involves designing the arms similar to a rake. By doing this the user can test up to six samples at once. It involves a motor in the y-direction applying a similar load onto each sample. A motor in the x-direction is used to slide the aluminum counter sample against the samples. Cooling and heating are connected to the aluminum counter sample to regulate heating and cooling. The advantage of this concept is the high throughput of samples. Figure 8 is a rough sketch of the concept.

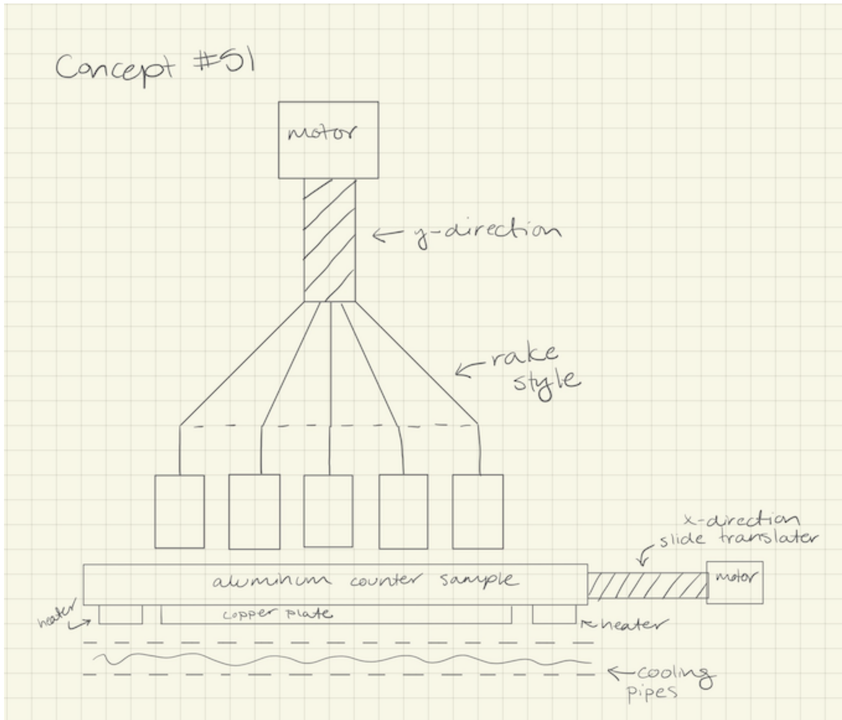


Figure 8. Rake Tribometer.

Concept 89: Modular Tribometer

This concept involves designing a system for a tribometer that will have interchangeable parts which can include sample holders, load cells, stages and sensors. This versatility of the tribometer will allow for the test of multiple samples depending on the conditions needed for the test. The idea behind this concept is to design the tribometer in a way that it can be easily assembled and disassembled. Standardized interfaces, rail systems, mounting plates, quick release fasteners, and interchangeable stages are all ways to make a modular tribometer. The advantages of this design will be the flexibility it offers, the reduced cost due to the interchangeable parts and the scalability for future use. Figure 9 is a rough sketch of the concept.

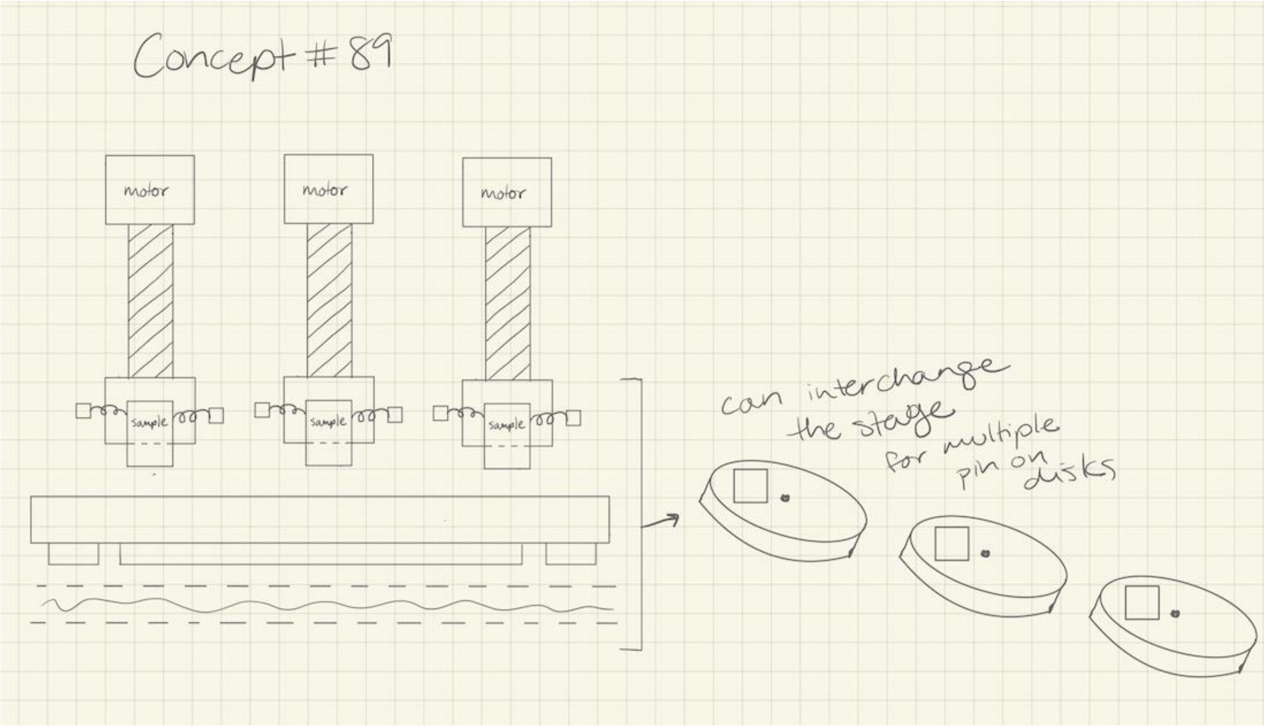


Figure 9. Modular Tribometer.

1.6 Concept Selection

The process of selecting and identifying the highest quality concept involves a variety of important tools. We were able to utilize the Binary Pairwise Comparison (BPwC), House of Quality (HoQ), Pugh Charts, Analytical Hierarchy Process, and a Final Concept Selection Chart. All the charts utilized in the process of selecting and identifying the highest quality concept are found in Appendix E.

1.6.1 House of Quality (HoQ)

The process to pinpoint the highest quality concept begins in the BPwC. This chart works by comparing the customer needs with each other. The need listed in each row was juxtaposed against itself in each column, assigning a value of 1 when deemed more critical, and a 0 for less critical, while a dash marked the matrix's principal diagonal. The results of this matrix produce priority targets that are utilized inside of the House of Quality. The customer needs used in the BPwC are listed in the table below.

Table 5
Customer Needs Used in BPwC.

Customer Needs
1. Works Inside a Vacuum
2. Operate in Spacelike Conditions
3. Reads and Stores input
4. Test 4-6 Samples
5. Compatible with previous GUI
6. Applies Unique Inputs to Unique Samples
7. Tests Multiple Samples Simultaneously
8. Reads and Stores Inputs

The priority target customer needs were given a weight factor and categorized from most important to least important. The target customer's need with the greatest weight factor was works inside a vacuum. The target customer need with the least weight factor was tied between test multiple samples simultaneously and returns outputs and critical targets.

Using these weight factors in the HoQ as well as engineering characteristics that originate from our targets and metrics, we were able to rank the customer needs. To begin, the needs were ranked in the form of a value of 0, 1, 3, or 9. In this case zero correlates to a null impact from the engineering characteristic on the specific target requirement. Whereas nine correlates to a large impact from the engineering characteristic on the specific target requirement. The values given were multiplied by their respective weights and then summed up. This results in a respective raw score value. The raw score value was then divided by the summation of all raw scores to produce a relative weight percent. The engineering characteristics were then ranked according to the largest relative weight percent calculated. That is, the highest percentage is equivalent to the most important characteristic whereas the lowest percentage is equivalent to the least important characteristics. According to the HoQ the most important engineering characteristic of designing our system is the holding of the samples followed by analyzing applied loads and processing electrical power. The two least important characteristics are the calculation and display of outputs. This is acceptable because of sponsor, Dr. Krick, has expressed the main focus of this project to be the simultaneous testing of multiple samples. The complete HoQ chart is in Appendix E.

Table 6
Ranked Engineering Characteristics.

Engineering Characteristics
1. Holds Samples
2. Analyzes Applied Loads
3. Processes Electrical Power
4. Measures Internal Pressure
5. Senses Changes in Temperature
6. Emergency Stop
7. Display Outputs
8. Calculates Outputs

1.6.2 Pugh Chart

The Pugh Chart is used to compare viable design choices. The design choices selected were the high and medium fidelity options – they are outlined in section 1.5. To utilize a Pugh Chart effectively, a market leading datum is to be selected, so that our concepts can be benchmarked against the datum. Our team decided it was advantageous to use the current leading tribometer style that is utilized in the tribology lab in the AME building as our datum. To develop and produce accurate comparisons our team utilizes '+', '-', and 'S' characters. The '+' character suggests that the particular idea achieves the customer's needs better than the current solution. The ‘-’ character suggests that the particular idea achieves the customer’s needs worse than the current solution. The ‘S’ character suggests that the idea achieves the customers’ needs at the same satisfaction as the current solution. As the process continues the medium ranked solution is selected as the datum, the highest ranked solutions are selected for comparisons, and the lowest ranked solutions are removed from the process. The initial Pugh Chart is shown below split between Table 7 and Table 8.

Table 7
Market Pugh Chart.

Market Pugh Chart						
			Concepts			
Selection Criteria	**Criteria Weight**	**AME Humidity Tribometer**	**Pin on Disk Tribometer that Can Run Four Different Samples at Four Radii**	**Inverted Existing Tribometer**	**Rake Tribometer**	**Modular Tribometer**
Processes Electrical Power	13.4%	Datum	S	S	S	S
Holds Samples	22.4%		-	+	-	-
Measures Internal Pressure	12.6%		+	+	+	+
Analyzes Applied Loads	16.8%		-	+	-	-
Senses Changes in Temperature	12.6%		+	+	+	+
Calculates Outputs	6.4%		S	S	-	-
Emergency Stop	8.1%		+	+	+	-
Display Outputs	7.6%		S	S	S	-
Pluses			3	5	3	2

Minuses	2	0	3	5

Table 8
Market Pugh Chart Cont'd.

Market Pugh Chart Cont'd.						
			Concepts			
Selection Criteria	**Criteria Weight**	**AME Humidity Tribometer**	**Six Mini-Identical Tribometers Side by Side**	**Cross Headed Sample Holder**	**Weights Loaded on Samples to Produce Normal Load**	**Tribological Samples are Nested Together**
Processes Electrical Power	13.4%	Datum	S	S	S	S
Holds Samples	22.4%		+	+	+	-
Measures Internal Pressure	12.6%		+	+	+	+
Analyzes Applied Loads	16.8%		S	-	+	-
Senses Changes in Temperature	12.6%		+	+	+	+
Calculates Outputs	6.4%		S	S	S	S
Emergency Stop	8.1%		+	+	+	+
Display Outputs	7.6%		+	S	S	S
Pluses			5	4	5	3
Minuses			0	1	0	2

Based on the data, the Cross Headed Sample Holder idea was our medium successful idea. Thus, it became the next Pugh Chart iterations datum. The ideas that were deemed quality and continued in the selection process were Six Mini-Identical Tribometers Side by Side, Weights Loaded on Samples to Produce Normal Load, and the Inverted Existing Tribometer.

We followed the same comparison process as we did in the initial Pugh Chart and achieved results that could be used in the final Pugh Chart. We found that the Inverted Existing Tribometer would become our new datum. It became our new datum because it was better than the Cross Headed Sample Holder at calculating and displaying outputs. By this, it means that the new datum can obtain more outputs at a faster rate and display them in a shorter amount of time. Additionally, we found that the Six Mini-Identical Tribometers Side by Side and the Weights Loaded on Samples to Produce Normal Load would be the final ideas to be compared. The final Pugh Chart is show below in Table 9; however, all the Pugh Charts are shown in Appendix E.

Table 9
Final Pugh Chart.

Concept Pugh Chart				
			Concepts	
Selection Criteria	Criteria Weight	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Processes Electrical Power	13.4%	Datum	S	S
Holds Samples	22.4%		S	-
Measures Internal Pressure	12.6%		S	S
Analyzes Applied Loads	16.8%		S	+
Senses Changes in Temperature	12.6%		S	S
Calculates Outputs	6.4%		S	+
Emergency Stop	8.1%		S	S
Display Outputs	7.6%		S	S
Pluses			0	2
Minuses			0	1

1.6.3 Analytical Hierarchy Process (AHP)

Using the Analytical Hierarchy Chart, we can establish weights for our selection criteria so it can help us to determine our desired final selection. The chart compared our criteria against each other to determine how better one criterion was compared to the other. We ranked each comparison with odd numbers from 1 to 9, and the criteria that we determined to be more important gets to keep its rank number while the one that is less important gets the inverse value of the rank. A value of 1 would mean equivalent importance, but a higher value would mean dominance from that criterion over the other.

After assigning a value for each comparison in the table, we proceeded to normalize these values in a different comparison matrix. The normalized criteria comparison was made by dividing the value of each individual cell by the total addition of the entire column. Using the results of the normalized chart, we set criteria weights by averaging each row horizontally outputting values that will establish the influence each criterion in our design selection. Now, with these weights the Weighted Sum Vector and Consistency Vector were calculated using matrix operations and vector division. Finally, with these two values a consistency ratio was calculated.

1.6.4 Final Selection

To identify the best solution for our problem, we applied the aforementioned procedure to each established criterion. We pitted the three remaining concepts from the Pugh chart, Inverted Tribometer, Six Mini-identical Tribometers, and Weights loaded on samples Tribometer, against each other. Ideally, the consistency ratios (CR) should be below 0.10, this indicates little to no bias is involved. This assessment was conducted for all eight criteria under consideration for this project, and detailed tables and charts presenting the results can be found in the document's appendix. A CR of 0.55 was established in the holds sample criterion signifying there may be some bias.

We computed a Final Rating Matrix to show the performance of each concept across each criteria. These values were then employed to assess the overall performance of each concept by multiplying them with the pre-established criteria weights determined in the AHP. The matrix operation involved transposing the Final Rating Matrix and subsequently multiplying it by the criteria weight matrix, yielding three final values. The highest among these values signifies a design that is best for the given task and is our final selection.

It was determined from the Final Rating Matrix that a tribometer with weights loaded on samples to produce normal load is the best solution to testing multiple samples simultaneously using a tribometer in a vacuum. However, the concept of six mini-tribometers side by side came in a close second place. Therefore, we will consult with our sponsor, Dr. Krick, with both ideas indicating our preference for a system that uses weights loaded on samples to produce normal load as shown in Figure 4.

1.8 Spring Project Plan

Chapter Two: EML 4552C

2.1 Spring Plan

Project Plan.

Build Plan.

Appendices

Appendix A: Code of Conduct

Mission Statement

The mission of our team is to support Dr. Krick and 3M by designing a tribometer that functions in space-like conditions.

Modes of Communication

The primary modes of communication will be Microsoft Teams, email, and text messages or phone calls. Microsoft Teams will be used to communicate responsibilities and deadlines with fellow team members. Emails will be used to communicate with our sponsor. Text messages or phone calls will be used for rapid communication. Response times to all modes of communication should be as quick as possible.

Team Roles

Branham Channell

Mechanical engineer for the project. Will act as the primary materials engineer. As the materials engineer, this individual will make the final decision on all things pertaining to material selection, manufacturing processes, and testing material properties under space-like conditions.

Cobi Johnson

Mechanical engineer for the project. Will act as the primary systems engineer. As the systems engineer, this individual will make the final decision on all things pertaining to the installation, configuration, and integration of the system's working parts.

Javier Ibanez

Mechanical engineer for the project. Will act as the primary structural engineer. As the structural engineer it is expected that the final decision will be made by this individual on all things pertaining to final mechanical design, ensuring that the design is stable and can withstand space-like conditions such as extreme temperatures and vacuum.

Madison Retherford

Computer engineer for the project. Will act as the primary mechatronics engineer. As the mechatronics engineer, this individual is expected to decide on all things pertaining to designing the electronic control systems, including sensors and data acquisition.

Joshua Wesley

Electrical engineer for the project. Will act the primary computer hardware engineer. As the computer hardware engineer, this individual will make the final decision on all things pertaining to selecting, designing, and testing the computer hardware components.

Note: All members are expected to participate in the final decisions for the project. However, it is up to the primary engineer of each respective category to be the face of the final decision. Should other duties arise, individuals will be assigned on an as needed basis.

Outside Obligations

Branham Channell

Monday: Class 11:00-12:15 pm, Work 1:00--5:00 pm

Tuesday: Class 3:30-7:45 pm

Wednesday: Work 6:00-10:30 am, Class 11:00-12:15 pm, Class 5:30-8:00 pm

Thursday: Class 3:30-7:45 pm

Cobi Johnson

Tuesday: Class 2:00 – 3:15 pm, Class 3:30 - 7:45 pm

Thursday: Class 2:00 – 3:15 pm, Class 3:30 - 7:45 pm

Work Schedule TBD

Javier Ibanez

Monday: Work 8:00-1:00 pm or Work 1:00-6:00 pm

Tuesday: Class 8:00-7:30 pm

Wednesday: Work 8:00-1:00 pm or Work 1:00-6:00 pm

Thursday: Class 8:00 -6:00 pm

Friday: Class 1:15-2:30 pm, Work 6:00-11:00 pm Work 8:00-1:00 pm or Work 1:00-6:00 pm

Saturday: Work 1:00-6:00 pm, Occasional Association Events (Whole Day)

Sunday: Occasional Association Events (Whole Day)

Madison Retherford

Monday: Class 11:00-12:15 pm, Class 12:30-1:45 pm

Tuesday: Class 11:00-12:15 am

Wednesday: Class 11:00-12:15 pm, Class 12:30-1:45

Thursday: Class 11:00-12:15 am

Friday: Senior Design class at 9:30 but not required because I follow

Mechanical SD

Saturday: Flexible availability

Sunday: General flexible availability

Joshua Wesley

Monday: Class 9:30 -10:45 am, Class 2:00-3:15pm

Tuesday: Class 9:30-10:45 am, Class 11:00-12:15 am

Wednesday: Class 9:30-10:45 am, Class 11:00-12:15 am

Thursday: Class 9:30-10:45 am, Class 11:00-12:15 am, Lab 3:30- 6:15Friday: Class 9:30-10:45 am,

Saturday: Times may vary on availability

Sunday: Church 10-12, Times may vary on availability

Meeting

Weekly meetings will occur according to the best available time according to the when2meet. Extra meetings will occur as needed or at the sponsor's request. If a team member misses a meeting, one days' notice to the team via email is required. If notice is not given, it will be noted as an offense against the guilty team member.

Team Rules

Each team member is expected to perform assigned tasks to the best of their abilities and on time. If an individual is unable to complete a task on time, one days' notice to the team via email is required. Also, team members are expected to represent the team inside and outside of the classroom professionally. Lastly, an email or Team's chat is to be sent to all team members prior to the submission of an assignment.

Dress Code

Business professional attire is required at all design reviews. Casual attire is required at all sponsor meetings and at all team meetings.

Attendance Policy

Individuals are expected to attend all meetings. If a conflicting commitment arises, one days' notice to the team via email is required. A running attendance log will be maintained throughout the project and uploaded to the team's page for archives.

Conflict Resolution

Offenses: Missing team meetings, missing deadlines for assignments, lack of quickness in response time to team members. All offenses will be recorded and uploaded to the team's page for archives.

- First Offense: The team will contact the guilty party via one of the modes of communication.
- Second Offense: The team will contact the guilty party via email, and Dr. McConomy will be carbon copied on the email.
- Third Offense: Dr. McConomy will be contacted to explain the issues.
- Four or more: For subsequent offenses, Dr. McConomy will subtract 2% from the team member's final grade.

Making Amendments

Amendments to documents will occur only in the case of a majority vote - 3 people. A running log of amendments with their respective dates will be added to the end of the Code of Conduct.

Statement of Understanding

By signing the document below, each member affirms that they have read the rules and principles outlined in the Code of Conduct and agree to all terms.

Printed Name	**Signature**	**Date**
Branham Channell		01/11/24
Javier Ibanez		01/11/24
Cobi Johnson		01/11/24
Madison Retherford		01/11/24
Joshua Wesley		01/11/24

Jung Typology Personality Test Results

Branham Channell

ENFJ

Extravert(78%) iNtuitive(13%) Feeling(44%) Judging(28%)

- You have strong preference of Extraversion over Introversion (78%)
- You have slight preference of Intuition over Sensing (13%)
- You have moderate preference of Feeling over Thinking (44%)
- You have moderate preference of Judging over Perceiving (28%)

Cobi Johnson

INTJ

Introvert(16%) iNtuitive(3%) Thinking(44%) Judging(28%)

- You have slight preference of Introversion over Extraversion (16%)
- You have marginal or no preference of Intuition over Sensing (3%)
- You have moderate preference of Thinking over Feeling (44%)
- You have moderate preference of Judging over Perceiving (28%)

Javier Ibanez

ENTJ

Extravert(75%) iNtuitive(28%) Thinking(31%) Judging(12%)

- You have distinct preference of Extraversion over Introversion (75%)
- You have moderate preference of Intuition over Sensing (28%)
- You have moderate preference of Thinking over Feeling (31%)
- You have slight preference of Judging over Perceiving (12%)

Madison Retherford

ISTJ

Introvert(19%) Sensing(6%) Thinking(1%) Judging(47%)

- You have slight preference of Introversion over Extraversion (19%)
- You have slight preference of Sensing over Intuition (6%)
- You have marginal or no preference of Thinking over Feeling (1%)
- You have moderate preference of Judging over Perceiving (47%)

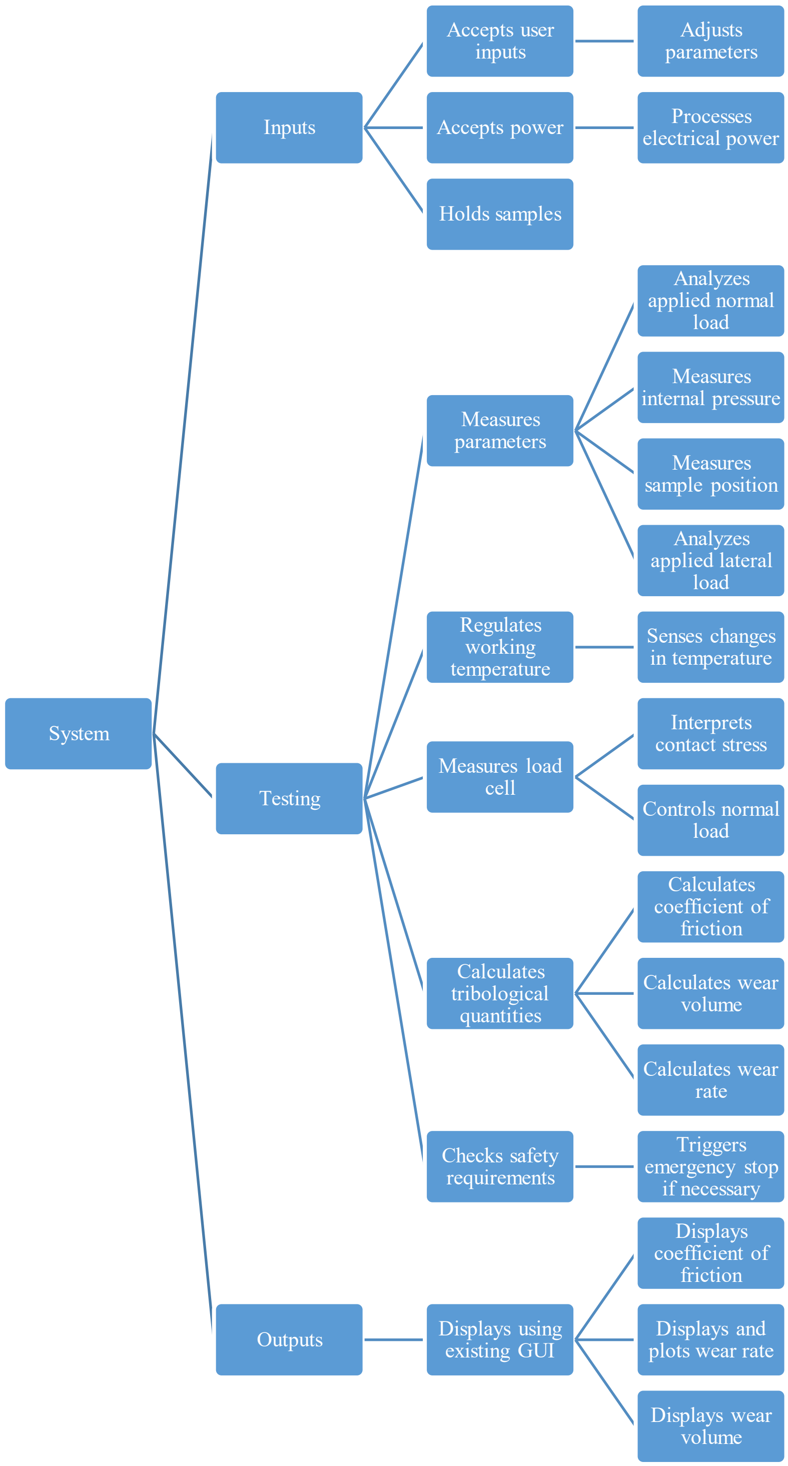
Joshua Wesley

INTJ

Introvert(75%) iNtuitive(19%) Thinking(12%) Judging(9%)

- You have distinct preference of Introversion over Extraversion (75%)
- You have slight preference of Intuition over Sensing (19%)
- You have slight preference of Thinking over Feeling (12%)
- You have slight preference of Judging over Perceiving (9%)

Appendix B: Functional Decomposition



Appendix C: Target Catalog

System	Function	Metric	Target	Units
Inputs	Adjusts parameters	Parameters can be adjusted	Yes	Boolean
Inputs	Processes electrical power	DC power input	120	Volts (V)
Inputs	Holds samples	Number of samples held	4-6	Count
		Types of samples held	2	Count
		Time to load samples	30	Minutes (min.)
Testing	Measures internal pressure	Resolution of pressure	5	Percent (%)
		Max pressure	10^{-5}	Torr
		Min pressure	10^{-6}	Torr
Testing	Measures sample position	Distance of cycle	0.05	Meters (m)
		Number of cycles	10,000 - 1,000,000	Count
Testing	Analyzes applied lateral load	Max load applied	100	Newtons (N)
		Resolution of load	100	Millinewtons (mN)
Testing	Senses changes in temperature	Resolution of temperature	1	Celsius (°C)
		Ideal error for readjustment	±1	Celsius (°C)
		Marginal error for readjustment	±5	Celsius (°C)
		Readjustment while transient	±10	Celsius (°C)
		Max temperature	200	Celsius (°C)
		Min temperature	-100	Celsius (°C)
Testing	Interprets contact stress	Resolution of load	100	Millinewtons (mN)
		Ideal error for readjustment	±3	Percent (%)
		Marginal error for readjustment	±5	Percent (%)
		Factor of safety for load cell	2	

Testing	Controls normal load	Max load applied	100	Newtons (N)
		Error required for readjustment	300	Millinewtons (mN)
		Resolution of load	100	Millinewtons (mN)
		Nominal servo of normal load	1	Per cycle
		Ideal servo of normal load	1	Kilohertz (kHz)
Testing	Calculates coefficient of friction	Calculates value	0 - 1	
		Error of calculation	10	Percent (%)
		Ideal resoluble range	0.01 - 0.5	
		Marginal resoluble range	0.05 - 0.4	
Testing	Calculates wear volume	Calculates value	0.05 - 50	Millimeters cubed (mm^3)
		Height loss resolution	5 - 50	Micrometers (μm)
Testing	Calculates wear rate	Calculates value	10^{-4}-10^{-7}	Millimeters cubed per Newton meter (mm^3/Nm)
		Error of calculation	±5	Percent (%)
Testing	Trigger emergency stop	Time to kill	0.3	Seconds (s)
Outputs	Displays coefficient of friction	Displays value	Yes	Boolean
		Plots coefficient of friction vs time	Yes	Boolean
Outputs	Displays wear volume	Displays value	Yes	Boolean
		Plots wear volume vs time	Yes	Boolean
Outputs	Displays wear rate	Displays value	Yes	Boolean
		Plots wear rate vs time	Yes	Boolean
Additional	Stage position	Ideal velocity	1	Meters per second (m/s)

		Marginal velocity	100	Millimeters per second (mm/s)
		Min velocity	0.1 - 1.0	Millimeters per second (mm/s)
Additional	Test set up	Ideal time	300	Minutes (min.)
		Max time	480	Minutes (min.)
Additional	Data acquisition	Rate	1	Kilohertz (kHz)

Appendix D: Concept Generation

1. Six mini-identical tribometers side by side.
2. Electric actuators normal load applications.
3. Pneumatic normal load applications.
4. Weights loaded on samples to produce normal load.
5. Create unique load cells out of carbon fiber.
6. Create unique strain gauges to calculate the normal force.
7. Design a clean room that mitigates contamination and allows for faster loading time by reducing cleaning time.
8. Pin on disk tribometer that can run six different samples at six different radii.
9. Use Minco space heaters to heat the tribometer slide up to temperatures.
10. Use liquid nitrogen to cool the tribometer slide down to temperatures.
11. Use Minco space heaters to prevent the system from dropping below -100 Celsius.
12. Use liquid nitrogen to prevent the system from rising above 200 Celsius.
13. Use Swagelok plumbing system to run the liquid nitrogen around the slide.
14. Create a mini tribometer with similar specs to what they use out of vacuum.
15. Use a leaf spring to analyze lateral loads.
16. Use a light sensor to determine if the sample is flat.
17. Use a switch above and below the sample to determine if the load is uniformly distributed across the top and bottom planes.
18. Use MATLAB to calculate resolution of normal load.
19. Use MATLAB to calculate resoluble of normal load.
20. Use MATLAB to perform error calculations.

21. Use design like what’s being used with an added second head “back-to-back".
22. Use a design like what’s being used but have four heads, two back-to-back beside one another.
23. Use automatic loading to speed up setup time for samples.
24. Use a vacuum compatible piezo sensor for changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge.
25. Use a vacuum compatible capacitive sensor to measure displacement.
26. Use multiple test modes.
27. Be able to use clockwise/counterclockwise as well as linear modes simultaneously (maybe the different heads could do different test modes?).
28. Ball on flat tribometer that can test four different samples.
29. Use one platform for multiple tests.
30. Use a unique platform for each test to ensure one sample stopping will not affect other samples.
31. Use ultrasonic sensors fixed to the platform to measure displacement.
32. 6 different sections of the tribometer with the ability to be snapped onto each other.
33. Using ultrasonic waves to measure speed with the vacuum chamber.
34. Capacitor tachometer that uses capacitance to measure rotation speed in the vacuum chamber.
35. Multiple tribometers with different platforms all under one system.
36. Force sensors are used to measure and control the force on a sample.
37. Amplifier circuits made in lab for load cells.
38. Premade amplifier circuits for load cells.

39. Designing a power management system to improve efficiency and better the management of power resources.
40. Design the heads of the tribometer to be multiaxial for better precision and movement.
41. Control panels that are vacuum compatible making easy access to control samples.
42. AI integrated system that helps prevent sample failure and automates sensor readings and measurements.
43. The ability to remotely monitor the system.
44. Noise reduction system to reduce electrical noises.
45. Wirelessly transmit data to the GUI.
46. Vacuum compatible cameras that will monitor the samples during testing.
47. Utilizing programmable logic controllers to automate the testing features.
48. Adding multiple microcontrollers to control many functions of the tribometer.
49. Digital displays outside the vacuum chamber to view testing parameters and results.
50. Integrating a power monitoring system to view power consumption.
51. Tribometer styled after rake with multiple heads that utilizes actuators to apply loads.
52. Tribometer utilizing current design but inverting it.
53. Calculating volume loss using a profilometer on sample after entire test is run.
54. Using clamps to hold samples instead of set screws.
55. Using a double-sided tape to hold samples.
56. Use an Arduino microcontroller (pricey).
57. Use a TI MSP430 microcontroller (low power alternative to Arduino).
58. Use an STM32 microcontroller (multi-tool versatile alternative to Arduino).
59. Use a Teensy 4 microcontroller (fast Arduino alternative).

60. Different testing methods support each other so we can make it compact.
61. Corrosion-Resistant Tribometer: Select the materials based on their corrosion resistance for applications in low-pressure environments.
62. Chemical Resistance Tribometer.
63. Droplet Impact Tribometer: test the wear and coefficient of friction using a sudden shock or impulse load.
64. Tape-Peel tribometer: test the wear rate and coefficient of friction using adhesion and cohesion forces.
65. Water Jet Erosion Tribometer: test wear rate and coefficient of friction using high velocity water jet erosion.
66. Rolling Pin Tribometer: use rolling contact on coated surfaces to evaluate wear. Rate and coefficient of friction.
67. In-situ Imaging Rolling Tribometer: The same mechanism of the rolling pin tribometer but using an electron microscope to watch sample response for the output.
68. In-situ Imaging Pin-on-Plate Tribometer: The same mechanism of the pin on plate tribometer but using an electron microscope to watch sample response for the output.
69. In-situ Imaging Impact Tribometer: The same mechanism of the droplet impact tribometer but using an electron microscope to watch sample response for the output.
70. Vibration-Enhanced Ball-on-Plate Tribometer: controlled vibrations to simulate dynamic conditions with ball on plate tribometer.
71. Dynamic Inclination Ball-on-Plate Tribometer: changing the inclination of the surface to simulate.
72. Dry ice system for controlling temperature instead of liquid nitrogen.

73. Sty-cast Black to encapsulate the wires.

74. One-time test launched into space to test space conditions without using a vacuum chamber.

75. A rotating multiple head tribometer that switch samples after finalizing a test.

76. A tribometer where the sliding motion and the applied load is done by the contact surface and the sample remains steady held by the set of screws.

77. Multiple samples in a rotating disk tribometer adjusted at different radiuses.

78. A pin on disk tribometer where the motor of the disk is attached to a sun and planet gear that generates reciprocating motion so we can have a pin on plate tribometer on the side.

79. A cross-headed sample holder that rotates after finishing each pin on plate test. The samples do not make contact until it is their turn to be tested.

80. Develop multiple chambers inside the vacuum to isolate each sample tested.

81. Have a quick release sample mount that allows quick transitions to test samples.

82. Design a system that can remotely control the tribometer inside the vacuum.

83. Develop an automatic vacuum compatible sample feeding mechanism.

84. Have multiple levels inside the vacuum that each tests its own sample.

85. Design a self-cleaning system that can clear the debris from the tribometer.

86. Explore the use of micro-electromechanical system (MEMS) is reduce the size of the tribometers inside the vacuum.

87. Create grooves on the stage that the sample displacement follows.

88. Use smaller and lighter materials to reduce the footprint of the tribometers.

89. Use modular design so the tribometer is easy to assemble and disassemble.

90. Design a tribometer that has connections for extra arms.

91. Design a system where the displacement of the samples can overlap.
92. Design a system that can fold, so that it reduces the footprint of the system.
93. Have a dead man's switch that activates when the sample loses contact with the counter surface.
94. Reduce the vertical space needed by the tribometer.
95. Have two rows of tribometers facing each other.
96. Use magnets to move the samples.
97. Create sample holders that can nest within each other.
98. Design compact tribometer heads that can fit tightly together.
99. Have multiple counter sample stages inside the vacuum.
100. Use high resolution imaging to track the sample movements.

Appendix E: Concept Selection

Table 10
3Binary Pairwise Comparison.

Binary Pairwise Comparison	1	2	3	4	5	6	7	8	Total
1: Test Multiple Samples Simultaneously	-	0	0	0	0	0	1	0	1
2: Reads and Stores Inputs	1	-	1	0	0	0	1	1	4
3: Returns Outputs and Critical Targets	1	0	-	0	0	0	0	0	1
4: Compatible with Previous GUI	1	1	1	-	0	0	0	0	3
5: Operate in Spacelike Conditions	1	1	1	1	-	0	1	1	6
6: Works Inside a Vacuum	1	1	1	1	1	-	1	1	7
7: Applies Unique Inputs to Unique Samples	0	0	1	1	0	0	-	0	2
8: Test 4-6 Samples	1	0	1	1	0	0	1	-	4
Total	6	3	6	4	1	0	5	3	n-1=9

Table 11
House of Quality.

House of Quality									
		Engineering Characteristics							
	Improvement Direction	↑	↑	↑	↑	↑	↓	↑	↓
	Units	Newtons	Meters	Newtons	Meters	Celsius	Newtons	Volts	Seconds
Customer Needs	Priority	Processes Electrical Power	Holds Samples	Measures Internal Pressure	Analyzes Applied Loads	Senses Changes in Temperature	Calculates Outputs	Emergency Stop	Display Outputs
1: Test Multiple Samples Simultaneously	1	0	9	0	1	0	1	1	1
2: Reads and Stores Inputs	4	9	0	3	3	3	1	1	1
3: Returns Outputs and Critical Targets	1	3	1	3	3	3	3	1	9
4: Compatible with Previous GUI	3	1	1	1	3	1	3	1	3
5: Operate in Spacelike Conditions	6	0	3	1	1	1	0	1	0
6: Works Inside a Vacuum	7	0	1	3	1	3	0	0	0
7: Applies Unique Inputs to Unique Samples	2	3	3	0	9	0	1	1	0
8: Test 4-6 Samples	4	0	9	0	1	0	1	3	1
Total		16	27	11	22	11	10	9	15
Raw Score		48	80	45	60	45	23	29	27
Relative Weight Percent		13.4%	22.4%	12.6%	16.8%	12.6%	6.4%	8.1%	7.6%
Rank Order		5	8	7	6	4	2	3	1

Table 12
Market Pugh Chart.

Market Pugh Chart										
			Concepts							
Selection Criteria	**Criteria Weight**	**AME Humidity Tribometer**	**Six Mini-Identical Tribometer Side by Side**	**Cross Headed Sample Holder**	**Weights Loaded on Samples to Produce Normal Load**	**Tribological Samples are Nested Together**	**Pin on Disk Tribometer that Can Run Six Different Samples at Six Radii**	**Inverted Existing Tribometer**	**Rake**	**Modular Tribometer**
Display Outputs	Total	Datum	S	S	S	S	S	S	S	S
Improvement	0.0%		+	+	+	-	-	+	-	-
↑	1600.0%		+	+	+	+	+	+	+	+
↑	2700.0%		S	-	+	-	-	+	-	-
↑	1100.0%		+	+	+	+	+	+	+	+
↑	2200.0%		S	S	S	S	S	S	-	-
↑	1100.0%		+	+	+	+	+	+	+	-
↓	1000.0%		+	S	S	S	S	S	S	-
Pluses			5	4	5	3	3	5	3	2
Minuses			0	1	0	2	2	0	3	5

Table 13
Concept Pugh Chart.

Concept Pugh Chart					
			Concepts		
Selection Criteria	Criteria Weight	Cross Headed Sample Holder	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	Inverted Existing Tribometer
Processes Electrical Power	13.4%	Datum	S	S	S
Holds Samples	22.4%		+	-	-
Measures Internal Pressure	12.6%		S	S	S
Analyzes Applied Loads	16.8%		-	+	-
Senses Changes in Temperature	12.6%		S	S	S
Calculates Outputs	6.4%		+	+	+
Emergency Stop	8.1%		S	S	S
Display Outputs	7.6%		+	+	+
Pluses			3	3	2
Minuses			1	1	2

Table 14
Concept Pugh Chart Cont'd.

Concept Pugh Chart				
			Concepts	
Selection Criteria	Criteria Weight	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Processes Electrical	13.4%	Datum	S	S
Holds Samples	22.4%		S	-
Measures Internal	12.6%		S	S
Analyzes Applied Loads	16.8%		S	+
Senses Changes in	12.6%		S	S
Calculates Outputs	6.4%		S	+
Emergency Stop	8.1%		S	S
Display Outputs	7.6%		S	S
Pluses			0	2
Minuses			0	1

Table 15
Criteria Comparison Matric [C].

Criteria Comparison Matrix [C]								
Selection Criteria	#1	#2	#3	#4	#5	#6	#7	#8
Processes Electrical Power	1.00	3.00	7.00	3.00	7.00	5.00	1.00	3.00
Holds Samples	0.33	1.00	3.00	2.00	4.00	2.00	3.00	7.00
Measures Internal Pressure	0.14	0.33	1.00	1.00	7.00	3.00	1.00	5.00
Analyzes Applied Loads	0.50	0.50	1.00	1.00	4.00	0.50	3.00	1.00
Senses Changes in Temperature	0.33	0.25	0.14	0.25	1.00	3.00	1.00	3.00
Calculates Outputs	0.20	0.50	0.33	2.00	0.33	1.00	5.00	1.00
Emergency Stop	1.00	0.33	1.00	0.33	1.00	0.20	1.00	1.00
Display Outputs	0.33	0.14	0.20	1.00	0.33	1.00	1.00	1.00
Sum	3.84	6.06	13.68	10.58	24.67	15.70	16.00	22.00

Table 16
Normalized Criteria Comparison Matric [NormC].

Normalized Criteria Comparison Matrix [NormC]									
	#1	#2	#3	#4	#5	#6	#7	#8	Criteria Weights {W}
Processes Electrical Power	0.260	0.495	0.512	0.141	0.284	0.318	0.063	0.136	0.276
Holds Samples	0.087	0.165	0.219	0.141	0.162	0.127	0.188	0.318	0.176
Measures Internal Pressure	0.037	0.055	0.073	0.141	0.284	0.191	0.063	0.227	0.134
Analyzes Applied Loads	0.130	0.083	0.073	0.047	0.162	0.032	0.188	0.045	0.095
Senses Changes in Temperature	0.087	0.041	0.010	0.015	0.041	0.191	0.063	0.136	0.073
Calculates Outputs	0.052	0.083	0.024	0.328	0.014	0.064	0.313	0.045	0.115
Emergency Stop	0.260	0.055	0.073	0.141	0.041	0.013	0.063	0.045	0.086
Display Outputs	0.087	0.024	0.015	0.047	0.014	0.064	0.063	0.045	0.045
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 17
Consistency Check.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
3.333	0.276	12.072
1.953	0.176	11.106
1.493	0.134	11.160
1.108	0.095	11.670
0.818	0.073	11.197
0.993	0.115	8.616
0.727	0.086	8.429
0.509	0.045	11.416

Random Index Values (RI)	
λ	10.708
RI	1.400
CI	0.301
CR	0.215

Table 18
AHP Processes Electrical Power.

Processes Electrical Power			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	0.33	3.00
Six Mini-Identical Tribometers Side by Side	3.00	1.00	3.00
Weights Loaded on Samples to Produce Normal Load	0.33	0.33	1.00
Concepts			
SUM	4.33	1.67	7.00

Table 19
Normalized Comparison For Processes Electrical Power.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.231	0.200	0.429	0.286
Six Mini-Identical Tribometers Side by Side	0.692	0.600	0.429	0.574
Weights Loaded on Samples to Produce Normal Load	0.077	0.200	0.143	0.140
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 20
Consistency Check for Processes Electrical Power.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
0.897	0.286	3.133
1.853	0.574	3.230
0.427	0.140	3.049

λ	3.137
RI	0.520
CI	0.069
CR	0.132

Table 21
AHP Holds Samples.

Holds Samples			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	3.00	1.00
Six Mini-Identical Tribometers Side by Side	0.33	1.00	3.00
Weights Loaded on Samples to Produce Normal Load	1.00	0.33	1.00
Concepts			
SUM	2.33	4.33	5.00

Table 22
Normalized Comparison of Holds Samples.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.429	0.692	0.200	0.440
Six Mini-Identical Tribometers Side by Side	0.143	0.231	0.600	0.325
Weights Loaded on Samples to Produce Normal Load	0.429	0.077	0.200	0.235
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 23
Consistency Check of Holds Samples.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.649	0.440	3.745
1.177	0.325	3.626
0.784	0.235	3.332

λ	3.568
RI	0.520
CI	0.284

Measures Internal Pressure			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	1.00	1.00
Six Mini-Identical Tribometers Side by Side	1.00	1.00	1.00
Weights Loaded on Samples to Produce Normal Load	1.00	1.00	1.00
Concepts			
SUM	3.00	3.00	3.00

Table 24
AHP Measures Internal Pressure.

Table 25
Normalized Comparison for Measure Internal Pressure.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.333	0.333	0.333	0.333
Six Mini-Identical Tribometers Side by Side	0.333	0.333	0.333	0.333
Weights Loaded on Samples to Produce Normal Load	0.333	0.333	0.333	0.333
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 26
Consistency Check for Measure Internal Pressure.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.000	0.333	3.000
1.000	0.333	3.000
1.000	0.333	3.000

λ	3.000
RI	0.520
CI	0.000
CR	0.000

Table 27
AHP Analyzes Applied Loads.

Analyzes Applied Loads			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	0.33	5.00
Six Mini-Identical Tribometers Side by Side	3.00	1.00	5.00
Weights Loaded on Samples to Produce Normal Load	0.20	0.20	1.00
Concepts			
SUM	4.20	1.53	11.00

Table 28
Normalized Comparison for Analyzes Applied Loads.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.238	0.217	0.455	0.303
Six Mini-Identical Tribometers Side by Side	0.714	0.652	0.455	0.607
Weights Loaded on Samples to Produce Normal Load	0.048	0.130	0.091	0.090
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 29
Consistency Check Analyzes Applied Loads.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
0.954	0.303	3.145
1.965	0.607	3.238
0.272	0.090	3.031

λ	3.138
RI	0.520
CI	0.069
CR	0.132

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Table 30
AHP Senses Changes in Temperature.

Senses Changes in Temperature			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	1.00	1.00
Six Mini-Identical Tribometers Side by Side	1.00	1.00	1.00
Weights Loaded on Samples to Produce Normal Load	1.00	1.00	1.00
Concepts			
SUM	3.00	3.00	3.00

Table 31
Normalized Comparison for Senses Changes in Temperature.

Normalized Comparison			DAP	
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.333	0.333	0.333	0.333
Six Mini-Identical Tribometers Side by Side	0.333	0.333	0.333	0.333
Weights Loaded on Samples to Produce Normal Load	0.333	0.333	0.333	0.333
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 32
Consistency Check for Senses Changes in Temperature.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.000	0.333	3.000
1.000	0.333	3.000
1.000	0.333	3.000

λ	3.000
RI	0.520
CI	0.000
CR	0.000

Table 33
AHP Calculates Outputs.

Calculates Outputs			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	1.00	5.00
Six Mini-Identical Tribometers Side by Side	1.00	1.00	5.00
Weights Loaded on Samples to Produce Normal Load	0.20	0.20	1.00
Concepts			
SUM	2.20	2.20	11.00

Table 34
Normalized Comparison for Calculates Outputs.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.455	0.455	0.455	0.455
Six Mini-Identical Tribometers Side by Side	0.455	0.455	0.455	0.455
Weights Loaded on Samples to Produce Normal Load	0.091	0.091	0.091	0.091
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 35
Consistency Check for Calculates Outputs.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.364	0.455	3.000
1.364	0.455	3.000
0.273	0.091	3.000

λ	3.000
RI	0.520
CI	0.000
CR	0.000

Table 36
AHP Emergency Stop.

Emergency Stop			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	3.00	0.33
Six Mini-Identical Tribometers Side by Side	0.33	1.00	0.20
Weights Loaded on Samples to Produce Normal Load	3.00	5.00	1.00
Concepts			
SUM	4.33	9.00	1.53

Table 37
Normalized Comparison for Emergency Stop.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.231	0.333	0.217	0.260
Six Mini-Identical Tribometers Side by Side	0.077	0.111	0.130	0.106
Weights Loaded on Samples to Produce Normal Load	0.692	0.556	0.652	0.633
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 38
Consistency Check for Emergency Stop.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
0.790	0.260	3.033
0.320	0.106	3.011
1.946	0.633	3.072

λ	3.039
RI	0.520
CI	0.019
CR	0.037

Table 39
AHP Display Outputs.

Display Outputs			
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load
Inverted Existing Tribometer	1.00	1.00	1.00
Six Mini-Identical Tribometers Side by Side	1.00	1.00	1.00
Weights Loaded on Samples to Produce Normal Load	1.00	1.00	1.00
Concepts			
SUM	3.00	3.00	3.00

Table 40
Normalized Comparison for Display Outputs.

Normalized Comparison				DAP
	Inverted Existing Tribometer	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	
Inverted Existing Tribometer	0.333	0.333	0.333	0.333
Six Mini-Identical Tribometers Side by Side	0.333	0.333	0.333	0.333
Weights Loaded on Samples to Produce Normal Load	0.333	0.333	0.333	0.333
Concepts				
SUM	1.000	1.000	1.000	1.000

Table 41
Consistency Check for Display Outputs.

Consistency Check		
{Ws}=[C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.000	0.333	3.000
1.000	0.333	3.000
1.000	0.333	3.000

λ	3.000
RI	0.520
CI	0.000
CR	0.000

Table 42
Final Rating Matrix.

Final Rating Matrix			
Selection Criteria	Six Mini-Identical Tribometers Side by Side	Weights Loaded on Samples to Produce Normal Load	Inverted Existing Tribometer
Processes Electrical Power	0.286446886	0.573626374	0.13992674
Holds Samples	0.44029304	0.324542125	0.235164835
Measures Internal Pressure	0.333333333	0.333333333	0.333333333
Analyzes Applied Loads	0.303343999	0.607001694	0.089654307
Senses Changes in Temperature	0.333333333	0.333333333	0.333333333
Calculates Outputs	0.454545455	0.454545455	0.090909091
Emergency Stop	0.260497956	0.106156324	0.63334572
Display Outputs	0.333333333	0.333333333	0.333333333

Table 43
Alternative Value Matrix.

Alternative Value								
Selection Criteria	Processes Electrical Power	Holds Samples	Measures Internal Pressure	Analyzes Applied Loads	Senses Changes in Temperature	Calculates Outputs	Emergency Stop	Display Outputs
Six Mini-Identical Tribometers Side by Side	0.28644689	0.44029304	0.33333333	0.303344	0.33333333	0.45454545	0.26049796	0.33333333
Weights Loaded on Samples to Produce Normal Load	0.57362637	0.32454212	0.33333333	0.60700169	0.33333333	0.45454545	0.10615632	0.33333333
Inverted Existing Tribometer	0.13992674	0.23516484	0.33333333	0.08965431	0.33333333	0.09090909	0.63334572	0.33333333

Table 44
Final Concept Selection.

Concepts	Alternative Value	RANK
Six Mini-Identical Tribometers Side by Side	0.34404114	2
Weights Loaded on Samples to Produce Normal Load	0.418	1
Inverted Existing Tribometer	0.237	3

Table 4
The Word Table and the Table Number are Normal Font and Flush Left. The Caption is Flush Left, Italicized, Uppercase and Lowercase

Level of heading	Format
1	**Centered, Boldface, Uppercase and Lowercase Heading**
2	**Flush Left, Boldface, Uppercase and Lowercase**
3	***Indented, boldface lowercase paragraph heading ending with a period***
4	***Indented, boldface, italicized, lowercase paragraph heading ending with a period.***
5	*Indented, italicized, lowercase paragraph heading ending with a period.*

References

There are no sources in the current document.