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Eaton – Vacuum Testing For Carbon Face Seals

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Vacuum Testing For Carbon Face Seals

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Abstract

The objective is to work with our sponsor Eaton in creating or improving the current carbon face seal testing equipment they already have in place. In doing so the idea is to improve the current system, make the system more efficient, and automate the test to eliminate the multiple step processes the operator has to implement. To create an automated vacuum test it is a complex task with many details to consider. Initially the main focus was on the housing fixture and the entirety of the vacuum system could be broken down into various subsystems which work together in achieving the goal of carrying out a successful test. For ease of completion the project was broken down into the air plumbing/fluids system, control system and data acquisition. Within these systems progress has been made through conducting an in depth literature and patent search, conceptual design generation and engineering analysis. Through these efforts a proof of concept prototype CAD model has been designed and verified through an in-depth analysis proving that our current design is capable of meeting all our design requirements as well as satisfying the problem definition and objectives of this project set forth by Eaton. Taking all of this research and implementing it was the final step to create our system using an app created by Python/Kivy and running it on a Raspberry Pi. Testing then pursued at Eaton's facility and the results came back with satisfaction from Eaton.

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Introduction

A seal is a device for closing gaps and helps in joining systems or mechanisms together by preventing leakage, containing pressure and preventing contaminants from passing through. Seals play a crucial role in many modern engineering devices, and the failure of seals may result in catastrophic events. For aerospace applications, mechanical seals are used against traditional packing seals since they offer more durability and prevent more leakage. There are various types of mechanical seals depending on the application however the most common for aerospace applications is the rotating-face seal. This features mating surfaces as the primary sealing elements incorporating rings of ceramic, carbide, carbon and other composites which are lapped flat in the range of less than one micron on an axial end face. These lapped faces fit flat against each other, one rotating with the shaft and the other stationary. The sealed fluid will interface between the two flat faces and develop a thin lubricating fluid film. This is absolutely vital especially during shaft rotation where the face materials will heat up and wear quickly without any lubrication. Many face seals that are placed inside the working areas of a turbine cannot be removed without complete disassembly of the turbin. Therefore the testing of such sealing components is of utmost importance to ensure that systems can withstand the arduous environments they are subjected to, especially in aerospace applications.

One way of evaluating the efficiency of a seal is by determining the leakage rate between the interfacing surfaces. In practice, this is commonly done by conducting a pressure-decay test which involves creating a vacuum between the sealing surface and part interface then monitoring the pressure loss in the vacuum environment over a period of time. This technique is used by many companies which are considered leaders in the sealing industry such as Eaton. Eaton is the sponsor for this project, want advance their current testing procedure and technology which incorporates this technique on their carbon face sealing components.

The scope of the project is to develop vacuum test equipment for in-production aerospace seals. Currently their existing equipment is functional but antiquated and does not possess the ability to record data or provide a print-out of the result. The intent of each machine is to generate a vacuum across the sealing surface and measure the leakage rate over a length of time. The results are not tracked by the machine and often times no discrete data is presented. The machines need to be upgraded to use new, modern equipment, as well as provide discrete data print-outs with the ability to modify the duration of the testing cycle with simple operator inputs. A large focus of the project is put into the development of a system which will record the decay rate in real time in a text file allowing the possibility for post processing of results through programs such as Microsoft Excel.

Literature Search

Before starting the design of a concept there are a few critical steps to consider. One of which would be a literature search on any relevant work that is related to the concept that is being considered. Looking for articles, writings, and any kind of literature based on the project being studied will help in generating initial designs and learning about possible solutions that have already been developed. Finding the proper documentation from authors who have already considered ideas may help new ideas flow, or innovation in the next step. Passing this procedure can lead to fatal flaws in the concept or could cause one to waste time on research that has already been started or completed. Listed below are some of the relevant literature searches to creating a modernized vacuum test control system.

Title: Improve Your Vacuum Test
Date: August, 2007
Rights owned by: Modern Casting, Daniel Groteke
Abstract: Described in this article is the causes of finished castings being returned or faulty after production. Goes into depth on what porosity is and the different types of porosity that occur during the creation of finished castings. Once the article addresses the different types of issues being tested for it then goes into the actual testing part. The article gives a good understanding of what vacuum tests are, and why they are common practice in many industries. Next is described the different techniques used to create a test and the different type of machinery used to do so. Once vacuum testing is described in detail the article then transfers to the part of improving a vacuum test even further. Lastly this article describes a sampling performed on a test they performed on their own. All very good information for people trying to understand and create a vacuum test of their own.

Relevance: Our group is in the process of creating a vacuum test for seals, and this article is a piece that explains the process of improving a testing and is written by people who have already created vacuum testing equipment. This article has helped us greatly during the process of brainstorming techniques.

Title: A Vapor-Free Vacuum Seal

Date: August, November 19th, 1919
Rights owned by: National Academy Of Sciences
Abstract: In the study of Vacuum testing it is very important to assure a leak free performance. This article goes over the process of creating a vacuum test with different types of substances as grease, and it goes in-depth on the reasons certain types of situations happen such as vapors leaking, liquid or any form of failure in a vacuum test. The experimental example in this article used is a cylindrical object and the author tests their theory on this object. After the experiment is performed the author writes of the benefits using this type of object. In the study of vacuum testing this article gives good demonstration of vacuum testing and a good example of a cylindrical application. The study of this article will help assist anyone studying vacuum testing with their designs.

Relevance: Once of the important factors and whole purpose of a vacuum test is to perform the test and make sure there is no leaks involved at the same time. This article is a great source relevant to the study of our product because we have to make sure our test performs leak free and as expected.

Title: Owners manual for Duoseal Vacuum pump models: 1402B-01 & 3Z655
Date: August, 2008
Rights owned by: WELCH-ILMVAC
Abstract: This manual used as a reference is not an article to be used for research like the others. This literature research is just as important as all other references used to make sure our vacuum test performs properly. Having a manual of our pump will educate the group on how to use the vacuum pump properly and help troubleshoot any issues that may come up while performing a vacuum test.

Relevance: One of the parts used for in every vacuum test is a vacuum pump. This part is a important factor to our product performing properly. There for this manual on the type of pump our group may use is very important to our procedure to make sure we are operating our vacuum pump properly.

Title: Design and Experimental Study on the Controllable High-Speed Spiral Groove Face Seals
Date: December 27, 2013
Rights owned by: Modern Casting, Daniel Groteke
Abstract: The article goes in-depth on the study of a spiral groove face seal. Starting with the description of what type of seal this is and how it is used, to the applications of the seal. The author explains the difference between electro-magnetic loading devices (EMLD) and friction torque testing devices (FTTD). The fluid used in this experimental article is water and helps give a good demonstration to anyone on the study of how to control a high-speed spiral groove face

seal. To end the article the author performs a test and achieves the desired results wanted, a perfect example for anybody who wants to research the study of seals before moving forward with any type of concept based on seals.

Relevance: In the process of creating a vacuum testing unit for carbon face seals, it is important to understand how a seal operates and the study of seals. This article helps the group understand the experimental part of seals at a higher level so that designing a testing unit for them will be an easier process.

Title: Pressure Activated Leaf Seal Technology Readiness Testing
Date: August, 2015
Rights owned by: ASME
Abstract: Applications Eaton are involved in include aerospace technology. This article is based on shaft sealing for the aerospace industry and goes in depth on the study of advanced seals. Shaft sealing is an application for power generation and aerospace turbine performance. To open the article it explains how the seal operates in low pressure scenarios and how the product does its job. Following the brief description of what the seal does, the author starts to dig in to different referenced test examples and the results that were achieved in these results. Next the author explains what the test seal design would be and what the facility will be like where the test is performed. The final step in the report is a detailed experiment with results achieved and a dissection of what the results achieved actually mean and the backing of their conclusion. Studying this article will be a benefit to anybody that is trying to run seal tests of their own.

Relevance: Similar to other references used, this article is critical to the study of testing seals. This experiment is performed to test and control carbon face seals for our sponsor and this article helps demonstrate how to create a test and what type of ways to do so.

Title: A Laboratory Vacuum Gage
Date: March, 1925
Rights owned by: Trinity College
Abstract: This article dives deep into the daily use of a vacuum pump for common laboratory experiments using 3 to 0.005 mm of mercury. Using a vacuum pump to achieve desired results means a gage to read the results of the pump are highly critical to the success of your product. Certain manometers are not efficient enough in giving the best results. The author describes the process he used to create his own gage used for his vacuum pump during experiments. Reading this article will help somebody build their own gage, calibrate it and make sure that is performs up to the standards required.

Relevance: A vacuum pump will be used during every test that is performed. This article gives much detail in the process of creating a gage to read the results that the vacuum pump will produce. This article will help in the set up of our vacuum pump and to make sure that the readings achieved are accurate.

Title: Improve Electric Valve Actuator
Date: August, June, 1994
Rights owned by: Mechanical Engineering; ABI/INFORM Collection
Abstract: This article is a brief article that describes the use of electric valve actuators in applications. The author describes different applications that the actuators are used for and the difference each application needs. A short read but a useful reference if a concept will be using any sort of actuator.

Relevance: The unique part of the vacuum tester our group is creating is the controlled aspect of it. This article will be very important to the creation of our product in the later stages. Once the mechanical design is complete, the knowledge gained from reading this article will help us better understand how to use an actuator for what we need.

Title: Fundamentals of Vacuum
Date: January, 2012
Rights owned by: Informa PLC
Abstract: This article describes the theory of vacuum and dives into the basics of vacuum systems. Various vacuum measurement methods are described as well as important terminology and equations such as the time required to pump down a system given certain input parameters. Industrial vacuum systems are looked at in a glance as well as tips into selecting the right pump for the job or application.

Relevance: Understanding the basic theory of vacuum is vital for developing a solution to our problem. It is also necessary to be aware of the various mechanical pumps used in industry today and why some pose advantageous to others. Also the formula supplied for evacuation time of a system is critical in estimating how long a test can take given the pumps performance ratings.Overall, this article was referenced many times for our preliminary design presentation.

Patent Searches

During the beginning stages of an invention or creation of a concept patent research is a critical to coming up with a new, and unique concept. Proceeding to design a new concept could result in copyright infringement of somebody else's hard work. To avoid this happening would result in saving a lot of resources coming in the form of physical resources, money, time and not stealing somebody else's work. There are positive steps towards creating your concept in this step as well. By looking at current patents that are already being worked on you may gain a better knowledge of your product, see ideas that people may have already attempted and perhaps think of new ideas for your concept all together. Listed below are some of the relevant patent searches our group have come up with.

Title: Method and apparatus for testing relative permeability of materials
Date: December 25th, 1990
Rights owned by: Morris & Daniel Schupack
Patent #: 4,979,390
Abstract: This patent was submitted for the permeability of materials in different types of structures than will be used in this project. Permeability refers to the state of a material that allows liquid or gasses to pass through it. This search is in the use of concrete applications that have a gasket, chamber and seals. This patent will not affect the design of a vacuum testing unit but the study of what this patent resulted in can quite possibly help in similar techniques for our concept.

Relevance: This patent lays claim to certain methods and apparatus for testing gaskets, chambers, and seals. Mostly for applications that are different than that of which are using but researching the use of these applications could come in play when designing gaskets, chambers and seals for our product.

Title: Vacuum Actuated Test Fixtures
Date: November 20th, 1986
Rights owned by: Hewlett-Packard Company

Patent #: 4,771,234

Abstract: In this patent found in the United States database for patents, based on vacuum actuated test fixtures, the author describes a circuit board being used to actuate a vacuum test. There is not a certain application that is listed for the use, but the application is a reference that can be used in doing a vacuum actuated test for a certain type fixture which in this case would be for carbon face seals.

Relevance: This patent is more related to a vacuum testing unit than other patents and can be studied in the use of controlling a vacuum test. The author of this patent details their uses of this patent and the study of it can greatly help with our own concept.

Title: Method and apparatus for testing a sealed container
Date: August 13th, 1985
Rights owned by: Motorola Inc.
Patent #: 4,534,208
Abstract: Connecting a vacuum test to a vacuum pump is crucial for the test to be a success. This patent by Motorola Inc. describes techniques on how to connect a container of some sort to a vacuum pump. More specifically it describes ways to create a leak free connection port to connect the the container (vacuum test) from the vacuum pump. This patent also details how to determine if a leak or failure in the system has occured.

Relevance: This patent is a description of a technique to make a connection that hooks up to a vacuum pump to create a seal that is leak free from gases and liquids. This application works perfectly for our vacuum test because it will require a vacuum pump to perform the action. Researching this patent will give knowledge to us on how to hook up our vacuum pump

Title: Air Compressor
Date: June 6th, 2015
Rights owned by: Wen-Sen Chou
Patent #: 10,077,770
Abstract: A portable air compressor includes a box and a compressor unit accommodated in the box. The compressor unit includes a main frame, a cylinder fitted with a piston body, a motor, and a transmission mechanism. The motor drives the transmission mechanism to have the piston body conduct reciprocating motion in the cylinder to produce compressed air, which is transferred to an air storage container. The cylinder and the main frame are integrally formed of plastic. The cylinder defines an exit hole communicating with an inner space thereof. A metal seat is integrally formed at the cylinder. The central hole of the metal seat communicates with the exit hole of the cylinder. A plug is urged by a compression spring to seal the central hole of

the metal seat. The metal seat can endure high temperature within the cylinder to ensure air-tightness between the plug and the metal seat.

Relevance: Similar air compressors may have been developed when creating designs for our individual vacuum seal testing unit. Having available this information prevents future altercations if similar design occur within both products.

Title: Air pressure sensing system
Date: August 11th, 2016
Rights owned by: Merry Electronics
Patent #: 10,072,999
Abstract: An air pressure sensing system including a first sensing unit and a second sensing unit is provided. The first sensing unit includes a substrate, a diaphragm, and a supporting member. The substrate has a cavity connected with an exterior environment. The diaphragm is movably and deformably disposed at the substrate and suspended in the cavity. An electrostatic force is provided to the substrate and the diaphragm to move the diaphragm, such that a portion of the base, the supporting member and the diaphragm are contacted with each other and a closed space is formed therebetween in the cavity. The closed space and the exterior environment are divided by the diaphragm, and the diaphragm is deformed due to an air pressure difference between the closed space and the exterior environment. An air pressure sensing method is also provided.

Relevance: Similar sensor systems within compressors may have been developed when creating designs for our individual vacuum seal testing unit. Having available this information prevents future altercations if similar design occur within both products.

Title: Suction nozzle
Date: November 10th, 2010
Rights owned by: Fuji Machine Manufacturing Co Ltd
Patent #: 10,040,205
Abstract: In a suction nozzle which sucks and holds a component on a suction surface by using negative pressure air and detaches the sucked and held component from the suction surface by using positive pressure air, the positive pressure air and the negative pressure air used when the component is held and detached selectively flow through an air flow path. In addition, a rod is advanced and retracted toward the suction surface in an inside section of the suction nozzle. The rod protrudes from the suction surface by the positive pressure air flowing through the air flow path and is retracted to the inside section of the suction nozzle when the negative pressure flows through the air flow path.

Relevance: Similar nozzle designs for attachment to compressive mechanism may have been developed when creating designs for our individual vacuum seal testing unit. Having available this information prevents future altercations if similar design occur within both products.

Evaluation Of The Competition

A vacuum test machine for carbon face seals is a very specialized piece of test equipment that has a limited market for seal manufacturers. The manufacturers that would be interested in the vacuum test machine being built need to be manufacturing a face seal under eight inches in diameter and ideally testing with a vacuum pressure of twenty five inches of mercury. This limits the viability of the product within the face seal market but does provide an avenue into other markets as well. Any container that is meant to withstand a sustained vacuum or applied outward pressure would need to be tested to prove the container's sealing capability under desired test conditions. Examples being waterproof electronics cases or a waterproof container meant for storing sensors at depth for oceanographic studies. The designed vacuum test machine that this report is covering would be able to test these containers with a small adaptation to the transducer attachment element. Current fixture designs are meant specifically for the Eaton Corporation and and the carbon face seals they produce but this does not limit the vacuum test control system from being useful in these other markets. Using the same control system and a desired vacuum pump capable of reaching the pressures needed for testing the same test can be performed with simple adaptations to the fixture.

Adapting the fixture brings the market viability of the vacuum test machine back to the original point of limited viability within the face seal market. If only the control system and pressure transducers are marketed and sold the system as a whole becomes much more marketable. It directly opens up the market to much larger face seals and possibly radial seals depending on fixture design. The only limitation to the system is the maximum pressure that the transducers, and air plumbing can handle. Looking into every market that this control system would be able to be applied to would require extensive research and product redesign for flexibility. For the purpose of this qualitative analysis of the market viability and competitiveness the focus will be on the testing products requested by Eaton, carbon face seals of diameter eight inches or smaller. The vacuum test machine as a whole was determined to need to adhere to the following criteria to meet the desired design specifications that were created after meeting with Eaton and determining their needs for the vacuum test machine.

1. Reliability
2. Time Per Cycle
3. Target Pressure
4. Modernization
5. Recordability
6. User Friendliness
7. Number of specimens to run
8. Low cost to operate
9. Work area

These have been determined as the minimum demanded quality requirements to create a vacuum test machine that Eaton finds suitable. How these qualities affect the other qualities and how important each qualities implementation is to the project as a whole is displayed in the figure below.

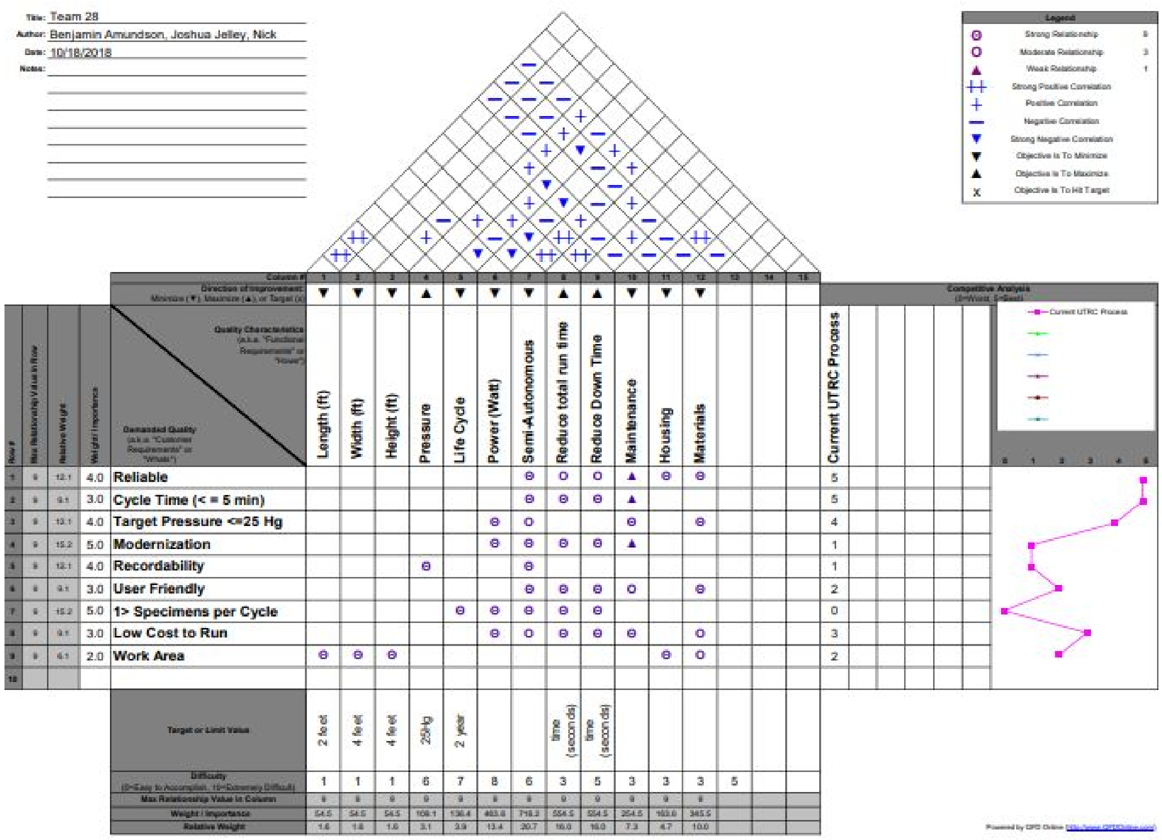


Figure 70: QFD Analysis

From the above figure it is shown that the modernization and automation of the system will provide the ability to reach almost all of the design specifications laid out by the discussion held with Eaton. The Automation keeps the cycle times low and saves power by only using the minimum amount of power to reach the desired test states. By automating the system the addition of serial communication with a USB or SD card is easily implemented to store desired data even when conducting multiple tests of different seals which completes the recordability requirement for the system. This can be further improved upon to increase the recordability and the user friendliness by introducing a barcode scanner. The barcode scanner allows the work orders used by Eaton to be used by the system as the work order number, part number, and quantity to be stored with every test and keep the recorded data inline with what Eaton is currently doing. This would also make the system more viable for future use as barcodes are used in a wide range of manufacturing and do not have a replacement in the foreseeable future as many robotic system use barcode scanners as well to document processes. The limitations currently set on the vacuum test machine are almost solely due to the fixture elements and not the control system. This keeps the product market competitive as anything that can be tested using a vacuum pressure test can realistically be adapted to the system widening the applicable uses and market share.

Design Specifications

Eaton gave an objective of creating a vacuum test system that can be controlled to ease use for the operator of the device. Some of the desired improvements asked of us to consider in the making of this concept were to improve the amount of test that are able to performed at a given time, make the system more efficient, and control the system. The equipment already being used was built 40 years ago and therefore is outdated and clunky. Each test is completed, making their unit a reliable source of testing. What we were tasked with doing was to implement a more modernized technology to their current system and make it work better.

In the beginning stages there was a lot of research on designing improvements for the fixture they have due to the size of their current equipment. Any seal that fits under the given lapped plate can be tested, which at this point would be any carbon face seal 8” in diameter or less. There will be two set values for testing at low vacuum testing, 10” of Hg, and high vacuum testing, 25” of Hg. These test will be set to 1 minute with flow rate of 3.7 cfm running through the system, a pass or fail will be triggered by a pressure test in the system. Decay rate of pressure will be calculated over the 1 minute of time and if the test is within 2% of the initial pressure reading, it will be a pass.

In order to conduct these test an application is created to run the parameters in the system to indicate the pass or fail. This application is run through a Python library called Kivy and is installed onto a Raspberry Pi 3 model B. A vacuum transducer is connected from the Raspberry

Pi to Eaton's current vacuum setup and the results can be calculated through the software and placed into a test file. Current equipment can not save data and makes it difficult to monitor what happens in the pass/fail test. These are some of the design specifications given to the team from Eaton. Listed below is a table of these values.

Table 1: Design Specifications table.

Test Fixture	
Testable units	One at the moment
Fixture size	8" diameter
Testable seals	Any seal 8" or less
System Specifics	
Pressure in system	25" of Hg
Pipe diameter	0.8125"
Average volumetric flow rate	3.7 cfm
Pass/Fail	2% from target pressure
Test Duration	1 minute
System Control	
Device	Raspberry Pi 3 model B
Software	Python/Kivy

Vacuum	High pressure vacuum pump
Transducer	Vacuum pressure transducer
Screen	7” touchscreen LCD

Concept Design

After the research was performed on literature and patent searches, the next task was for each member to create 30 concepts in which they could begin their designs on. This step is critical to gathering information and coming up with as many practical resolutions for the project. Listed below are each members original 30 concepts described briefly and listed in figure form.

Joshua Jelley’s Concepts and Evaluations

1. **Vacuum test unit with 1 test fixture:**

Eaton is a high quality low output manufacturer that can perform a test for one unit currently. This concept does not improve the amount of test that can be performed but it shows a concept that is similar to the setup they already have but in a design that would take up less space than the current design.

2. **Vacuum test unit with 1 test fixture and adjustable plate**

A concept that was originally thought of which has the single text fixture with a lapped plate which can be lowered on top of the seal to perform the vacuum test. This plate can be lowered manually or within the controlled system

3. **Vacuum test unit with 1 test fixture & setup underneath**

This concept was thought of for convenience and space purposes. If the vacuum is stationed underneath the fixture then this means it can be placed in a housing of some sort and that housing can be moved around the manufacturing port very easily by wheels or by picking up depending on the end size.

4. **Vacuum test unit with 1 test fixture and vacuum gauge**

One of the early concepts that were thought of would have the text fixture stationed in the middle, with a pressure gauge stationed to the side of it. With a stationed gage on the side of it the user performing the test can instantaneously see the through out the system. Have this ability the test operator will have a general understanding of what the pressure should be in the system and know prior to it finishing if the test is in line to pass or fail.

5. **Vacuum test unit with 2 test fixtures & no valve set up**

One of the beginning specifications given to us was the possibility of testing multiple units at a time because they can only test one right now. With this concept it would be possible for two tests to be run at the same time. Not a huge improvement from where the current system is, but it is still a 100% improvement from one.

6. **Vacuum test unit with 2 test fixtures and adjustable plate**

Similar to the concept listed with one fixture, this one has two fixtures with adjustable plates on it. This way the operator can put the seal on to the face and have the plate adjusted onto the seal to begin the tests.

7. **Vacuum test unit with 2 test fixtures & setup underneath**

This concept was also a similar one to the single fixture idea. The ability to have the vacuum and all the wiring below the actual test units will allow easier transportation of the device. Having it with this design allows it to be put into a housing so it can be moved around the manufacturing floor easily. Perhaps this concept could even have wheels on the bottom of the station to transport even easier.

8. **Vacuum test unit with 2 test fixtures and vacuum gauge**

Like the single fixture design, this one will have the option to put gauges on side of each test fixture. This will allow the operator to view both units pressure readings at the same time to make sure that the test is indeed being performed on both test fixtures and not just one. Our original concept of gages did not make the final cut, because we will be automating everything and sending it to the computer. There for this concept doesn't seem like the best option.

9. **Vacuum test unit with 2 test fixtures and valve set up**

This concept is the first concept to introduce the valve set up. With the valve in between the two fixtures this allows one unit to be tested at a time instead of testing both. If only one seal needs to be run then the operator can activate the valve to shut the test off to the second unit. This is a critical concept for ease of use purposes.

10. **Vacuum test unit with 4 test fixtures and no valve set up**

In the thought process of improving the amount of test that can be run at a time there was that factor of how many test at a time is the optimal amount. This test allows four test to be run at the same time, and this is a big improvement over the original concept of one test at a time. Once the operator begins the test, the system will automatically run the test on all four test fixtures at a given time.

11. Vacuum test unit with 4 test fixtures and 2 vacuums

One of the points brought to between a team meeting had one of the members mentioning that depending on the type of vacuum being used one, that one vacuum may not be strong enough to run all four tests at a time. This being said, a second vacuum was added to the system. With research being done more recently we know that one vacuum will be strong enough to run all the test at once and so this concept is one of the ones that our group did not go with for the final concept.

12. Vacuum test unit with 4 test fixtures and one vacuum

The previous concept was four test fixtures with two vacuums for power purposes. As stated we do not need two vacuums to perform the test, so this concept has the four test fixtures with one pump underneath. Once the seals are placed on top of the fixture the operator can signal for the test to begin.

13. Vacuum test unit with 4 test fixtures and vacuum gauge

This concept is of four test fixtures with four pressure gages stationed on side of each fixture. Each one will be stationed forward towards the operator for ease of use and reading the gage. With the gauges the operator can make sure that all systems are working properly, and will know if a station isn't operating properly before the test is done running.

14. Vacuum test unit with 4 test fixtures and valve set up

This concept has four test units with individual valves set up between each test fixture. This allows the operator to run one, two, three, or all four tests at the same time. This gives the operator more flexibility with the tests.

15. Vacuum test unit with 4 test fixtures and setup underneath

This concept has the four test fixtures with one pump underneath. Once the seals are placed on top of the fixture the operator can signal for the test to begin. This concept with everything stationed underneath is more significant once the device starts to get bigger in number of test fixtures due to size.

16. Vacuum test unit with 6 test fixtures and no valve set up

Of all the concepts, i believe 6 is the perfect amount of test fixtures. Any amount less than 6 is workable and an improvement over the current test that can run one and any amount of 6 seems to be too many tests at once. The next few concepts with 6 test fixtures are the concepts that are more likely to be used going forward in the design process.

17. Vacuum test unit with 6 test fixtures and 2 vacuums

Like some of the previous concepts, this concept had two vacuum pumps set up for power reasons. More recently it has been proven that one pump is more than sufficient in performing the tests.

18. Vacuum test unit with 6 test fixtures and adjustable plates

This concept has the six test fixtures and adjustable lapped plates on top of the seal fixtures. This allows the operator to press start and the plates will automatically be lowered on top of the plates for the tests to be performed.

19. Vacuum test unit with 6 test fixtures and setup underneath

With six test fixtures, having the setup underneath seems to be more practical for saving space on the manufacturing floor. Instead of having the device lifted on to a table it can be all stationed in a housing for the vacuum testing equipment to be transported at a much easier means.

20. Vacuum test unit with 6 test fixtures and vacuum gauges

Having everything stationed underneath, and having everything wired underneath for neatness will allow more space on the base of the device to station the six gauges to maintain the pressure reading on all six devices at once.

21. Vacuum test unit with 6 test fixtures and 1 vacuum

Along with the last few concepts this will be a test fixture that allows the operator to perform six test at a given time. Instead of having the vacuum hook on the side of the fixture it will be stationed right underneath for ease of transporting and space.

22. Vacuum test unit with 6 test fixtures and valve set up

With as many test fixtures as six, a valve setup is more important. The operator will not always have six seals to test at once, this way the operator can perform a test on one, two, three, four, five, or six test at any given point. All with a single click of the button due to the system being controlled.

23. Vacuum test unit with 8 test fixtures and no valves

As discussed in prior concepts, i believe six test fixtures is the optimal amount of tests to run. This concept was created just in case the option of more than six test fixtures was preferred.

With recent research and discussion our group will be going with one fixture for proof of concept and six or less fixtures for the final product.

24. Vacuum test unit with 8 test fixtures and 2 vacuums

Due to there being eight test that have to all be run at once, this concept was designed to help the system have enough power to run all eight test at once. Having two vacuum pumps stationed underneath the unit to run four test each. After more research recently, it has been come to our realization that two pumps will not be needed so this concept is not one of the finalist.

25. Vacuum test unit with 8 test fixtures and 1 vacuum

This concept has the eight test fixtures with the 1 vacuum set up. The vacuum is stationed underneath for ease of transportation and space.

26. Vacuum test unit with 2 test fixtures and adjustable plates

The device has two test fixtures both with an adjustable lapped plate that will lower onto the seal to create the vacuum. This will be performed once the system automatically runs through its tests.

27. Image of what the seal holding

Most of the concepts discuss amount of fixtures and accessories to the fixtures. This concept shows what the actual fixture itself will look like with dimensions of the surface, and the hole in the middle where the vacuum pump will pull through.

28. Original idea for base

A very basic concept of the base in which the fixtures will be mounted on to. This shows the size and dimensions of the base in which is to be used.

29. Original cup to close seal

This original concept was a picture of what an individual capsule could look like if our group decided to go with a fully encapsulated test instead of using lapped plates. After more research as of late, our group will not be going with detachable capsules of any sort.

30. Fixture with threads to hold cup

If our group decided to go with the capsule idea then this concept shows what the fixture would look like with the threaded are being on the outside of the fixture for the cup to be sealed around.

Listed below are the figures for the previously discussed concepts.

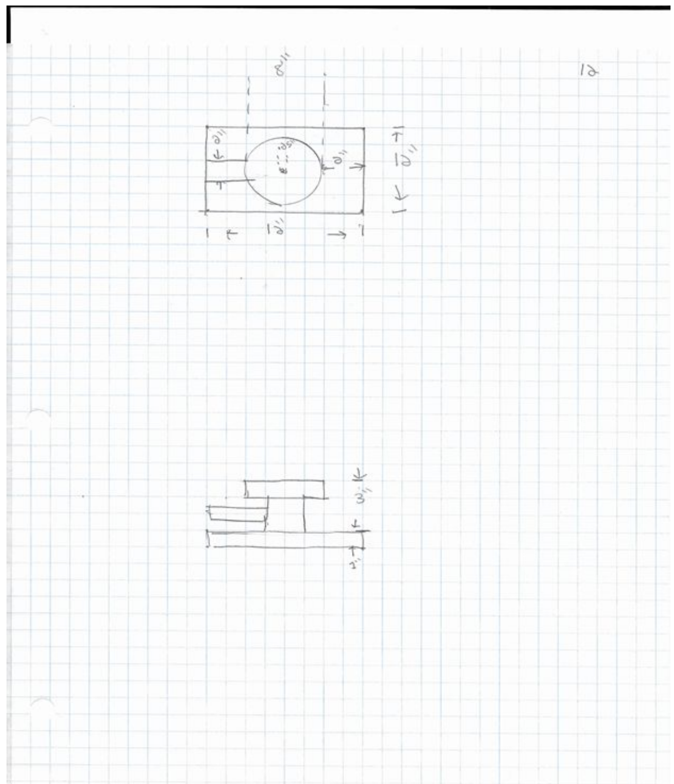


Figure 2: Josh concept 1

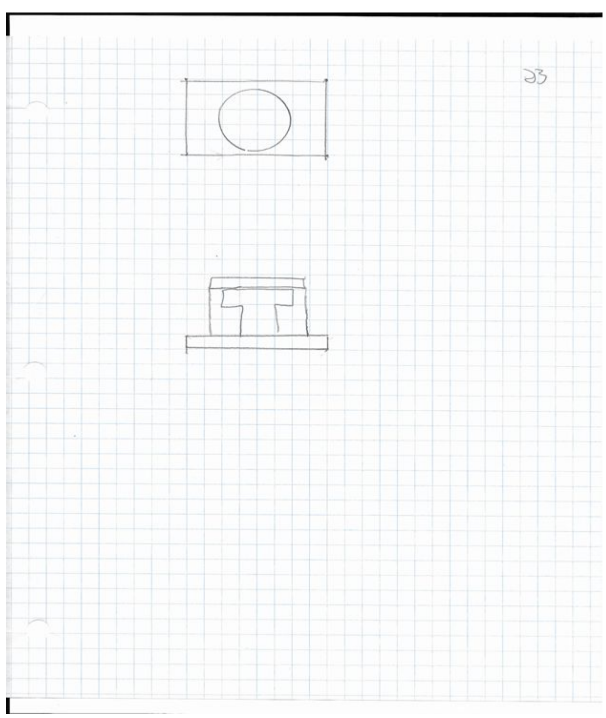


Figure 3: Josh concept 2

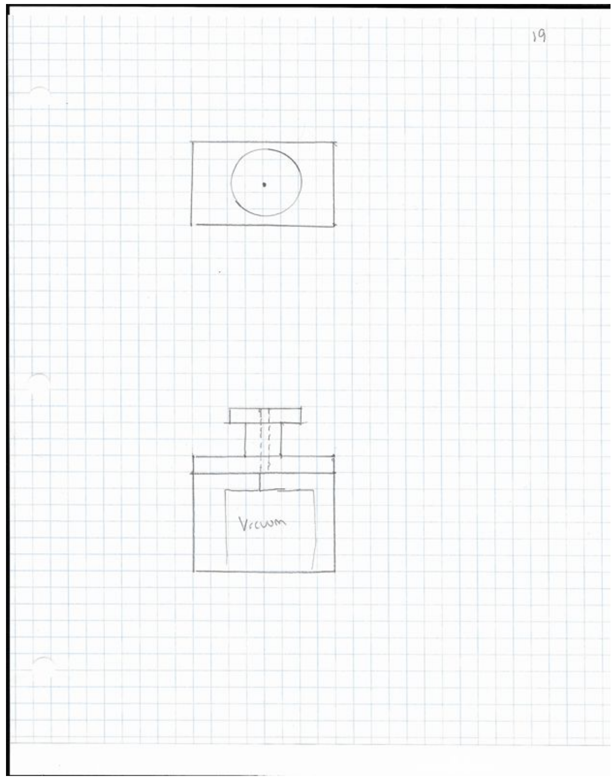


Figure 4: Josh concept 3

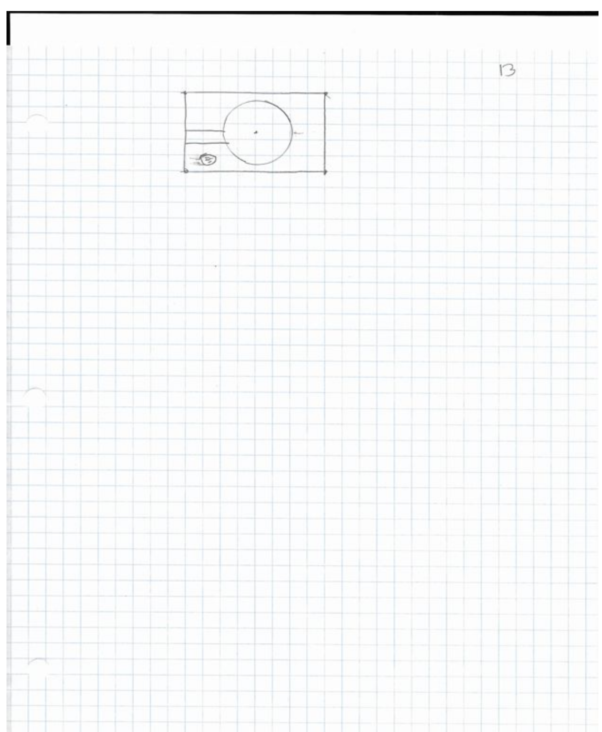


Figure 5: Josh concept 4

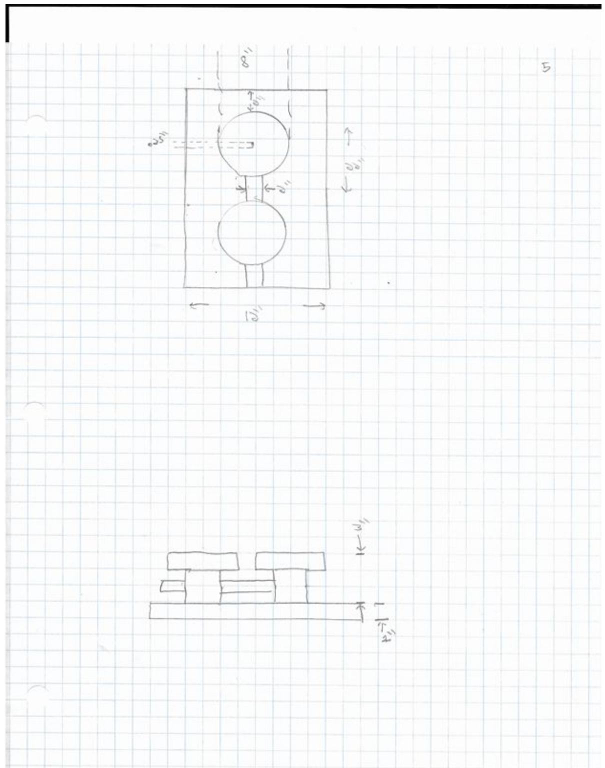


Figure 6: Josh concept 5

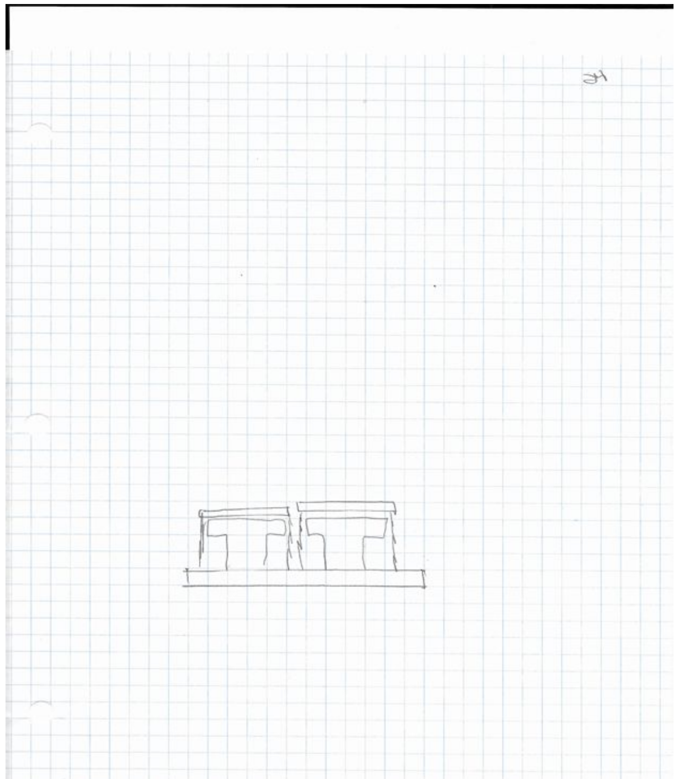


Figure 7: Josh concept 6

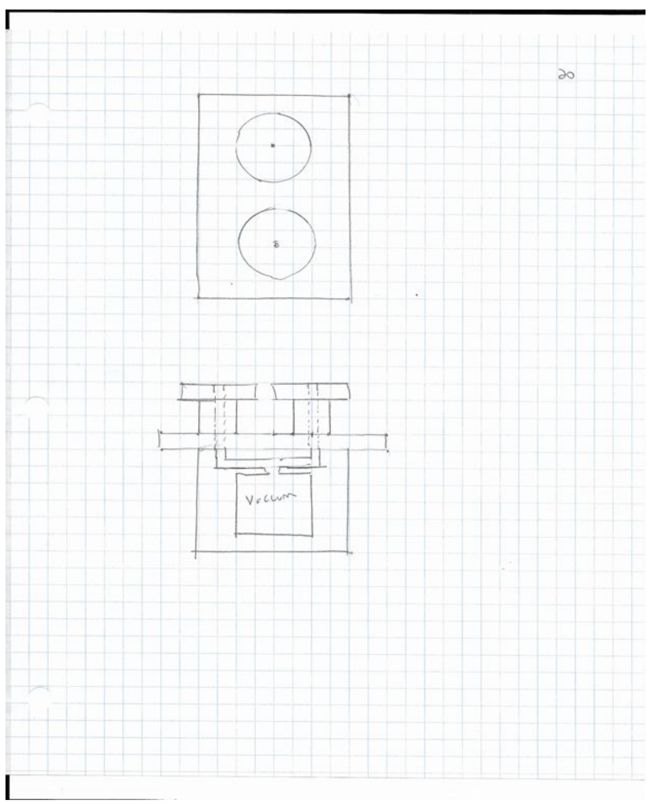


Figure 8: Josh concept 7

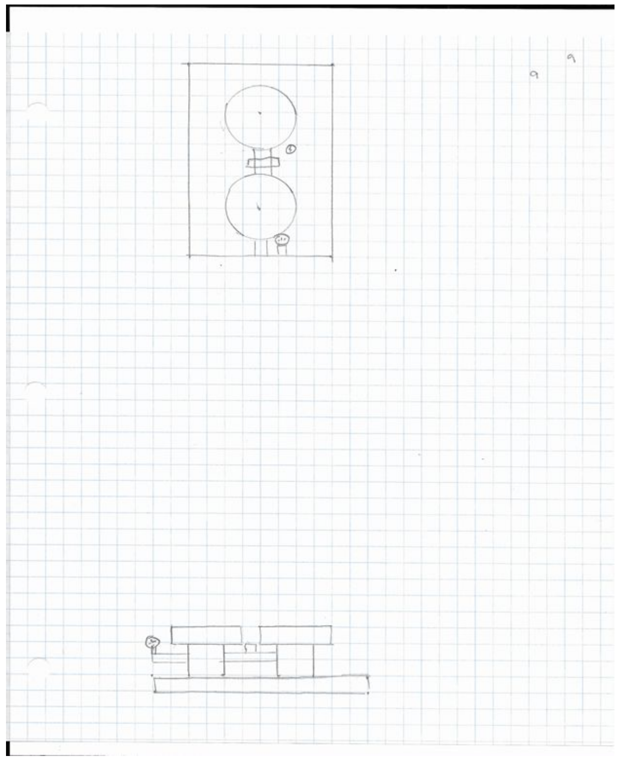


Figure 9: Josh concept 8

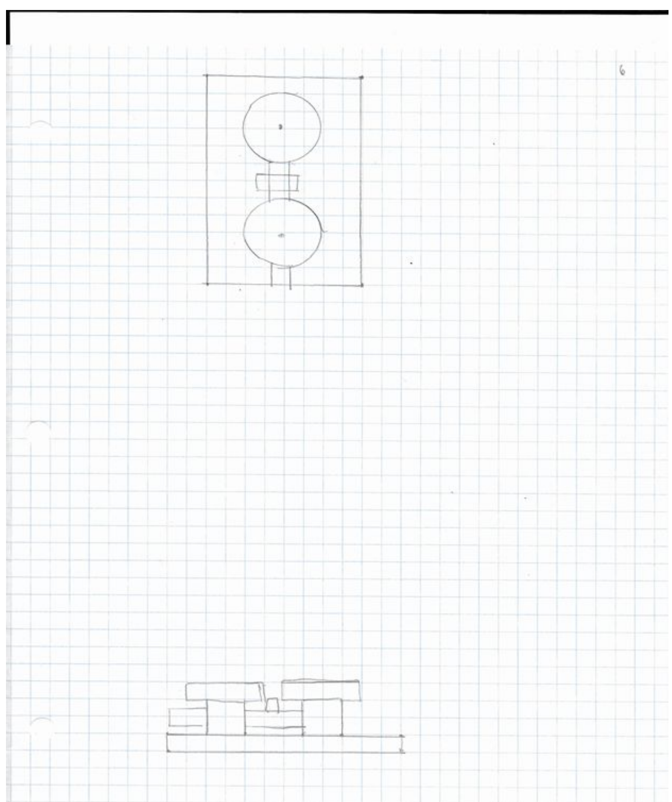


Figure 10: Josh concept 9

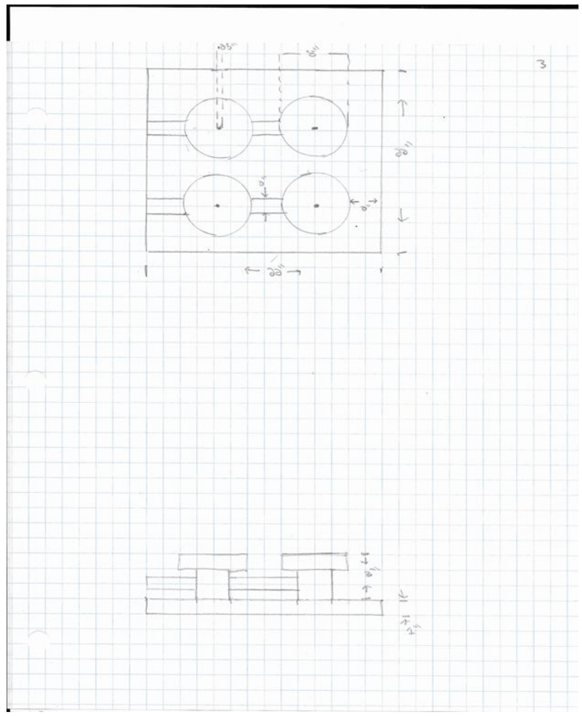


Figure 11: Josh concept 10

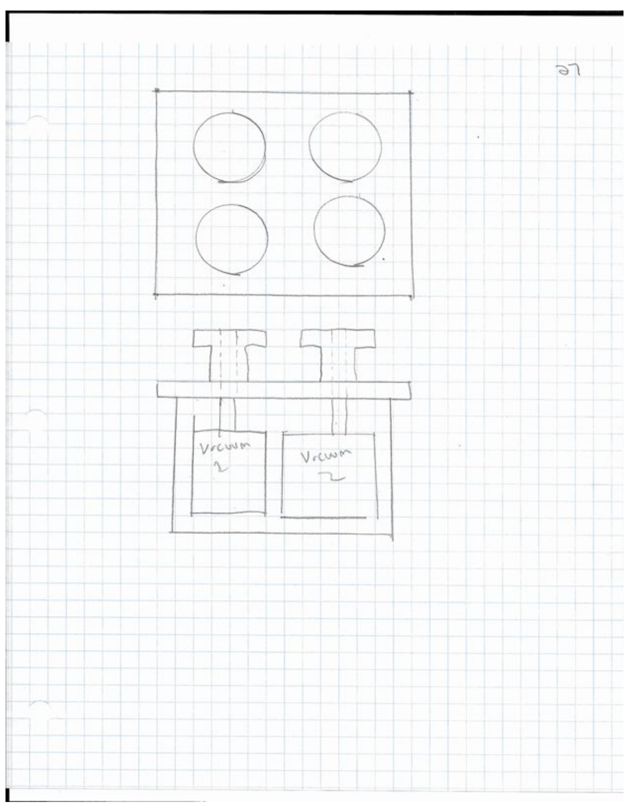


Figure 12: Josh concept 11

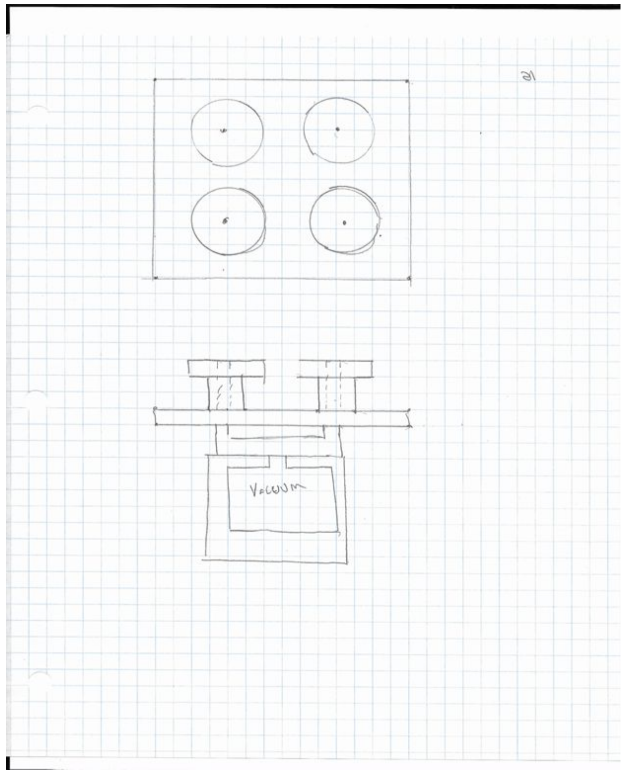


Figure 13: Josh concept 12

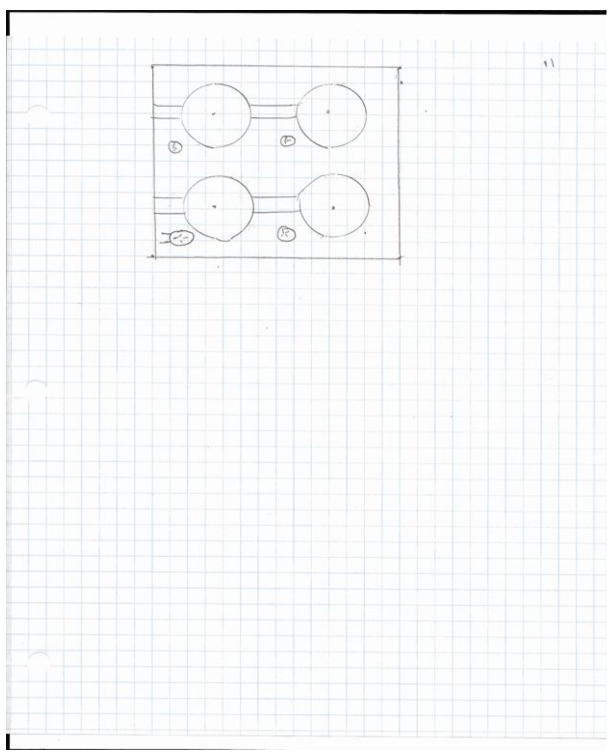


Figure 14: Josh concept 13

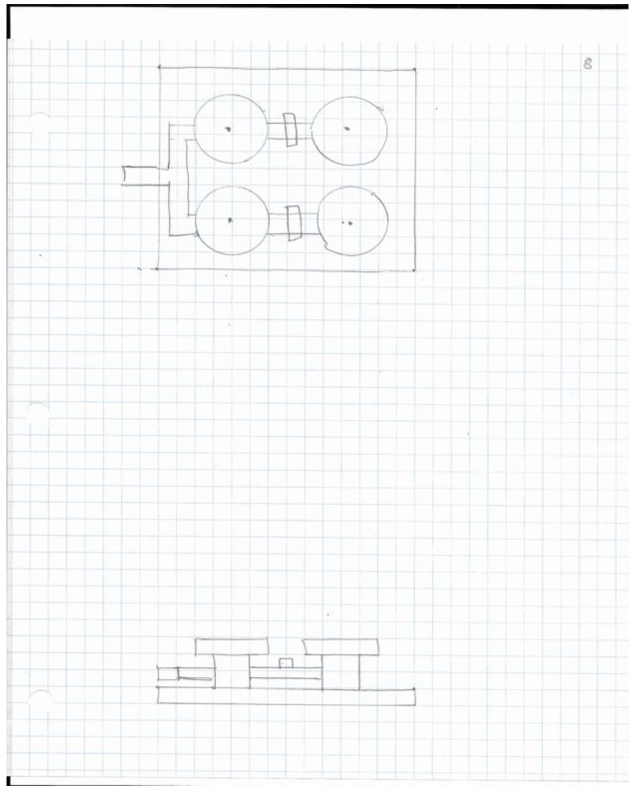


Figure 15: Josh concept 14

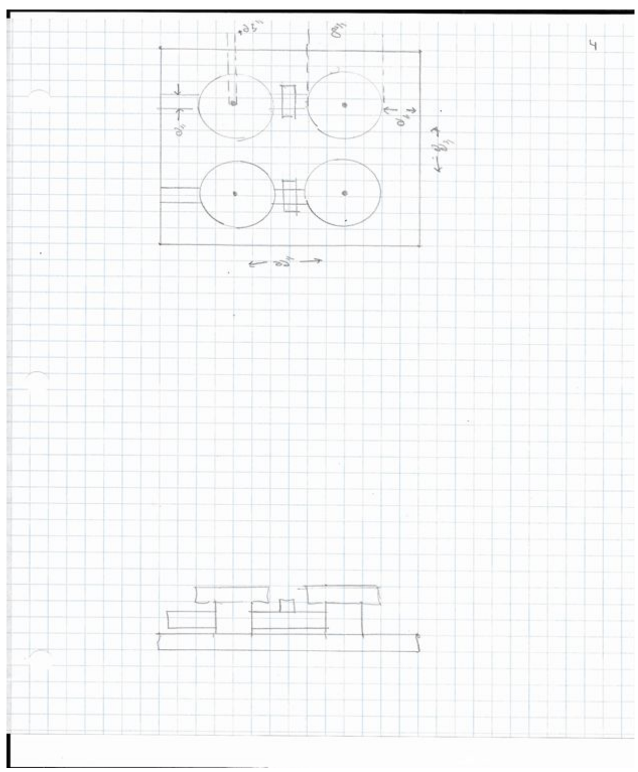


Figure 16: Josh concept 15

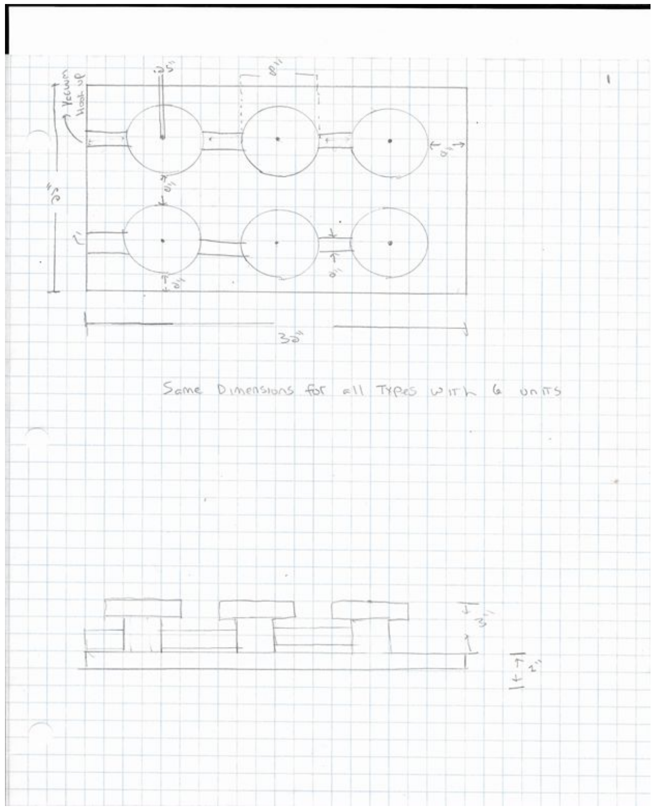


Figure 17: Josh concept 16

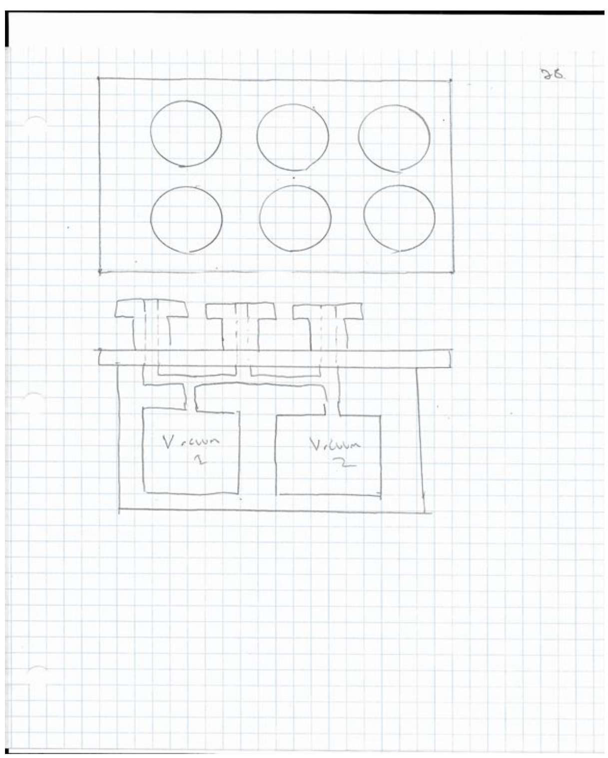


Figure 18: Josh concept 17

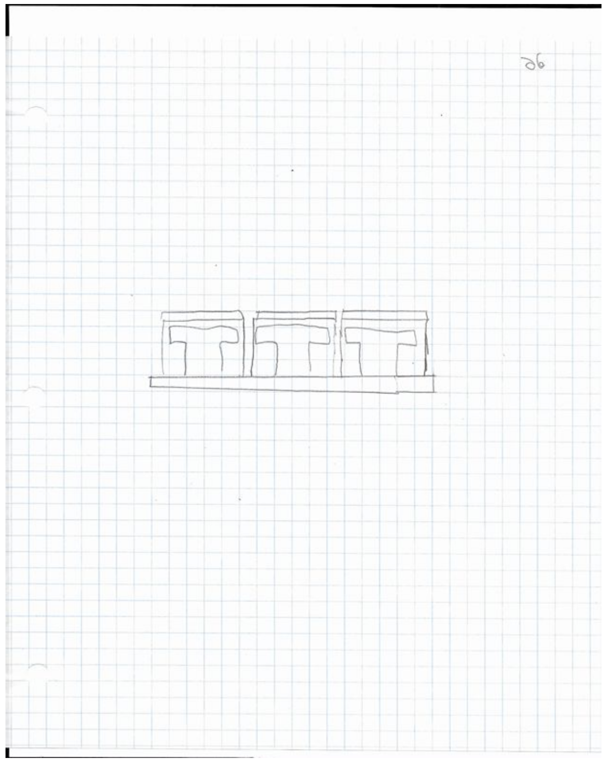


Figure 19: Josh concept 18

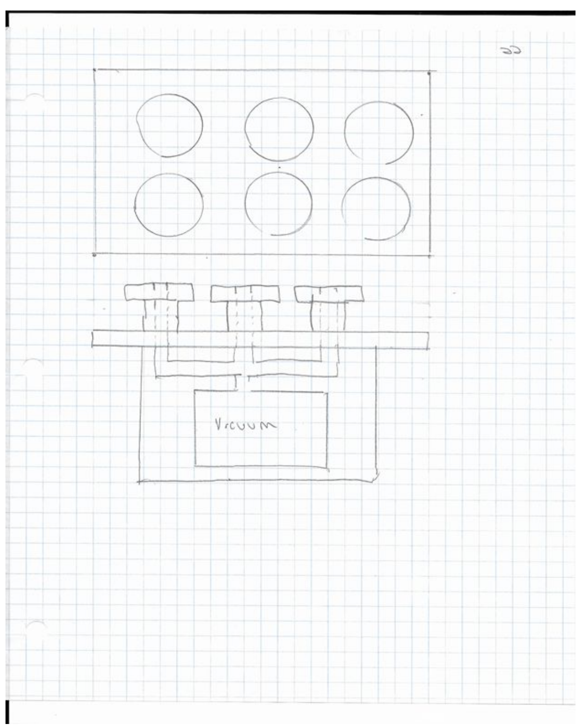


Figure 20: Josh concept 19

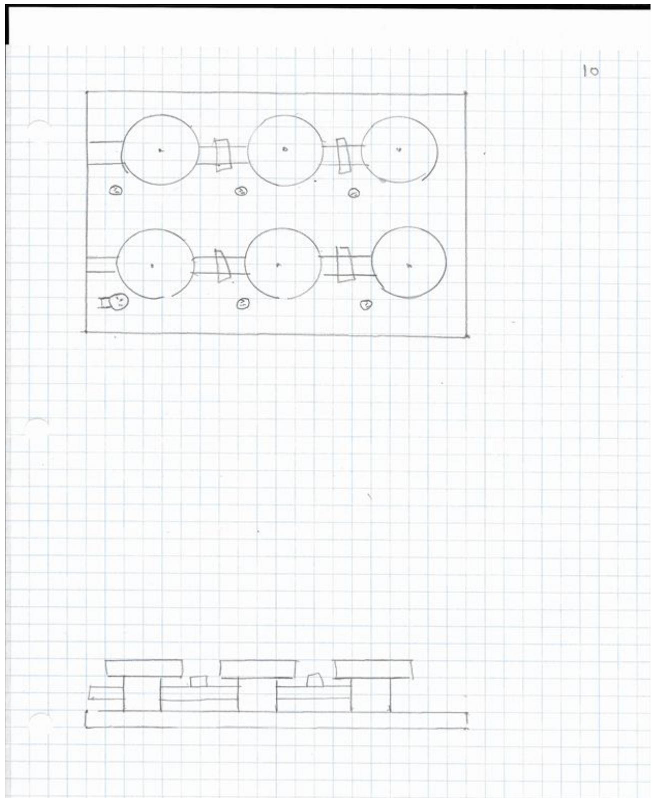


Figure 21: Josh concept 20

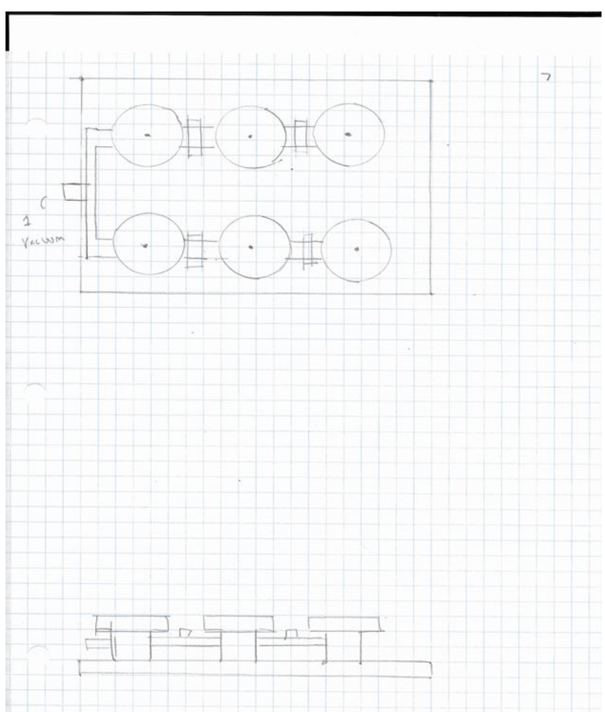


Figure 22: Josh concept 21

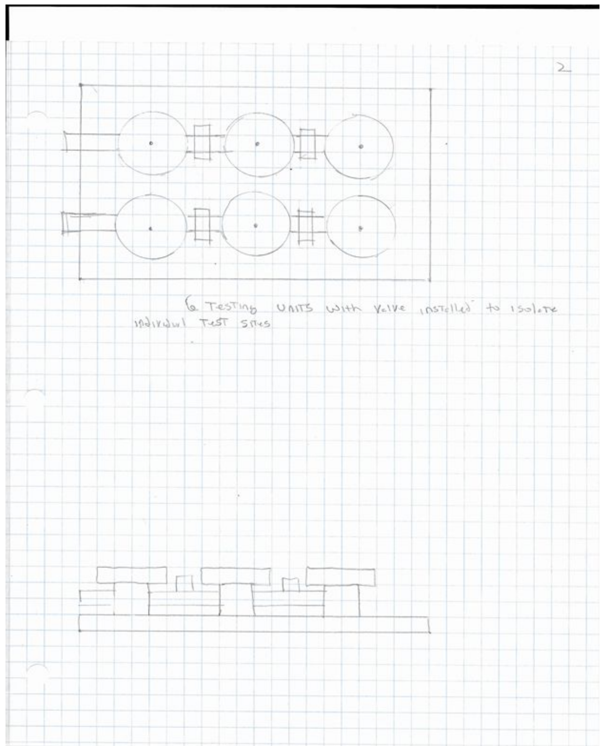


Figure 23: Josh concept 22

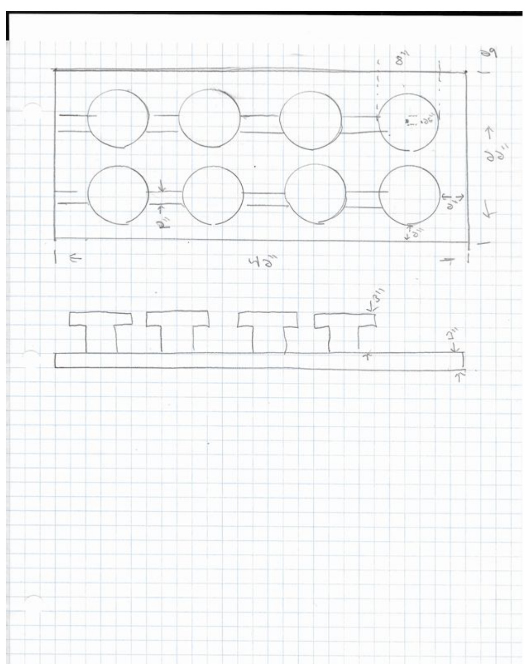


Figure 24: Josh concept 23

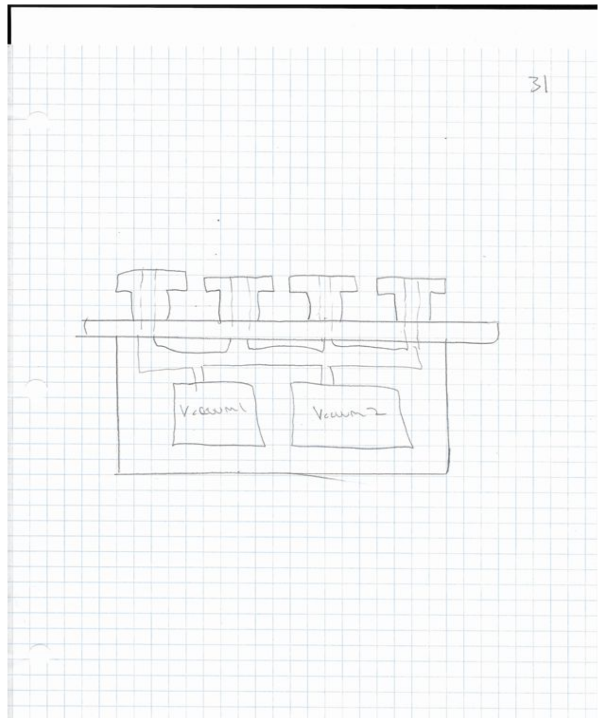


Figure 25: Josh concept 24

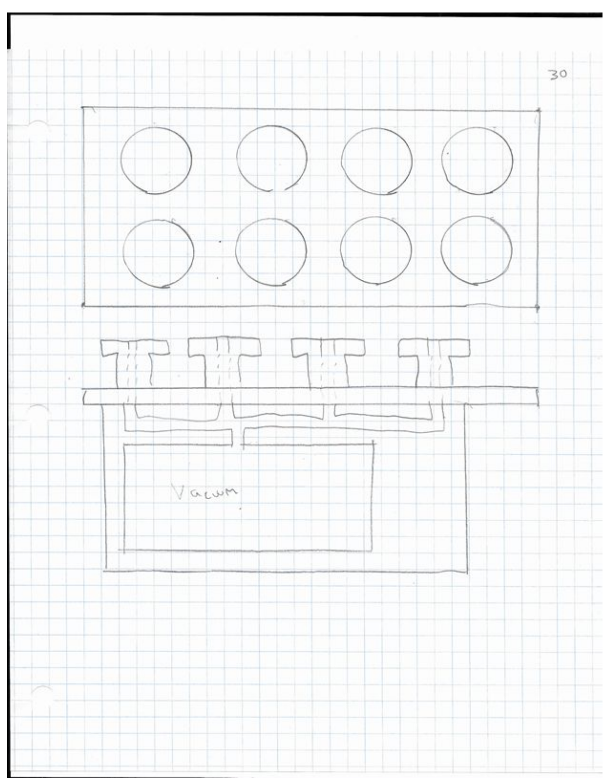


Figure 26: Josh concept 25

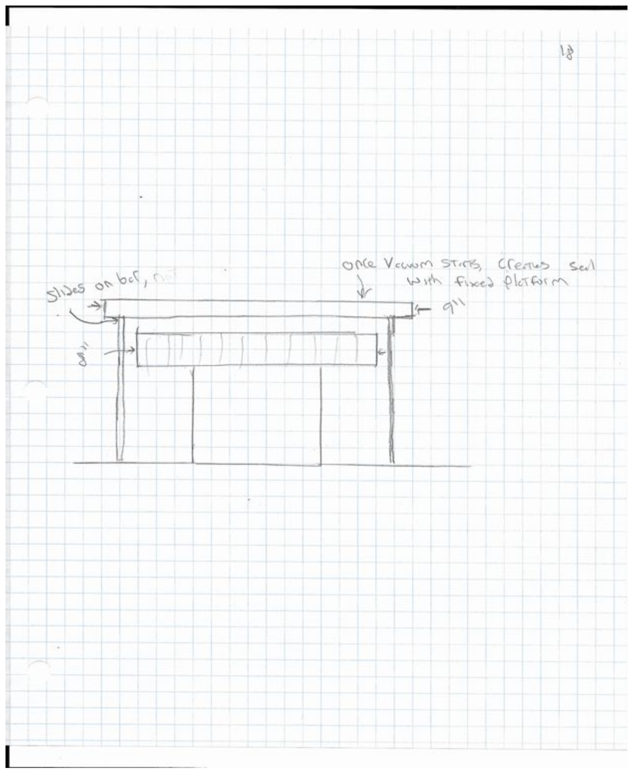


Figure 27: Josh concept 26

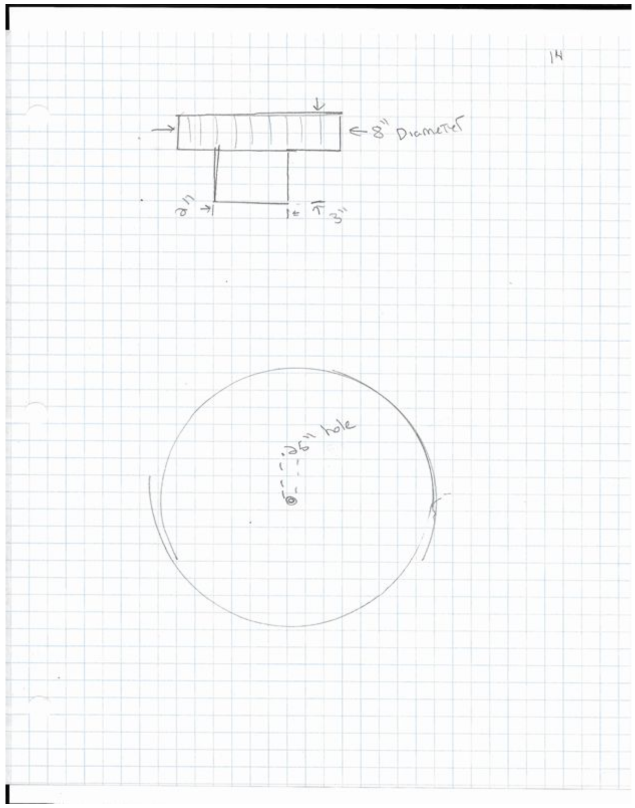


Figure 28: Josh concept 27

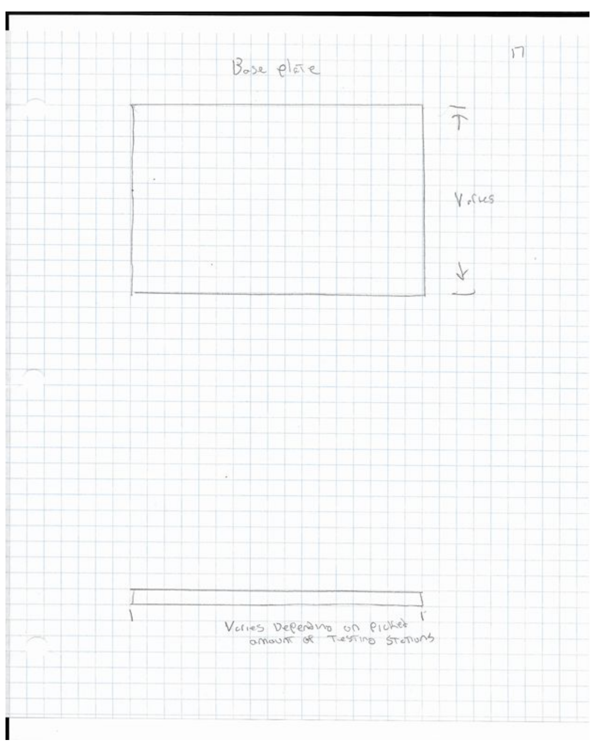


Figure 29: Josh concept 28

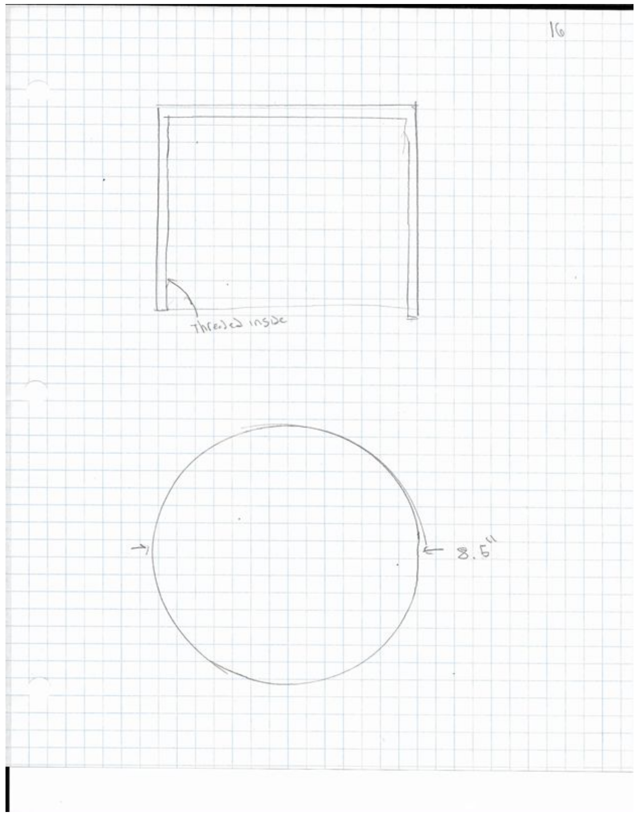


Figure 30: Josh concept 29

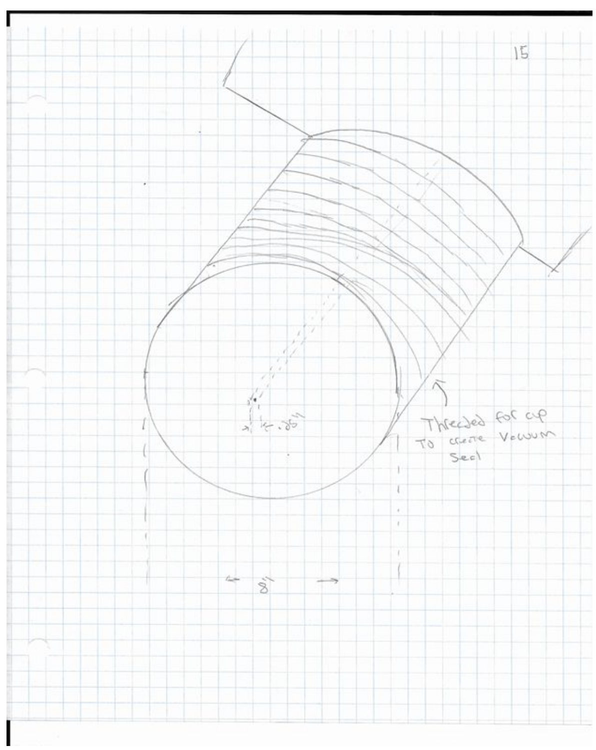


Figure 31: Josh concept 30

Matthew Baccaro's Concepts and Evaluations

1. **Base Plate with Multiple Plugs.**

   This concept involves the design of the laped plate which is necessary in creating the bottom sealing surface with the carbon sealing component of the mechanical face seal. This design incorporates a lapped plate which covers a large area and has upwards of six plug holes bored into it to allow the possibility of a six seal test configuration at one time. This is beneficial in allowing Eaton to test more seals at one time.

2. **Modified Upper-Plate Configuration V1**.

   This design involves the upper plate which is critical in creating the upper sealing surface for the seal test. The purpose of the top plate is to create a top seal which is leak free. Currently Eaton applies these to each individual seal being tested. The purpose of this design is to provide an upper plate which can cover up to two seal tests at once removing the need to add one to each individual seal.

3. **Modified Upper-Plate Configuration V2.**

   This design is similar to design #2 except it involves a larger upper plate which can cover up to three seals at a time and spans the entire length of the bottom lapped plate.

4. **Compressor with splitter.**

   The following is a subsystem design for the pneumatic aspect of the project. To supply a pathway from multiple plug holes to the air pump the design of a splitter is necessary to do so. This design incorporates one single hose from the pump to the splitter followed by a three way connection of three more hoses which connect to three separate seal testing rigs.

5. **Air Plumping Assembly V1.**

   This assembly design allows for a modded base plate as well as many seal configurations as needed. This is done with a piping system which surrounds the main base plate with multiple NPT connections for hoses to connect into leading to the air pump.

6. **Modified Upper-Plate Configuration V3.**

   This top plate alternative incorporates a suction cup instead to create a top seal. The suction cup will have a threaded connection to the base plate to allow it to stay stationary during testing procedures.

7. **Modified Upper-Plate Configuration V4.**

This alternative incorporates a rubber o-ring which fits snuggly into the top of the seal creating the upper seal required for testing.

8. **Circular Test Bench.**

This design incorporates a large circular test bench with multiple plug holes to allow multiple seal tests to be carried out at once.

9. **Pressure Gauge Configuration.**

This concept incorporates a mounted pressure gauge at each seal testing rig to allow for ease of testing. Here the operator could clearly visualize how each test is running side by side.

10. **Apparatus with GUI.**

This concept involves a USB plug-in from a computer to the vacuum testing apparatus. A GUI generated by a computer program specific for running these tests will prompt the operator through the whole process and provide real time data visualization and measurements which can later be saved and exported in a text-file for post processing.

11. **Detachable Base Plates.**

This concept allows for various sized base plates to be assembled through multiple NPT connections which funnel into the air pump.

12. **Multi-Pump Design.**

This design incorporates the use of multiple pumps which feed into the test bench in order to supply enough vacuum into the system. This would greatly reduce the testing time.

13. **Control Theory V1.**

This control system design involves a feedback loop between the pressure sensor and vacuum process to allow for a controlled vacuum test.

14. **Control Theory V2.**

This control system design incorporates the air pump for a vacuum supply, software to monitor the pressure, and a pressure sensor to measure vacuum in the system.

15. **Pressure Relief Valve.**

This design incorporates an air flow meter followed by a pressure relief valve downstream so that once vacuum in the system has been reached it can be equalized with the relief valve back to atmospheric pressure.

16. **Manual Valving System.**

This valving system is a manual shut on-off design for ease of build since an automated one might be complex to design and lead to slow downs in our build. A manual one with a lever to open and close the system guarantees that air flow is controlled in the system.

17. **Automatic Valving System.**

This design incorporates an automatic valving system on a feedback loop so that once vacuum reaches 25”Hg a solenoid will close off air flow in the system to control the vacuum reached.

18. **Emergency Shut-Off Button.**

This concept incorporates an emergency shut-off button which would be located on the apparatus as a safety feature for any operator conducting the test in case a part of the structure fails under vacuum.

19. **Three Plate Design.**

This design incorporates three base plates of 3”,5” and 8” diameter to incorporate various seal sizes for testing.

20. **Retractable Air Hose.**

This concept incorporates a hose which wraps around the air pump in a coiled manner making it retractable for ease of conducting tests. The hose can then connect to any NPT valves at the workbench to run tests on specific seals.

21. **Tracer Gas Leak Test.**

This concept involves the use of helium tracer gas which would fed into the system to allow for an easy visualization on where any possible leaks in the system could be occurring. This would provide shorter maintenance and down times working on the system.

22. **Stacked Testing Units.**

This concept involves up to six testing platforms which are staggered in height so that the testing station does not take up too much space on the floor.

23. **Alternate Valving Configuration.**

This valving configuration involves the use of NPT connections to ensure an airtight fit and minimal leakage at all connector locations.

24. **Multiple Seal Configuration**.
Use the existing vacuum testing apparatus and design except include more vacuum plugs to allow the testing of more seals.

25. **Multi-Valve System.**
Long flat plate with up to six through holes in it for creating a vacuum seal. This would be attached to the plumping system so multiple shut off valves for each plug would need to be incorporated with pressure sensors and pressure gauges to conduct multiple tests at once.

26. **Leak Detection System**.
This leak detection system will use helium tracer gas to optically determine leakage. Tracer would be fed through the air pump and plumbing system to a vacuum pressure of 25" Hg and then valved off and have seal inspected for leakage.

27. **GUI.**
Graphical User Interface that is simple and user friendly. Operator will be prompted with a message "Begin Carbon face sealing test" after selecting a loading screen will pop up for duration of test which is around 10 seconds. After test user will be prompted with message "Export" where data can be exported to a csv file**.**

28. **Pass-Fail System.**
Indicator light that flashes if pressure leakage exceeds 2'' Hg in 10 second time period.

29. **Alert System.**
Mini display screen that notifies the operator when test is running and when it has ended. Also, will display error messages and specify if the seal passed or failed inspection.

30. **Internal Display.**
Computer interface mounted internally into the testing apparatus instead of externally connected via cable.

Listed below are the figures for the previously discussed concepts.

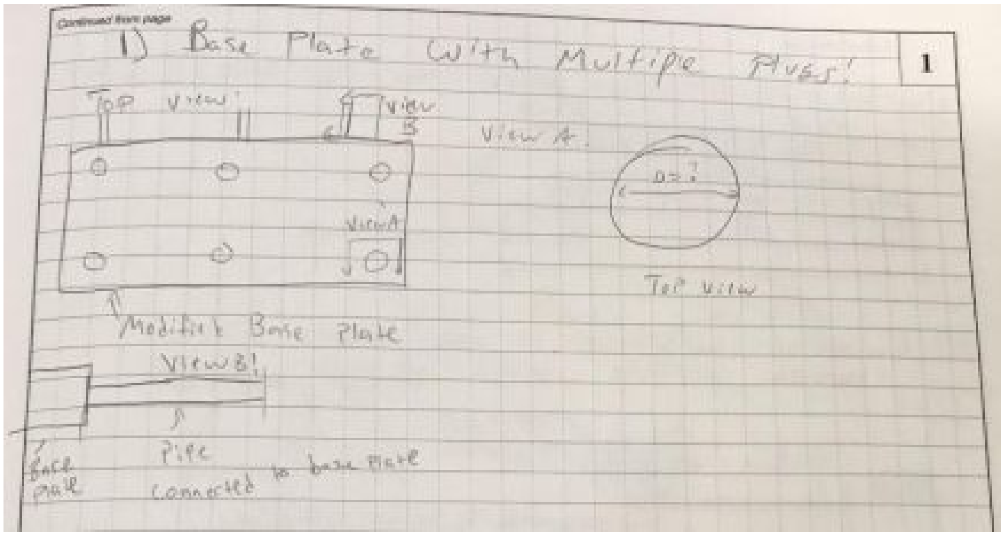


Figure 32. Concept 1

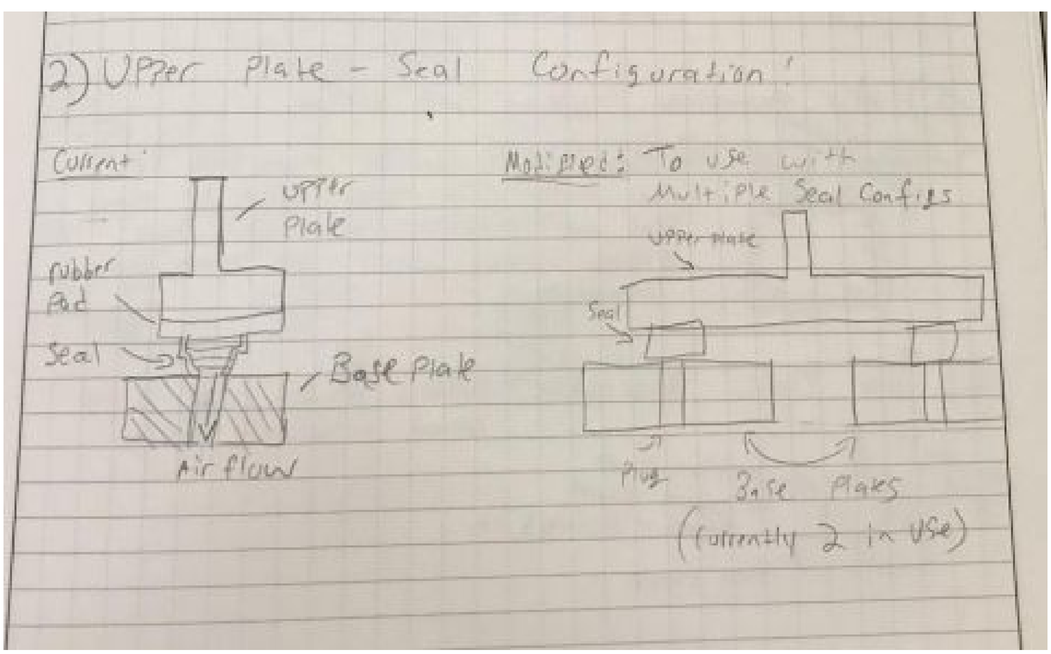


Figure 33. Concept 2

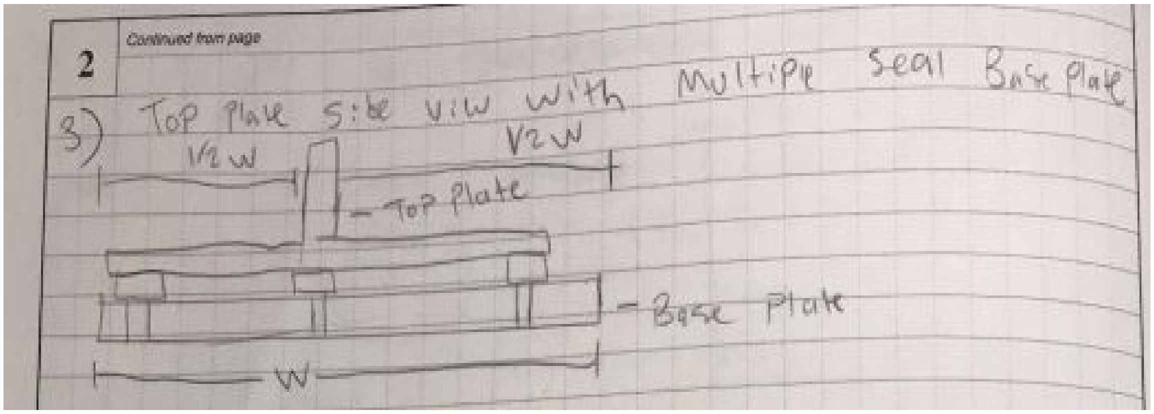


Figure 34. Concept 3

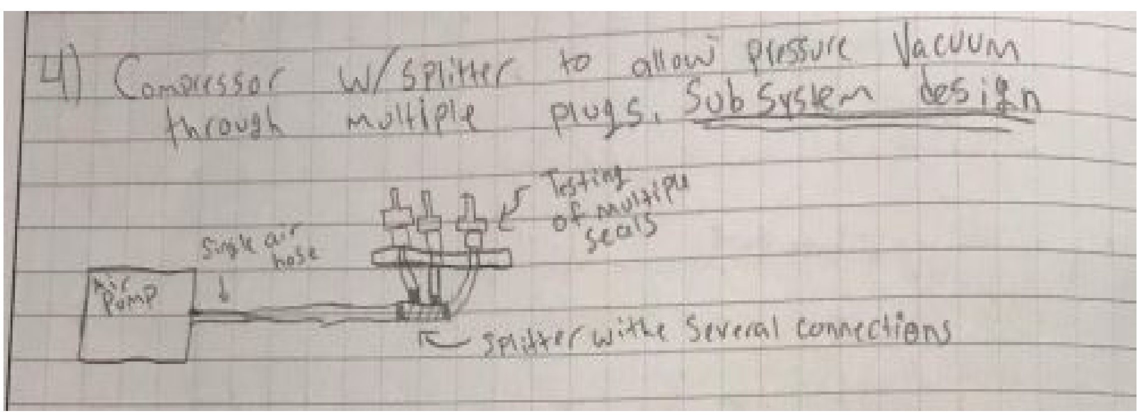


Figure 35. Concept 4

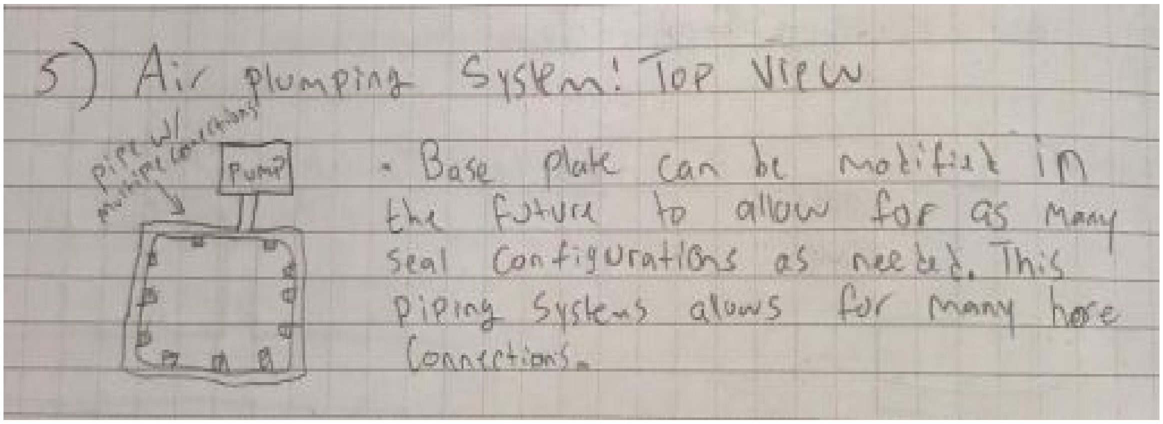


Figure 36. Concept 5

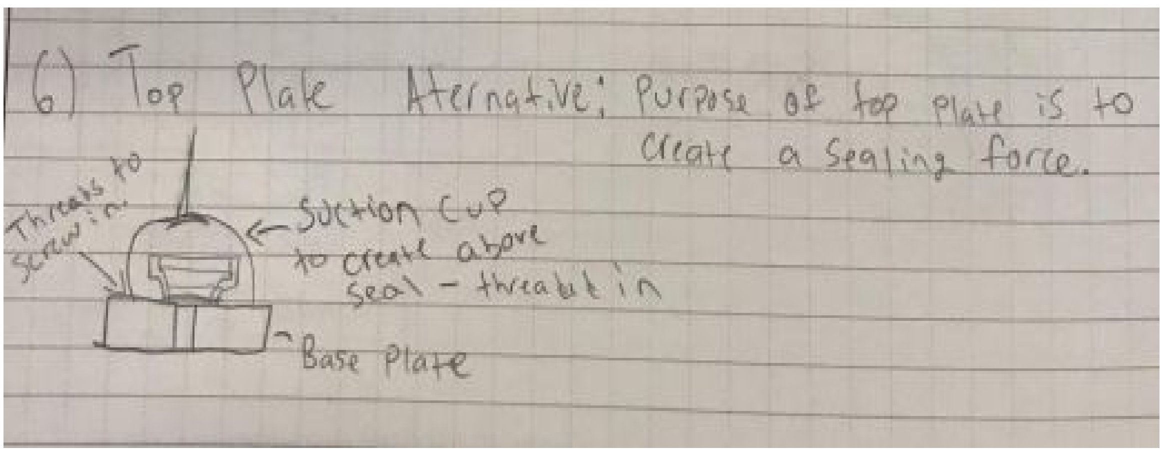


Figure 37. Concept 6

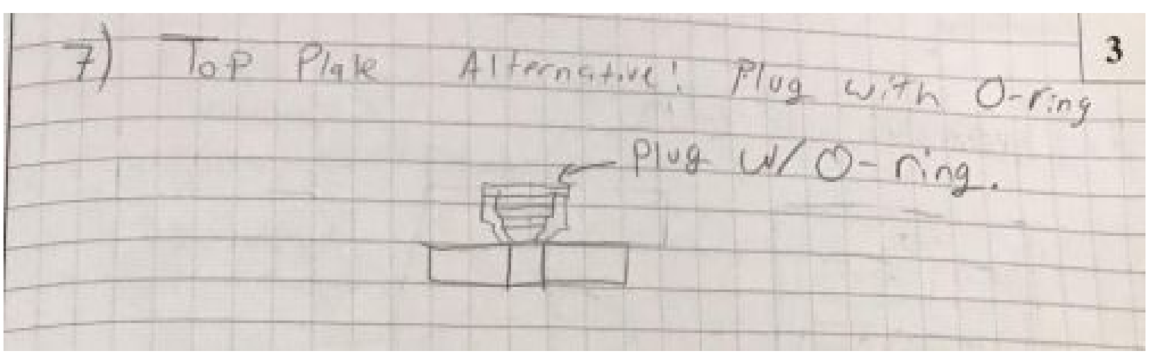


Figure 38. Concept 7

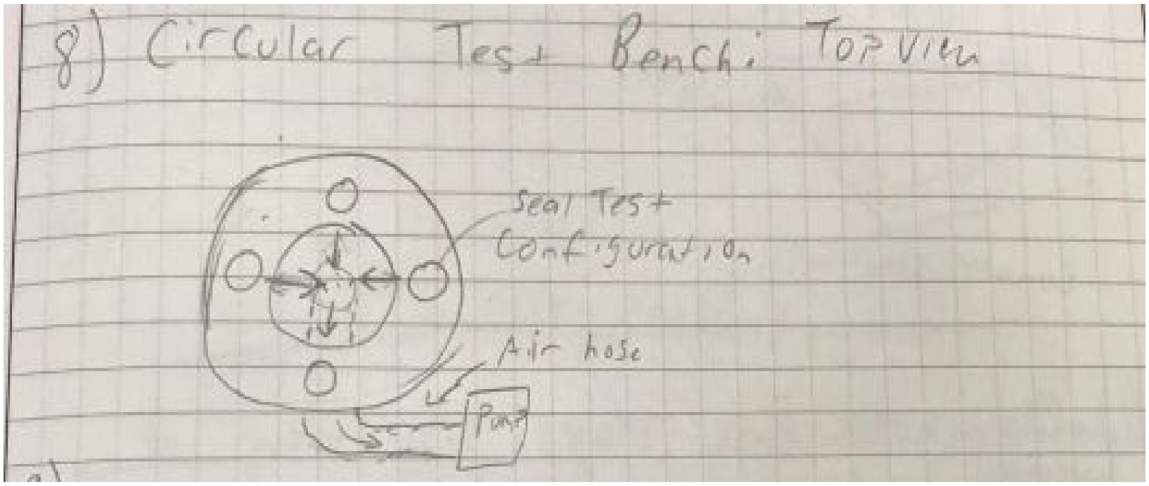


Figure 39. Concept 8

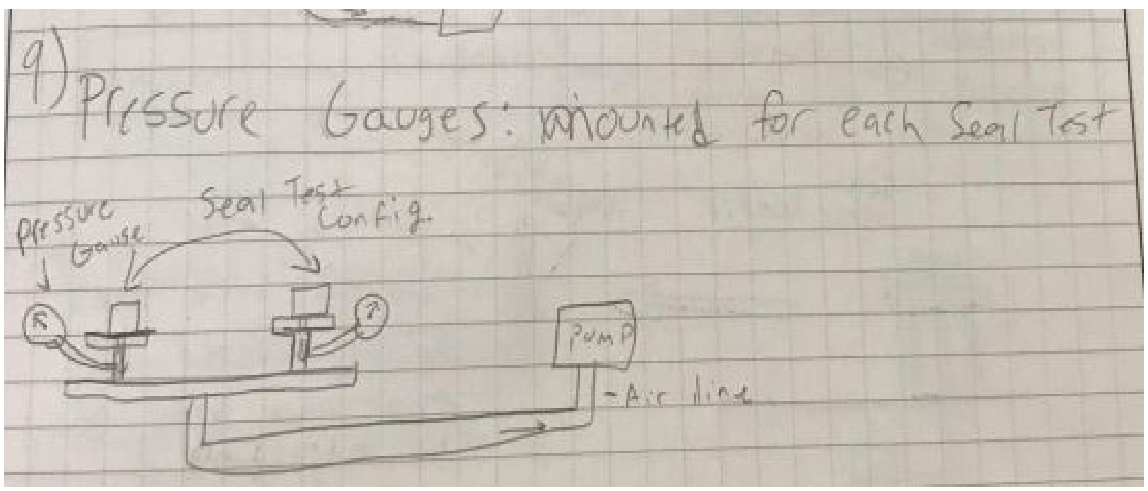


Figure 40. Concept 9

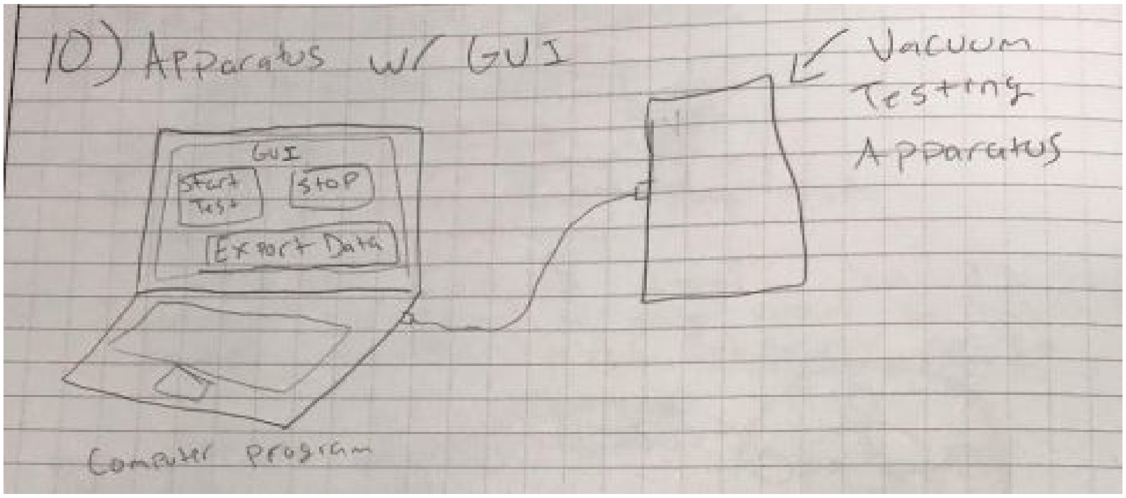


Figure 41. Concept 10

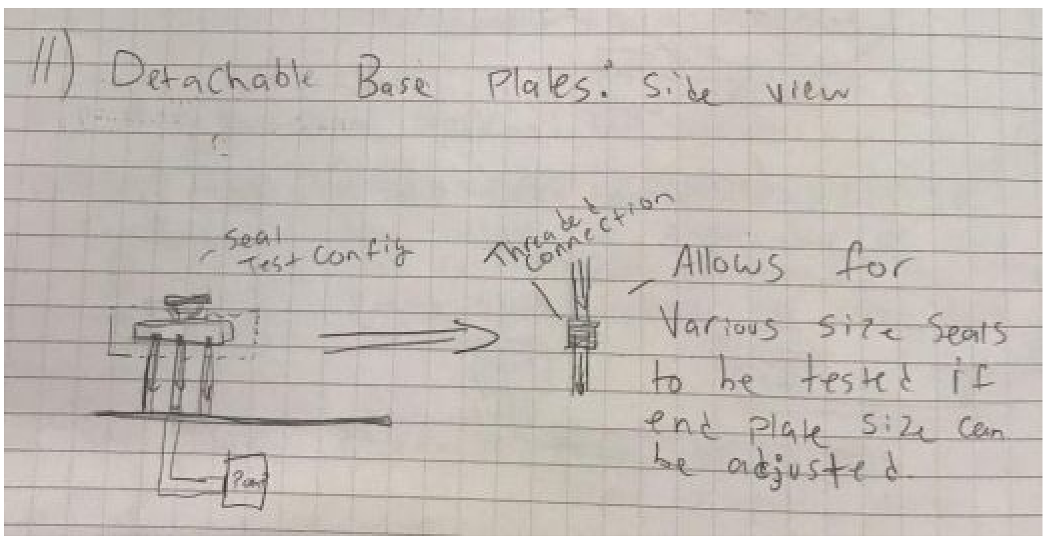


Figure 42. Concept 11

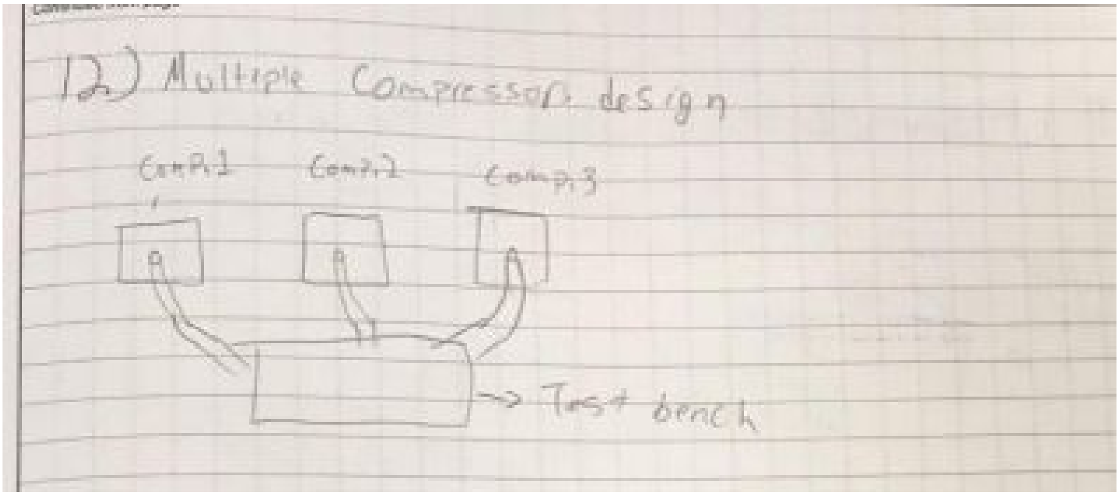


Figure 43. Concept 12

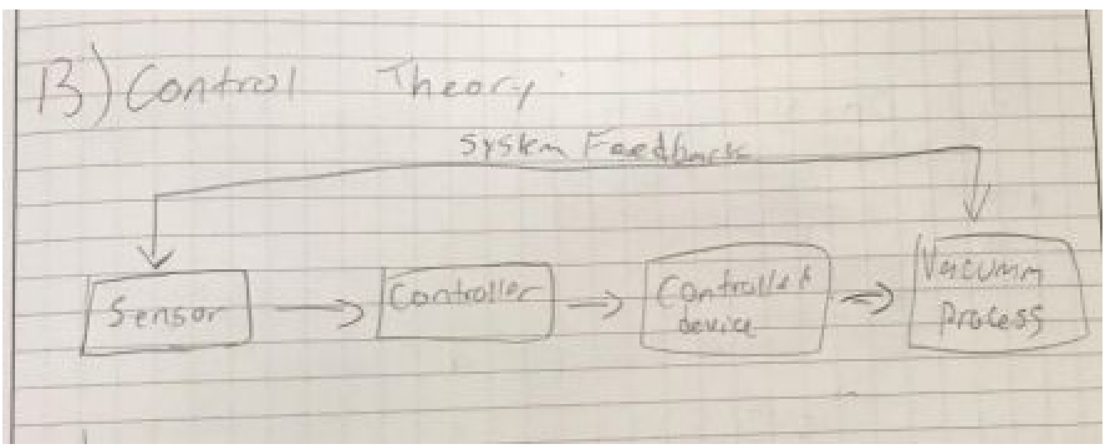


Figure 44. Concept 13

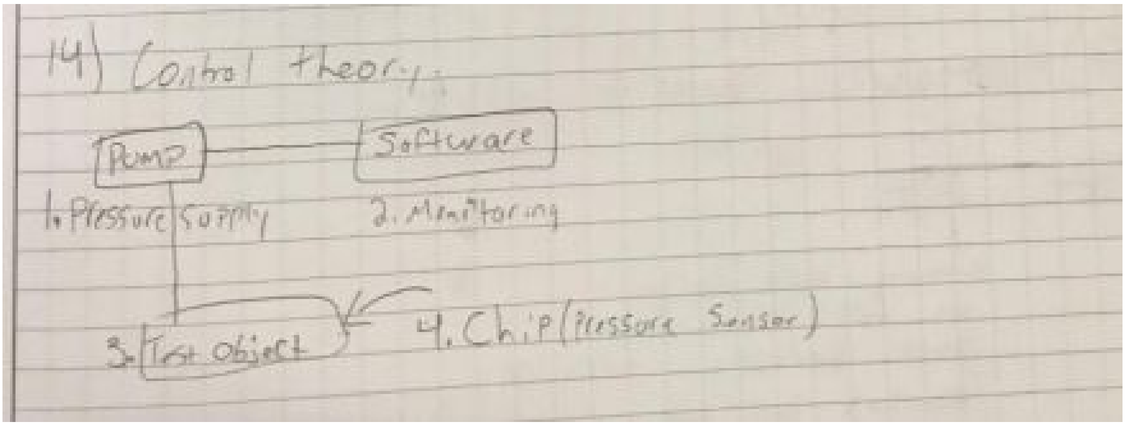


Figure 45. Concept 14

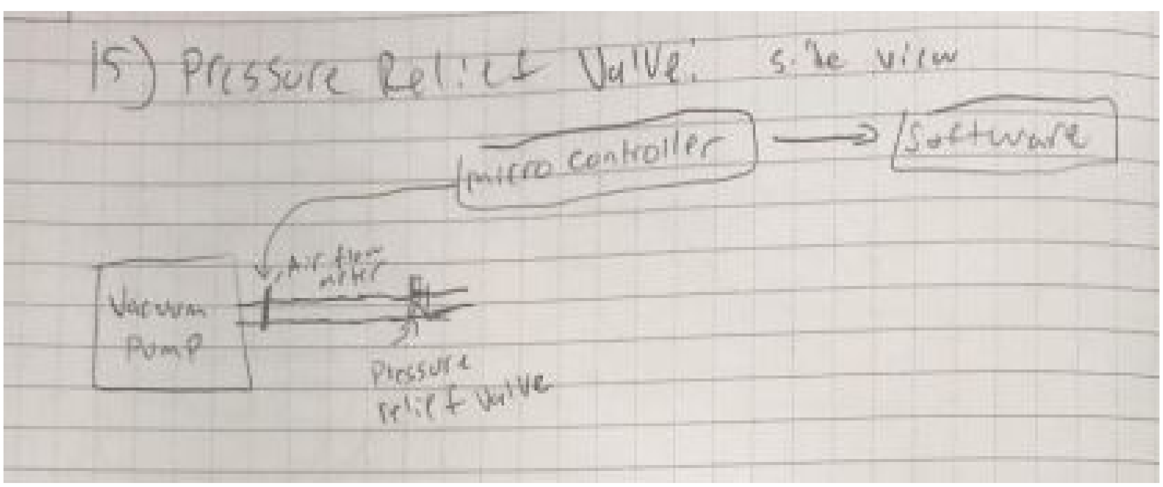


Figure 46. Concept 15

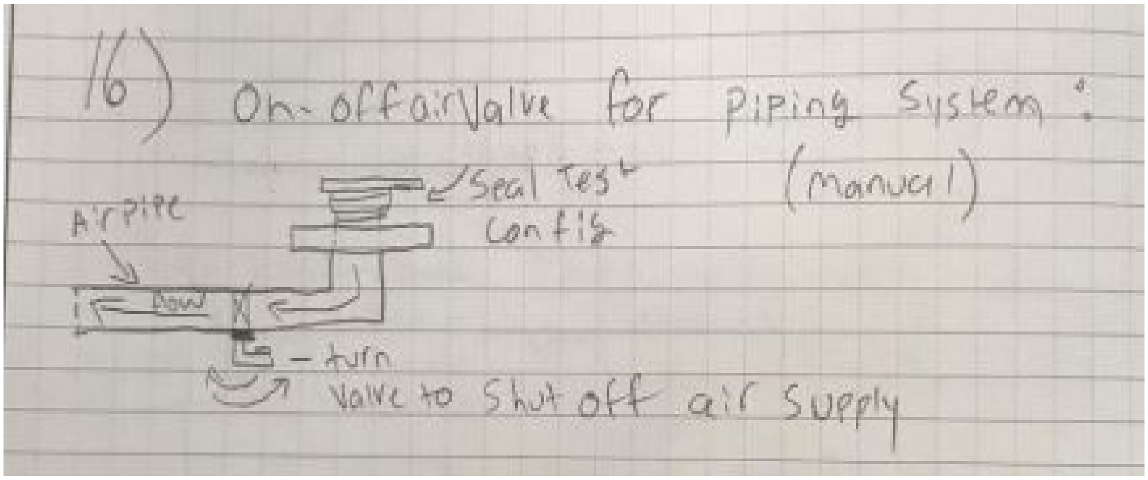


Figure 47. Concept 16

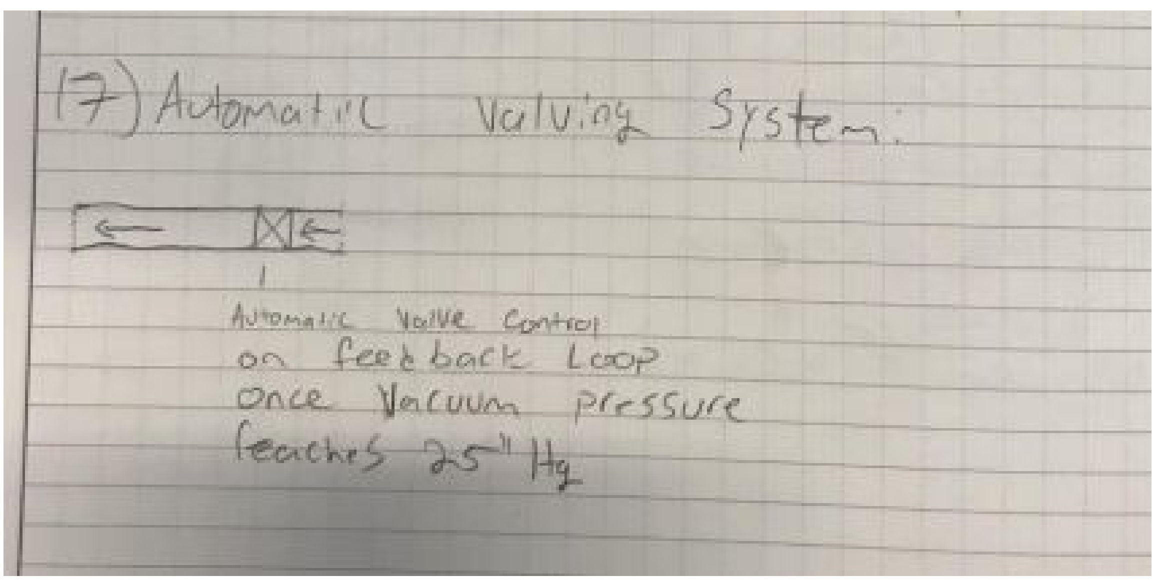


Figure 48. Concept 17

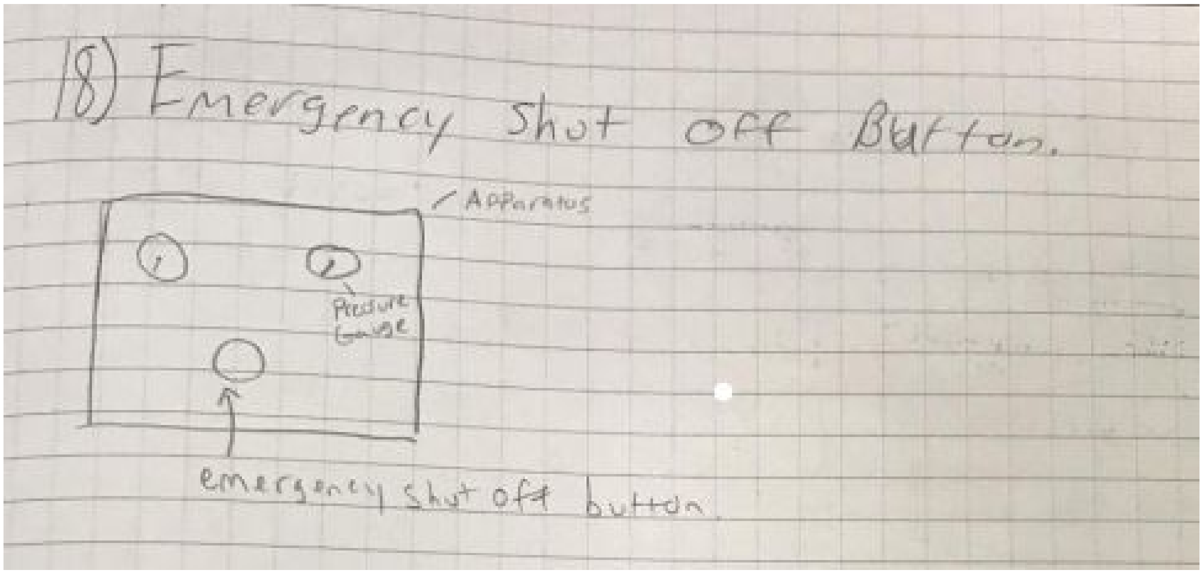


Figure 49. Concept 18

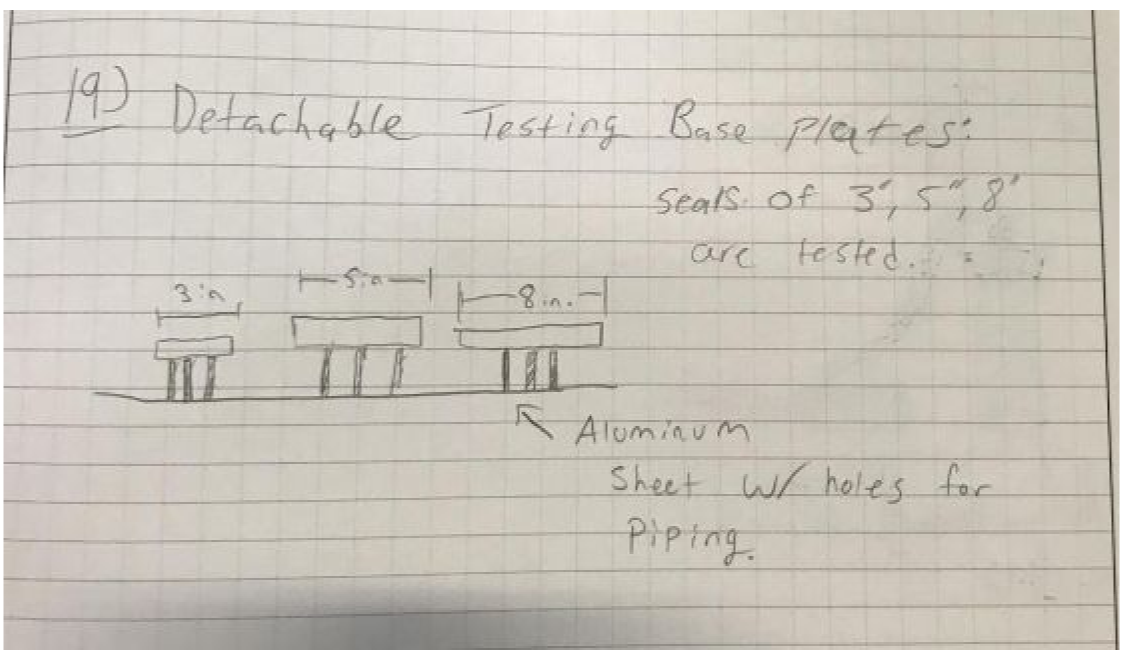


Figure 50. Concept 19

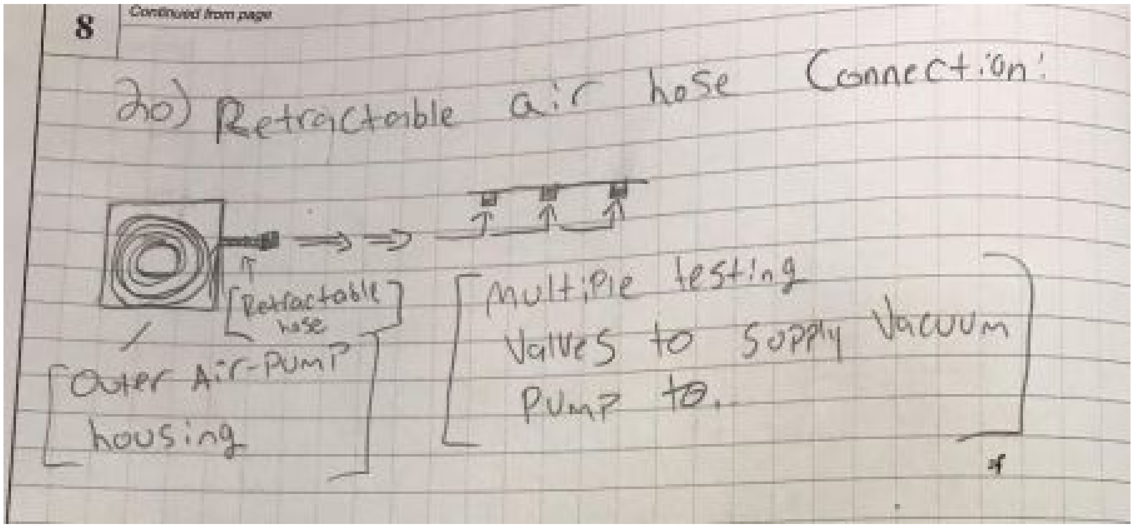


Figure 51. Concept 20

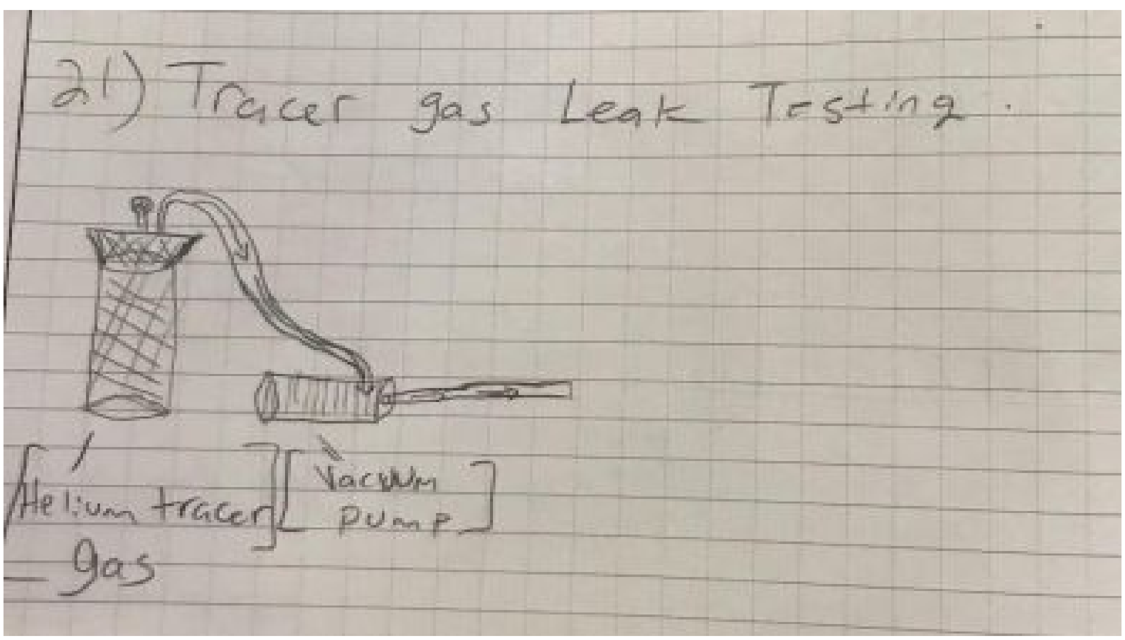


Figure 52. Concept 21

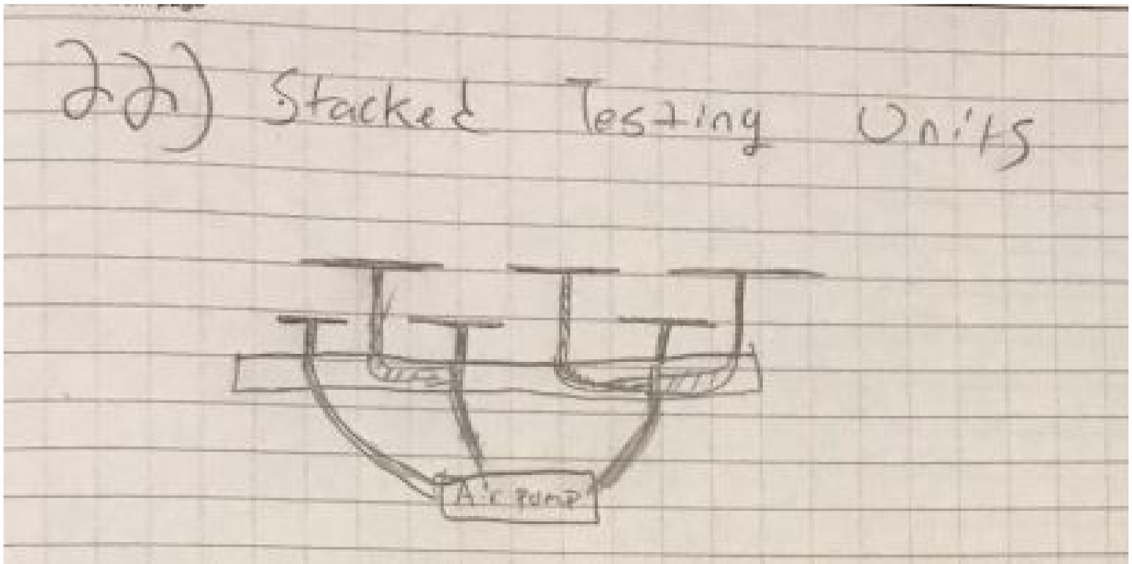


Figure 53. Concept 22

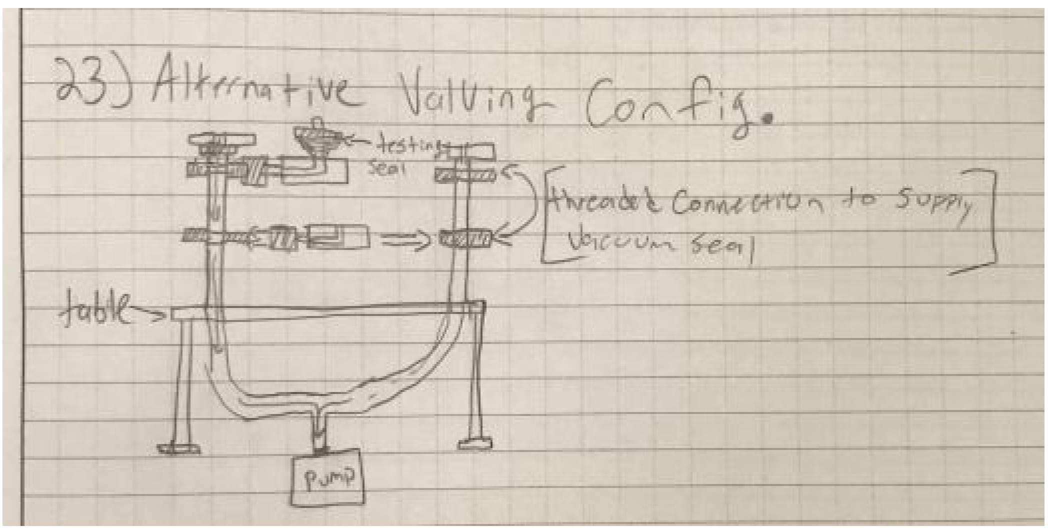


Figure 54. Concept 23

Benjamin Amundson's Concepts and Evaluations

1. **Pressure and Timing User Interface #1**

    A three row LCD screen mounted with two sets of two momentary switches marked increase and decrease. These buttons allow user control of pressure and time for the current test with the current pressure and time displayed on the LCD.

2. **Pressure and Timing User Interface #2**

A three row LCD screen mounted with two sets of potentiometers marked pressure and time. These buttons allow user control of pressure and time for the current test with the current pressure and time displayed on the LCD.

3. **Single Phase Compressor Control**

A single phase compressor is attached wired to a thyristor. The thyristor gate is attached to a control board which when activates opens the gate of the thyristor. When the vacuum pressure sensors read the correct value, the gate is closed, and the test begins.

4. **Three Phase Compressor Control**

A three phase compressor is used in conjunction with a motor control unit. This motor control unit can be used to adjust the power used by the compressor to reduce energy cost and adjust the speed at which the vacuum is reached based on the volume of seals being tested.

5. **Laptop Control**

The single-phase compressor is used but not user interface is attached to the vacuum test machine. A PC is plugged into the onboard control unit and all controls and data acquisition is done directly from the PC.

6. **8” carbon face seal fixture**

A lapped metal block that contains 5 channels through it spaced to allow up to five 8” carbon face seals to be tested at once.

7. **3” carbon face seal fixture**

A lapped metal block that contains 12 channels through it spaced to allow up to 12 3” carbon face seals to be tested at once.

8. **5” carbon face seal fixture**

A lapped metal block that contains 8 channels through it spaced to allow up to 8 5” carbon face seals to be tested at once.

9. **Multiple carbon face seal fixture**

A lapped metal block with 6 channels that can fit a mixture of seal sizes ranging from 3” to 8” in diameter.

10. **Lapped fixture sensor mounting**

A permanently fixed strain gage onto the fixtures mounted above, sits in the channel and outputs vacuum pressure from there.

11. **Air plumbing fixed sensor**

A strain gage affixed to the air plumbing that is connected to the compressor. Sits just after and electronic actuator that closes the air plumbing for the start of the test. Once the air plumbing is closed the same signal that closes the electronic actuator initiates the test.

12. **ARM mbed based controller**

ARM mbed lcp1768 is a compact control unit that is programmable using the online mbed compiler. Contains one micro usb port, can supply 3.3v output, has digital, analog, and pwm output and inputs.

13. **Arduino uno based controller**

Less compact than the ARM mbed but contains many of the same output and input pins. Has the advantage of more usb, display, and ethernet ports connected.

14. **Raspberry pi controller**

Same advantages as the Arduino but contains more I/O and has a standalone operating system. With the standalone operating system converting the pi to purely an embedded system will be more difficult that the Arduino and ARM mbed but will have more capability.

15. **8 seal air plumbing fixture**

A machined block that attaches the main compressor to the correct number and size of pneumatic tubes to supply vacuum pressure to each individual seal being tested for the corresponding fixtures above.

16. **12 seal air plumbing fixture**

A machined block that attaches the main compressor to the correct number and size of pneumatic tubes to supply vacuum pressure to each individual seal being tested for the corresponding fixtures above.

17. **5 seal air plumbing fixture**

A machined block that attaches the main compressor to the correct number and size of pneumatic tubes to supply vacuum pressure to each individual seal being tested for the corresponding fixtures above.

18. **Data recording via removable storage**

For test data storage a usb is plugged into the control board and all information is stored and can be removed and saved to a pc for statistical analysis and confirmation of test pass/fail.

19. **Data recording via ethernet/usb**
For test data storage an ethernet/usb cable is used to connect the control board to a pc and all information is saved to a pc for statistical analysis and confirmation of test pass/fail.

20. **Data recording via wifi**
For test data storage a wifi bridge is attached to the control board where it transmits test data to a server or local pc.

21. **Data recording via bluetooth**
For test data storage a Bluetooth receiver is attached to the control board where it transmits test data to a Bluetooth receiver on a pc or a local compatible server.

22. **PC based user interface for the vacuum test machine**
A GUI used to control and monitor test parameters during vacuum test.

23. **Raspberry Pi based user interface for the vacuum test machine**
A GUI used to control and monitor test parameters during vacuum test used in the raspberry pi OS.

24. **Workstation integrated test machine**
A lower profile machine than what Eaton currently uses, compressor and air plumbing are encased below the Eaton workstations. Air plumbing comes up to a fixture on top of the work station along with a usb cable were a pc controls the entire test and data storage. This keeps the machine out of the way until ready to be used.

25. **Standalone test machine**
The machine has a stand that can hold all materials relevant to testing such as fixtures and additional air plumbing, takes up the same amount of space as the current machine.

26. **Emergency shutdown switch**
Large momentary button on top of the machine that can cut power in case of electrical short and resulting fire or any other emergency that requires quick shutdown of test apparatus.

27. **Emergency shutdown lever**
Same as above but the addition of a lever decreases the chance of accidental test stoppage
.

28. **Indicator light single pass fail**

One indicator light that remains green from start of the test until significant leakage is detected then it switches to red.

29. **Pass fail lcd**

An lcd that reads off corresponding pneumatic tube numbers as a fail leakage is detected.

30. **Pass fail error message**

Sent to pc or connected device, pop up window indicating relevant fail data and which sensor detected the fail.

Listed below are the figures for the previously discussed concepts.

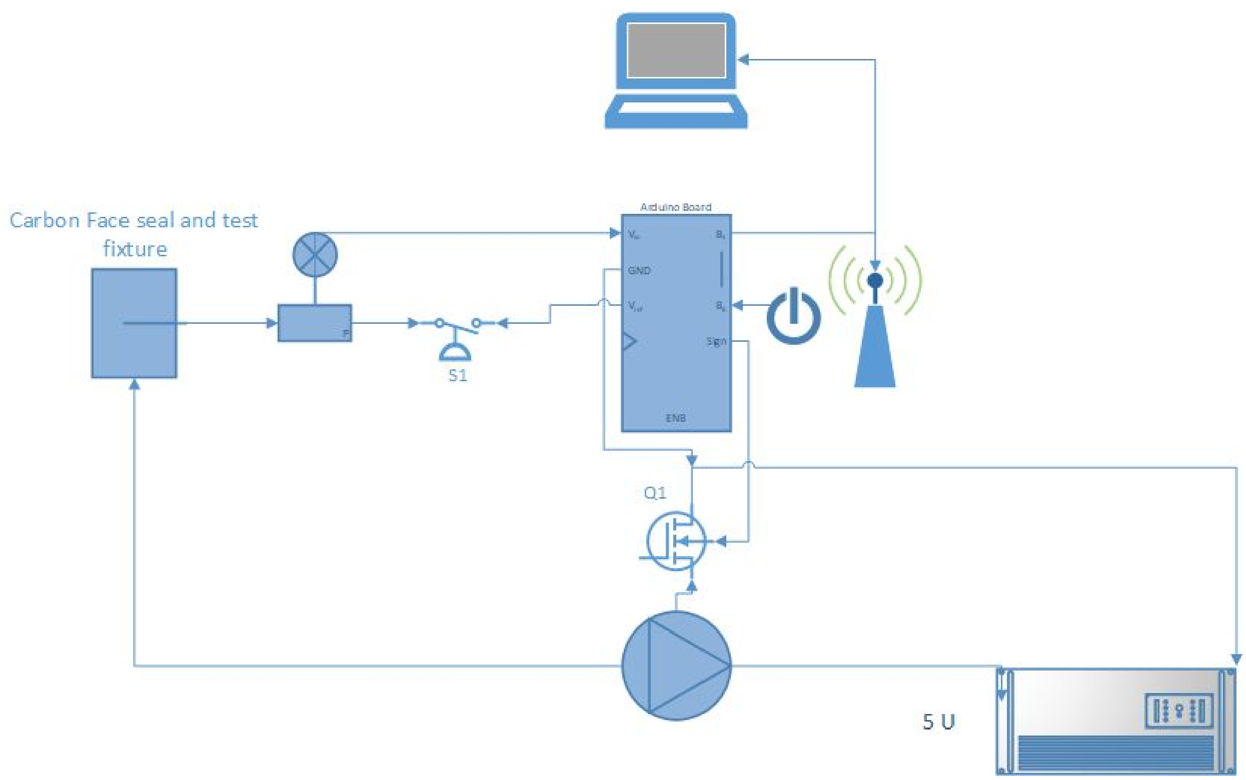


Figure 55. Concept 20

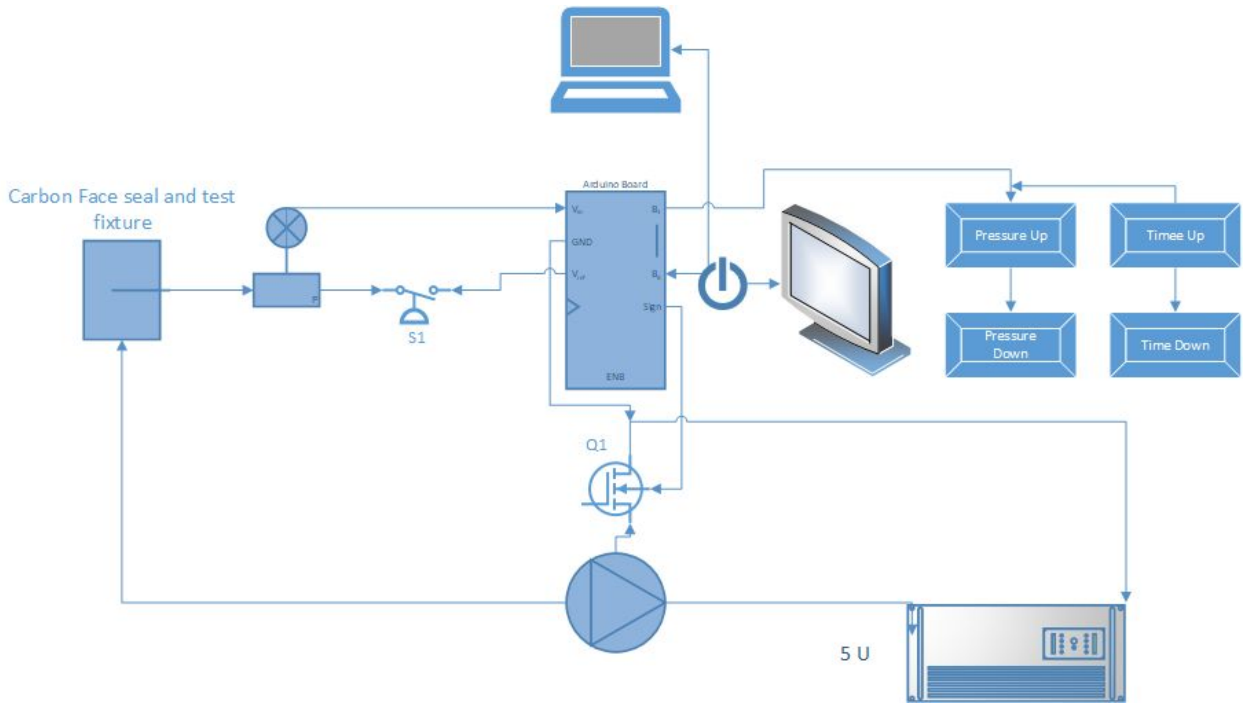


Figure 56. Concept 24

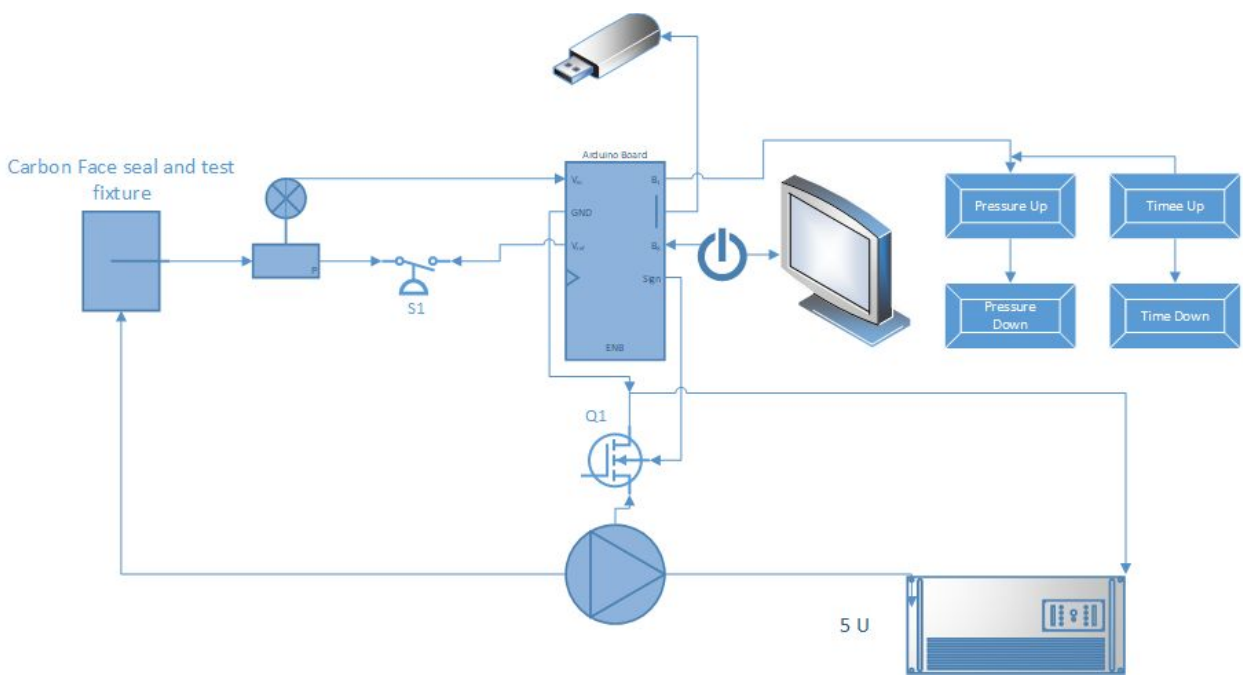


Figure 57. Concept 18

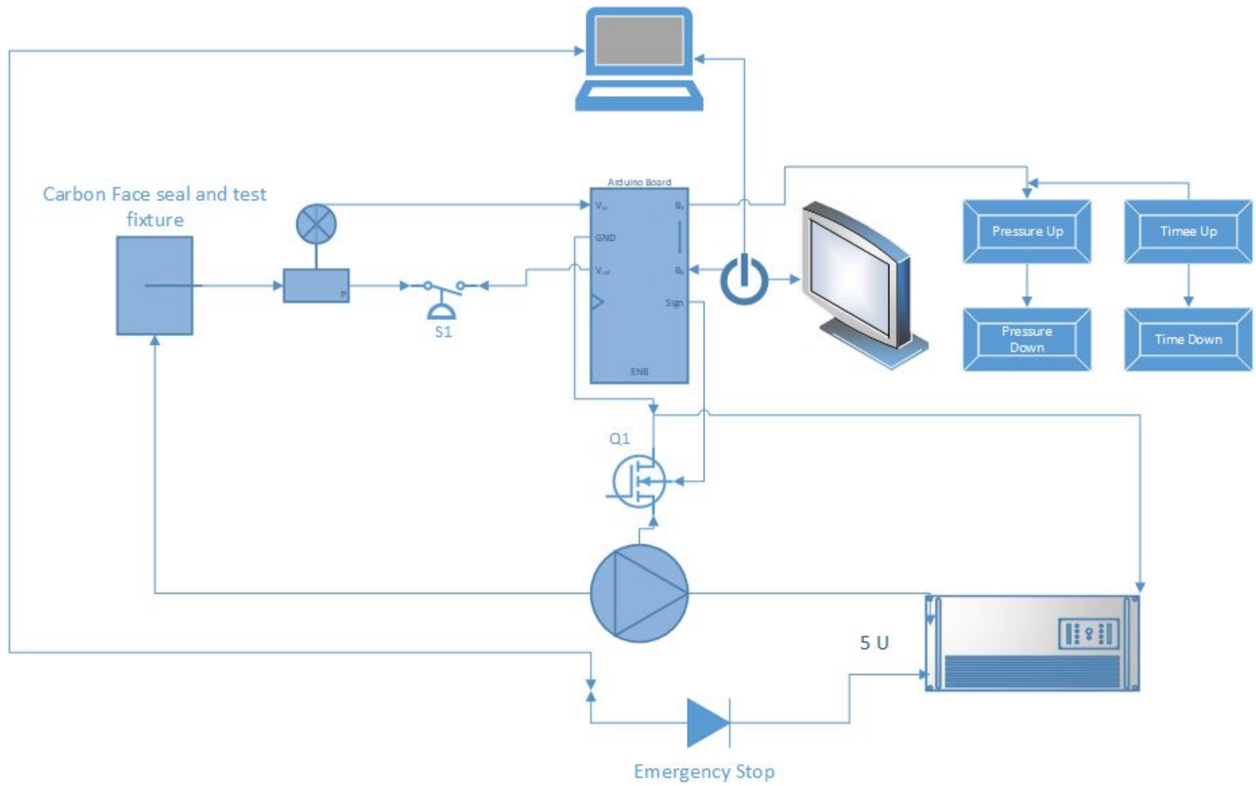


Figure 58. Concept 22

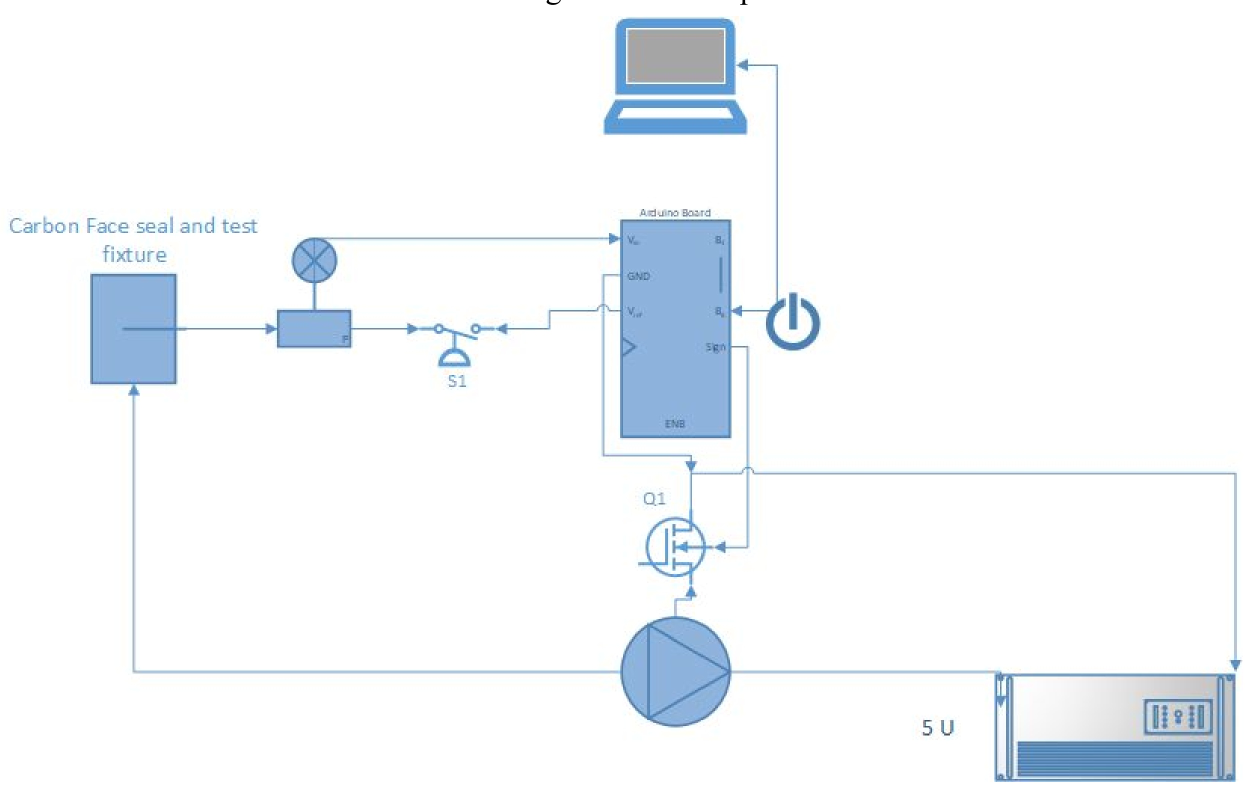


Figure 59. Concept 26

Nicholas Chaves' Concepts and Evaluations

1. **Multiple test layout design**

Multiple testing fixture layout, specifically 5 testing stations within one padding base for testing, set up in an "X" formation. Attachable hoses on the bottom of the platform for easy access to testing station for both repair and testing availability.

2. **Mechanical based pressure system**

Mechanical pressure system designed to avoid the use of a compressor using kinematic motion for compressive like action for single testing unit. Available with mini compressors for release valves.

3. **Cover with compressive response capability**

Cover with sensor available embedded within layers. Testing station is within a closed system rather than laying on top of a flat testing surface. This allows multiple systems to work together locking in air with responses.

4. **Adjustable cover**

Spring within the cover in combination with adjustable latch creating opportunity to use any of these covers to test any sized seal. Flexible rubber padding to secure coverage to any sized seal.

5. **Four seal cover (1)**

Four testing system based seals each with same material to cover seal in testing completely while testing four at once. Flexible rubber padding to secure coverage to any sized seal.

6. **Four seal cover (2)**

Same formation as concept #5. Contains adjustable arm sleeve and handle for leverage.

7. **Four seal cover (attachable)**

Similar to concepts #5 and #6. Attached at the edge of the testing platform with a hinge directly attached to the cover preventing use of directly picking up the cover (concepts #5).

8. **Portable testing unit**

Torque and pressure based. Electrical components converts voltage to mechanical motion allowing torque to be used as the concentrated force.

9. **Pressure transducer-based mini-compressor**

Strain gauge sensor compatibility, increasing in pressure within a closed system created stress about the system. Allowing a difference in strain to be a substitute to original method of testing.

10. **Attached cover**

Containment unit for individual seals.

11. **Double compressor-based testing method**

Double pressure based testing method with pulley reaction/connection. Allows 6 seals to be tested at once.

12. **Spring response method (1)**

Spring available testing response method. Allows testing pulleys used in compressive action to reset to original position for further testing.

13. **Leveled nozzle**

Original testing method with ground level based connection to seals in a funnel shaped design.

14. **Weighted testing cover**

Weight in the cover creates secure holding around testing unit. Spring adjustment available for varying seal sizes.

15. **Compression sensor**

Size smaller than seal size within inner radius of the seal. Air compression activates sensor turning on, compression of air pulls mini sensor to secure wiring confirmation with spring response for leakage.

16. **Double sensor unit**

Sensor configuration within pressure mechanism. Size sensor within set limits adjacent to volume limited compression within chamber.

17. **Spring response method (2)**

Spring location similar but different to concept #11.

18. Single compressive tube connected to four testing fixtures

Each testing unit within one compressive action. Response is within limits of each working seal. Determines if all seals in testing will work, only at once.

19. Double compressor design layout

Combination of concept #8, #11, #12 in double compressive layering within design.

20. Single station, multiple seal testing layout

Multiple seal testing station. Uses multiple covers for various seal sizes or single cover for single seal size.

21. Three stations, attachable covers with varying sizes

Covers 1,2,3 and vary in depth. Dependent on company's seal size range. Categorizing product range to larger, medium, and smaller size stations with adjacent cover proportional to corresponding size status.

22. Indented testing units

Cover with indented stations creating air lock.

23. Sixteen testing units, methodized using four seal cover

16 total testing units on 4 individual stations with a single pipe connection to each station. 4 [4 Seal] covers used at each station.

24. Single handle, multiple testing cover

Single handle, multiple testing over with adjustable pads. Combines concepts #5, #6, and #14.

25. Electrically activated cover

Electrically activated covering systems with single push button configuration. Each cover stops with response to touching seal so it can adjust to any size seal in testing.

26. Digital response gages

Indicates psi in testing. Reading error when seal fails or if leakage occurs.

27. Sensor system outside pressure valves

Attached to pulley system concept #2. Metal bar in transition track for sensor responses.

28. Nine seal testing unit design

Scaling testing platforms in type-write fashion. Tests 9 seals maximum.

29. Alternating (direction) compressive method

Alternating compressive method applies to multiple unit testing. Compressive properties in alternating voltages allow time to change seal in testing.

30. Pressure transducer-based single compressor

Pressure gauge application. Wire attachment indicates proper pressure in testing time.

Listed below are the figures for the previously discussed concepts.

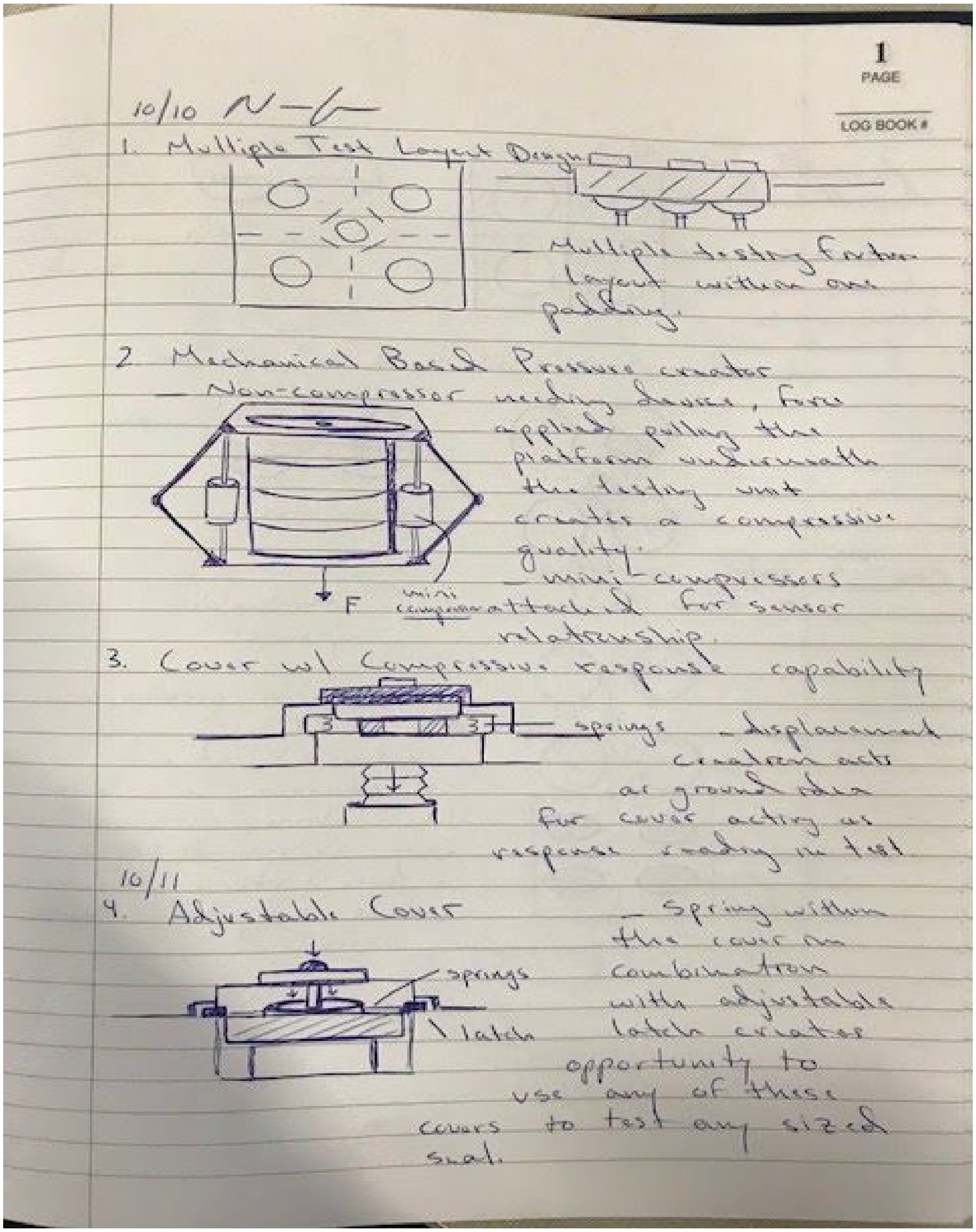


Figure 60. Concepts 1-4

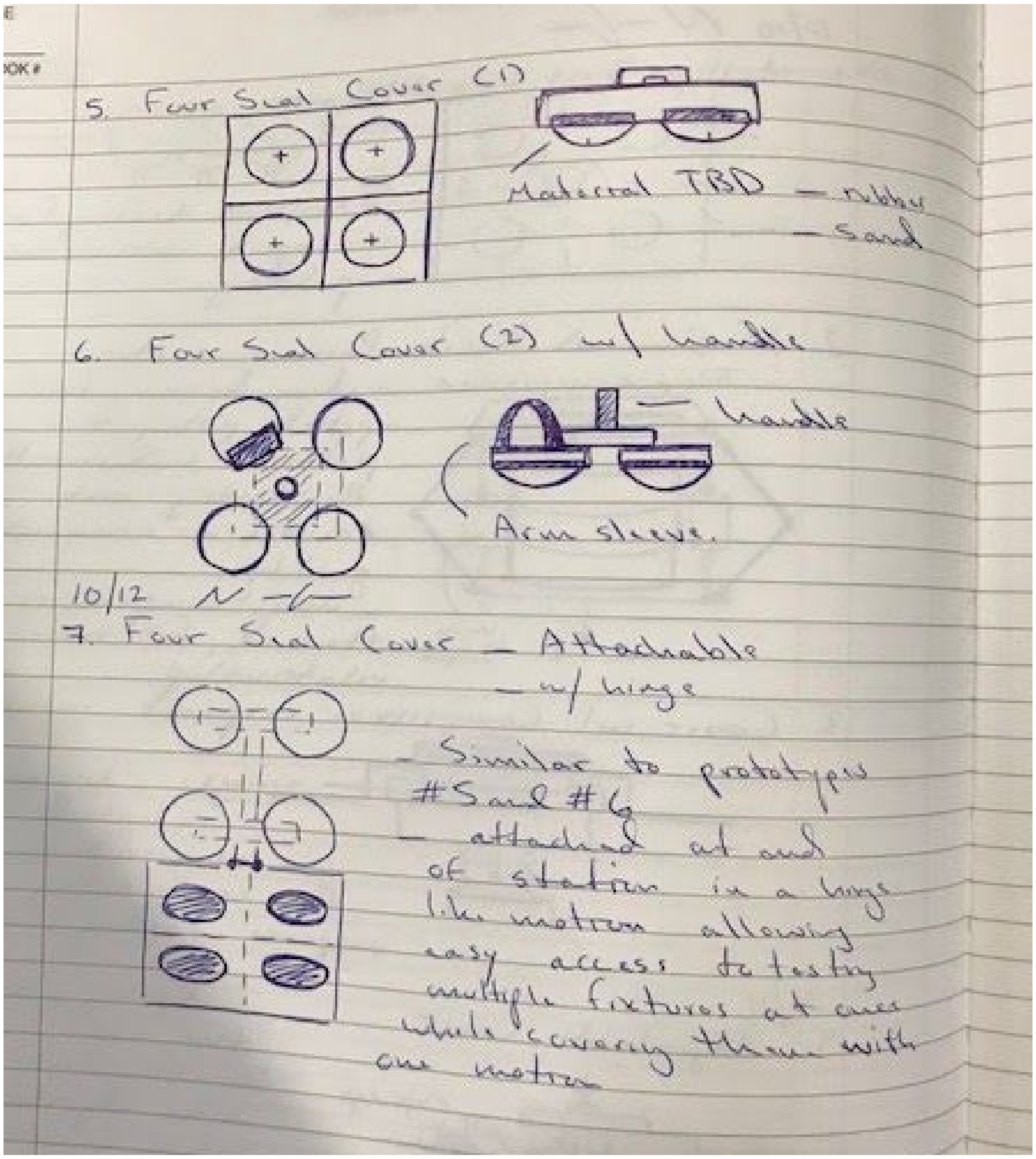


Figure 61. Concepts 5-7

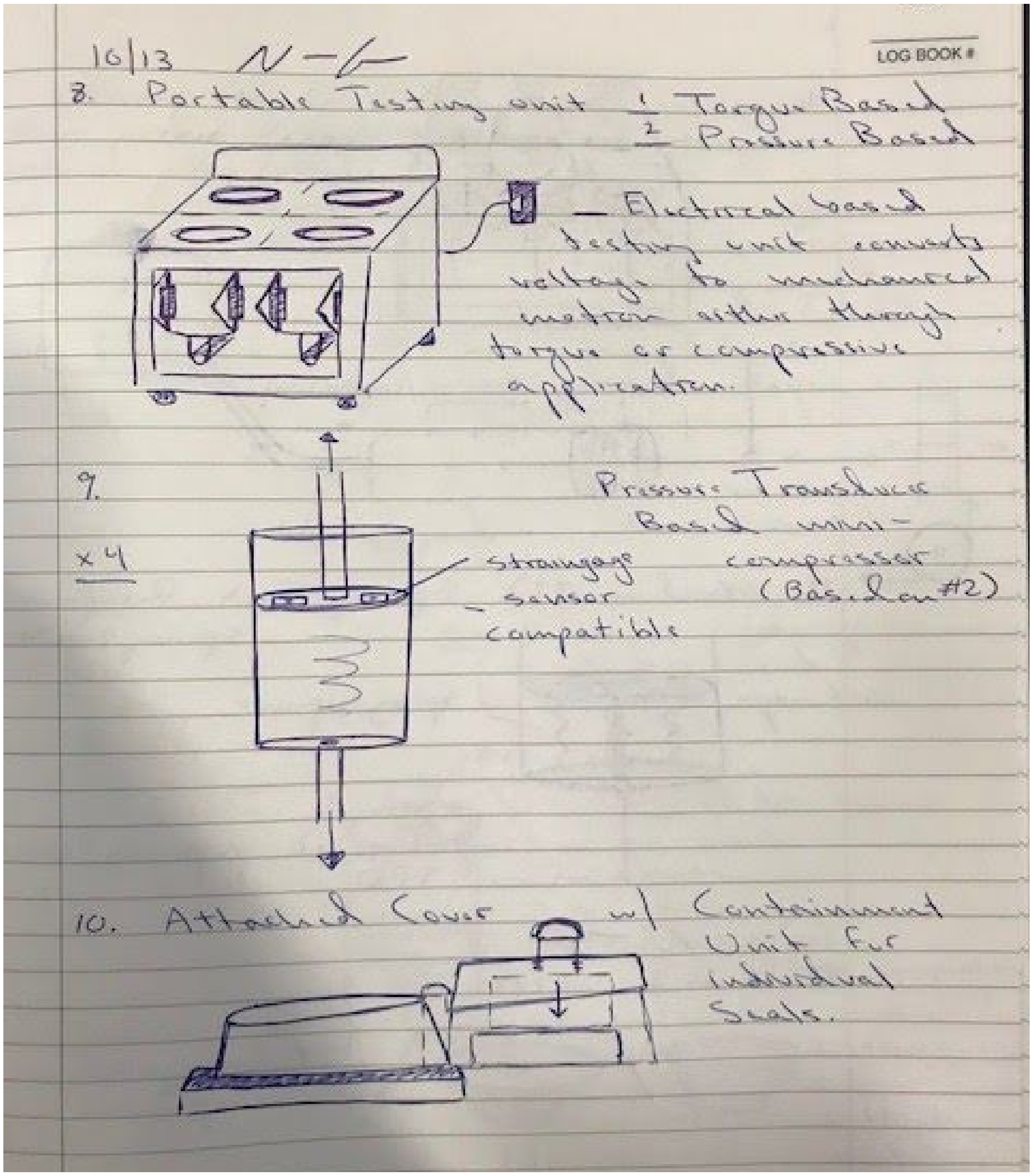


Figure 62. Concepts 8-10

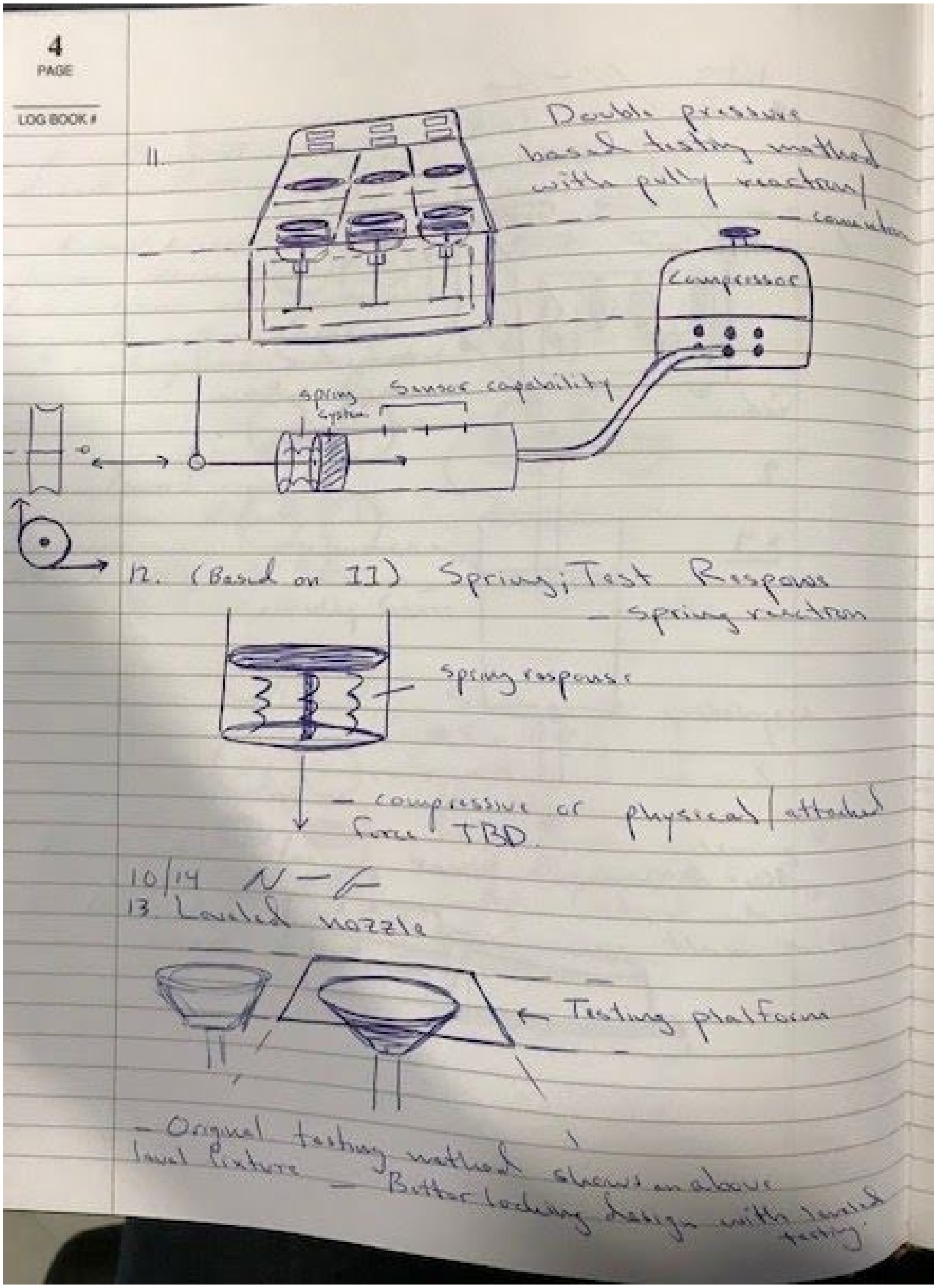


Figure 63. Concepts 11-13

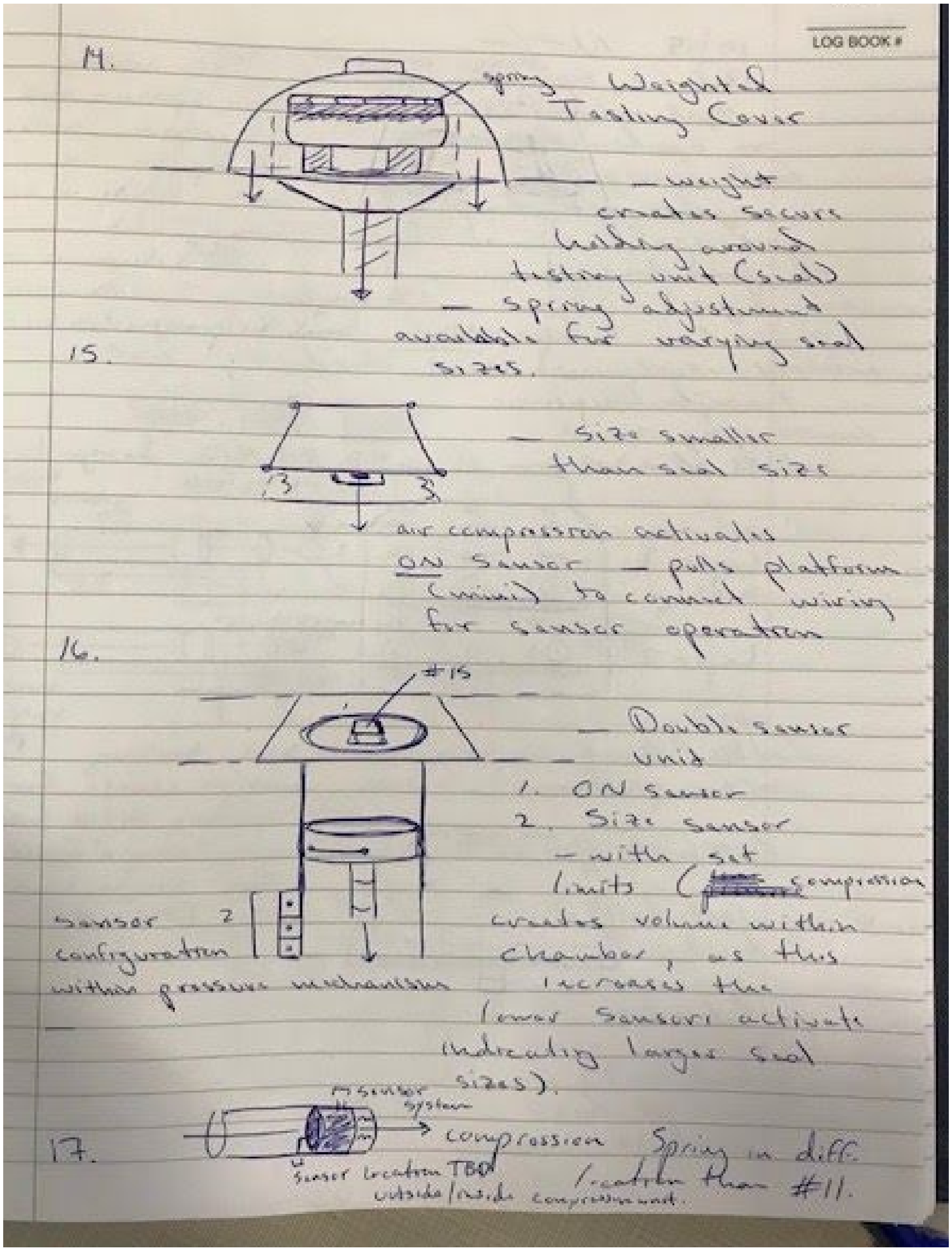


Figure 64. Concepts 14-17

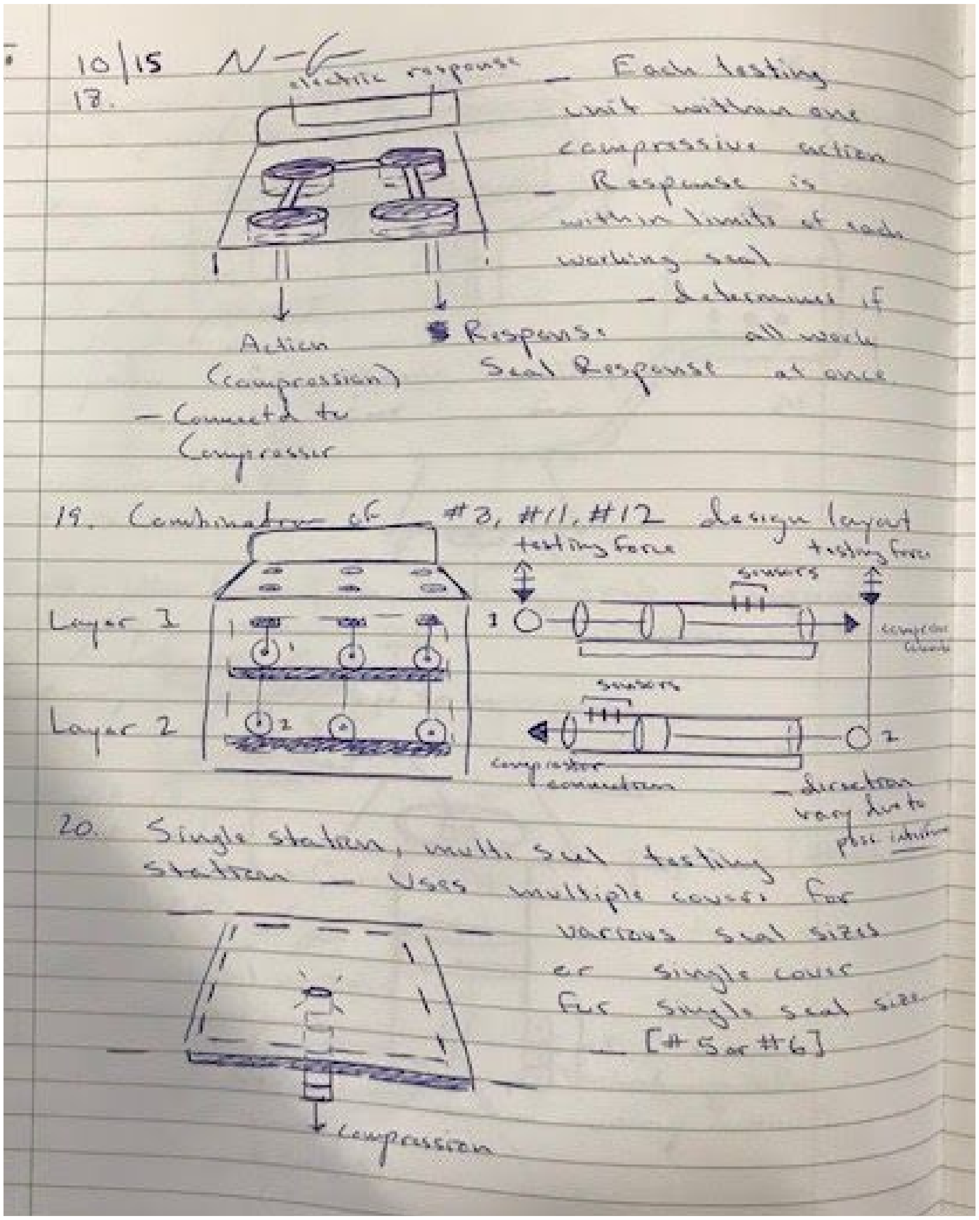


Figure 65. Concepts 18-20

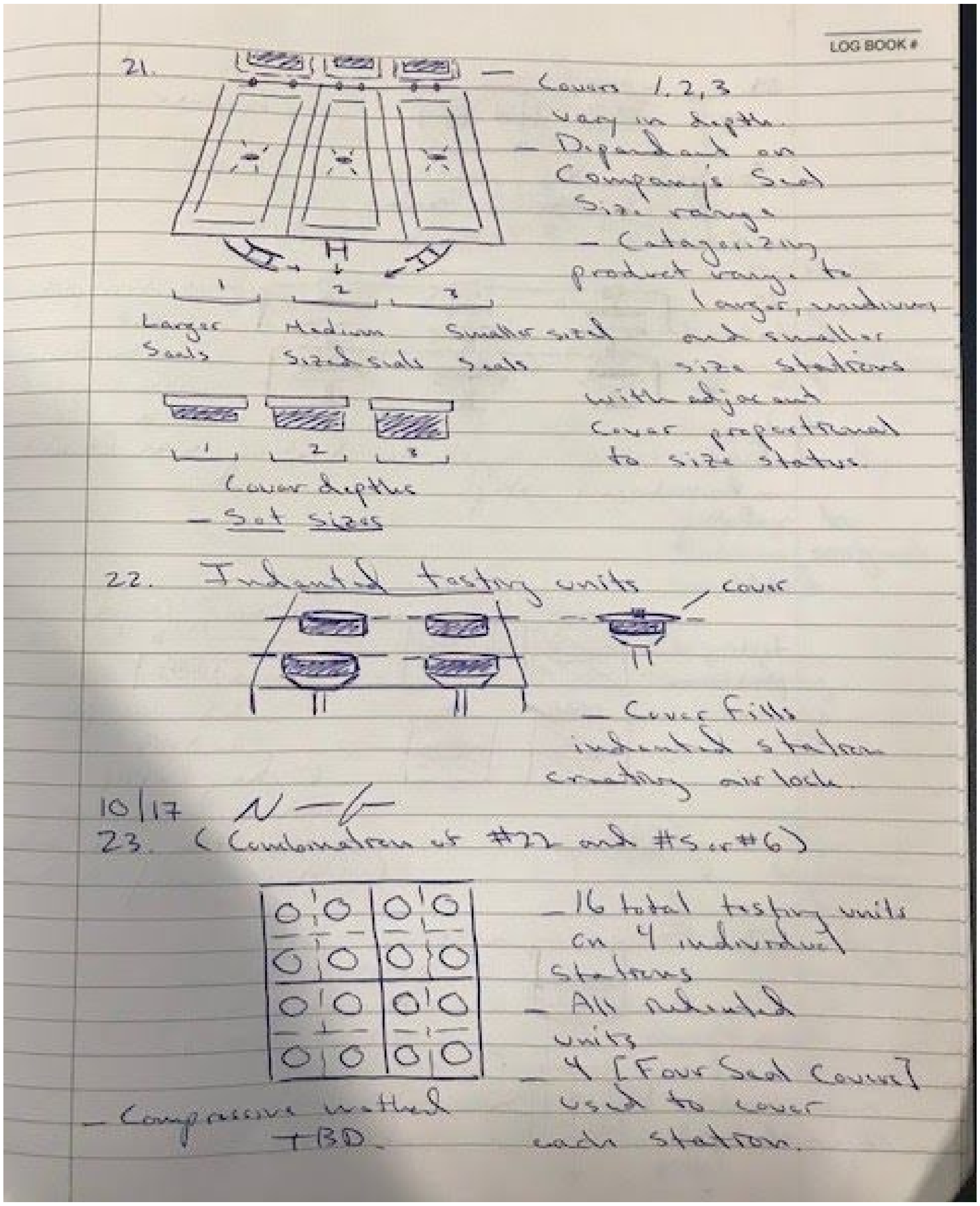


Figure 66. Concepts 21-23

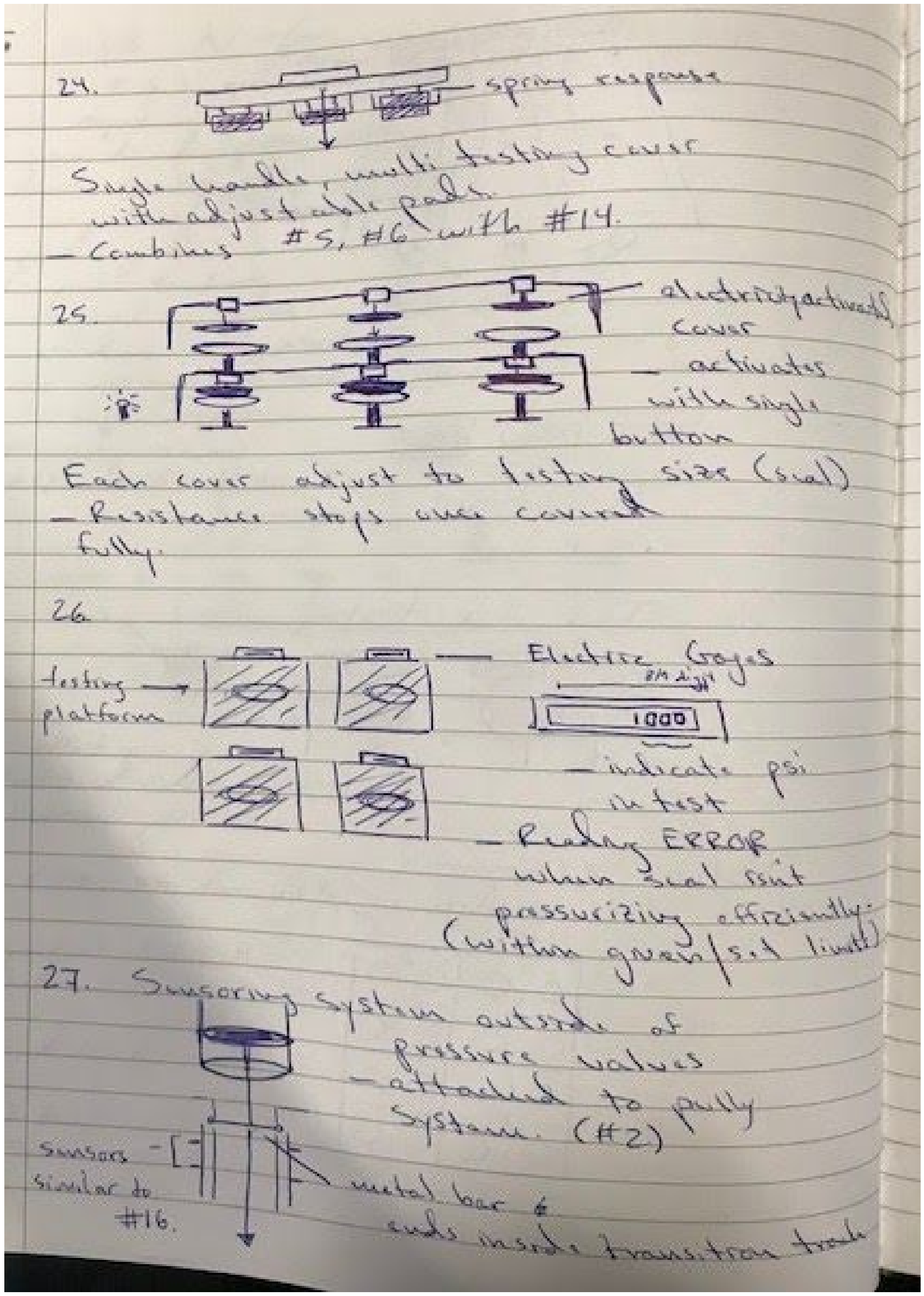


Figure 67. Concepts 24-27

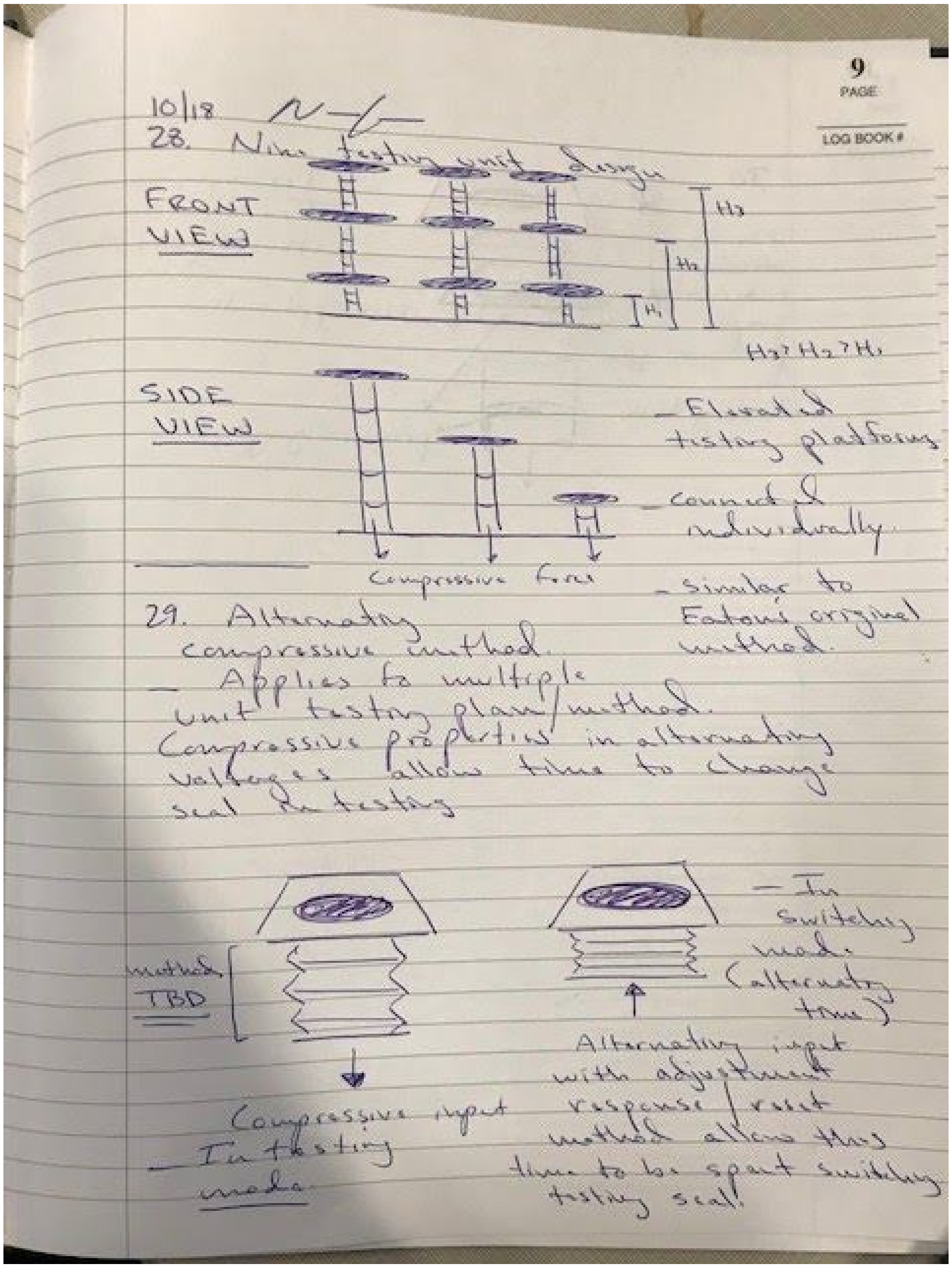


Figure 68. Concepts 28-29

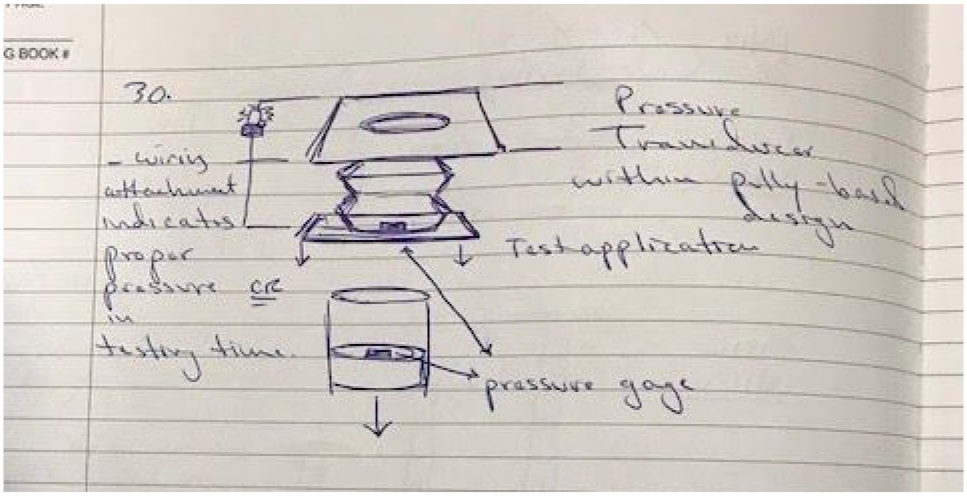


Figure 69. Concept 30

Design for Vacuum test for carbon face seals

The following subcategories are to describe the three primary parts of the vacuum test prior to digging in to a deeper explanation in the following section. The text fixture where the seal will be mounted and the test will be performed. The application that runs the GUI that was created using Python. Last is the controlled system that allows the connection between the application and the fixture to perform the test.

Design for fixture

Shown in the figures below are two systems, the first being Eaton's current system. The system has been working for decades but is too big and has its limitations. What our team implemented was to use their current system with our own controlled element to it.

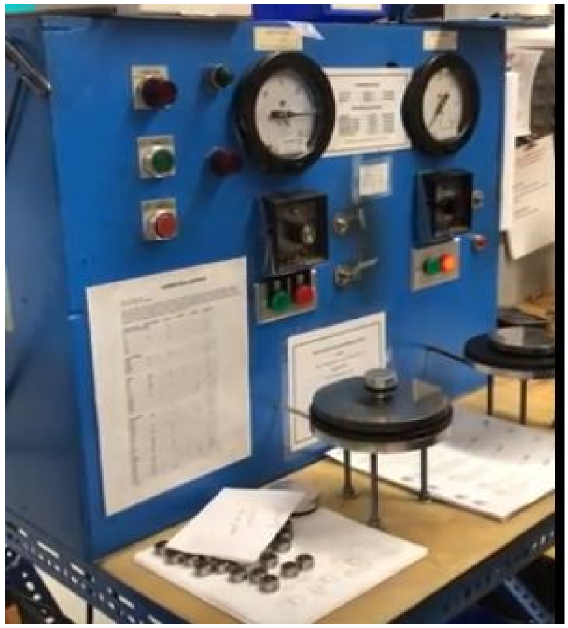
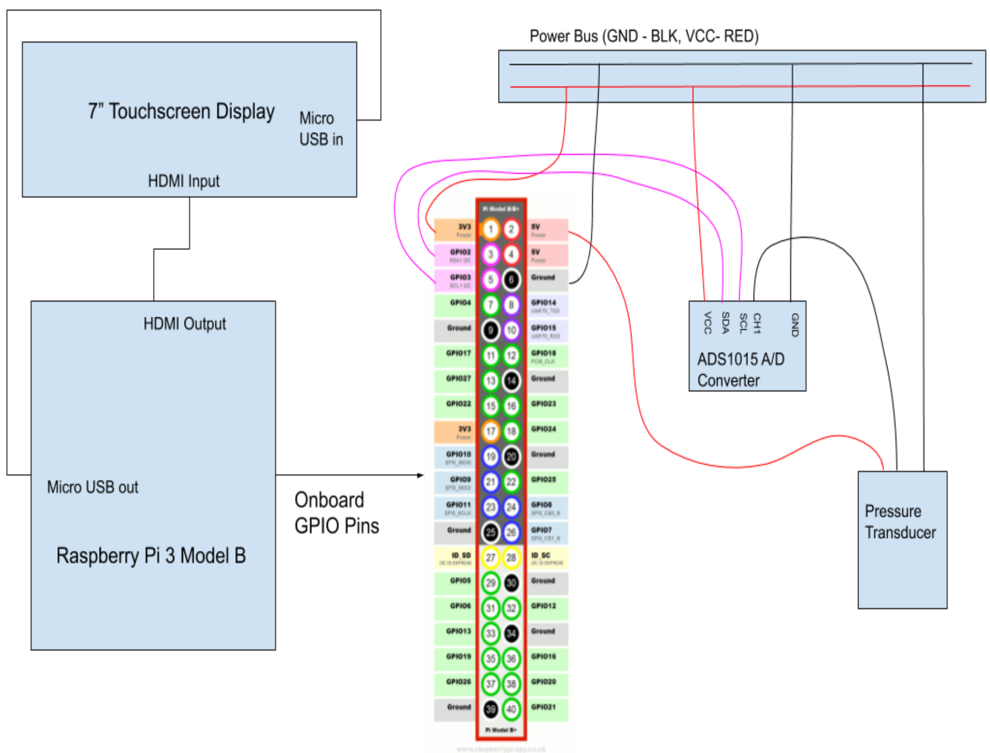


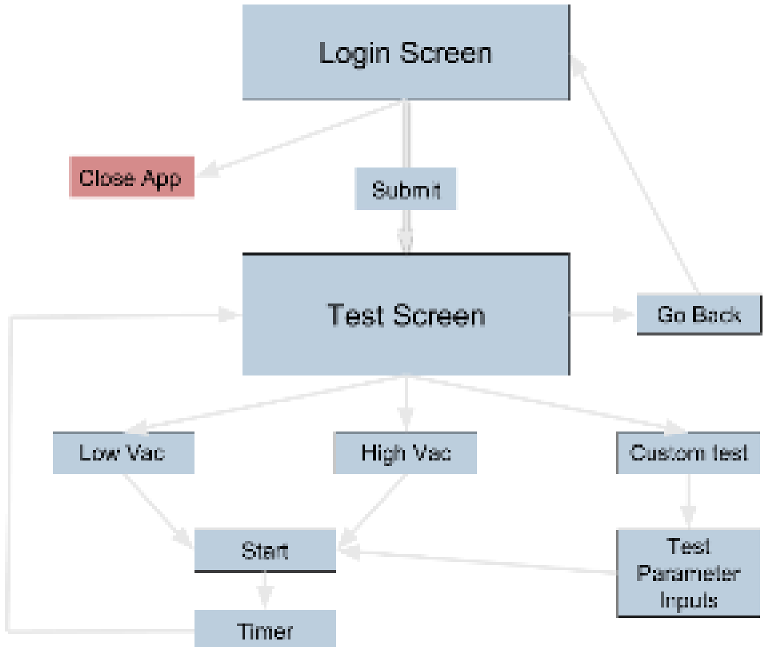
Figure #: Eaton’s current system

Below is a picture of the vacuum test unit hooked up to the vacuum. A pressure transducer is attached to the fixture and will be able to translate the information from the pressure to the Raspberry Pi. The Raspberry Pi in return will report the results of the test. This setup will reduce the overall space consumed by the equipment and free up more space on the manufacturing floor. All results will be exported to a text file for more function than the current system has.

Figure #: System with pressure transducer

Design for system control





Project Specific Details & Analysis

The current demand for the vacuum test machine that will be used exclusively by Eaton is four machines. This is the current number of test machines that Eaton used in day to day operation on the manufacturing floor. The current machines have been in operation for decades and rely on outdated equipment. With the modernization of the new vacuum test machine there is no reason to believe that these machines will need to be completely replaced within a time span of ten years. Buyers other than Eaton that conduct similar tests that could purchase the vacuum test machine as it is built for Eaton includes Magseal. Magseal produces face seals for aerospace applications but it is unsure whether they require enough to justify a larger scale production of the vacuum test machine. Looking beyond the purchase of the vacuum test machine, repairs will be needed but even if the entire system were to die the control board will be the only part that needs to be replaced and the cost of a new LPC 1768 is forty dollars. This means the system will rely heavily on the profits earned from the initial purchase requiring access to other markets to allow for a sustainable business model built solely off of the sale of the vacuum test machine. To increase the availability of the vacuum test machine to the market the considerations that are listed above under “Competitive Analysis” to expand the usage of the vacuum test machine can be implemented. Creating specific fixtures or test beds that build off of the control system for the vacuum test machine can expand to make the production of these devices more profitable and desirable as a larger market becomes available.

Detailed Product Design

Fixture

A number of variables were considered when constructing a design plan for the project. The following figures and drawings will demonstrate the evolution in structural design of the developed vacuum testing equipment system for carbon-based face seals, created using Eaton's original mechanism as a base structure to improve upon with the given task of improving the system by creating multiple testing stations. Additional constructive fixtures were also considered when analysing possible outcomes of approach to purpose for certain designs such as concepted pieces thought best fit for the products overall design worth. A differential transducer and pressure based solenoid configuration was developed to meet the requirement for multiple locking systems as the design specifications demanded. The inclusion of the transducer and solenoid requires consideration when accomplishing the desired multiple stations. Knowing this, the design process for this specific seal testing product will be broken down into steps; initially creating an individual station, focusing on creating a testing system with both the solenoid and transducer within the design, and further being available to attach to various other pumps for testing if needed while simply also acquiring the ability to test multiple at once depending on piping layout. Overall piping dependency has to be able to withstand 25" Hg being tested on each seal over a testing time of approximately 30-60 seconds per seal. The system has to withstand a relatively small compressive loading of approximately -12 psi throughout the system to maintain testing specifications and reach 25" Hg. Pipe lengths are considered small variables to consider since the pressure response within the system is based on reaching 25", the overall volume of air travel just needs to be small enough to achieve vacuum conditions while also meeting 25".

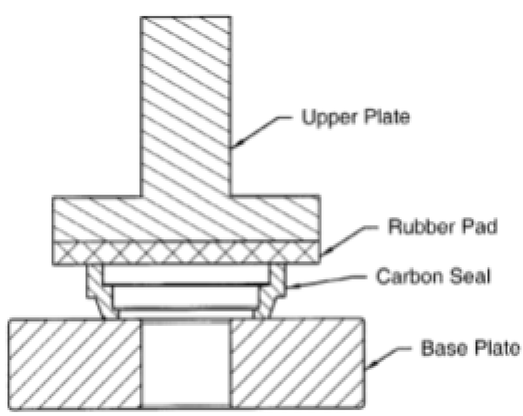


Figure 71. Original Covering System

One system initially considered to be involved within the design plan was the idea of changing the method of covering the seals when being tested. The current method is shown as cross-sectional diagram in Figure 1, demonstrating how the seal is covered completely during testing ensuring no leakage occurs unless done by fault of the seal. Only a few ideas arose when discussing the possibility of changing the system within the team. Our first idea in brainstorming being an automatic sealing system attached within each station however to stay within budget the idea remained merely a concept. Another idea afterwards included the transducer embedded within the upper plate connecting the seal directly, thus gaining a near direct reading of the seal leakage rates. That idea however was scrapped mainly due to the transducer having a number of wiring components, and constantly being physically handled in testing would most likely result in disonnections, being a high maintenance priority and not worth implementing.

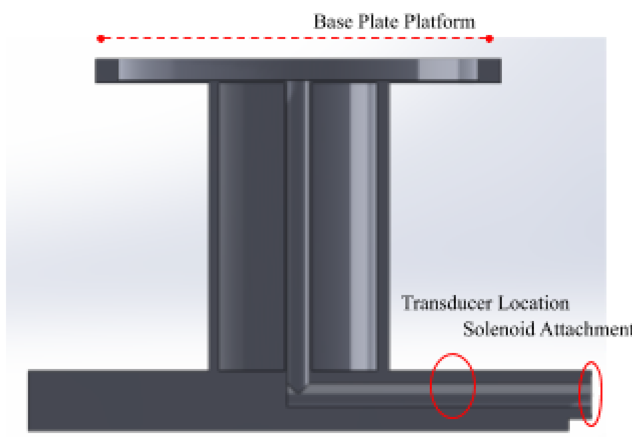


Figure 72. P0 Initial setup consideration

The next step was to be able to create a basis for design, as shown in Figure 2 is the initial design created in SolidWorks. The L-shape design, documented as prototype 0 (or P0), was created as a function of being an individual testing model available to setup with a single attachment. That attachment is located on the right of the figure, attaching specifically a solenoid to the end of the fixture along with drilling and created a section along the piping in the base of structure known as the transducer location for the solenoid and transducer configuration relatively close to one another for simple electrical connectivity. The shell around the piping is used as a loading dock for the base plate platform along with simple lapped plate connection when suction occurs thus fastening the plate and piping together.

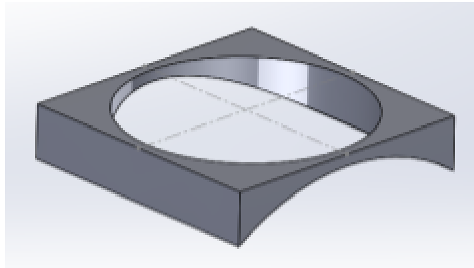


Figure 73. Transducer Fitting

After considering the use of prototype 0 it seemed illogical to create a piping system within a rectangular base rather than simple piping or tubing connection, thus coming to the conception of allowing the transducer to sit on the pipe directly. That being considered also lead to the possibility of slippage or leakage arising due to the flat transducer base being against the rounded tubing. Shown in figure 3 is the transducer fitting for transducer to pipe connection, further placing a seal between the two faces to secure air lock within the system. The fitting can be shown in future prototypes (figures 4,5,10).

Once the conception for transducer to pipe or tubing connection was considered and the fitting being developed this allowed a few design ideas to be considered for different purposes allowing different points of contact. Shown in figure 4 is the first official prototype to be considered for simulation and testing, while beside the image is figure 5 also displaying another prototype considered for testing. The transducer location and solenoid attachment points were considered for both prototypes I and II. Both prototypes benefit from their ability to use the shell as a stable pressure condition for differential pressure readings in seal testing. The only difference in design layouts is the transducer location.

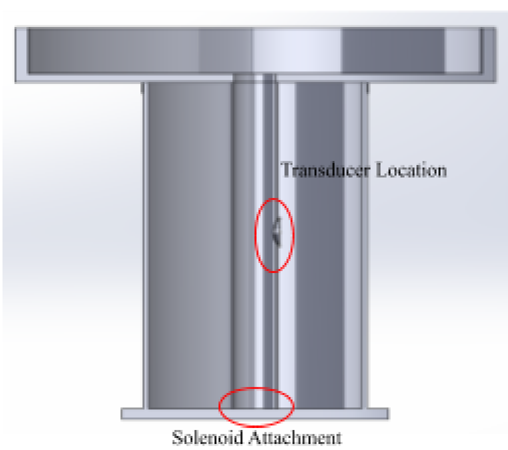


Figure 74. Prototype I

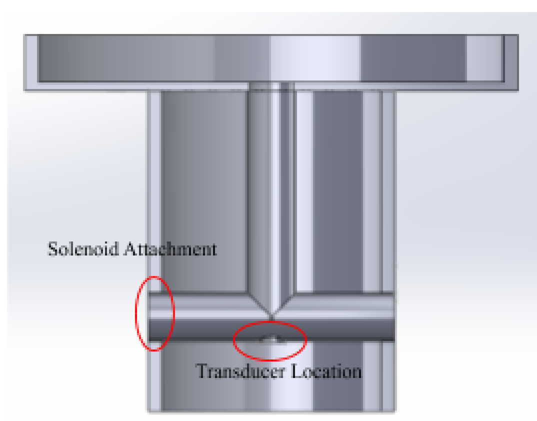


Figure 75. Prototype II

Prototype I has a transducer location along with vertical piping present within the shell of the testing fixture. This would be considered with an attachable bottom for easy access to transducer wiring, while the method of attaching the bottom would be either from drilling or magnetic connection. Prototype II is designed to make the availability for transducer access simpler for the user or person repairing the system. Both designs would only require one connection located at respective solenoid attachment locations. Prototype II had been considered more user friendly than its counter prototype so further analysis was considered for preparation of assembly.

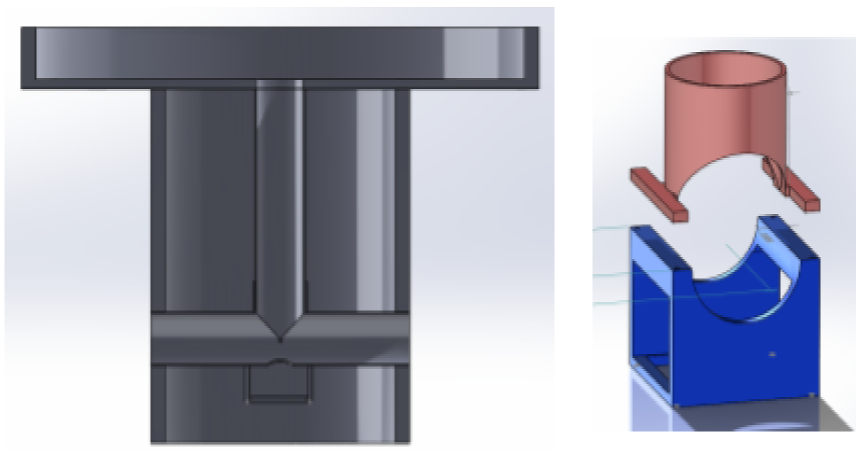


Figure 76. Prototype III

Due to the transducer being in a location more available for the user it oppositely makes it more difficult to connect to the piping while also being attachable and available for physical repair. With the use of SolidWorks the ability to create 3D fixtures and printing operations allows access for the material to be used in each system as long as it is not used to without high amounts of pressure due to the material being purely structural and in small scaled designs. The use of an additional fixture was created to allow the transducer to be attached directly while having a detable base to allow easy access to wiring about the transducer Shown in figure 6 is prototype III being a two piece transducer platform available to wrap around tubing (available for adjustment within SolidWorks if different dimensions are used). Shown in red within the image is the top piece to the platform that wraps around the piping while the blue is the bottom piece with open sides for wiring to be easily fixed within the platform while the attachable bottom is available for use of repair, location considered and shown in figure 7.

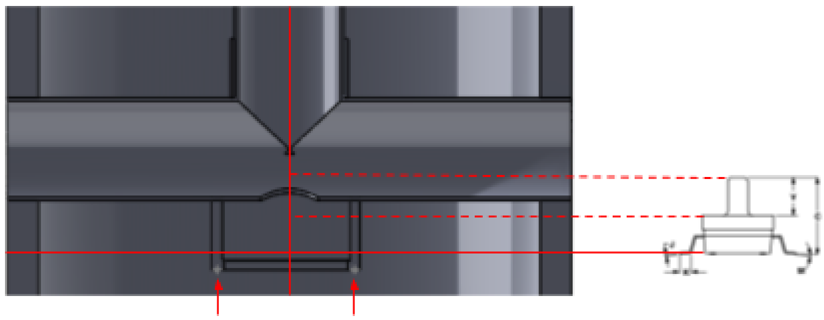
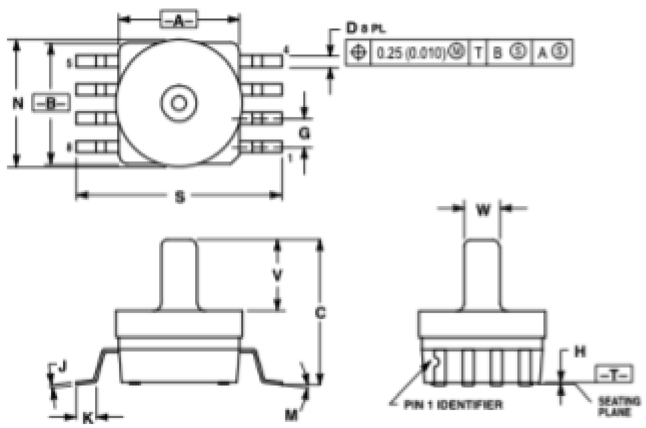


Figure 77. Transducer to pipe setup using prototype III

If prototype I had been further considered for operation then a similar type of transducer platform would have been developed for the same purpose. While figure 7 displays the transducer placement about the piping, the dimensions of the transducer originally considered are displayed below.



DIM	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	0.415	0.425	10.54	10.79
B	0.415	0.425	10.54	10.79
C	0.500	0.520	12.70	13.21
D	0.038	0.042	0.96	1.07
G	0.100 BSC		2.54 BSC	
H	0.002	0.010	0.05	0.25
J	0.009	0.011	0.23	0.28
K	0.061	0.071	1.55	1.80
M	0°	7°	0°	7°
N	0.444	0.448	11.28	11.38
S	0.709	0.725	18.01	18.41
V	0.245	0.255	6.22	6.48
W	0.115	0.125	2.92	3.17

The use of finite element analysis had been considered for prototype II, involving prototype III, however beforehand the team had considered the pressure flow around the corners of prototype II, concluding that the original placement of the transducer may lead to future complications in testing. Furthermore the design needed to contain the least amount of unpredictable cross-sectional piping areas within the system itself, thus preventing issues alike prototype II, while this also created an opportunity in reconsidering transducer location along with its availability. Ideally the easier accessible the transducer while working properly is needed to consider the design layout successful. Having the transducer leveled with the platform of the testing unit allowed the possibility of a single platform to connect outlets for both the testing plate platform and transducer, while if further available for successful individual testing the one connection to the solenoid is available with proper configuration for testing. Shown in figure 10 is the latest prototype consideration (prototype IV) containing the previously stated possibility of having the transducer leveled with the testing platform. The transducer location and solenoid attachment locations are displayed within the figure. The design is further analysed in finite element analysis (SolidWorks) for simulation purposes, along the team to understand whether the current prototype design works properly, while understand flow simulation for further consideration and development.

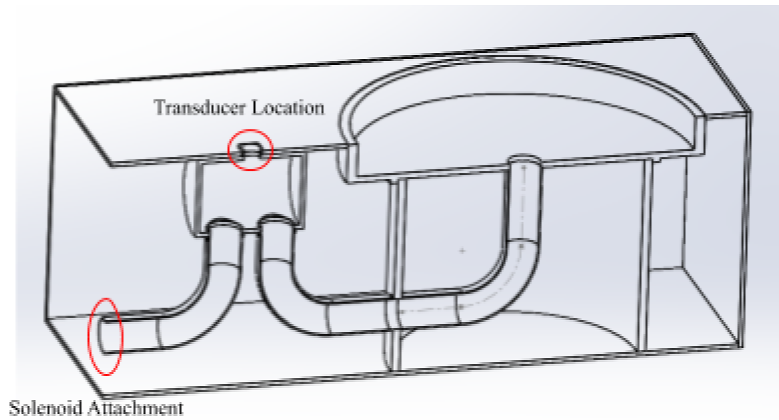


Figure 78. Prototype IV

With the aid of the shell wall underneath the testing platform as a piping loading fixture can be adjusted the gain a thinner prototype unit for individual seal testing. The cube design creates and individual and unique design for individual testing stations. If multiple stations are needed for multiple seal tests to be conducted at once the compressive source is to be properly connected to all stations. The cylindrical vessel with the transducer fitted along its edge is also connected to the solenoid and seal directly, and further analysed if pressure behavior is similar to the theorized behavior of prototype II. In doing so the system needs to be able to withstand enough pressure to move 25" Hg over the course of a maximum testing time of 60 seconds averaging testing around 30 seconds. While noticeably floating next to the testing platform, a structural loading system will be developed for the cylindrical vessel. If adjustments are needed, the dimensions will be reconsidered in CAD requiring little effort to adjust, and having 3-D printing available within the university is beneficial to maintaining budget within the project.

Application

Various considerations came to the design of the application created to run the vacuum testing system. In the creation of the application the team wanted to make the process easy for the operator to navigate through and run the test. Multiple iterations have been worked on going off Eaton's recommendations and desired functionality of the interface. The GUI was created using Python and a library called Kivy. The Kivy library made it easy for the Python file to only have the function required of it. The application has multiple screens that are easy to navigate and allows for different testing types for the operator.

On the opening screen of the application it is a simple input page where the operator will enter the employee ID, work ID, and the part number of the seal that will be tested. Once the operator clicks the submit button the information will be saved to a text file that can be exported to a text file.

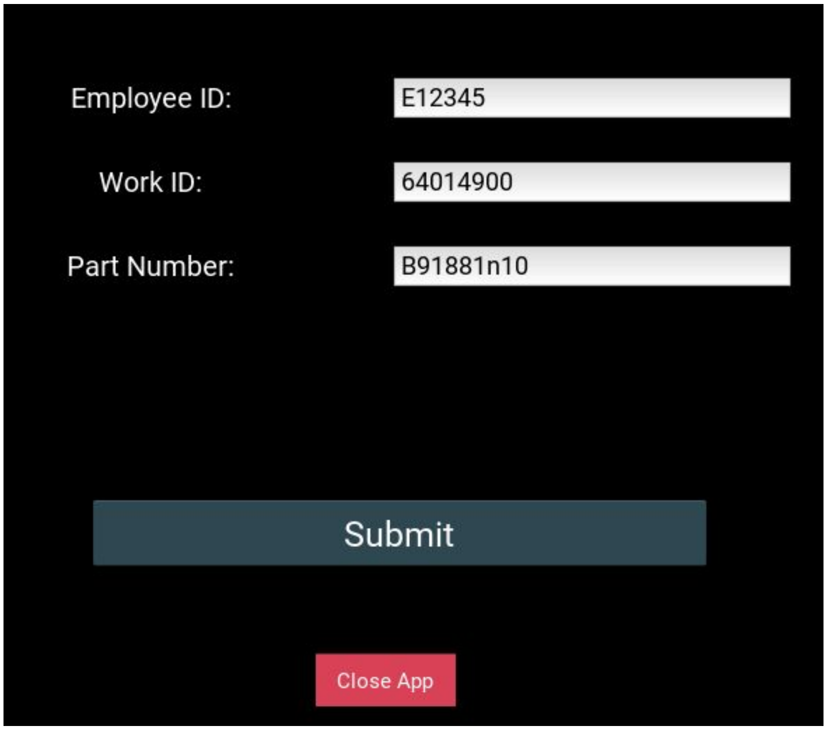


Figure: 79

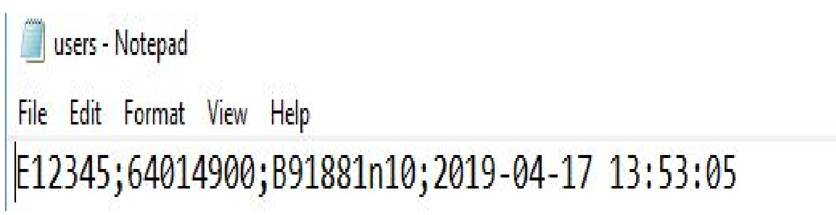


Figure #: Recording of text input

Once the submit button is clicked on the main information page it directs you to the vacuum testing screen. Starting on the top left a type of vacuum test is selected. If the operator selects high vacuum, or low vacuum test the 25” of Hg or 10” of Hg is automatically entered into the system. There is a third option for custom testing for special seal types, on this menu the operator will be able to manually enter values to run the test. Once the type of test is selected the operator will click start test to run. A timer will indicate the test countdown in the middle and the decay rate of pressure in the system will be measured. If the decay rate measured from the beginning amount of pressure inputted into the system is within the boundary conditions then a pass or fail will be signaled. The results for the test will also be saved to the text file along with the operators information from the first screen.

Figure: 80 Test screen

Eaton's current testing equipment is large, does not record data, and does not give the engineers the chance to analyze data from the test to understand what happens in a pass or a fail. With this application the operator can run the test with a click of only a few buttons and more importantly data is saved every few seconds for. With data being saved to a file an engineer can see step by step results and produce graphs showing when the test failed and see more clearly where a leak in the system is.

Engineering Analysis

Finite Element Analysis

A finite element analysis was conducted on our proof of concept prototype CAD model in order to verify a proper design that could withstand the vacuum environment that it would be subjected to daily during standard testing procedures without failure. To properly simulate our problem definition, great care was taken into consideration for the setup of the finite element analysis. Due to the curvature in our proof of concept CAD model, a curvature based mesh was created which incorporated finer grid spacing around the pipe sweeps yielding more accurate results (see Fig. x). The piping inlet and outlet were set as fixed points in the simulation since these will realistically be threaded connections which prohibit any movement. For external loads on the structure, gravity and a pressure of -12.28 psi was applied on the entire structure to simulate a vacuum of 25”Hg which is what the maximum vacuum required during testing. Alloy steel was selected as the structural material for this simulation. Based on the results from Figure x below, the resultant max stress is concentrated on the side of the cylindrical walls indicating that they should be thickened to be more resistive to deformation due to high vacuum levels. The Von Mises stress indicates that this max stress on the side walls was around 623 psi. The yield strength of alloy steel in this application is listed at 90,000 pis indicating that our current prototype is more than capable of handling the max vacuum that it would be subjected to during an actual test.

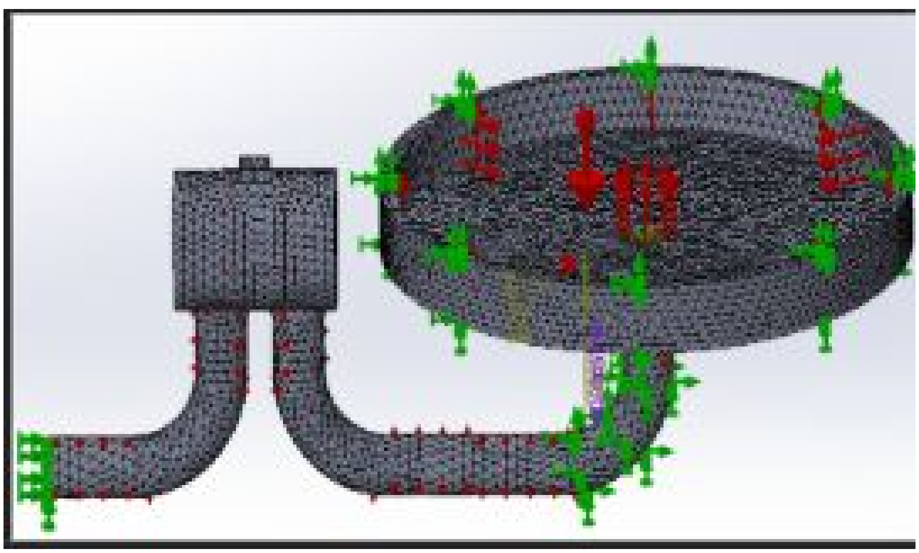


Figure 81: FEA Setup on Current Prototype

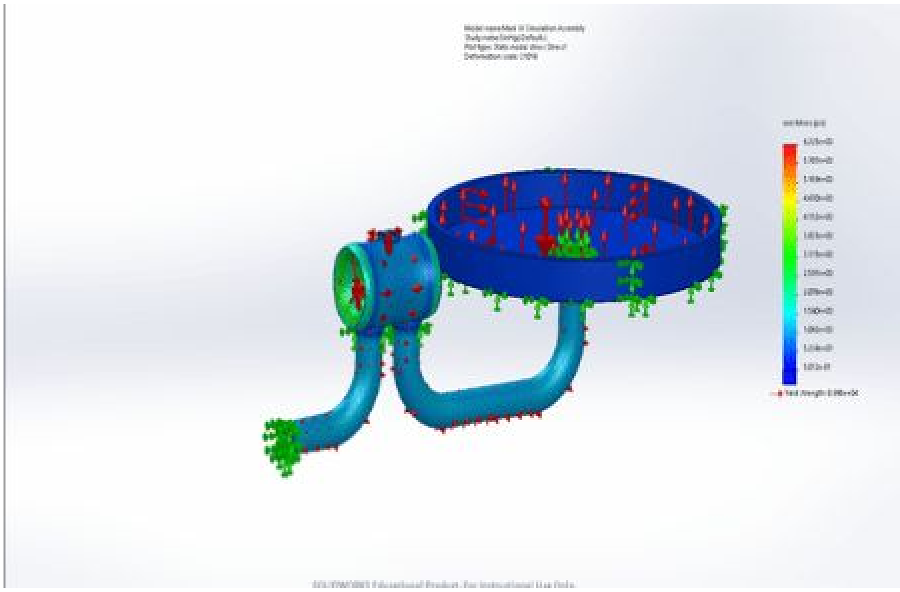


Figure 82: FEA on Current Setup

Flow Analysis

An internal flow analysis was conducted on the piping geometry of our model to ensure that the desired location of our pressure transducer could provide accurate pressure readings due to minimal pressure drops in our system.The flow was driven with a pressure gradient of -7 psi in order to generate a high velocity in our system that would be similar to that of the velocity due to the work of the air pump. Realistically our system will also include pressure drop due to wall friction and leakage. Therefore the boundary conditions were set at 7psi at the outlet and 14.7 psi at the inlet. Although they are not the exact boundary conditions our system will be subjected to the goal was to understand the effects that our geometry would have on the air flow throughout. The results shown in figures… illustrate the relative pressure and flow velocity contours in the system. These results show that the transducer housing which contains sharp corners is causing recirculation zones in the top corners which is problematic if a transducer were to be placed near it because this would skew the accuracy of the pressure reading at that point and at any location near the seal. Therefore to limit this pressure drop, the corners of the housing could be rounded and the transducer location could be placed elsewhere such as the bottom of the housing unit to ensure more accurate readings.

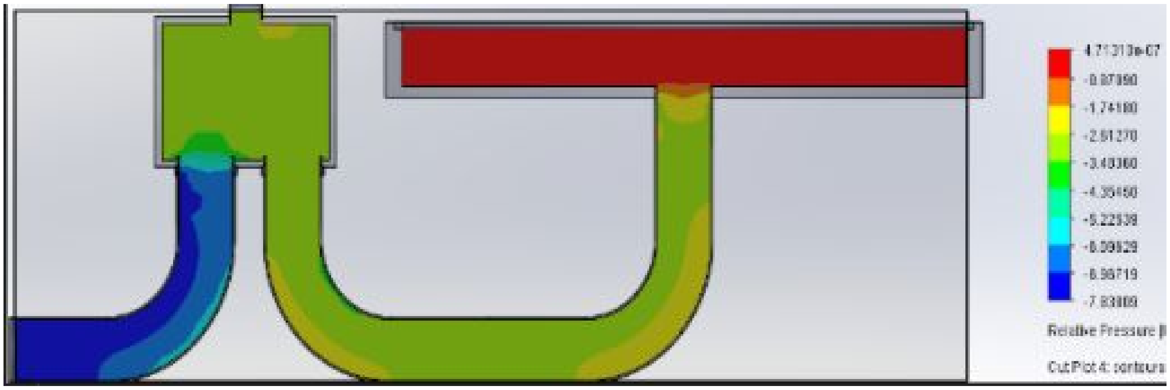


Figure 83: Relative Pressure Contours

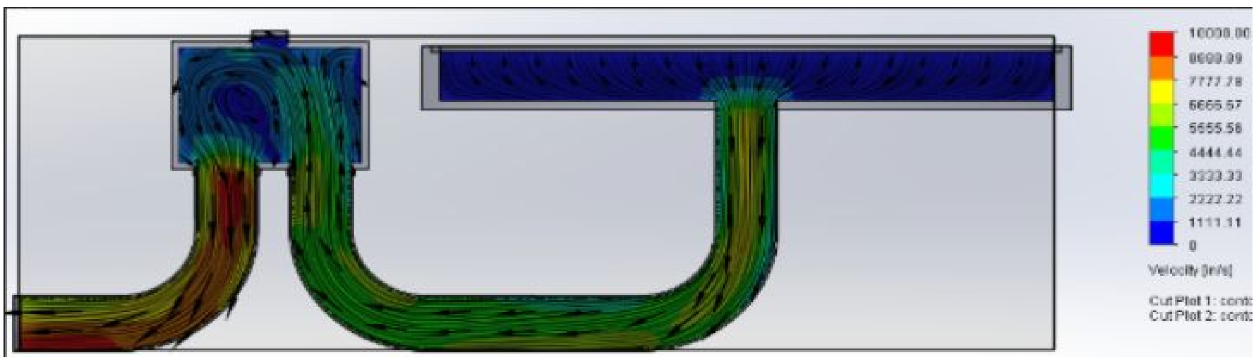


Figure 84: Velocity Contours

Build/Manufacture

The building and manufacturing processes implemented in the vacuum testing system began with the SolidWorks design of a single unit. The design aspect focuses on the ability to perform multiple tests, as the individual unit can be replicated, an additional that Eaton would consider beneficial to their testing processes. With this Eaton could have the ability to test multiple carbon seals at once, if the design had gone further in production. Shown below is the general idea of an individual testing unit Eaton can implement in the future.

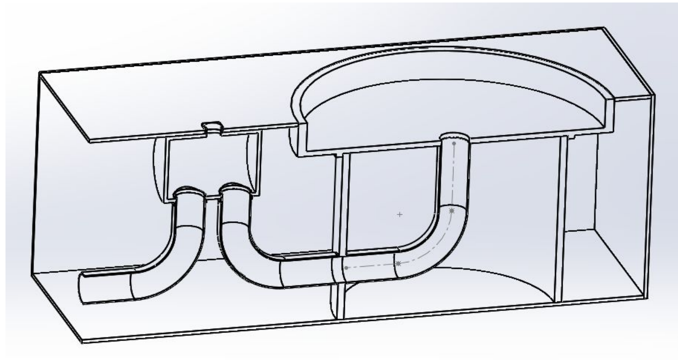


Figure 85: Single testing unit

With additions made, the single testing unit can potentially be accessible to multiple outlets with the proper fittings. The rectangular container and shell can be printed using SolidWorks while the piping was simulated in order to account for curved piping available at a number of local manufacturing facilities. A lapped plate would be attached above the shell as the platform for the seal in testing. That would be connected to the curved piping, passing through the shell and meeting a cylinder holding the pressure transducer leveled with the lapped plate. The transducer and seal are designed to be leveled to allow the user to easily access the transducer if maintenance is required. The end of the cylinder holding the transducer is connected to another curved pipe that would fit into the wall of the single testing unit, leaving an opening that would connect to the vacuum. The project design shifted between semesters, later focusing on the automated system aspect of the project. The automated system could be integrated with the single testing unit, allowing the automated system to control the vacuum levels and read the decay rate provided by the pressure transducer, while additionally saving test data.

Testing

System testing needed to be completed in two parts. The first part is testing the pressure transducer and the second is testing the user interface. Pressure transducer testing was done initially with an initial pressure set by a regulated pressure valve and an air compressor. The air compressor was set to a thirty pounds per square inch output and the transducer was attached via pneumatic tubing and then activated. This test was just to verify the functionality of the transducer and that the libraries and header files used to interface with the Raspberry Pi and analog to digital converter worked as intended. More in depth testing was completed at Eaton’s manufacturing facility in East Providence, Rhode Island. This testing was done on much more accurate measuring devices and with vacuum as a opposed to positive pressure to more accurately simulate the actual testing environment that the system will be used in. All air plumbing was done using hardline tubing and the vacuum pump used is currently used for vacuum tests. Three tests were conducted to test the pressure transducer, a standard vacuum test, a drift test, and a response test. The standard vacuum test is the test conducted by Eaton for inspecting all of their carbon face seals and is a 30 second test which measures vacuum decay over time. The second, a drift test, compared the pressure transducer to a known accurate measurement device and a constant vacuum pressure. The point of this was to make sure there were no random fluctuations or unexplained rises in measured vacuum pressure. This test was a key indicator whether we had a faulty transducer or not because transducers that deviate from a steady value after many years of operation are not uncommon but a new sensor that does is extremely liable to fail. A response test was done after which was done ensure that the transducer was able to react quickly to changes in vacuum pressure. Setting the sample rate to take ten measurements every second, much more data collection than required by Eaton, and then changing the vacuum pressure through a pressure relief valve showed how quickly the transducer can react to changes. The transducer handled these changes and showed no sign of mis-reading data or suffering from sudden changes in pressure.

Testing the user interface was tricky and different from the pressure transducer because it was not measured against numerical values but the ease of use with an operator. The user interface needed to be easy to understand and easy to operate. Ease of operating was handled by creating an attractive user interface with large easily identifiable buttons. Feedback was received from Eaton on two occasions to help tailor the project with their feedback to be more user friendly. Keeping common mistakes that can happen due to unintentional key presses or stuck keys needed to be handled and were considered when selecting the programing language. Python can dynamically declare variables which significantly decreases the chances of overflow errors or invalid characters due to operator input. This handles most expected errors due to operator error. Other testing needs to be completed for the options discussed in the conclusion section but a comprehensive test of the user interface was not completed due to the time spent fixing known bugs in the system and getting the pressure transducer and user interface working together.

Redesign

From the testing phase no changes were made to the transducer selection but the User Interface underwent two design iterations. The two were striving to make the user interface more natural feeling and easier to understand. Feedback from Eaton all followed along the same idea of reading from left to right to naturally draw the operator’s eye to where it needed to go for the next step of the vacuum test. Other changes included already entered information being displayed as the operator advanced through the test to ensure the same seal was being tested throughout the process and keep an information from being overlooked. This is redesign through the testing phase but a major redesign was done much before the testing took place. Originally the project was to create a fully automated vacuum test machine for carbon face seals but this was soon determined to not be a feasible expectation for this project. Due to the switch from C++ used in the proof of concept to Python due to user interface limitations in C++ a lot of time was lost to learning Python and working out bugs in the system we did have. The idea of a fully automated system was abandoned and instead the focus was brought to developing a control system that is able to be expanded on and with more time accomplish the original goal the project set out to do. The work left to be done to complete the original scope of the project can be found in the conclusion section of this report.

Project Planning

Project planning is critical to a successful engineering project. The planning program used was Microsoft Project. The Gantt chart created in this program can be seen below. It contains important tasks, dates, and deadlines. The chart shows each entry as a bar with respect to the dates of the entry. This gives a visual representation of the plan and deadlines. The project plan keeps the team on task and ensures that important deadlines are met in time. All team members met twice a week in order to delegate tasks and communicate progress effectively. In order to communicate this progress with our sponsor the team constantly sent email updates to Jonathan Bedard the sponsor from Eaton as well as met with the sponsor and other engineers bi-weekly to discuss progress and receive critical feedback.

In the beginning of the year the project was research heavy focusing on literature and patent searches.Each member of the team completed an individual patent search but all relevant patents were shared and discussed as a team. This phase of the project was critical for understanding the project problem and developing a sound solution. This was a notable milestone for the team and all deadlines were met with a 100% completion rate. This research was critical for the next steps of the project which was focused on conceptual design. This was a big milestone for the team and through this a lot of brainstorming was conducted. Each member contributed 30 of their own designs and concepts including an analysis of each design into how each one fit in meeting all the design requirements. Again, all deadlines were met on time with 100% completion.

After a successful concept generation, the next milestone was to sort through all the top concept generations to complete a critical design review. Part of this phase was to do a QFD analysis on the chosen designs and then presenting our work in a well prepared presentation to our capstone class as well as our sponsors. During this phase all members of the team chose which roles of the project they would like to focus on and specialize in. This would make it easier going forward for the overall product development and completion. For this milestone, all deadlines were met on time with 100% completion.

The next big milestone of the semester was the proof of concept. For this, the critical design review phase. was brought to the next level and a final design was chosen and created with a SolidWorks scale model. In proving that this design would work a finite element analysis and flow analysis was conducted in SolidWorks to simulate the model functioning in the vacuum environment that it would be subjected to during a standard test. A lot of time was spent creating the scale model, running the FEA and flow simulations and preparing for the presentation. For this milestone, all deadlines were met with 100% completion. Overall, the weekly progress reports and project plan submissions proved to be beneficial in keeping the team progress moving forward and ensuring that deadlines were being met.

Following the fall semester, the spring semester gained a larger focus on testing and validation. The next milestone was a test review where the adequacy of the design must be verified as well as a detailed test matrix for all components and systems. A major component of the system was the user interface built using Kivy therefore the UI required testing and feedback.This was able to be done at the Eaton facility where real operators on the production floor who in the future might be using this software were able to give critical feedback on how well the application performs with respect to their day to day responsibilities. For this milestone, all deadlines were met on time with 100% completion.

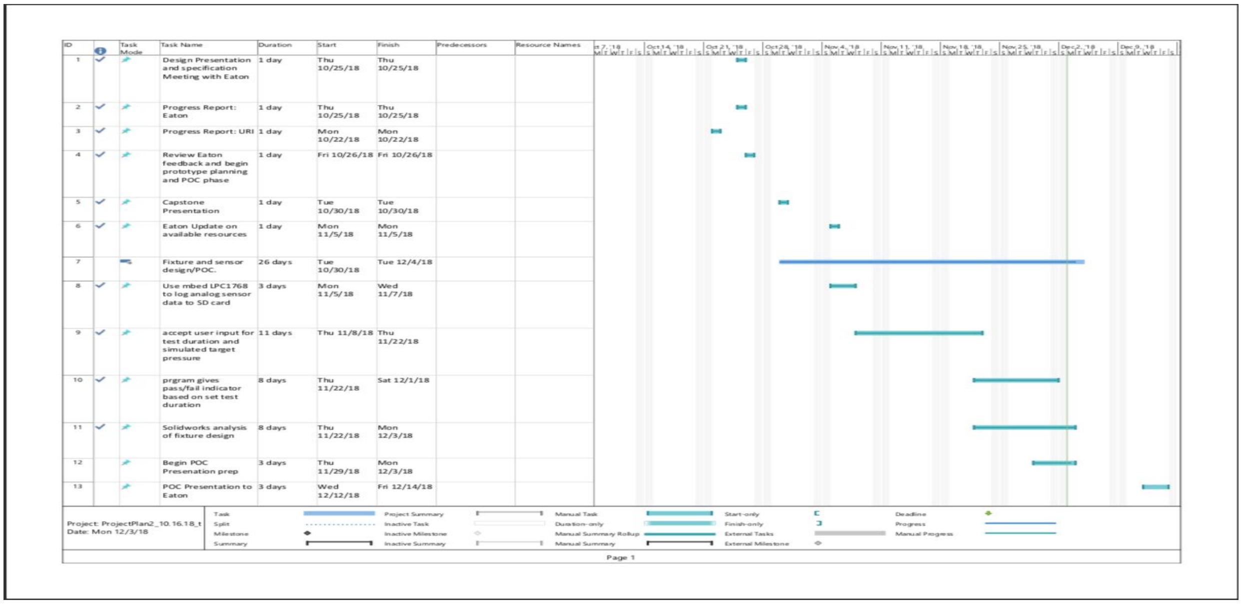


Figure 86: Gantt Chart

Proof Of Concept

Proving the viability of the vacuum test machine was done in two parts. First is simulations done on proposed fixture elements to prove their ability to withstand the desired pressure that occurred during testing. The proposed design uses flexible tubing for added modularity to the vacuum test machine and a seperate transducer box to where the measurements are taken. The main area of concern for this test was the transducer box. The thin walls we had designed it to have initially were to save material and total weight of the system but might not be able to withstand the twenty five inches of mercury that the test requires. The tests were run in the Solidworks simulation environment with a twelve psi applied external force across the entire surface of the transducer box. This is similar to a 12 psi vacuum pressure and will show any areas of catastrophic failure. As expected the transducer box was the highest area of interest for this simulation. Thin walled material on the ends of the transducer box showed some deformation caused by the pressure but no failure. This confirms that the proposed design, even with thin walls, is viable and is a good starting spot for physical prototyping. The flow map of the air plumbing system also showed ways that the system could be optimized. Recirculation occurs around the corners of the transducer box and if the prototype utilized rounded corners this can be reduced for a more efficient system.

Second is the is a simulated control sensor that uses similar analog inputs to the final pressure transducers that will be used for the final product. The requirements for the control system were that it can take user inputs for the test duration and target pressure, accurately track the analog sensor input to determine pass/fail criteria, and save all relevant test data. This was accomplished through the use of an mbed LPC 1769. User inputs were recorded by setting a start point of 25" of mercury for target pressure and sixty seconds. From here by pressing the "U" or "D" key on the keyboard these can be adjusted by integer values of one and ten respectively. This covers the user input requirement and sets the system up to run the test. From here the limits for pass fail are calculated and the system begins collecting data. Should sensor data during the target test duration be outside of these limits the test will indicate pass or fail. All of the set test parameters and every sensor reading is recorded and saved to an SD card. This simulated test used the same analog inputs that the real system will use and managed to meet all of the basic requirements needed for the final product. Between the two parts of the proof of concept for the vacuum test machine there is a good base to move forward with more advanced parts of the project.

Financial Analysis

In the development of our vacuum testing system there are many different types of financial cost that go into the creation of the concept. For a physical value our group has a budget of $3,000 to build our concept. Every member of our group has spent countless hours in the production of the vacuum testing with multiple aspects of financial cost. Listed below are some of the cost that went into this project. Materials, manufacturing, concept generation, human resources and some miscellaneous cost.

Material

All the material that will be used and priced out are described in the concept section of financial analysis along with the components that will be used. Using the material we have decided to use leaves a lot of the budget unused. If the project is expanded on more next semester then improvements to materials can be made.

Manufacturing

The final design for our project has been complete, we can simulate a test on one device and output results for the operator. Eaton has stated their satisfaction with the results and could possibly implement the production of a few more units. Listed below is the cost of one unit which will make production of new units easy and cheap.

Concept

Detailed in the table below is a list of the different materials and components that go into controlling one fixture unit. Eaton will be providing the team with their current equipment, allowing us to modify and add certain components to update the system. The fact they are allowing us to work off their current system will save a lot of money on the budget and in return save them money.

Eaton also provided our group with a lapped plate along with a vacuum pump. In the fall semester there was a significant amount of research done into the purchase of a vacuum pump. Eaton providing us with a vacuum pump was very crucial, the cost of one would have easily been more than the full budget given. The lapped plate is what sits on top of the seal to create the vacuum tight vacuum to run our tests. Not having to manufacture a lapped plate saved a ton of time and resources as well.

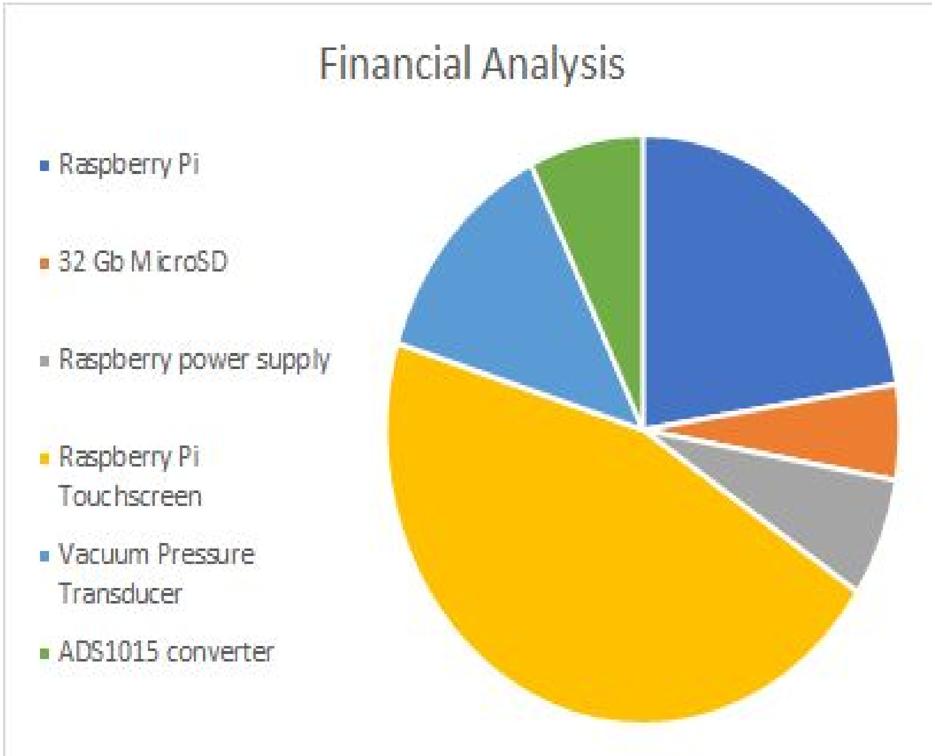
The total cost for a test fixture will ring up at $153.05 to produce. With a budget of $3,000, the total savings of this project is $2846.95. A major benefit of this project being controlled based is the affordability of the parts. The most expensive part was the 7" Raspberry Pi touchscreen which is how the operator runs the test. The Raspberry Pi it self cost $34.49 and the power supply for the Raspberry Pi cost $9.99. A 32Gb MicroSD was needed to contain the system which was created using Python and to save text files for the results achieved. The last part was a pressure transducer which was used to convert the pressure to the Raspberry Pi to calculate the decay rate over time. Below is a table of all the cost used to create this project.

Table 2: Concept generation cost

Financial Analysis

Budget	$3,000
Raspberry Pi	$34.49
32 Gb MicroSD	$7.99
Raspberry power supply	$9.99
Raspberry Pi Touchscreen	$69.59
Vacuum Pressure Transducer	$20.00
ADS1015 converter	$10.99
Budget Used	$153.05
Budget Remaining	$2846.95

Table 3: Pie Chart



Shown in the chart above is a break down of the cost allocated towards the build of our vacuum test. As stated in the previous section the total cost involved in the build only cost \$153.05. Of that \$153.05 the Touch screen for the Raspberry Pi and the Raspberry Pi took up most of the budget.

Human Resources

An aspect that does not have a numerical cost to it is the amount of time the group put into this project during the span of the whole semester. During the semester each person was in charge of doing their own patent search, literature search, SolidWorks designs and simulations, engineering analysis, QFD and many more. There has been a lot of research put into this project and this cost is not a measurable cost.

Miscellaneous

Among some other costs to be addressed are figuring total amount of resources and money to be spent on upkeep of the project, and how much it will cost to teach each of the operators on how to use the new product. The product is user friendly and quick to learn, but it is yet seen how much it will take to train each operator.

Operation

The purpose of this project is to vacuum test seals for durability and sustainability purposes. The system created has a very user friendly interface and team 28 believes that the product will work perfectly on Eaton's manufacturing floor. The process of the operation begins with the operator placing a seal onto the fixture and placing a lapped plate over it to create a vacuum tight seal. The system is stationary and already setup for the ease of the operator, no setup will be required. If setup is needed, connect the pressure transducer to the fixture and turn on the Raspberry Pi. The Raspberry Pi is programmed to go right to the main page for ease of use. Once the system is turned on it is ready to run.

Enter the information of the operator and the part that is being worked on, click submit. Once the submit button is selected the information input will be saved to a text file and the application will direct the operator to the test window. Select low, high, or custom vacuum test from the drop down bar and submit the test. The countdown will begin for the test and a pass/fail will be indicated from the vacuum test once completed.

If starting a new test, select back on the bottom left hand side of the screen. This will take the operator back to the information screen to enter the new part number. From this point the operator can follow the instructions for a new test and continue.

Maintenance

Maintenance for the unit will need to be done regularly to make sure operations run as intended. The vacuum testing equipment can be done easily and is designed for the operator to have access to the hardware inside. The Raspberry Pi is placed into a housing box with the board, wiring, and configuration inside. If any wiring or equipment goes faulty it is easy to access and cheap to fix. Most of the equipment is software based which will make it require little maintenance other than Eaton's engineers updating the system to how they would like.

Additional Considerations

Listed below are additional considerations that our group considered during our research and build of our product and future groups that work on improving the vacuum testing may also consider as well.

Economic Impact

The Vacuum testing for carbon face seals was created by the team in means to improve the overall process of testing seals and making sure they work properly prior to distribution to customers. The vacuum system only cost $153 to create therefore can be implemented on the manufacturing floor in multiple locations. Power management is a fundamental part of any company and will have increased value for years to come. Eaton's demand in this department will continue to increase and having such equipment will create a more efficient procedure to follow for their manufacturing process. The value this product will have on creating better efficient testing will prove to be priceless.

Societal and Political Impact

The purpose of the project is to prevent non conforming parts manufactured by Eaton from being delivered to the customer. The new system developed by our group during this project is intended to further reduce the number of non conforming seals which make it to Eaton's customers. Preventing customers such as GE or Pratt and Whitney from receiving and malfunctioning seals means that society as a whole would be safer as a result of improving the aviation industry with this device to ensure all seals will perform as intended.

Ethical Considerations

From an ethical standpoint the user interface created by the team ensures that operators conduct a full test as the application records all aspects of the vacuum test. Whereas before test automation operators are manually required to follow all procedures and record values manually.

The possibility of an operator to fabricate false test results is now eliminated with the incorporation of automated data acquisition.

Health / Ergonomics / Safety considerations

Unfortunately due to time constraints no safety features were able to be fully implemented into the control system. If given more time an emergency stop feature would be implemented into the kivy application to stop all vacuum testing if any issues were to arise. Ergonomically the raspberry PI touch screen is a huge improvement for the company as opposed to the currently outdated machinery being used. The touch screen is light and mobile reducing the risk of injury during transportation.

Environmental and Sustainability considerations

The incorporation of the newly designed system for vacuum decay testing of mechanical seals would result in a positive environmental impact. The current outdated machines being used by Eaton to perform these tests require a lot of maintenance and repairs. This results in the waste of a lot of energy in order to keep these machines running. However, with the new system maintenance is very fast and easy reducing energy consumption needed for costly repairs.

Conclusions

Based on the analysis conducted on the design of our vacuum system, the results indicate that the design is more than capable of meeting all the design specifications set forth. The scale model built in SolidWorks includes a pipe diameter of D = 0.8125 inches, meeting the sizing requirement needed from the vacuum pump inlet connection. The design has also shown that it is capable of withstanding a vacuum environment of 25” Hg as simulated using finite element analysis. A simulation has also been conducted on a control sensor which proves that a parameter such as pressure can be measured and the signal noise can be filtered to provide discrete data which can then be exported for post processing in a program such as MS Excel or Matlab. Up until this point, between the simulated mechanical/structural system and simulated control system the design specifications have in theory been satisfied and proves to be very promising results. Successful testing and validation of the pressure transducer and user interface from the development of the kivy application also proves that all the design specifications laid forth by Eaton are met. In addition to being able to fully satisfy all requirements the design proves to be cost effective and manufacturable if there is interest in commercializing this product. The next steps required include debugging any coding issues that may arise in the future with the kivy application as well as improving onto the control system within the user interface which allows for the user to control the vacuum pump with the push of a button.

Acknowledgements

Team 28 would like to give a special thank you to Dr. Nassersharif and the Teacher's assistants for our capstone class for leading the way this semester in the guidance of our concept. We would also like to give thanks to Jonathan Bedard and the engineering team at Eaton for their constant help with our concept and the sharing of their knowledge on their product.

References

Groteke, D. (2007, August) Improve your vacuum test, 97,8.

Pfund, A.H. (1919, November) A Vapor-Free Vacuum Seal, 551,552.

Welsh-ILMVAC. (2008, August) Owner's manual for DuoSeal Vacuum pump

Zhang, G. (2013, December) Spiral Groove Face Seal Experimentation

ASME, (2015, August) Pressure activated leaf seal technology readiness testing

Hamlin, M. L. (1925, March) A Laboratory vacuum gage

Mechanical Engineering. (1994) Electric Valve Actuator, 116,6.

Schupack, M & D. (1990, December) Method and apparatus for testing relative permeability of materials.

Hewlett-Packard Co. (1986, November) Vacuum actuated test figures

Motorola Inc. (1985, August) Method and apparatus for testing a sealed container

Chou, W. (2015, June) Air Compressor

Merry Electronics. (2016, August) Air pressure sensing system

Fuji Machine Manufacturing Co Ltd. (2010, November) Suction nozzle

Appendices

Appendix A: POC code for simulated system

File "/VTM_POC_2/main.cpp" printed from os.mbed.com on 12/17/2018

```
#include "mbed.h"
#include "SDFileSystem.h"


DigitalIn testStart (p23);
Serial pc(USBTX, USBRX);
SDFileSystem sd(p5, p6, p7, p8, "sd");
FILE *file;
Timer timer;
AnalogIn currentPressure(p20);

float targetPressure;
float targetTestDuration;
float lowPressureLimit;
float highPressureLimit;
float P;

int main()
{

   while(1){
       if(testStart == 1){
           targetPressure = 25;
           pc.printf("Adjust Target Test Pressure (inches Hg):\n\r");
           pc.printf("U key to increase target, D to deccrease\n\r");
           pc.printf("Current Target Pressure: %f \n\r", targetPressure);
            while (1) {
                char c = pc.getc();
                wait(0.001);
                    if(c == 'u'){
                        targetPressure = targetPressure + 1;
                        pc.printf("Current Target Pressure: %f \n\r", targetPressure);
                        }
                    else if (c=='d'){
                        targetPressure = targetPressure - 1;
                        pc.printf("Current Target Pressure: %f \n\r", targetPressure);
                        }
                    else{
                        break;
                        }
                }
           targetTestDuration = 60;
           pc.printf("Adjust Target Test Duration (Seconds):\n\r");
           pc.printf("U key to increase target, D to deccrease\n\r");
           pc.printf("Current Target Test Duration: %f \n\r", targetTestDuration);
           while (1) {
                char c = pc.getc();
                wait(0.001);
                    if(c == 'u'){
                        targetTestDuration = targetTestDuration + 10;
                        pc.printf("Current Target Test Duration: %f \n\r", targetTestDuration);
                        }
                    else if (c=='d'){
                        targetTestDuration = targetTestDuration - 10;
                        pc.printf("Current Target Test Duration: %f \n\r", targetTestDuration);
                        }
                    else{
                        break;
                        }
                }
```

```
        lowPressureLimit = targetPressure - (targetPressure*0.02);
        highPressureLimit = targetPressure + (targetPressure*0.02);
        pc.printf("Current Test Parameters\n\r");
        pc.printf("Target Pressure: %f\n\r", targetPressure);
        pc.printf("Target Test Duration: %f\n\r", targetTestDuration);
        pc.printf("Failure limits: %f  %f\n\r", lowPressureLimit, highPressureLimit);

        file = fopen("/sd/test_data.txt", "w");
            if ( file == NULL ) {
                    error("ERROR: Could not open file for writing!\n\r");
                    return -1;
                }
        timer.start();
        fprintf(file, "Timer %2.2fs: %3.2f target inches Hg %3.2f target seconds %3.2f lowest allowable pressure %3.2f highest allowable pressure C\n\r", timer.read(), targetPressure, targetTestDuration, lowPressureLimit, highPressureLimit);
        fclose(file);
        file = fopen("/sd/test_data.txt", "a+");
        if ( file == NULL ) {
                    error("ERROR: Could not open file for writing!\n\r");
                    return -1;
                }

        while(1){
            if(timer.read() <= targetTestDuration){
                P = ((3300-(3300*currentPressure)) * 0.01);
                fprintf(file, "%2.2f %2.2f\n\r", timer.read(), P);
                wait(0.01);
                }
            else if (timer.read() > targetTestDuration){
                break;
                }
            }
        fclose(file);
        pc.printf("Done! Safe to remove SD card\n\r");


        }


        else if(testStart == 0){

            }
       }
       }
```

Appendix B: Main Python File for Kivy Application

```
import kivy
from kivy import Config
from kivy.app import App
# OpenGl bug fix import os os.environ['KIVY_GL_BACKEND'] = 'angle_sdl2'
from kivy.uix.label import Label
from kivy.uix.gridlayout import GridLayout
from kivy.uix.textinput import TextInput
from kivy.uix.button import Button
from kivy.lang import Builder
from kivy.uix.floatlayout import FloatLayout
from kivy.uix.boxlayout import BoxLayout
from kivy.uix.relativelayout import RelativeLayout
from kivy.uix.widget import Widget
from kivy.core.window import Window
from kivy.uix.screenmanager import ScreenManager, Screen, FadeTransition
import time
from kivy.properties import BooleanProperty
from kivy.properties import StringProperty
from kivy.properties import ObjectProperty
from kivy.properties import NumericProperty
from kivy.animation import Animation
from kivy.uix.image import CoreImage
from kivy.uix.progressbar import ProgressBar
from database import DataBase
from kivy.factory import Factory as F
import threading
from kivy.clock import Clock
from datetime import datetime
import time
from kivy.uix.dropdown import DropDown
from kivy.uix.spinner import Spinner
from kivy.core.window import Window
from kivy.uix.popup import Popup


open("users.txt", "w+")  # creates text file called "users"

class Variables():
    def __init__(self):
        self.workInfo = []
        self.employeeID = ''
        self.workID = ''
        self.partnumber = ''


    def get_vars(self, CreateMainWindow):

        eID = CreateMainWindow.employeeID.text
        wID = CreateMainWindow.workID.text
        pN = CreateMainWindow.partnumber.text

        self.workInfo.append(eID)
        self.workInfo.append(wID)
        self.workInfo.append(pN)
        print(self.workInfo)

    def set_vars(self, AnotherWindow):
        self.employeeID = self.workInfo[0]
        self.workID = self.workInfo[1]
        self.partnumber = self.workInfo[2]
        print(self.employeeID)
```

```
class CreateMainWindow(Screen):

    def __init__(self,**kwargs):
        super(CreateMainWindow,self).__init__(**kwargs)
        self.a = App.get_running_app()

        employeeID = ObjectProperty(None)
        workID = ObjectProperty(None)
        partnumber = ObjectProperty(None)

    def submit(self):
        #open("users.txt", "w+")  # creates text file called "users"
        print(self.workID.text, self.partnumber.text, self.employeeID.text)
        db.add_user(self.workID.text, self.partnumber.text, self.employeeID.text)

    def clear(self):
        self.workID.text = " "
        self.employeeID.text = " "
        self.partnumber.text = " "

    def cancelapp(self):
        App.get_running_app().stop()
        Window.close()

db = DataBase("users.txt")

class AnotherWindow(Screen):
    standardTest = BooleanProperty(False)
    customTest = BooleanProperty(False)
    variables = ObjectProperty(None)
    Var1 = StringProperty('')
    Var2 = StringProperty('')
    Var3 = StringProperty('')

    def count(self, *varargs): #Use clock function
        self.start = datetime.now()
        Clock.schedule_interval(self.on_timeout, 1)

    def on_timeout(self, *args): #current placeholder for where pressure values will go
        d = datetime.now() - self.start
        self.plbl.text = datetime.utcfromtimestamp(d.total_seconds()).strftime("%H.%M.%S")

    def reset(self):
        self.workID.text = ""
        self.partnumber.text = ""
        self.employeeID.text = ""

    def test_over(self):
        self.ids.highvac.disabled = True
        self.ids.lowvac.disabled = True
        self.ids.rtest.disabled = True
        self.ids.stop_test.disabled = True
        self.ids.timeoutput.text = "RESULTS"
# Once fully connected, the test_over will be dependent on the seals decay rate

    def unlock(self):
        self.highvac.disabled = True
        self.lowvac.disabled = True

    def clear(self):
        self.partnumber.text = " "
        self.workID.text = " "
        self.employeeID.text = " "

    def cancelapp(self):
        App.get_running_app().stop()
        Window.close()

    def open_standard_test(self):
        if self.standardTest == False and self.customTest == False:
            self.ids.container.add_widget(F.Timer(total=10))
            self.standardTest = True

    def open_custom_test(self):
        if self.customTest == False and self.standardTest == False:
            self.ids.container.add_widget(F.Timer(total=10, parameters = False))
            self.customTest = True

    def on_pre_enter_callback(self, variables):
        self.variables = variables
        #self.partnumber = str(variables.partnumber)
        self.Var1 = str(variables.workInfo[0] )
        self.Var2 = str(variables.workInfo[1] )
        self.Var3 = str(variables.workInfo[2] )
        variables.set_vars(self)

    def open_popup(self):
        the_popup = CustomPopup(self.variables)
        the_popup.open()
```

```python
class CustomPopup(Popup):
    eID_text = StringProperty('')
    wID_text = StringProperty('')
    pN_text = StringProperty('')


    def __init__(self, variables, **kwargs):
        super(CustomPopup, self).__init__(**kwargs)
        self.eID_text = str("Employee ID:" + variables.employeeID)
        self.wID_text = str("Work ID:" + variables.workID)
        self.pN_text = str("Part Number:" + variables.partnumber)
        print(self.eID_text)


class Timer(F.BoxLayout):
    active = F.BooleanProperty(False)
    paused = F.BooleanProperty(False)
    complete = F.BooleanProperty(False)
    parameters = F.BooleanProperty(True)

    # Total time, and time remaining (in seconds)
    total = F.NumericProperty(0)
    remaining = F.NumericProperty(0)

    # Angle and color for progress indicator; these are used
    # in canvas instructions in kvlang to represent the timer
    # visually. Angle is progress from 0-360.
    angle = F.BoundedNumericProperty(0, min=0, max=360)
    color = F.ListProperty([0, 1, 0, 1])

    def __init__(self, **kwargs):
        super(Timer, self).__init__(**kwargs)
        App.get_running_app().add_timer(self)
        self.remaining = self.total

    def set_total(self, total):
        self.stop()
        self.total = self.remaining = total

    def start(self):
        if self.total:
            self.angle = 0
            self.active = True
            self.complete = False

    def stop(self):
        self.active = self.paused = self.complete = False
        self.remaining = self.total
        self.angle = 0

    def pause(self):
        if self.active:
            self.paused = True

    def resume(self):
        if self.paused:
            self.paused = False

    # Called by App every 0.1 seconds (ish)
    def _tick(self, dt):
        if not self.active or self.paused:
            return
        if self.remaining <= dt:
            self.stop()
            self.complete = True

        else:
            self.remaining -= dt
            self.angle = ((self.total - self.remaining) / self.total) * 360

class InputFileDropDown(FloatLayout):
    pass


class CustomWindow(Screen):
    pass

db = DataBase("users.txt")

class WindowManager(ScreenManager):
    variables = ObjectProperty(None)
    createMainWindow = ObjectProperty(None)
    anotherWindow = ObjectProperty(None)

    def __init__(self, **kwargs):
        super(WindowManager, self).__init__(**kwargs)
        self.variables = Variables()     # Instantiate object variables


presentation = Builder.load_file("App.kv")
```

```python
class MyApp(App):
    title = "Welcome to Team 28's Capstone Project"
    _timers = []
    _clock = None

    def build(self):
        return presentation

    def add_timer(self, timer):
        self._timers.append(timer)
        if not self._clock:
            self._clock = Clock.schedule_interval(self._progress_timers, 0.1)

    def remove_timer(self, timer):
        self._timers.remove(timer)
        if not self._timers:
            self._clock.cancel()
            del self._clock

    def _progress_timers(self, dt):
        for t in self._timers:
            t._tick(dt)

MyApp().run()
```

Appendix C: Database Python File for Kivy Application

```python
import datetime



class DataBase:
    def __init__(self, filename):
        self.filename = filename
        self.users = None
        self.file = None
        self.load()

    def load(self):
        self.file = open(self.filename, "r")
        self.users = {}

        for line in self.file:
            workID, partnumber, employeeID, created = line.strip().split(";")
            self.users[partnumber] = (workID, employeeID, created)

        self.file.close()

    def get_user(self, partnumber):
        if workorder in self.users:
            return self.users[partnumber]
        else:
            return -1

    def add_user(self, workID,employeeID, partnumber):
        if partnumber.strip() not in self.users:
            self.users[partnumber.strip()] = (workID.strip(), employeeID.strip(), DataBase.get_date())
            self.save()
            return 1
        else:
            #print("Work Order exists already")
            return -1

    def validate(self, partnumber, workID):
        if self.get_user(partnumber) != -1:
            return self.users[partnumber][0] == workID
        else:
            return False

    def save(self):
        with open(self.filename, "w") as f:
            for user in self.users:
                f.write(user + ";" + self.users[user][0] + ";" + self.users[user][1] + ";" + self.users[user][2] + "\n")

    @staticmethod
    def get_date():
        #return str(datetime.datetime.now()).split(" ")[0]
        return str(datetime.datetime.now()).split('.')[0]
```

Appendix D: Kivy File for Kivy Application

```
#: import FadeTransition kivy.uix.screenmanager.FadeTransition
#:import F kivy.factory.Factory

WindowManager:
    id: screen_manager
    transition: FadeTransition()

    createMainWindow: CreateMainWindow
    anotherWindow: AnotherWindow

    CreateMainWindow:
        name: "mainscreen"
        id: CreateMainWindow
        manager: screen_manager

    AnotherWindow:
        name: "testscreen"
        id: AnotherWindow
        manager: screen_manager
        on_pre_enter: self.on_pre_enter_callback(app.root.variables)
        on_pre_enter: self.open_standard_test()

    CustomWindow:
        name: "customscreen"



<CreateMainWindow>:
    name: "mainscreen"
    employeeID: employeeID
    workID: workID
    partnumber: partnumber
    transition: FadeTransition()

    FloatLayout:


        Button:
            id: closeapp
            text: "Close App"
            font_size: 15
            size_hint: 0.125,0.0625
            pos_hint: {"x": 0.45, 'y':0.085}
            background_normal: ''
            background_color: 1, .3, .4, .85
            on_release: root.cancelapp()


        Button:
            text: "Submit"
            font_size: 25
            size_hint: 0.55,0.08
            pos_hint: {"x": 0.25, 'y':0.25}
            background_color: (0.529,0.808,0.922,1.0)
            on_release: print("Name:",employeeID.text, "Work ID:", workID.text, " Part Number:", partnumber.text)
            on_release: root.submit()
            on_release: app.root.current = "testscreen"
            #on_press: container.add_widget(F.Timer(total=30))
            on_release: app.root.variables.get_vars(root)


    GridLayout:
        #f_name: name
        f_workID: workID
        partnumber: partnumber
        #f_testduration: testduration
        rows: 3
        padding: 100
        spacing: 30

        Label:
            text:'Employee ID:'
            font_size: 20
            size_hint: 0.5,None
            height: 30


        TextInput:
            id:employeeID
            font_size: 18
            size_hint: 0.5,None
            height: 30
            multiline: False
            padding_y: [self.height / 2.0 - (self.line_height / 2.0) * len(self._lines), 0]
            text: "E12345"


        Label:
            text: 'Work ID:'
            font_size: 20
            size_hint: 0.5,None
            height: 30
```

```
        TextInput:
            id: workID
            font_size: 18
            size_hint: .5, None
            height: 30
            multiline: False
            padding_y: [self.height / 2.0 - (self.line_height / 2.0) * len(self._lines), 0]
            text: "64014900"

        Label:
            id: partnumber
            text: 'Part Number:'
            font_size: 20
            size_hint: 0.5, None
            pos_hint:{"x": 0.3, 'y':0.7}
            height: 30

        TextInput:
            id: partnumber
            font_size: 18
            size_hint: 0.5, None
            height: 30
            multiline: False
            padding_y: [self.height / 2.0 - (self.line_height / 2.0) * len(self._lines), 0]
            text: "891881n18"

<AnotherWindow>:
    name: "testscreen"
    plbl: p_output
    container: container


    BoxLayout:
        id: container
        orientation: 'horizontal'
        spacing: 5
        #size_hint: 0.3,0.4
        pos_hint: {"x":0.29,'y': 0.3}
        size_hint: 0.8,0.4


    FloatLayout:
        id: floatContainer

    Label:

        id: p_output
        font_size: 20
        pos_hint: {"x": 0, "y": -0.3}
        text: "Pressure Values:"

    Label:

        font_size: 20
        pos_hint: {"x": -0.35, "y": 0.25}
        text: "Choose a Vac Test:"




    Label:
        text: "Test Results:"
        font_size: 20
        pos_hint: {"x": 0.33, 'y':0.25}



    Button:
        id: pass_test
        text: "PASS"
        font_size: 20
        size_hint: 0.25,0.2
        pos_hint: {"x": 0.72, 'y':0.50}
        background_color: (0,1.0,0,1.0)
        disabled: True
        on_press: timeoutput.text = "TEST PASSED"

    Button:
        id: fail_test
        text: "FAIL"
        font_size: 20
        size_hint: 0.25,0.2
        pos_hint: {"x": 0.72, 'y':0.28}
        background_color: (1.0,0,0,1.0)
        disabled: True
        on_press: timeoutput.text = "TEST FAILED"
```

```
    Button:
        text: "Back"
        size_hint: 0.2,0.1
        pos_hint: {"x": 0.75, 'y':0.05}
        font_size: 20
        background_normal: ''
        background_color: 1, .3, .4, .85
        on_release: app.root.current = "mainscreen"
        #on_press: root.open_popup()

    Button:
        text: "Info"
        size_hint: 0.2,0.1
        pos_hint: {"x": 0.4, 'y':0.05}
        font_size: 20
        #background_normal: ''
        #background_color: 1, .3, .4, .85
        on_press: root.open_popup()

<Timer>:
    vac_input: vacuumset
    time_input: timeset
    orientation: 'horizontal'
    Label:
        text: '{:.2f} remaining / {:.2f}'.format(root.remaining, root.total, root.angle)
        canvas.before:
            Color:
                rgba: int(not root.active), int(root.active), int(root.paused), 0.5
            Rectangle:
                pos: self.pos
                size: self.size

            Color:
                rgba: 1, 1, 1, 1
            Line:
                width: 3
                circle: self.center_x, self.center_y, self.width / 3
            Color:
                rgba: root.color
            Line:
                width: 5
                circle: (self.center_x, self.center_y,self.width / 3, 0, root.angle)

    FloatLayout:
        Button:
            id: btn_start
            text: "START TEST"
            font_size: 15
            size_hint: 0.8,0.25
            background_color: (0.529,0.808,0.922,1.0)
            pos_hint: {"x": -1.8, 'y': -0.62}
            on_press: root.start()
            disabled: True

        TextInput:
            id: timeset
            size_hint: 0.20,0.13
            pos_hint: {"x": -1.8, 'y':0.45}
            text: str(root.total)
            multiline: False
            disabled: root.parameters


        Label:
            text: 'Time: (sec.)'
            font_size: 15
            size_hint: 0.65,0.15
            pos_hint:{"x": -1.6, 'y':0.43}
            disabled: root.parameters


        Label:
            font_size:15
            size_hint: 0.65,0.15
            pos_hint: {"x": -1.63, 'y':0.23}
            text: 'Vacuum: (inHG)'
            disabled: root.parameters

        TextInput:
            id: vacuumset
            size_hint: 0.20,0.13
            pos_hint: {"x": -1.8, 'y':0.25}
            text: "25"
            multiline: False
            disabled: root.parameters
```

```
    Button:
        id: btn_set
        size_hint: 0.75,0.15
        pos_hint: {"x": -1.8, 'y':0.0}
        text: 'Set Parameters'
        font_size: 20
        background_color: (0.529,0.808,0.922,1.0)
        disabled: True
        on_press: root.set_total(int(timeset.text))
        on_release: btn_start.disabled = False


InputFileDropDown:

    Button:

        id: btn
        text: 'Select Test Here:'
        font_size: 20
        background_color: (0.529,0.808,0.922,1.0)
        on_parent: dropdown.dismiss()
        on_release: dropdown.open(self)
        size_hint: 0.75,0.3
        pos_hint: {"x": -2.8, 'y':0.7}


    DropDown:
        id: dropdown
        on_select: btn.text = '{}'.format(args[1])

        Button:
            text: 'High Vac'
            font_size: 20
            size_hint_y: None
            height: 65
            on_release: dropdown.select('High Vac')
            #on_press: root.open_standard_test()
            #on_press: root.start()
            on_press: btn_start.disabled = False
            on_press: btn_start.disabled = True
            on_press: btn_set.disabled = True
            on_press: timeset.disabled = True
            on_press: vacuumset.disabled = True
            on_press: vacuumset.text = str(25)
            on_press: root.set_total(int(10))


        Button:
            text: 'Low Vac'
            font_size: 20
            #background_color: (0.529,0.808,0.922,1.0)
            size_hint_y: None
            height: 65
            on_release: dropdown.select('Low Vac')
            #on_press: root.open_standard_test()
            on_press: btn_start.disabled = True
            on_press: btn_set.disabled = True
            on_press: timeset.disabled = True
            on_press: vacuumset.disabled = True
            on_press: vacuumset.text = str(25)
            on_press: root.set_total(int(10))



        Button:
            text: 'Custom'
            font_size: 20
            #background_color: (0.529,0.808,0.922,1.0)
            size_hint_y: None
            height: 65
            on_release: dropdown.select('Custom')
            #on_press: root.open_custom_test()
            on_press: btn_set.disabled = False
            on_press: timeset.disabled = False
            on_press: vacuumset.disabled = False
```