Making a Better Suction Cup

Final Report

Course: ME 450 Section 4
Sponsor: K Alex Shorter, Assistant Professor, University of Michigan Department of Mechanical Engineering

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Abstract

Our project sponsor, Professor Alex Shorter and his research team at ESTAR Lab, designs bio-logging tags for the purpose of tracking the dynamics and behaviors of cetaceans, such as whales or dolphins, in their marine habitats. Currently our sponsor utilizes suction cups to attach the bio-logging tags to whales for data collection. The tags create hydrostatic forces when attached to these mammals, potentially resulting in premature suction cup detachment and adverse effects on the well-being, behavior and energetics of the mammals. An experimental approach, including testing and analyses performed on the suction cups, will aid in design improvement and ultimately increase our understanding of suction cup parameters to achieve better overall cup performance.

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Project Background

A majority of the ocean remains unexplored and inaccessible to people which makes observation of marine life difficult. For around sixty years, research scientists have utilized bio-logging tags as a tool to enable the gathering of information on cetaceans that would otherwise be unattainable [1]. The motivation for collecting all of this data is to gain a better understanding of whale movements and behaviors. This gained knowledge facilitates in aiding wildlife conservation efforts and minimizing human impact on whales and their environment.

The recorded data from the biologging tags will contribute to animal protection, for example with the analysis of migration route and behavior and energy transportation within biological systems [2]. It will also help animal researchers study the behaviors and movement patterns of marine mammals as shown in Figure 1.

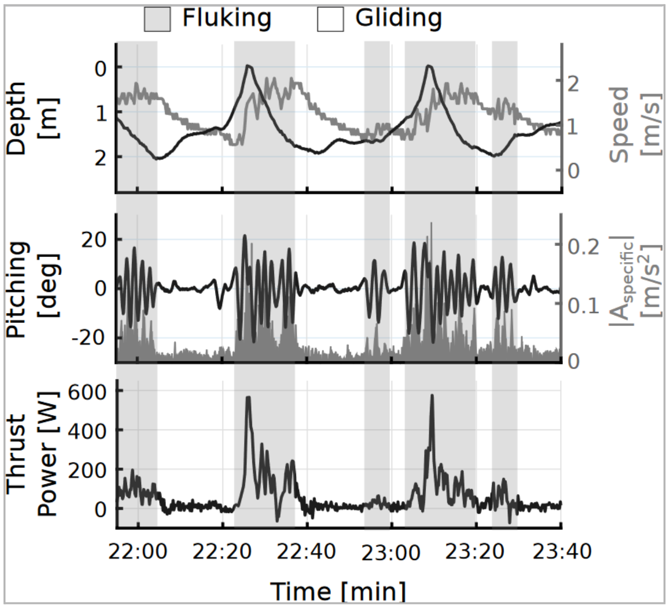


Figure 1. *Short sample of data from a bottlenose dolphin collected using a biologging tag.* This two minute section (provided by our sponsor) shows swimming data of the dolphin fluking and gliding as it dives and surfaces while swimming. The raw data was recorded via multiple sensors in the biologging tag: an inertial measurement unit recorded the pitching and acceleration; a pressure sensor recorded width; an impeller calibrated to estimate speeds based on the frequency of its rotation recorded speed. A simple model of dolphin swimming based on changes in width and instantaneous speed was used to calculate the thrust power of the animal (G. Antoniak, personal communication, April 19, 2023).

Development of understanding key design parameters will help researchers with the reliability and consistency of attachment so that the biologging tags can stay on for longer periods of time and collect a higher quality and quantity of data. Current, temperature, and ocean data can provide information to help guide future action on environmental protection with the consideration of human disturbance. More specifically, collected data will identify areas of whale habitats and can aid in minimizing negative human impacts on whales which is essential since many populations of whales are endangered. The North Atlantic Right Whale population consists of a mere 400 individuals despite over 80 years of protection. About 85% of the Right Whale population has been entangled in fishing gear at least once, and roughly

60% has been entangled more than once. The primary cause of death of these whales are due to fishing gear and vessel strikes, resulting from human activities such as commercial fishing [3]. Data acquired from bio-logging tags will aid researchers in understanding marine environments which will aid in the further protection of whales and hopefully the prevention of the predicted extinction of species, such as the Right Whale.

Each biologging tag is an electronic data collection instrument, comparable to the size of a hockey puck, that is capable of providing a variety of information about cetaceans and their environments. This data is collected using various different sensors embedded in each bio-logging tag which is then secured to the whale using one of several methods. The attachment method of the tags must be ethical and non-invasive to ensure the well-being of the mammals, researchers, and ocean.

Previously used configurations for attaching bio-logging tags that were considered include: anchored, bolt-on, and consolidated. Anchored tags are typically deployed using an airgun or crossbow and are attached using one anchor or more that puncture and terminate below the skin. Bolt-on tags use one or more bolts to pierce the skin, creating a through hole and exiting out the other side (similar to an ear-piercing). Consolidated tags require an anchor to be partially implanted in the whale, terminating internally to muscle/blubber [4]. It is important to investigate alternative attachment methods to replace these invasive methods due to a number of associated ethical and operational concerns. Illustrations of both invasive and non-invasive attachment methods can be found in Figure 2.

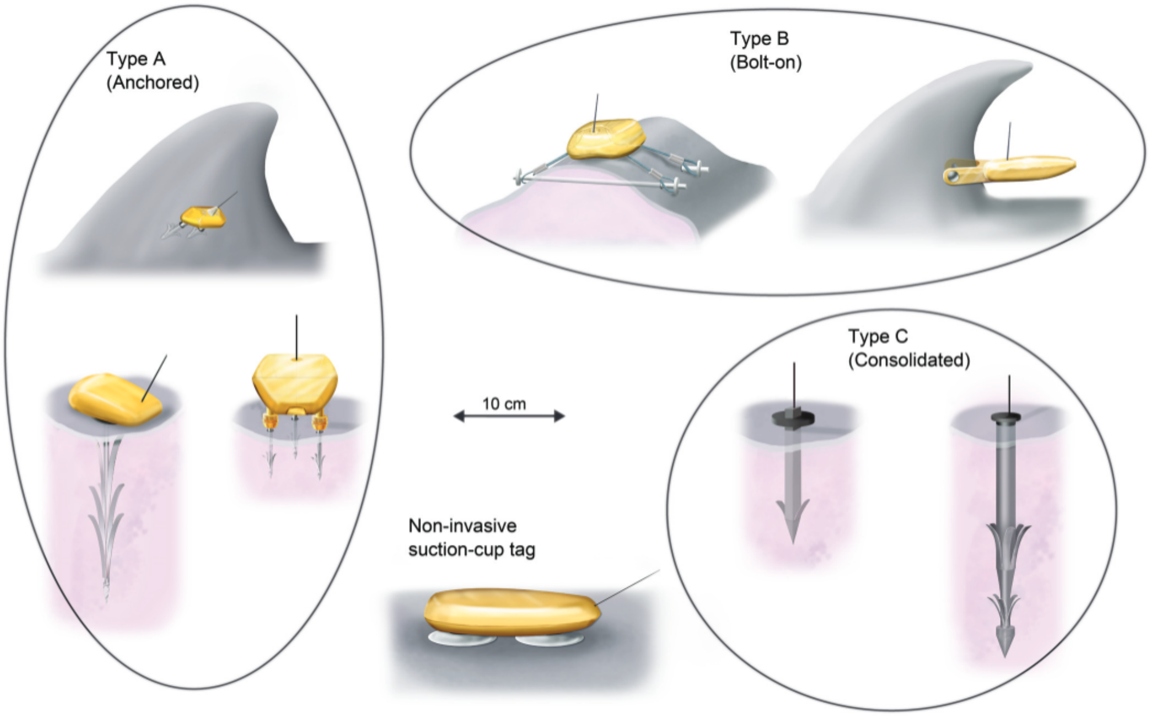


Figure 2. *Illustrations by Michael Ortiz of the non-invasive suction cup configuration (bottom-center), and of the three most common invasive (resulting in skin break) configurations, Type A: Anchored; Type B: Bolt-on; and Type C: Consolidated [4].*

Each of the invasive configurations causes a break in the mammal's skin which could cause discomfort/pain to the animal and also lead to infections. Operational issues result from these configurations due to the need for a boat to achieve proper deployment of the tag which can aggravate the whales and puts the safety of researchers at risk. Other previously used methods are harness and padded belt configurations [4]. Although these methods are considered non-invasive, they result in operational issues similar to the invasive configurations and ethical issues regarding safety of the researchers and aggravation of the whales.

There are two methods of attaching the suction cup configuration to cetaceans as shown in Figure 3. Each method requires the use of four suction cups which attach on the skin of a whale. No puncture wounds result from these non-invasive methods and therefore no harm is done to the animal.

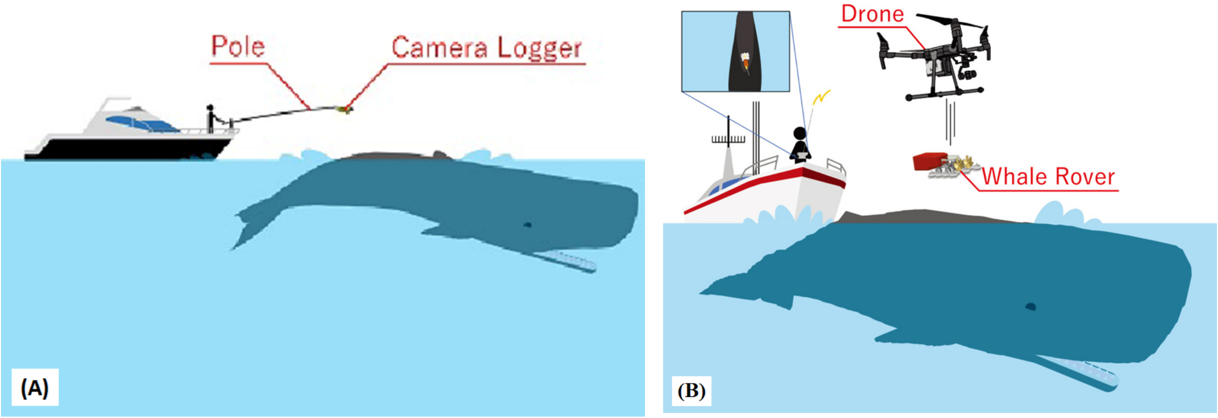


Figure 3. *Illustrations of non-invasive suction cup attachment methods; (A) pole-tagging [5] and (B) drone-tagging [6].* (A) A researcher on a boat uses a long pole to attach the tag with suction cups to the whale's skin. (B) A researcher on a boat uses a drone to remotely fly over the whale and then drop the tag with suction cups down onto the whale's skin.

The initial attachment method for the suction cups was complicated, similar to previous methods; this securement method required chasing whales with a boat and using a long pole to attach the biologging tag. This method is difficult, potentially dangerous, and can aggravate the whale being tagged. The current attachment method requires the use of an uncrewed aerial system (drone) which drops the tag from a distance above the whale that provides enough force for the suction cups to attach to the whale using a pressure differential. Fortunately, the minimally invasive use of suction cups in conjunction with the drone attachment method virtually eliminates any ethical issues and expedites operation by facilitating the application process and tag recovery and eliminating safety concerns for researchers and cetaceans.

To gather data more reliably further improvements on the current suction cup design are necessary. Professor Shorter and his team of researchers have been improving the design for years. For over a half century, suction cups have been used to attach the bio-logging tag on the skin of cetaceans, as shown in Figure 4. Although the current tag application process has evolved considerably during this time, a design problem still exists. Initial attachment is expected to impact cup performance, specifically having effects on contact area pressure differential outputs.

Figure 4. *Attachment of Bio-logging Tag on skin of Sperm Whale Using Suction Cup Method [7].* White suction cups secure an orange bio-logging tag to the nose of a sperm whale; four cups are required per tag. The tag contains various sensors for the purpose of tracking and recording relevant cetacean information i.e., depth, sound, and movement.

Issues in the current design include suction cup leakage and tag shifting [8]. This leads to unreliable attachment times and data collection, an issue that still needs to be addressed. For these bio-logging tags to be useful, they must reliably stay attached to the mammal for 24 hours. There are currently several prototypes of suction cups which support our sponsor's research, but Professor Shorter and his research team are eager to define parameters of the suction cups resulting in improvements on the attachment time, which is the goal of our project.

Suction cups are not limited to observing marine wildlife; they are also used in a range of applications. One application that our team explored was the use of cups in assembly lines. These cups are similar in shape and function, and are typically used in an automated process that involves picking up items to move them from place to place on an assembly line. A very important difference between this application and our sponsor's application is that typically the cups used in assembly lines are vacuum cups which may be more effective, but cannot be implemented for our purposes due to weight concerns [9].

Multiple studies on suction cups have been conducted by previous research teams and capstone design groups. Research including force analysis of the cup, leakage behavior, and pressure analysis [10] were performed previously which helped us to narrow down the research area of the design problem. Natural suction cups on various aquatic wildlife have also been studied to determine how they function to find a connection between them and the types of substrates on suction-based adhesion [11]. Models such as Taguchi Matrix with the categorization of material, curvature, and thickness were built to differentiate the influence of parameters on the attachment performance of the suction cup. Prototypes based on these models were manufactured and tests such as dragging forces test, normal force test, and high pressure contacting area test were performed by previous researchers. These tests provided valuable data and helped us to design experiments that defined parameters to suggest improvements on the cup design.

Problem Statement

The model currently used by our sponsor results in unreliable attachment times and performance. Our team is asked to test and validate the key parameters of a suction cup in a lab environment to better understand and make further improvements to the current design. More specifically, our team has been asked to investigate how design features (i.e., thickness or shape of cup) relate back to cup performance. Defining and understanding key features will aid in the ability to predict failure force, pressure differential, and internal cup volume at varying parameter values. Facilitating the optimization of overall cup performance in a lab environment would constitute a successful project outcome. To ensure success our team took an experimental approach to this problem rather than a modeling approach. We generated a method of data acquisition and a method of data analysis which has ultimately enabled us to define the parameters of interest.

Design Process

Our project design process has morphed significantly since our initial involvement in the project. We first chose to follow the ME 450 Capstone Design Process from the Learning Blocks, modifying it slightly to include what we thought were the necessary steps. As the semester has progressed, we have learned that this linear method is limiting and does not include any iteration or reflection. For this reason our team has decided to look into other methods that more closely align with our project

In particular we have adapted the design process from French since it provides a better representation of our specific project [12]. Figure 5 shows a visual representation of this chosen design process. This stage-based model allows for iterations to occur between key stages (problem definition and concept exploration) which ensures that analysis of the problem is prioritized and our sponsor needs are met. This is accomplished by revisiting and modifying the problem definition periodically after sponsor engagement/feedback. This has allowed our team to focus on the analysis of suction cups mechanics and the design of a scheme to empirically investigate suction cup mechanics. This scheme will be embodied in a controlled environment. For this project our sponsor suggested using a Taguchi design of experiments (DOE) as our empirical process which involves creating subsets of varied parameters at different levels. This minimized the number of experiments required as well as the quantity of cups that needed to be manufactured while providing an efficient and systematic method for design optimization. This handy analysis tool was utilized to great extent by previous students (for suction cup testing) and came highly recommended by our sponsor, and other mentors, for experimental iteration and co-evolution of cup design and performance.

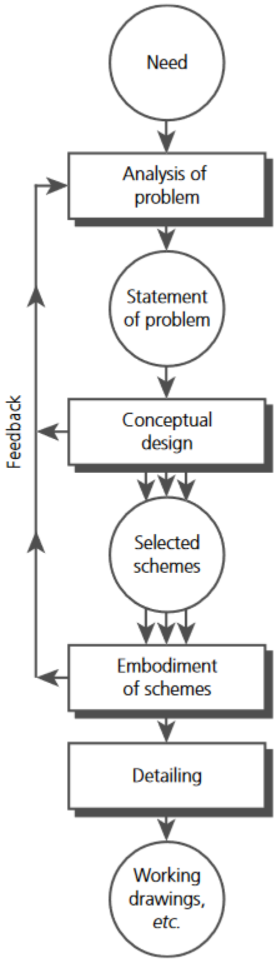


Figure 5. Visual representation of French's design process [12].

The Taguchi Orthogonal Array, also known as the Taguchi Design Matrix, is a fractional orthogonal design that allowed us to consider a subset of combinations of multiple factors at multiple levels . The varying levels of the tested factors, the dependent parameters of the suction cup in our case, are balanced throughout the entire array to ensure that they are all considered equally. Because of this balancing, all of the tested factors can be analyzed independently of one another even though the design of the array is fractional [13].

One of the big project challenges that arose was modeling an appropriate amount of new molds to create suction cups of varying parameters on which to experiment; if we were to create every iteration of a suction cup with our number of dependent parameters and levels of those parameters in mind, there would be far too many cups to test and analyze. With the utilization of the Taguchi Orthogonal Array, we created an array that told us how many molds and models need to be created to equally consider all desired key parameters. This significantly reduced the number of CAD models that needed to be designed, molds and cups that needed to be manufactured, and tests that had to be performed.

To determine the numbers of suction cups that needed to be created to fully satisfy the equity levels needed in the design matrix and acquire a full factorial analysis, we used Eq. 1:

$$N = L^{(P-1)} \qquad (1)\ [14]$$

where N is the number of required runs required, L is the number of levels that each parameter will have, and P is the number of parameters that want to be tested [14]. For each distinct parameter that was analyzed during experimentation, they were associated with three different values (levels). If we were to have three parameters with three levels each, then we would have a Taguchi array with nine distinct suction cups.

Embodying this design was useful because it is robust, provides useful results, and allows for flexibility and design iteration as we learned more about the design context and project overall.

Design Context

To understand the project in more detail, the design context was considered. Due to the working environment, the group of users, functions, and third parties related to the suction cup project the stakeholders were categorized in the following orders with respect to higher interest, lower interest, more power/influence, and less power/influence. Table 1 indicates the order of categorization.

Table 1. *Table of relevant stakeholders.* Regulating Agencies include: UN-Oceans and the Law of the Sea (UN-OLA), US-Marine Mammal Protection Act, US-Marine Debris Program, etc. [15].

	Higher Interest	Lower Interest
More Power/Influence	Sponsor: Professor Alex Shorter and his team of researchers	Government and regulating agencies
Less Power/Influence	Users (i.e. whales), conservationists, other research organizations or scientists	Local communities/general population, other marine life, manufacturers and material suppliers

Based on the table of stakeholders and primary user analysis the sponsor of our project, Professor Alex Shorter and his team of researchers, were our prioritized stakeholder. The secondary stakeholders include the group with lower interest but more power/influence and the group with higher interest but less power/influence. Secondary stakeholders include users/whales, government, conservationists, etc. The tertiary stakeholders are groups with lower interest and less power/influence such as local communities.

The priority stakeholder, Professor Shorter and his team, will benefit from our project because defining parameters of the suction cup will provide insight to making improvements to the cup design that result in a longer attachment period of the biologging tag. This additional time will allow the tag to record more data for our sponsor to analyze. Our sponsor directly expressed interest in allowing open access to all information and intellectual property pertaining to our project in the interest of promoting research on the subject. Obtaining this knowledge is made possible through publishing work and sharing online.

Secondary stakeholders, such as the users (cetaceans) and other research organizations or scientists, will also benefit from the project with the data collected by the biologging tag. It is possible that a handful of whales may experience discomfort from wearing the suction cups, but this short-term and minor negative impact is greatly overshadowed by the long-term significant benefits of entire populations of cetaceans. The positive impacts are expanding on previous knowledge for researchers, and aiding in conservation of marine mammals and the ocean, which also satisfies some of the lower priority stakeholders' interests. Whales are incredible creatures and we can learn a lot from studying them and the way they move. Any impacts on tertiary stakeholders, such as manufacturers and suppliers, are practically negligible since we require minimal materials for our project.

The order of stakeholder priority affected our project design but did not have any significant positive/negative social impacts since our team and sponsor prioritize ethical standards. The users/whales had the most effect on the suction cup design since we had to consider the well-being of the mammals and characteristics of the whales and their environment to create design specifications and ultimately relevant experiments to run.

To fully understand the context of our design, any potential ethical impacts, environmental, educational, social and economic, had to be addressed. Retrieving and recycling the biologging tags and suction cups is not easy, but is essential since improper disposal of the material results in pollution which will have a negative influence on the ocean environment. The product may have an impact on cetaceans such as influencing the movement and behavior due to the weight and feeling of the tag on their skin. In addition, unpredictable detachment of the biologging tag leaves the potential danger for ocean animals to mistakenly consume the tag [16].

The educational impact from our project has a strong, positive potential due to the vast amount of knowledge gained from the bio-logging tags, and from better understanding suction cup parameters and performance. The data retrieved via the biologging tags will contribute to animal and environmental protection. The broader social impacts are negligible since our product is used only by scientists for research purposes and is not commercially available to the public. Our values closely align with our project sponsor, which includes prioritizing environmental and educational impacts over profit. Throughout this project we made all attempts to be aware of and to minimize/eliminate any potential negative societal, environmental, social, political, cultural and global impacts that could result from our design of experiments.

Concept Generation

The extensive process of concept generation involved a variety of methods which aided in the creation of as many ideas as possible so that we would have enough novel and useful concepts to pass through concept screening. To facilitate this idea generation process a brainstorming map was developed using morphological decomposition and divergent thinking. This was followed by convergence and integration of the most promising ideas. Details of this idea generation process can be found in Appendix A.

Since our team decided on utilizing the Taguchi orthogonal array design of experiments, any generated ideas must result in the empirical collection of relevant data. Selecting the Taguchi method also meant selecting design parameters that are to be varied. After engaging with our sponsor and considering past research, our team decided to do a deeper dive on previously investigated design features. A visual representation of the selected parameters we chose to investigate (thickness; ratio between top and bottom thickness; ratio between width and depth) is shown in Figure 6.

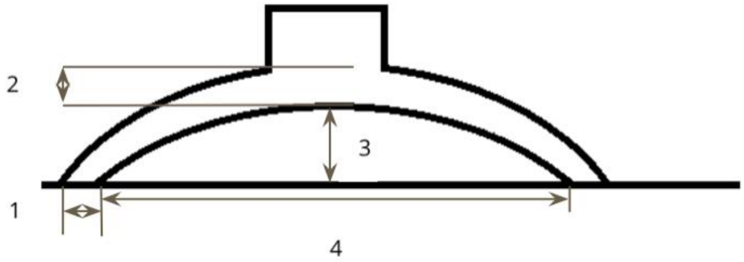


Figure 6. *Visual representation of key design parameters.* The key parameters that we have decided to design around are as follows: bottom thickness of the cup (1), top:bottom thickness ratio (2:1), and width:depth ratio (4:3). These design features were varied throughout experimentation to determine the effects they may have on performance parameters associated with a suction cup.

Suction Cup Mechanics

To analyze the design properly and determine the expected effects of varying these key parameters, the fluid mechanics and statics as well as the material properties of a suction cup must be understood. The suction cup can be attached to a surface such as imitation cetacean skin or flat plastic plates using a pressure differential. This differential is required to create a near vacuum environment within the curvature of the suction cup by applying external force to eject the air from within. Based on the goal of determining parameters that influence the performance of a suction cup, including stiffness and long attachment time, we have designed multiple experiments indicated in Appendix B.

In general, the performance of the suction cup was expected to be influenced both from the design of it and from the external environment such as forces caused by the fluid flowing around the cup and oscillations caused by cetacean movement/behavior. Understanding these external influences on the cup requires the knowledge of dynamics and fluid dynamics.

We also needed extensive knowledge on statics since we want the suction to remain stationary on the whale during attachment. The theoretical static force analysis of a suction cup is shown in Figure 7. Complex theoretical computations involving cup mechanics would be impossible and extremely time consuming to complete since there is no first principles model. Empirical testing is the most optimal and efficient method to define effects of changing cup parameters. Based on the existing test environment and considering the time restriction, the normal force test (relating to solid and fluid mechanics behaviors) was decided upon as the final concept of experiment.

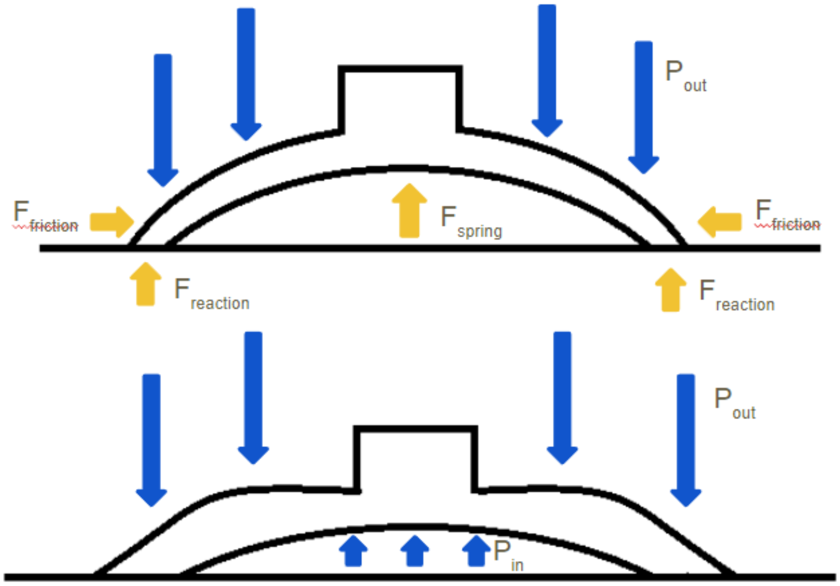


Figure 7. *Free body diagrams indicating some of the forces associated with the suction cup; just prior to attachment (top) and just after attachment (bottom).* Further investigation on these forces must be done to fully understand all of the forces involved.

The material behavior of a suction cup determines the force required to attach it to a surface, and the magnitude of spring force comes from the curvature. Based on previous research and empirical testing done by a former UM student, the material of the suction cup is determined as silicone which gives us one less parameter to test.

With previous research, theoretical considerations, and the empirical testing of dragging differently designed suction cups from the top, it can be concluded that different types of material, contact area, curvature, and thickness of the cups will influence output variables. We expect there to be a somewhat strong correlation between thickness and each one of the output variables, especially the force required to uncouple the cup from a flat surface and the pressure differential between the internal cup volume and atmospheric pressure. Specifically, the cup thickness, *t*, should influence the force in pounds, *F,* and also the vertical displacement, *Δh*, of the cup in inches. This is because the cup stiffness, *k*, largely depends on *t* and because *F* is proportional to stiffness as shown in Eq. 2:

$$k = F/x \qquad (2)\ [17]$$

Where *x* is the displacement in inches and, for our analysis, closely related to *Δh*. This theoretical equation is much too simplified to use in our actual analysis and only provides us with a general relationship. This relationship tells us that in order to increase force the spring constant must be increased, and therefore a larger thickness value would be expected to result in a cup that can withstand a larger applied force. The thickness should also influence the internal pressure, P_{in}, in pounds per square inch since force is proportional to pressure, as shown in Eq. 3:

$$P = F/A \qquad (3)\ [18]$$

Since we expect that increasing thickness would result in an increased force, from Eq. 3, an increase in pressure would be expected as well. The contact area, A_C, of the cup in inches squared is also expected to be influenced by the thickness since thickness is directly related to the contact area, as shown in Eq. 4:

$$Ac = \pi D t \qquad (4)\ [18]$$

Where D is the outer diameter of the flat cup face in inches. From this equation, it can be expected that increasing the thickness will result in an increased contact area. We suspect that thickness ratio and width ratio may also be influencing factors of these output variables but theoretical methods are time consuming and may not be sufficient in predicting outputs. Empirical testing provided our team with force, displacement, internal pressure and contact area data corresponding to the varied input parameters and confirmed our theoretical expectations by providing results to analyze cup performance.

An alpha empirical design was chosen with hopes that it would provide us with appropriate data and lead to useful results. To ensure success, our team considered stakeholder needs and looked to our sponsor for guidance in this selection process.

Sponsor Requirements & Engineering Specifications

An updated version of the sponsor requirements and engineering specifications can be seen in Table 2. As more information was gathered from stakeholder engagement we have gained a clearer perspective on the appropriate requirements and their associated engineering specifications. Due to sponsor engagement and the progression of our project, the size of our table has been minimized to reflect the current needs; the requirements have been reordered and the content of the engineering specifications has been modified to match new perspectives and our specific role in the project. For example, the ‘repeatable results’ requirement (in Table 2) was added to incorporate the importance of investigating part-to-part variation.

Table 2. *Updated version of sponsor requirements and engineering specifications for identifying key parameters of a suction cup.* The ordering reflects the requirements that must be prioritized during experimentation in order to satisfy the needs of our sponsor.

Requirements	Specifications
Must experimentally investigate cup parameters	Test at least 3 features/levels: top-thickness, ratio between top-thickness and bottom-thickness, and ratio between width and depth
Identify key cup parameters	Define cup stiffness (k), cup failure force (F), maximum diameter (Dmax), lip contour (cup shape)
Repeatable results	Conduct minimum of 3 trials for each cup
Minimal Cost	< $400

Defining and prioritizing these specifications and requirements aided in the final selection of an alpha design and allowed for integration of multiple experiments.

Final Concept Decision

The choice was made to move forward with the normal force loading experiment because the setup can be modified to integrate other ideas for experiments, increasing the amount of data acquired. The decision was facilitated by the concept selection process (shown in Appendix B). Force, displacement, contact area, and pressure data can be obtained by performing the integrated elastomer tensile test. This data was facilitated in defining cup parameters (i.e., stiffness or force) then related back to the design features (i.e., thickness, top:bottom thickness ratio, width:depth ratio). Developing the relationships between these design features and performance metrics provided insight to optimizing the design.

For the elastomer tensile experiment, a normal force to failure test, internal pressure test, and contact area test was integrated using an Instron 5542, shown in Figure 8. By choosing this singular, integrated data acquisition method, multiple useful data outputs could be collected without overextending the ability of our team to complete the project within the semester. The collected data came in four forms: failure force data, which comes in the form of position vs load data formatted into a graph; internal pressure data; which gives position vs pressure differential data; contact area data, which is the relationship between the position of the Instron and the area of the suction cup in contact with the plexiglass substrate; vertical displacement data, which gives position vs time data.

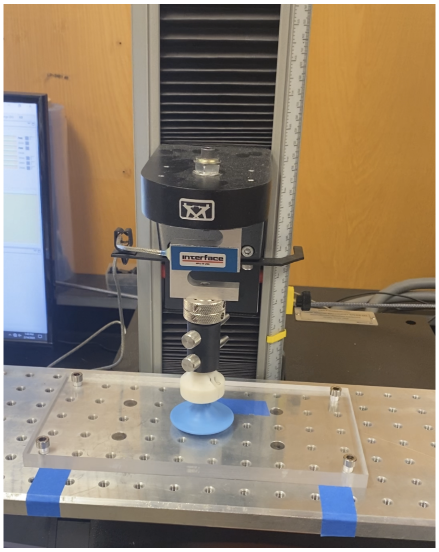


Figure 8. *Instron 5542 normal force test setup.* Suction cup with rim attached to plexiglass and top secured to Instron Tensile Tester with data collection software on computer. This test setup was modified during engineering analysis to integrate multiple methods of data acquisition into one singular experiment.

The failure force data was collected by loading each cup type into the Instron machine, then fully sticking the cup to the plexiglass board below. The Instron was programmed to input a certain displacement rate that pulls at the top of the suction cup, stretching it until the point of failure. This was the maximum resistance force the cup was able to contribute as measured by the machine before completely detaching from the plexiglass. A sample of the force vs displacement data is shown in Figure 9.

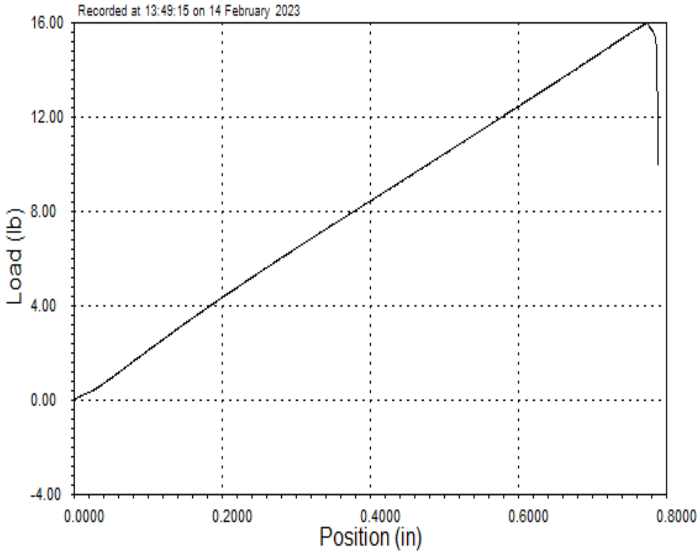


Figure 9. *Graphical representation of position vs load.* This shows a sample of the displacement and point of failure data that resulted from the sample test setup shown in Figure 8.

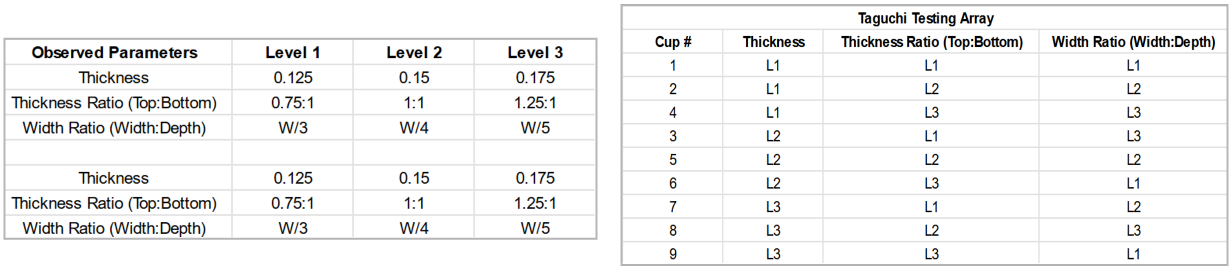
Simultaneously, our team had two GoPro cameras; one camera beneath the plexiglass directly in line with the bottom surface of the suction cup and another camera horizontally inline with the cup (see Fig 8, page 13). By videotaping at the same time that the Instron applied displacement, a data based relationship between Instron position, the proportional area of the cup in contact with the surface, and the vertical displacement of the cup was established. To measure the contact area, we took still frames at certain points in the experiment, and utilized computer software to outline and measure the total contact area for each image.

These four data collection methods were chosen because they yield the most useful data, and because all data can be collected simultaneously during the elastomer tensile test. This resulted in four sets of data for each of the nine suction cups being tested. The nine cups were determined using the Taguchi matrix and provided sufficient data to accurately draw conclusions about the behavior of suction cups based on the selected parameters.

Engineering Analysis

Embodiment of Taguchi DOE

To move forward with our selected analysis methods for actual application and utilization, we developed the Taguchi orthogonal array to determine the proper amount of different models needed for experimentation. We embodied this array by assigning values to each of the 3 levels for the three design parameters, as shown in Figure 10.



Observed Parameters	Level 1	Level 2	Level 3
Thickness	0.125	0.15	0.175
Thickness Ratio (Top:Bottom)	0.75:1	1:1	1.25:1
Width Ratio (Width:Depth)	W/3	W/4	W/5
Thickness	0.125	0.15	0.175
Thickness Ratio (Top:Bottom)	0.75:1	1:1	1.25:1
Width Ratio (Width:Depth)	W/3	W/4	W/5

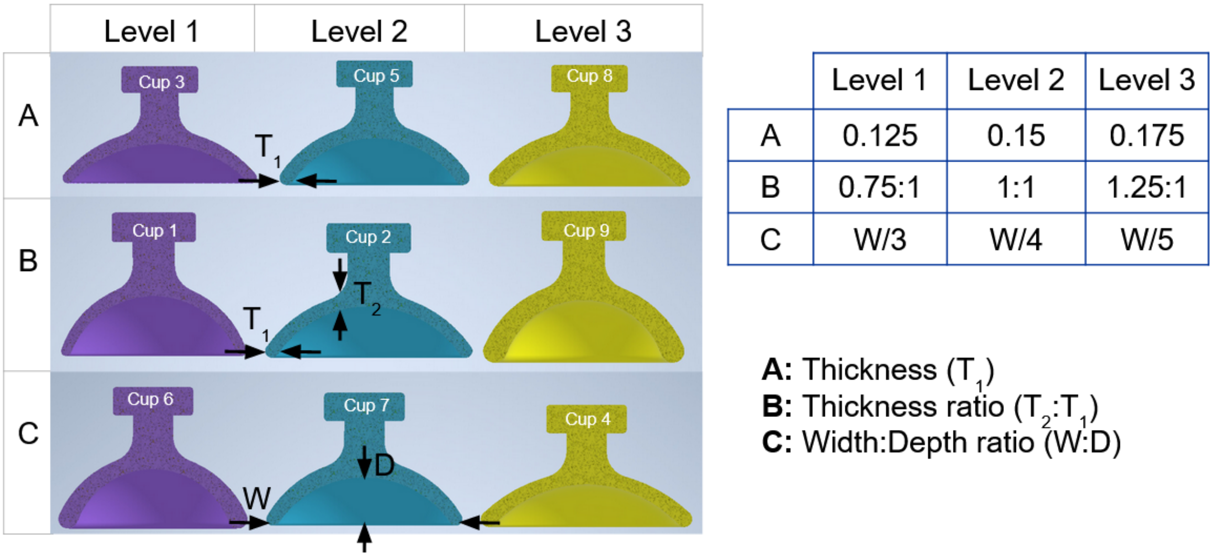
Taguchi Testing Array

Cup #	Thickness	Thickness Ratio (Top:Bottom)	Width Ratio (Width:Depth)
1	L1	L1	L1
2	L1	L2	L2
4	L1	L3	L3
3	L2	L1	L3
5	L2	L2	L2
6	L2	L3	L1
7	L3	L1	L2
8	L3	L2	L3
9	L3	L3	L1

(a) (b)

Figure 10. *Taguchi Design Matrix of suctions cups;* List of three levels of dependent parameters of the suction cups (a) and Taguchi testing array (b). (a) Each parameter has 3 different levels of values to observe how changing these values will affect output variables, such as the failure load. Values are based off of the best performing cup design from a previous student researcher. (b) Each of the different levels of the parameters are represented equally throughout the matrix so that they can be analyzed independently after experimentation. Note: An "*" will be used to differentiate between the previous and new cup designs (i.e.: 1*), but will be left out of this report for simplicity.

From these layers and levels, nine cups with varying key parameters were generated to reflect the requirements for our project and can be seen in Figure 11. This valuable and effective analysis method allowed us to obtain useful results while conducting significantly fewer tests. This level of analysis is appropriate for our design and simplifies the process without sacrificing accuracy and quality, and gives us a clear idea of what needs to be physically produced for testing.



	Level 1	Level 2	Level 3
A	0.125	0.15	0.175
B	0.75:1	1:1	1.25:1
C	W/3	W/4	W/5

A: Thickness (T_1)
B: Thickness ratio (T_2:T_1)
C: Width:Depth ratio (W:D)

Figure 11. *Visual representation of shape changes between suction cup CAD models that result from varied parameter levels.* Each parameter (thickness, thickness ratio, and width ratio) was varied between three different levels. The values of these levels can be determined by the table next to the cups. As shown these variations resulted in changes of cup shape which was expected to affect cup performance (see section on Suction Cup Mechanics).

Suction Cup Manufacturing Process

After finalizing the Taguchi matrix, we turned our attention to the design, manufacturing, and creation of the prototype molds and suction cups. First, each of the different CAD models of the cups with our varied layers and levels was created. This design process was facilitated thanks to a CAD model template for the suction cups, created and utilized by one of our sponsor's former UM student researchers, C. Hohl. The final CAD designs created reflect design criteria in the matrix, as seen in Figure 12. Because of the varied parameters, each cup displays a slightly different static shape and height; this is important as we expected it to help us understand how the varied parameters affect the peak load failure and overall performance.

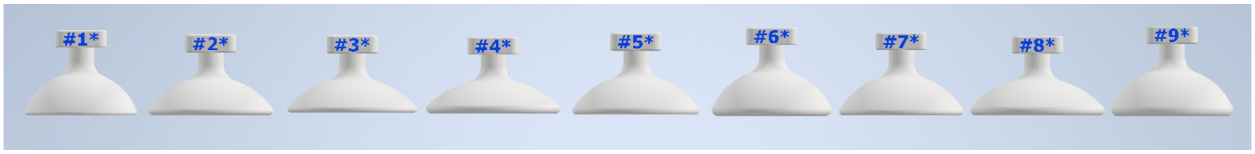
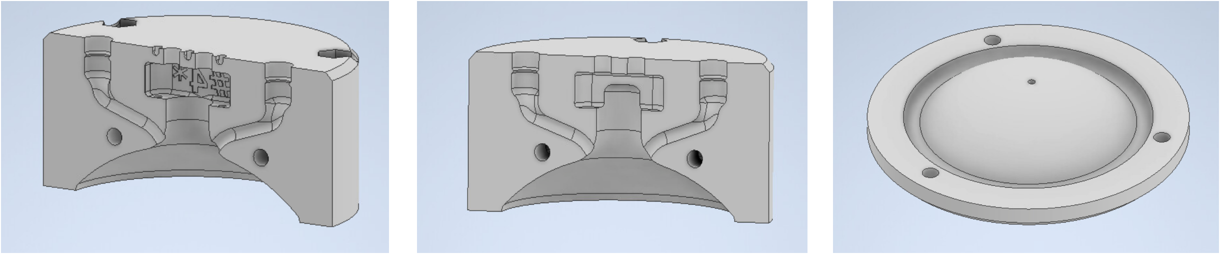


Figure 12. *Final CAD models of all nine suction cups with key parameters designated through the Taguchi design matrix.* The varied parameters allow each cup to have a slightly unique static shape and height. These differences resulted in different initial contact areas, vacuum areas, and pressure differentials during experimentation.

After CAD models of the suction cups were complete, we employed them all in the designs for their respective molds. Like the cups, a CAD template for the mold (created by the same former UM student) was provided to us by our sponsor. To design the molds, a revolve cut from the center of the mold template and in the shape of a cup was made. This was done for each of the different specs of the cups. A sample of a finalized mold model is shown below in Figure 13. Each model was split into three separate parts so that a manufactured cup can be safely removed from the mold: a left-side part, a right-side part, and a bottom base part.



(a) (b) (c)

Figure 13. *Sample CAD model for mold (corresponding to cup #4) split into part A (a), part B (b), and part C (c).* Final CAD cup mold designs for each of the cups were divided into three separate pieces: (a) a left-side body part; (b) a right-side body part; (c) a bottom base. (a) Part A was made by making a revolve cut at the base of the model, and then making an extrude cut at the middle of the mold. (b) Part B was made by reversing the extrude cut for A. (c) Part C was made by deleting the extrude cut and reversing the revolve cut from part A. This was done for each provided base model so that each of the molds adhered to the different levels of key parameters assigned to the cups.

All three parts for all nine molds were 3D printed using a Formlabs 3D printer. Once printed, it was important that each part go through automated post-processing to ensure consistency. This post-processing equipment is shown in Figure 14. After printing, the parts were placed in an Formlabs Form Wash, which submerged the parts in isopropyl alcohol to wash any extra resin from each part. Following the wash, each part was placed in a Formlabs Form Cure which rotates the printed parts while exposing them to heat and ultra-violet (405 nm) light to ensure consistent curing throughout. This curing process improves the strength and performance of each part by maximizing material properties [19]. Following the wash and cure processes, the printed parts were each taken to a belt-sander to smoothen any internal surfaces that may have been rough due to the printing process and remove any potential overhang. We were all confident that this process of cup/mold design and creation would show the proper level of detail for creating reliable suction cups for experimentation.

(a) (b)

Figure 14. *Automated post-processing Formlabs equipment; Formlabs Form Wash (a) and Formlabs Form Cure (b).* (a) The Formlabs Form Wash was used to remove any resin from the parts that may be leftover from the 3D printing process [20]. (b) The Formlabs Form Cure was used to strengthen the parts and improve their performance which ultimately increased the quality of the suction cups made using these printed mold parts.

A simplified overview of the mold and cup manufacturing and preparation process is shown in Figure 15. To begin the process for the suction cup creation, a clear coat of primer paint was applied to all parts of the mold, followed by an application of mold release. After drying, each of three mold parts were tightly fastened to each other using nuts and screws and finally had a two-tube system for the material injection inserted into the top part of both body pieces. Once all of the steps for preparing the mold were completed, we began the process for creating the material of the suction cups themselves; all of the tested cups will be made from the same material, Smooth-Silicone 950 Parts A and B(silicone and silicone thinner). The material of each of the cups was poured into a small mixture cup with a 100A:10B ratio by weight [21], thoroughly mixed together, and set into a vacuum chamber for 5-10 minutes to remove all excess air that was trapped in the material during mixing. After the material mixture was done in the vacuum chamber, it was poured into a 20 mL syringe and slowly injected into the mold so that undesired air bubbles would not form inside the mixture in the mold. The filled mold was placed into a vacuum oven where the material would cure for 24 hours at 40°C before disassembling the mold and having the finalized cup. This process was repeated for all the created molds until a full set of functional suction cups were created for our experimentation. A bill of materials and manufacturing plan for our project can be found in Appendix C, Table C.1 and Table C.2, respectively.

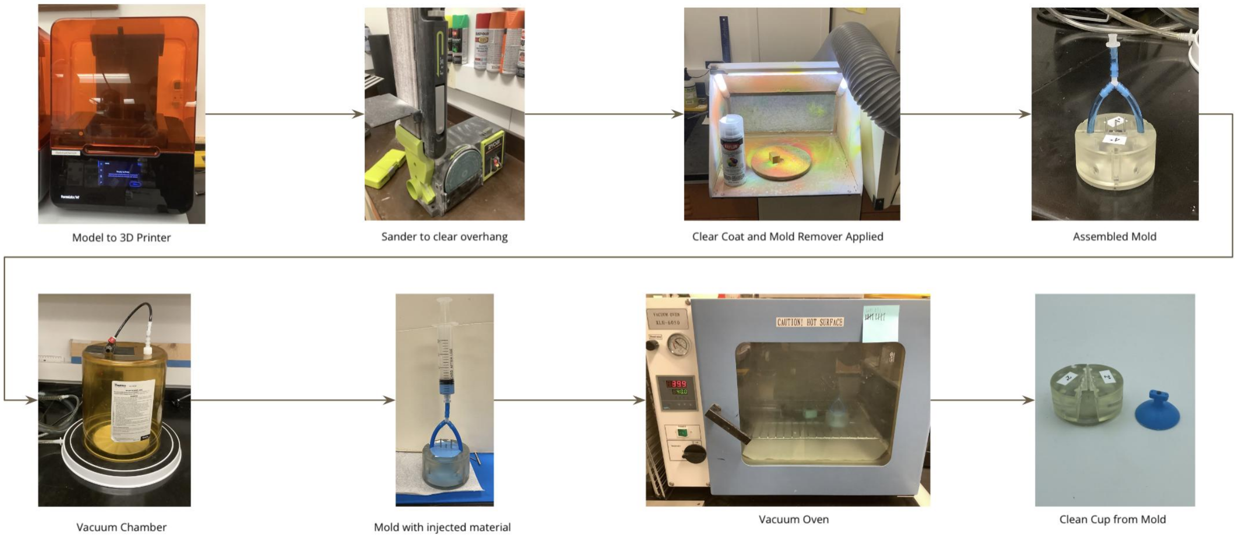


Figure 15. *Manufacturing and Creation Process for Molds and Cups.* Roadmap showcasing each of the steps taken to manufacture the cup molds and create the suction cups. It took about two days to create two cups, so the process lasted a total of 5-6 days to make up for rejected cups that were unfit for testing. A full set of functional suction cups was produced to fully utilize during the experimentation process.

Experimentation

After manufacturing the nine cups, we decided to proceed with the normal force testing protocol using the Intron. It developed into a three part process with four different data streams that allow us to complete our analysis: force, vertical displacement, pressure differential, and contact area. Using custom software, the Instron 5542 was used to obtain and record force (lb) vs. displacement (in) data that gives the maximum force that the cup can withstand. This was done using an elastomer tensile test following the industry standard ASTM D412-16/ISO 37 [22]. To measure the static and maximum pressure differential values within the cups, we decided to integrate a digital handheld manometer into the Instron test setup. This was a departure from our original plan, because we decided that we only needed to know the maximum magnitude of the pressure differential, and that multiple sampling points for each cup would not be necessary. Finally, we measured contact area and height change data by conducting imaging analysis on two GoPro video streams that were taken as the Instron conducted the pull test. Figure 16 shows a complete setup of the experimental test and tools.

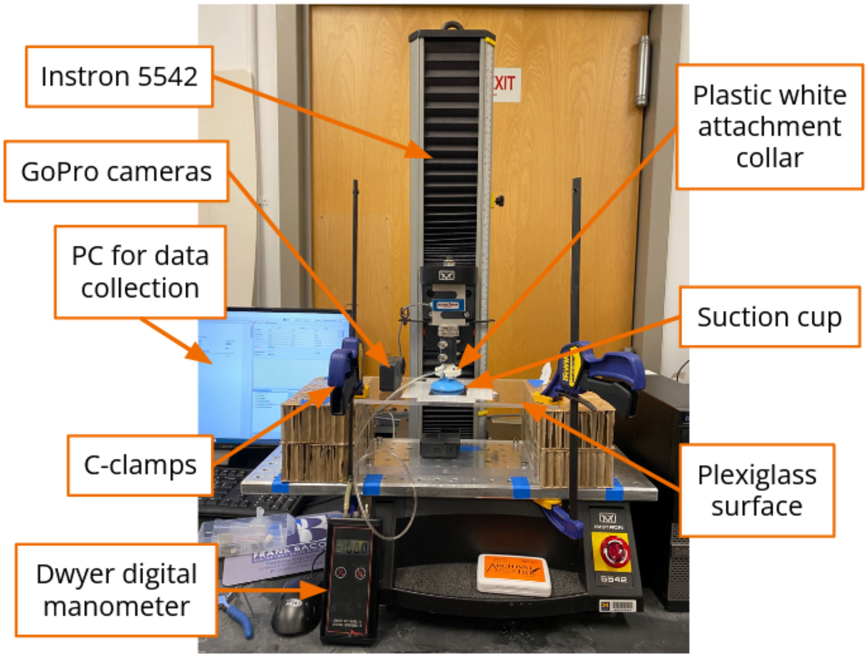


Figure 16. *Integrated elastomer tensile test setup.* The top of the blue suction cup was secured to the Instron 5542 using a plastic white collar, and the bottom was attached to the plexiglass surface using a pressure differential. The surface was secured to the instron using two C-clamps. The handheld Dwyer digital manometer was used to measure pressure differentials, the two GoPro cameras were used to record changes in vertical displacement and contact area, and software on the PC recorded force and displacement data from the Instron.

For each cup, the GoPro video recorded simultaneously while performing wet tests recording both the vertical displacement, in inches, and the contact area. Figure 17 shows sample still frames from the video recordings.

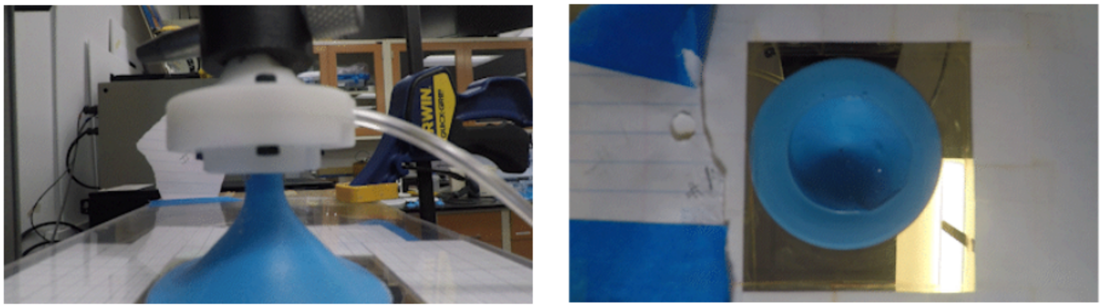
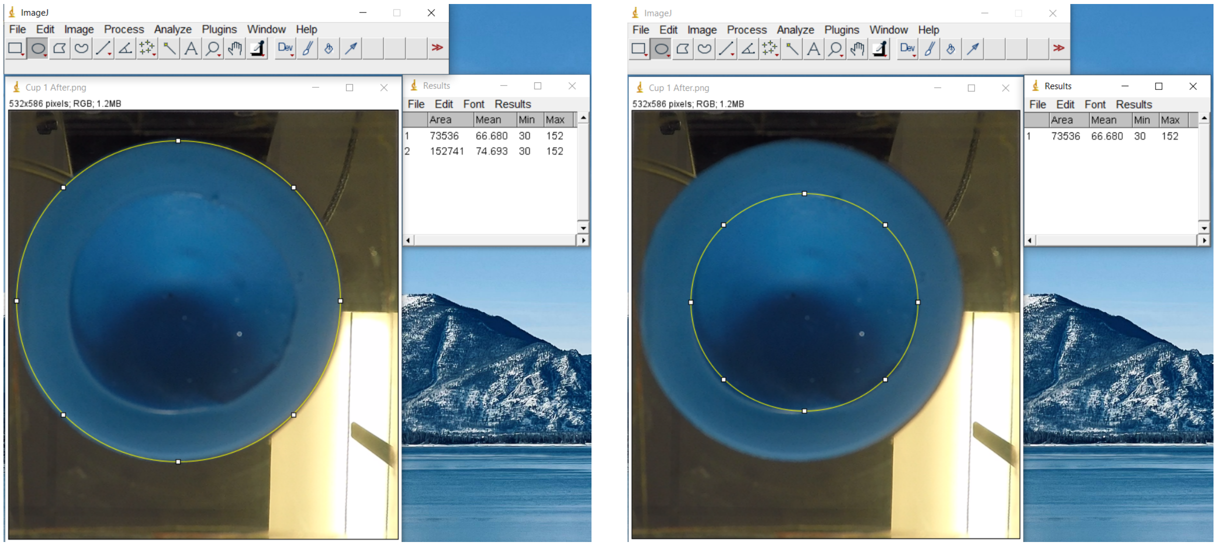


Figure 17. *Sample still frames from GoPro footage of (a) vertical displacement of cup, and (b) contact area change of cup.* Initial and final measurements were taken from each camera and for each cup using the same resolution. Both images (a) and (b) were taken at precisely the same moment of time during the experiment (just prior to cup failure).

The contact area of the cup was projected to the plexiglass surface and was recorded, ensuring each time that the GoPro was set to the same resolution. Two screenshots were taken: the moment that the cup was attached to the plexiglass and the moment right before it failed. Based on the same resolution of each screenshot, ImageJ software was used to calculate the number of pixels inside the drawn circle [23].

These pixels represent the contact area, as shown in Figure 18, which is the difference between the inner and outer circle. For consistency across all tests, all videos and pictures were recorded with the same equipment at the same resolution level and in the same position.



	Area	Mean	Min	Max
1	73536	66.680	30	152
2	152741	74.693	30	152

	Area	Mean	Min	Max
1	73536	66.680	30	152

(a) (b)

Figure 18. *Sample of contact area measurement (before failure of Cup 1) using software; (a) total area of suction cup face (including attached contact area), and (b) unattached inner area of suction cup face.* The measurement of contact area was obtained using ImageJ imaging analysis. The area of the drawn circle was represented by the number of pixels. All screenshots and referring videos were taken with the same resolution to ensure consistency.

Results

With the test result under wet conditions acquired from the Instron test machine, we determined the performance of each cup, mainly based on the peak force before failure, designed by the Taguchi design matrix. To compare the general performances, we grouped the cups. Each graph shown in the Figure 19 series shows data for three cups that inclusively represent the three levels of one varied parameter. This was done to show a visual comparison of how changing one of the three key cup parameters can positively or negatively affect cup performance. Figure 19a depicts cups of the three different thickness levels, Figure 19b depicts cups of the three different top:bottom thickness ratio levels, and Figure 19c depicts cups of three different width:depth ratio levels. Each of the graphs in the Figure 19 series shows force versus displacement data corresponding to the three cups in each figure, with the purple trendline representing the level L1,the turquoise trendline representing the level L2, and the yellow trendline representing the level L3. The test results for the dry condition were also plotted in a single graph shown in Appendix D, Figure D.1. The dry test data was not considered in analysis due to increased tearing of suction cups and contact area measurement inconsistencies during testing.

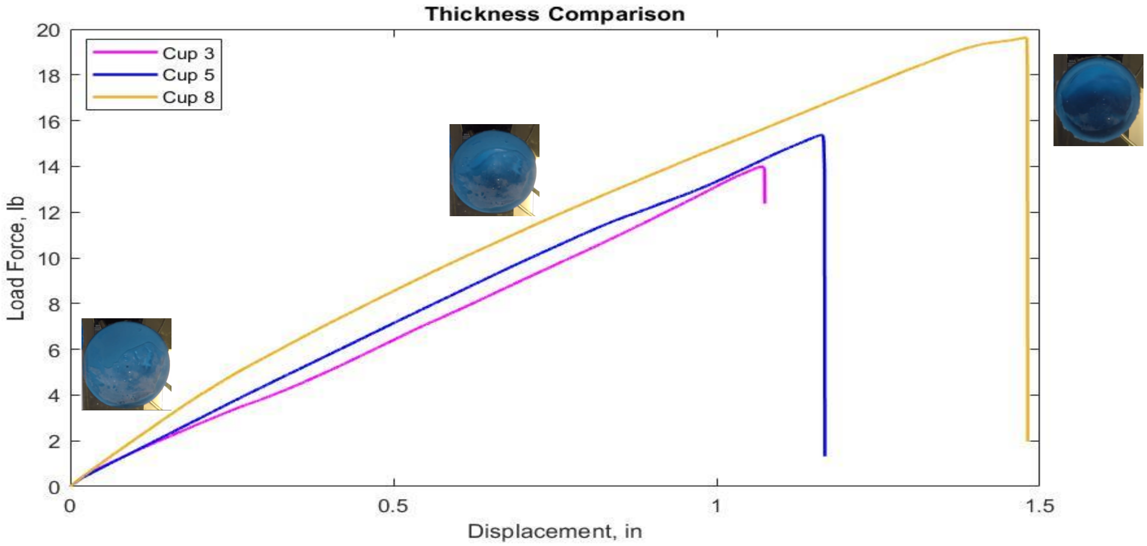


Figure 19a. *Thickness comparison of force vs displacement data of three cups: cup 3, cup 5, and cup 8.* Each cup had a different thickness value that aligns with the differently colored parameter levels (see Figure 11, page 15). Cup 8 with thickness level L3 had the highest load force of 19.63 lb and corresponding top displacement of 1.48 in.

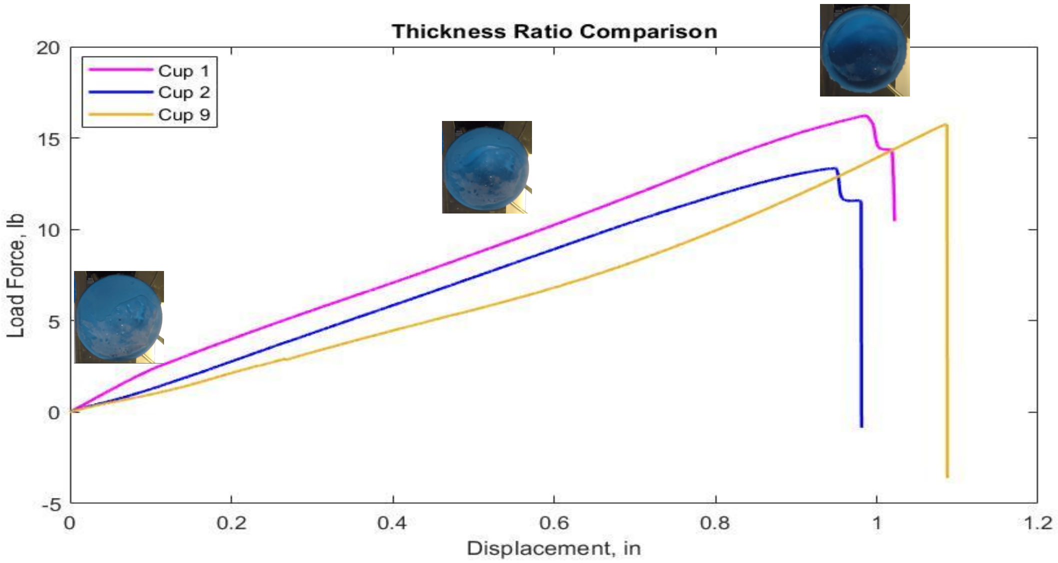


Figure 19b. *Top:bottom thickness ratio comparison of force vs displacement data of three cups: cup 1, cup 2, and cup 9.* Each cup shown had a thickness ratio value that aligns with the differently colored parameter levels (see Figure 11, page 15). When looking at different levels of this varying parameter, Cup 1 with ratio level L1 had the highest load force of 16.22 lb, but Cup 9 with ratio level L3 showed the maximum tip displacement of 1.09 in.

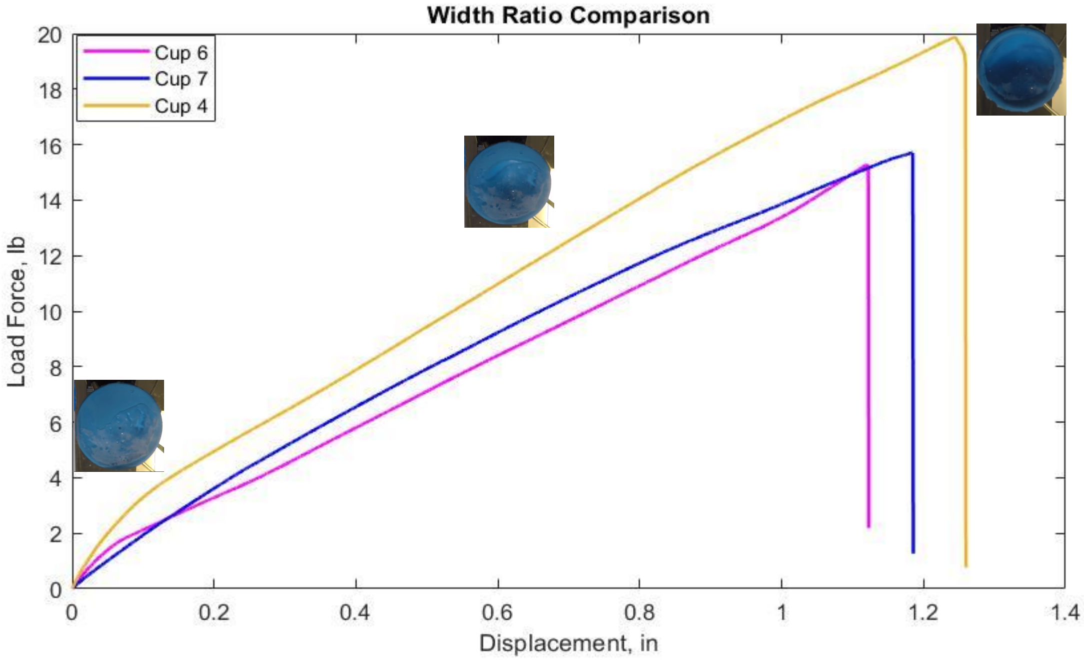
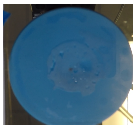
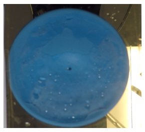
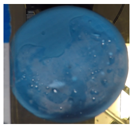
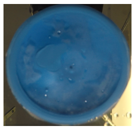
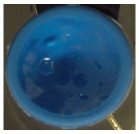
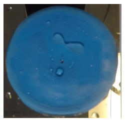
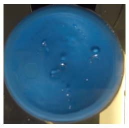


Figure 19c. *Width:depth ratio comparison of force vs displacement data of three cups: cup 6, cup 7, and cup 4.* Each cup shown had a width-to-depth value that aligns with the differently colored parameter levels (see Figure 11, page 15). Cup 8 (with ratio level L3) had the highest load force of 19.87 lb and corresponding top displacement of 1.24 in.

Based on the test results under the wet surface condition, cups 8 and 4 had the best performance in the normal failure force loading test. Compared to the previous suction cup design (cup 5), these two cups each had higher resistance to load force and higher tip displacement. These cup designs were kept in mind as we sorted through the remaining results.

After taking video recording during experimentation, we were able to measure the contact area of all 9 cups by using the ImageJ software analysis tool, indicating this area by the number of pixels. Table 3 shows pictures of the contact area for the moment of initial attachment and moment of failure (cup detachment). The result of contact area difference was also included for further analysis. The difference between the two situations helps us determine the volume change while pulling the tip of the suction cup outwards from the surface.

Table 3. *Initial and final contact area measurements under wet surface condition.* The contact area was represented by the difference of pixel numbers. See Experimentation section for methods used to determine this area. These contact area differences all had relatively similar magnitudes, despite the varied design features.

Cup #	$A_{C,initial}$	$A_{C,final}$	**Contact Area Difference (Pixels)**
1			91365
2			129981
3			102371
4			66532
5			51603
6			42689
7			67206
8			55051
9			28092

As the cup was pulled upward, the contact area decreased and the inner vacuum volume increased which increased the pressure differential that the cup was experiencing. Following our expectations, as the vacuum volume increased, the area of the suction cup attached to the surface grew decreased. The decreased contact area increases the chances for a leak to occur in the seal between the cup and surface which eventually eliminates the vacuum effect inside the cup. As indicated in the data, Cup 9, with the highest thickness, thickness ratio, and width ratio, resulted in the lowest contact area difference, and resulted in a relatively worse cup performance (seen in Figure 19b, page 21).

Based on the data indicated on Table 4, we determined Cup 4 had a larger pressure difference compared to the other cups. As the pressure difference increased, the change in vacuum volume increased too, which had a corresponding relationship with the force created by the inner vacuum volume.

Table 4. *Pressure differential of suction cups under wet surface condition.* Values of pressure differentials in pounds per square inch (PSI) were taken for each cup at the initial set up pressure and at the moment before failure/detachment. Cup 4 yielded the greatest difference between static and final pressure differential and resulted in the greatest final pressure differential.

Cup #	**$P_{\text{final, wet}}$ (PSI)**	**$P_{\text{static, wet}}$ (PSI)**
1	9.2	0.5
2	7.5	0.7
3	6.2	0.4
4	9.6	0.5
5	7.4	1.3
6	8.4	3.1
7	8.6	1,8
8	8.7	1.4
9	6.9	4.4

Results and data for each of the observed parameters was analyzed independently to determine which levels are required to optimize observed variables and to determine the influence of each design parameter on each output variable.

Statistical and Sensitivity Analysis

After obtaining results from empirical testing, sensitivity analysis was performed to determine which cup parameters had the most influence on significant output variables, and statistical analysis was performed to explore potentially optimal combinations of design variable values. This analysis was conducted utilizing the Computer Aided Engineering Network (CAEN) statistical software, Minitab, with the created Taguchi DOE and the observed data values for force, pressure differential, vertical displacement and contact area. This powerful and distinguished statistical software was chosen because of its ability to produce accurate solutions and to inform how to improve performance.

For each selected response characteristic Minitab provides a linear model analysis which includes an estimated regression coefficients table. The R-squared (R-sq) value from the model summary can range from 0 to 1; A value of 1 indicates that the response/output variable can be exactly explained by the predictor/input variable (without error) while 0 indicates that the response variable cannot be explained by the predictor at all. The R-sq values corresponding to each response variable were obtained from the linear model analysis of both the signal-to-noise (S/N) ratios and the means versus the predictor variables (thickness, thickness ratio, and width ratio). Table 5 contains these R-sq values along with the results of potentially influential sources [24].

Table 5. *R-squared values corresponding to model analysis of both S/N ratios and Means against each response variable.* The statistical analysis results from Minitab show that the data appears to be more consistent for pressure differential and contact area data which have R-sq of S/N values greater than 85%. Force and displacement data results show slightly more inconsistencies, but are adequately consistent with values between 70-80%. Force and vertical displacement both show a medium correlation of means (about 60% and 70% respectively), whereas the correlation of means associated with pressure differential and contact area appear to be very strong (>99%).

Response Variable	R-sq of S/N	R-sq of Means	Potential Influential Source(s)
Force	74.07%	59.83%	Width Ratio, Thickness
Pressure Differential	88.21%	99.70%	Width Ratio, Thickness
Displacement	77.16%	70.55%	Thickness, Width Ratio
Contact Area	85.36%	99.01%	Thickness Ratio, Thickness

A strong correlation of means (>99%) can be seen between two response variables and their corresponding influential sources: pressure differential and width ratio; contact area and thickness ratio. A width ratio appears to be the strongest potential predictor for force and pressure differential. thickness and thickness ratio appear to be the strongest potential predictors of means for displacement and contact area, respectively. A medium correlation coefficient (59.83%) was observed between force and width ratio. Main effects plots for means were generated for each response variable using the Minitab software. A main effects plot for means corresponding to each observed variable was created. A main effects plot for means corresponding to force and the design parameters is shown in Figure 20.

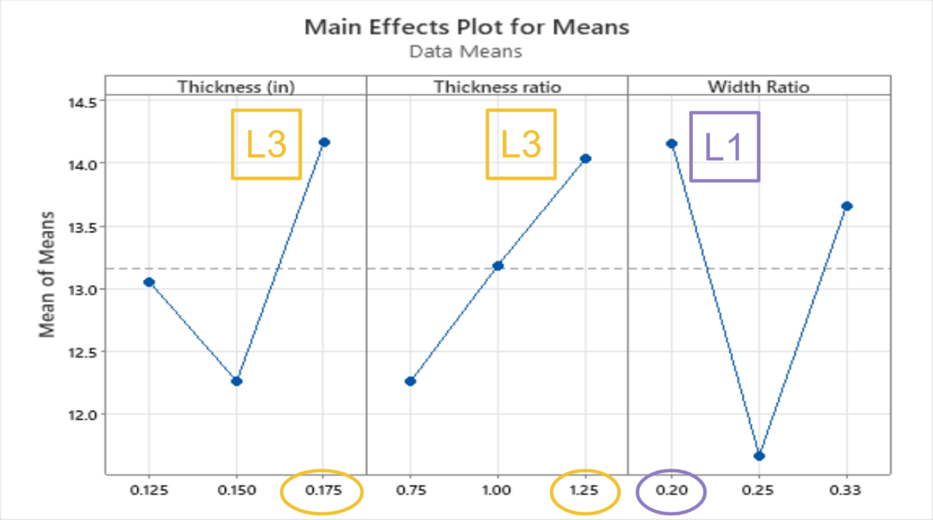


Figure 20. *Main effects plot for means of force results and the input design parameters: thickness, thickness ratio, and width ratio.* The mean of means for force is in lbs, thickness levels are in inches, and with the levels for remaining two design parameters as ratios. The combination of levels required to maximize force is level 3, level 3, level 1 for thickness, thickness ratio and width ratio respectively. Width ratio shows the most variability and therefore appears to have the most influence on force.

A main effects plot for means corresponding to pressure differential and the design parameters is shown in Figure 21.

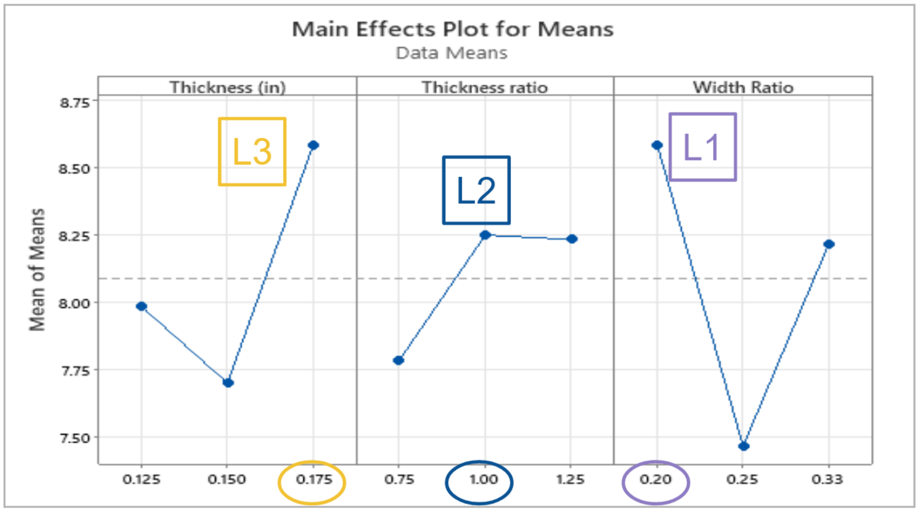


Figure 21. *Main effects plot for means of pressure differential results and the input design parameters: thickness, thickness ratio, and width ratio.* The mean of means for pressure differential data is in PSI, thickness levels are in inches, and with the levels for remaining two design parameters as ratios. The combination of levels required to maximize the pressure differential is level 3, level 2, level 1 for thickness, thickness ratio and width ratio respectively. Width ratio shows the most variability and therefore appears to have the most influence on pressure..

A main effects plot for means corresponding to vertical displacement and the design parameters is shown in Figure 22.

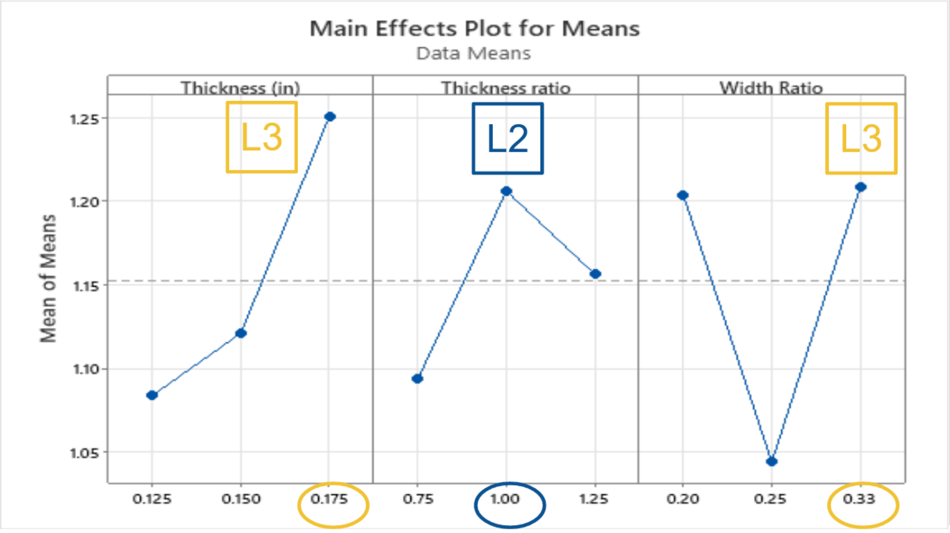


Figure 22. *Main effects plot for means of vertical displacement results and the input design parameters: thickness, thickness ratio, and width ratio.* The mean of means for vertical displacement data is in inches, thickness levels are in inches, and with the levels for remaining two design parameters as ratios. The combination of levels required to maximize vertical displacement is level 3, level 2, level 3 for thickness, thickness ratio and width ratio respectively. Thickness shows the most variability and therefore appears to have the most influence. Thickness and width ratio show the most variability and therefore appear to have the most influence on displacement.

A main effects plot for means corresponding to contact area and the design parameters is shown in Figure 23.

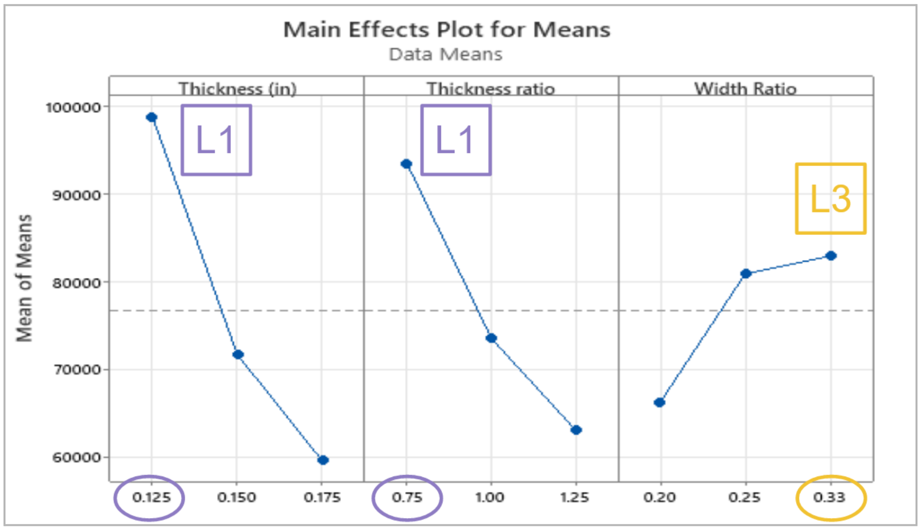


Figure 23. *Main effects plot for means of contact area results and the input design parameters: thickness, thickness ratio, and width ratio.* The mean of means for contact area data is in pixels, thickness levels are in inches, and with the levels for remaining two design parameters as ratios. The combination of levels required to maximize contact area is level 1, level 1, level 3 (for thickness, thickness ratio and width ratio respectively). Thickness shows the most variability and therefore appears to have the most influence on contact area.

These main effects plots were an important tool in the analysis process because they facilitate in predicting optimized key cup parameters required to achieve the desired response (i.e. maximized/minimized output variables) as well as the influence of the design parameters. From this inclusive analysis, four independent combinations of parameters were discovered that should each result in maximizing one of the four observed variables. Table 6 shows these parameter level combinations and their associated response variables.

Table 6. *Design parameter levels of a suction cup required to maximize response variables.* The three levels correspond to the design features thickness, thickness ratio, and width ratio respectively. These four different combinations of levels provide insight to converge on maximized response variable values. The combination of levels for cup 8 and cup 9 were created and tested as a part of our Taguchi design matrix. The combination of levels corresponding to cup 10 and cup 11 are new designs that have yet to be manufactured/tested.

Suction cup response variable	Levels required to maximize response variable	Cup #
Force	L3, L3, L1	9
Pressure differential	L3, L2, L1	10
Vertical displacement	L3, L2, L3	8
Contact area	L1, L1, L3	11

Conducting this statistical and sensitivity analysis enabled us to gain new knowledge and continue with our design process. These cup designs allow us to maximize each of the response variables and converge on optimized values for these design parameters.

Discussion

Both the data and results as well as the analysis were taken into consideration for determining the final steps in the design process. From the level combinations in Table 6, two of the cup designs, cup 9 and cup 8 (L3, L3, L1 and L3, L2, L3, respectively), were already included in our Taguchi design matrix, manufactured, and empirically tested by our team. Cup 8 and cup 9 both had an L3 thickness and therefore we expected these cups to perform better than other cup designs with relatively smaller thickness values. This aligns with our expectations that a larger thickness would result in a higher resistance to applied force, a higher pressure differential, a larger displacement and a larger contact area. Although increased thickness resulted in higher force resistance, it also led to greater difficulty in fully attaching the cups to the testing surface. Overall, we saw trends that suggest increased performance of the cup may lead to risk of lower usability.

The two new designs, cup 10 and 11 (L3, L2, L1 and L1, L1, L3), were not part of our Taguchi array and were determined through analysis. The CAD for these two new designs, cup 10 and cup 11, can be seen in Figures 24 and 25, respectively.

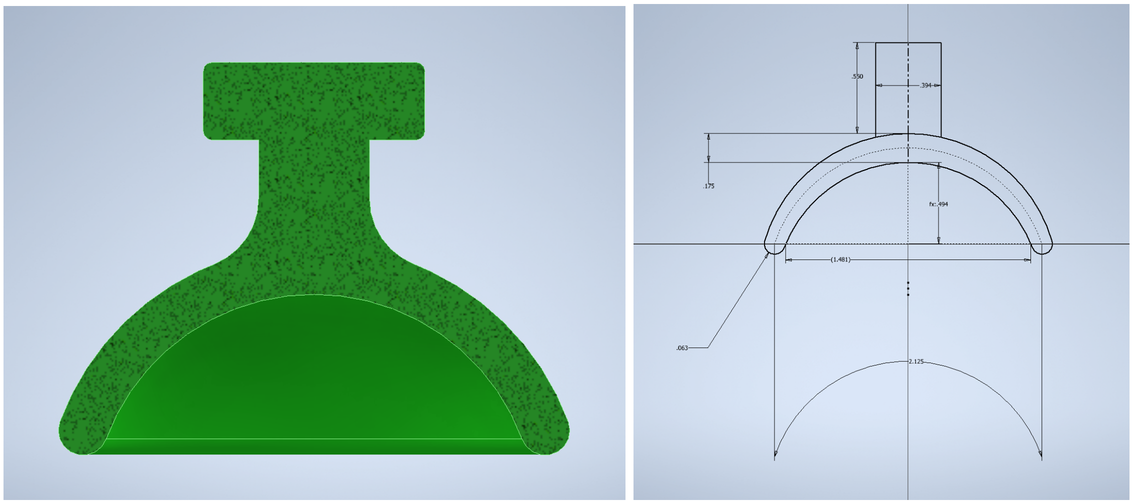


Figure 24. *CAD drawing of a cup that maximized internal pressure response.* From our statistical and sensitivity analysis, we produced a CAD model of the suction cup that maximized the internal pressure response. Following our leveling convention used in the Taguchi design matrix, this cup has parameter levels L3, L2, L1 for its design. We recommend for future groups taking on this project that this cup be created and tested alongside other cup designs.

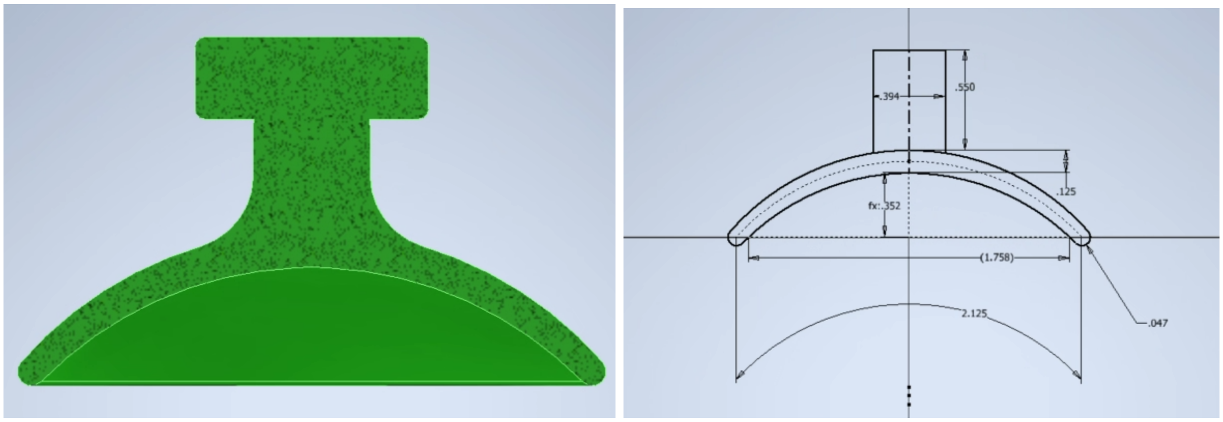


Figure 25. *CAD drawing of cup that maximized contact area response.* From our statistical and sensitivity analysis, we produced a CAD model of the suction cup that maximized the contact area response. Following our leveling convention used in the Taguchi design matrix, this cup has parameter levels L1, L1, L3 for its design. We recommend for future groups taking on this project that this cup be created and tested alongside other cup designs.

Molds and cups for the cup 10 and cup 11 designs have yet to be manufactured or empirically tested. These cups were not a part of the Taguchi array, but statistical and sensitivity analysis suggests that these cup designs be considered in future testing and analysis. It is worth noting that an L3 thickness value may lead to improved cup performance, according to a trend in analysis. Considering the raw force data collected, cup 4 also deserves further investigation, as it was the best performing cup overall. This new information helped to further enhance the values for each of the design parameters, and aided in the optimization of the overall cup design. Further testing, specifically concerning repeatability, must still be addressed.

Challenges

Our team encountered a number of issues throughout the project. One of the most prominent challenges during experimentation was the premature breakage of suction cups. When a cup was subjected to high forces in the Instron, there was a possibility of the cup tearing at the top rather than becoming detached from the testing surface. This resulted in data that was inconsistent and unreliable for further analysis and left the cup unusable for future testing. This forced the creation of new cups which took time away from testing. A related issue that became apparent was the improper injection of silicone into the cup molds. During the silicone pouring process, air bubbles/pockets may form if the mixture is not properly handled which often results in a poor-quality cup, prone to premature failure. Our team countered this issue by seeking guidance and learning the proper techniques to handle and inject the silicone into our molds.

Another issue with our testing was the inconsistent marking of initial and final contact areas for all the tested cups. This inconsistency was due to a number of factors: the lighting condition, the quality of the recording device, and the testing surface condition. Although the recordings were taken with GoPro cameras, our contact area measurements were difficult with the initial low levels of lighting in the lab. We tried to mitigate this by improving the light conditions in the areas of interest during testing. Contact area measurements were also inconsistent due to the surface conditions of the plexiglass and the silicone material of the cups not always behaving the same way, especially when performing the multiple tests on the same cup. Our team discovered that this issue was slightly mitigated by wetting the plexiglass testing surface before initial attachment of the suction cup to the surface. Despite efforts to improve consistency of contact area measurements, this area could still use more improvement moving forward.

Recommendations

Going forward with the project, we recommend that future students or research teams focus their efforts on the four cup designs that were highlighted through our statistical and sensitivity analysis. Additionally, from the notable performance of cup 4 (based on the raw force data), this cup design should also be considered moving forward, for deeper analysis on best performing cups. Future teams should 3D print molds for each of the two new cup designs (cup 10 and cup 11). These teams should then manufacture all five of the optimized cup designs (cups 4, 8, 9, 10, and 11) for further testing and analysis. Parameter values corresponding to the levels of the five optimized designs is shown in Table 7.

Table 7. *Design parameter values corresponding to each of the five best performing cups.* According to results and analysis, these five cups were the top performing, resulting in at least one maximized response variable. Molds corresponding to cups 4, 8, and 9 were manufactured and included in our Taguchi matrix. Molds for new cup designs (cups 10 and 11) have yet to be manufactured.

Cup #	Thickness	Thickness ratio	Width ratio
4	0.125	1.25:1	W/5
8	0.175	1:1	W/5
9	0.175	1.25:1	W/3
10	0.175	1:1	W/3
11	0.125	0.75:1	W/5

We also recommend that these students investigate part-to-part variation by conducting repeatability verification testing. This would involve conducting empirical testing with a similar set up as described in the engineering analysis section of this report and under the same conditions using a control variable method. Multiple cups with the exact same design parameter combinations should be manufactured and tested under the same conditions so that the consistency and repeatability of the cup can be more accurately explored. Statistical analysis should be done on the data obtained from these experiments for further verification. This will hopefully lead to identification of even better performing suction cups with higher repeatability.

Other recommendations for this project in the future include exploring the fluid dynamic relationships between design parameters and output variables, and testing the cups outside of a lab environment or in slightly more realistic operating conditions. The more realistic testing may involve making use of the imitation whale skin (available in our sponsor's lab) or conducting tests while the suction cups are submerged in water. Different silicone type materials may also be explored if so desired.

Conclusion

Using Taguchi orthogonal arrays was a little time consuming and required research in order to understand how to properly utilize and embody the process. Ultimately it was an informative process, minimizing the required amount of cup manufacturing and empirical testing. We believe that choosing this analysis tool was the right decision and would recommend using Taguchi for similar types of optimization projects.

Initially, our team hoped to have a predictive model that shows how the key parameters of a suction cup can positively or negatively affect the cup's attachment reliability. After completing all of the testing and data analysis with all of the different models of suction cups from our Taguchi design array, we determined that width ratio and thickness have the most impact on performance overall. As expected we determined that a higher thickness did improve performance (increased cup resistance to force), but were surprised to discover that this improvement comes at the cost of usability (increased difficulty to initially attach cup to surface). Four combinations of design parameters, corresponding to cup 8, 9, 10, and 11, were determined in order to maximize each of the four response variables. Additionally, the raw data was considered and a fifth cup, cup 4, was determined to maximize force resistance. Each of these five cups were recommended for further testing and analysis.

Ultimately the quantity and quality of data gathered from the conducted experiments and performed analyses resulted in the final goal: to obtain new knowledge that will facilitate the creation of better suction cups. Moving forward, further experimentation on the five chosen cup designs should focus on reliability testing to verify our results. Further optimization of the suction cup design will lead to higher performing cups which will result in higher quality and quantity data collection. Linking back to the contextual goals of our sponsor, better performing cups will lead to better understanding of marine mammals in their hard to reach habitats and provide much needed aid in wildlife conservation efforts.

We would like to thank: Prof. Shorter and his research team at ESTAR Lab, University of Michigan; John Laidlaw, Engineering Technician, University of Michigan Department of Mechanical Engineering; Eric Johnsen, Associate Professor, University of Michigan Department of Mechanical Engineering. It was with their help and support throughout our research that we achieved our project goals within the semester.

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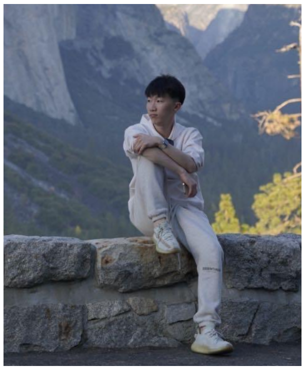
Biographical Sketches

Name: Alexis Beach
Pronouns: She/her
Year: 5th year
Major/Minor: Mechanical Engineering Major, Mathematics and Physics Minor
Hometown: Traverse City, MI
Future plans: To graduate and move on to a job where I get to dive deeper into design and problem solving, and to move to a different area of the country where I can experience new things.
Fun facts: I love physics, the outdoors, arts and crafts, and my dog.
Interests in mechanical engineering: My favorite mechanical engineering subjects have so far been statics, making things in the machine shop, and circuits, which I found challenging but fun. In the past I was also able to be a part of a space weather sensor package team.

Name: CarolAnne Harris
Pronouns: She/her
Year: Senior
Major/Minor: Mechanical Engineering
Hometown: Ypsilanti, MI
Future plans: This coming summer I plan to continue working for my father's niche underground construction company. I graduate from U-M in the fall.
Fun facts: I enjoy personal fitness, disc golfing, traveling, animals, and wilderness adventures.
Interests in mechanical engineering: I have always been enthusiastic about helping people, animals, and all living things. Creating solutions to potential problems they may face gives me purpose and brings me fulfillment. I am also passionate about protecting and improving freshwater ecosystems, which I feel that too many people take for granted. Other interests I have are cars, motorcycles, agriculture and general construction.



Name: Yining Wang
Pronouns: He/him
Year: Senior
Major/Minor: Mechanical Engineering
Hometown: Shenyang, China
Future plans: I will graduate from U-M after this spring semester and plan to either attend a graduate school concentrating in product design or do a R&D internship.
Fun facts: I love snowboarding, mountain biking, badminton, and many other sports.
Interests in mechanical engineering: My favorite part of mechanical engineering is the concentration on product design and manufacturing process. This concentration with the consideration of design for sustainability and green manufacturing gives me the opportunity to learn how I can protect the environment as an engineer.

Name: Robert West
Pronouns: He/Him
Year: Senior
Major/Minor: BSE of Mechanical Engineering
Hometown: Dearborn, MI
Future plans: After this semester I am graduating, so I hope to find a full-time position and go back to hobbies that I did not have the time to dive into because of school.
Fun facts: I am an avid rock climber, and enjoy exercising, hiking, biking, and playing video games during my free time. I also worked as an apprentice electrician before entering UfM.
Interests in mechanical engineering: I found through working at home and as an electrician that I am a problem solver and like to experiment with different possible solutions. I always feel satisfied whenever I am able to resolve an issue or help someone in need with anything. As a mechanical engineer, I can enter the workforce as an official problem solver and help more people I come across.

Appendix A. Concept Generation Details

Whenever we reached an obstacle or the flow of ideas slowed, it helped to implement divergent thinking to turn a single small idea into its own branch of the idea map. Once we had generated a satisfactory range of concepts, it was time to use convergent thinking and to conduct gut checks to see how this large variety of small ideas could be implemented into a single overall solution to our problem.
Listed here are some of the top ideas that resulted from our various methods of concept generation:

- Normal Force Failure Experiment - Using the Instron machine to pull vertically on the top of a suction cup that has been attached to plexiglass, and measuring the peak resistive force when the cup seal breaks and detaches from the plexiglass.
- Shear Force Failure Experiment - Similar to the normal force failure experiment, but rather than a vertical force, the cup would be rigged in a way that would allow the Instron to apply a horizontal force relative to the top of the suction cup.
- Internal Pressure Measurement - Using an Arduino setup in conjunction with a manometer to measure the pressure differential between the atmosphere and the inside of the partial vacuum cavity inside the suction cup.
- Contact Area Measurement - Setting up a camera beneath the plexiglass to take images of the area of the cup in contact with the surface as the Instron applies a force.
- Timed Attachment Test - Attaching the suction cup to a flat surface and timing how long it takes the cup to detach from the surface.

A concept generation map showing the top ideas can be seen in Figure A.1. The remaining generated concepts are listed in Table A.1.

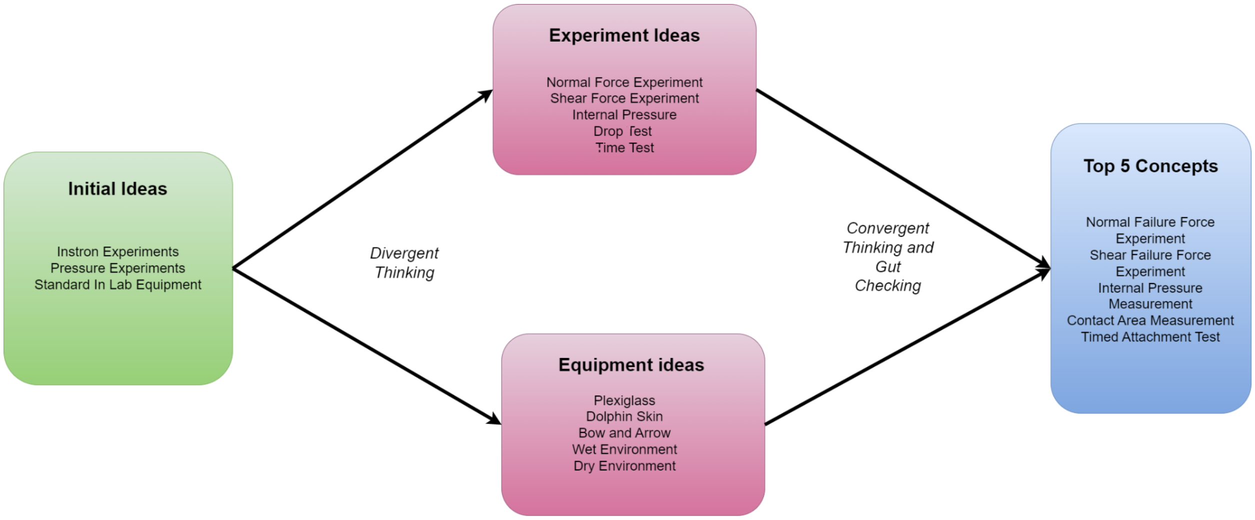


Figure A.1. *Concept generation map for experimental methods.* Divergent thinking resulted in new and more unique ideas and convergent thinking enabled us to concentrate on the most practical concepts.

Some of the concepts from Figure A.1 very closely relate to each other, such as the ideas of plexiglass vs dolphin skin and wet vs dry surface. We generated these ideas by asking ourselves how the suction cup contact surface could be changed, therefore many of our concepts stem from this single idea. This is evidence of our original divergent thinking process in which we expanded from one idea to many. Our team then used convergent thinking to bring our focus back to the main project focus. We classified all of our concepts into either experiment or equipment ideas for further screening against our sponsor needs.

Table A.1. *List of ideas generated during group brainstorming.*

Concept	**Description**
Strain Test	Measuring strain at different points in the Instron displacement process.
Vacuum Chamber	Inserting the cup into a vacuum chamber to check performance at low pressures.
Drop Test	Drop the cup from a long height onto a surface to see how well it can stick using its own falling force.
Fluid Test	Dragging the cups through a fluid testing system to see how the cups experience drag.
Plexiglass	Using a plexiglass surface to attach the cups to during Instron tests.
Dolphin Skin	Instead of a plexiglass surface, attaching the suction cup to the imitation dolphin skin provided in the lab.
Dry Test	Conducting experiments on a dry surface and analyzing suction cup behavior accordingly.
Wet Test	Using wet surfaces during experimentation to more closely simulate real world applications.
Bow and Arrow	Doing the drop test not just with the force of the cup's own gravity, but with the added velocity of being shot out of a bow and arrow.

Figure A.2 shows a sample of individual concept generation done by a member of our team.

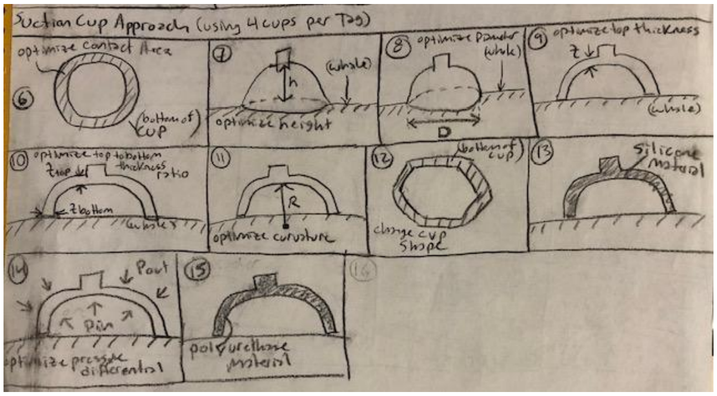


Figure A.2. *List of sketches and ideas generated during individual brainstorming*

Appendix B. Concept Screening & Selection Details

After developing an organized list of concepts from our generation session, we had to narrow the ideas down to only the most practical ideas that will be further evaluated. To do this, we utilized the gut check method to eliminate any ideas that we felt were not feasible and would not give us more information on the desired parameters that we want to analyze post-experimentation. This method was also used to evaluate all ideas pertaining to data analysis methodologies.

After talking through every experiment and method of data analysis, only the best ideas that had the most potential made the cut. A classification tree of our remaining concepts can be seen in Figure B.1.

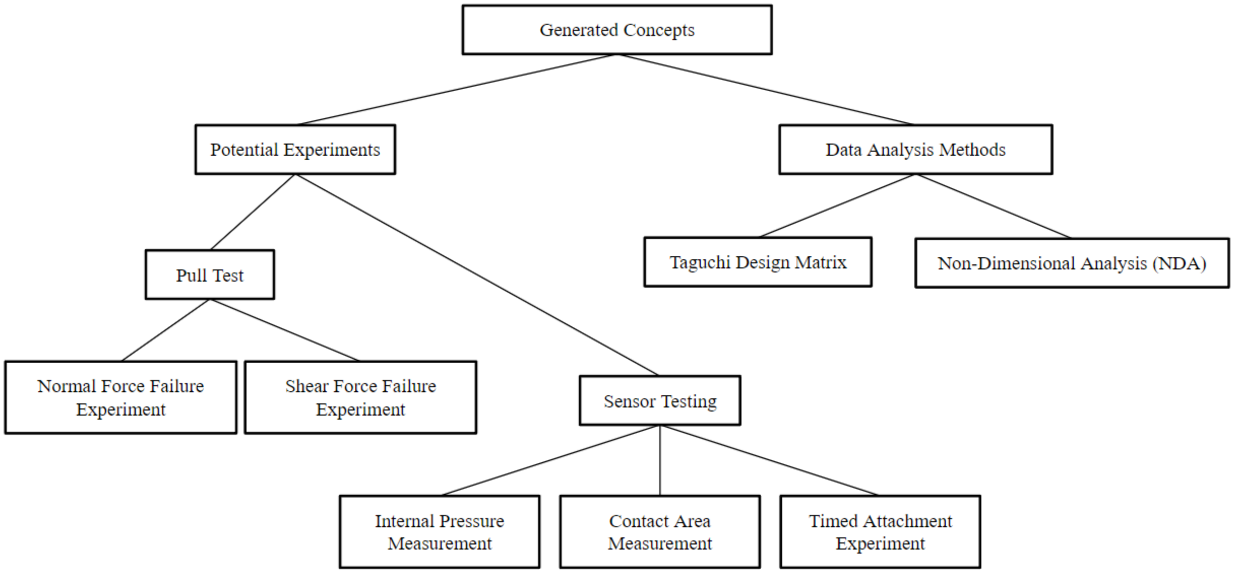
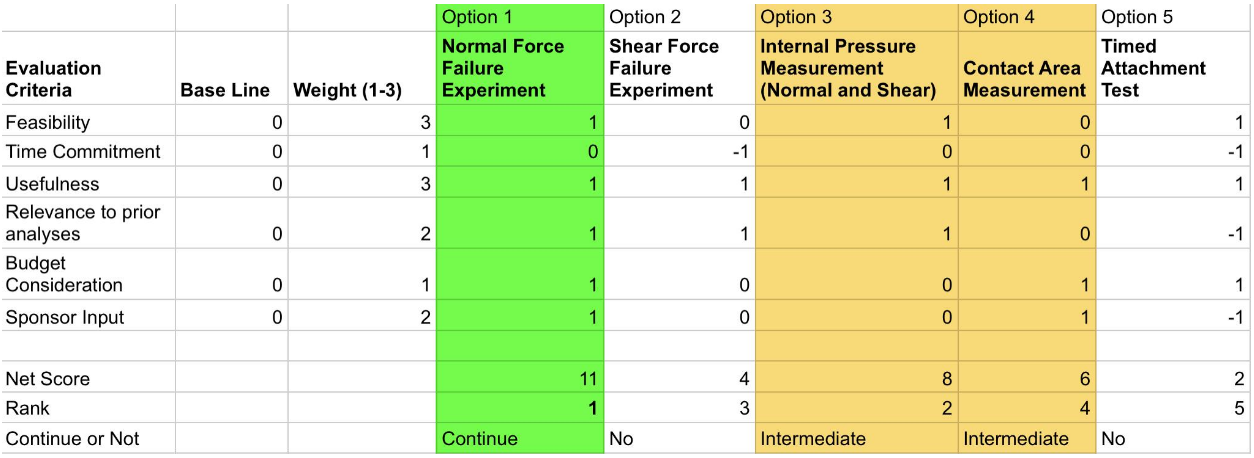


Figure B.1. *Classification Tree of Generated Concepts for Comparison.* The ideas that were taken away from the concept generation mainly focused on the potential experiments that could be performed and potential data analysis methods that could be utilized.

All of the concepts shown have advantages and disadvantages that distinguish them from one another. The normal force loading test would help us understand how changes in the desired parameters affect the attachment of the suction cup to a surface, but would take considerable time to cycle through every different cup design. Similarly, the shear force loading test would help us analyze the performance of cup parameters with respect to cup stiffness during attachment, but would require more time for setup and would need to purchase new tooling for a stable experimenting location. The internal pressure test would empirically help us understand how the changes in the desired parameters would positively or negatively affect the vacuum pressure on the inside area of the cup, but would require more technology in the experimentation and would not be easy to record properly. The contact area measurement experiment with a camera would help us see how the contact area of the suction cup changes as it experiences different forces during attachment, but would not give much relevant data in relation to our problem definition. The timed attachment test would show how changing the attachment time of the suction cups changes with different parameters, but would also not provide significant results that can be related to answering the defined problem.

To properly evaluate each of the different experiment ideas together, a Pugh chart was created to compare each concept to differently weighted criteria, as shown in Figure B.2. Within our Pugh chart, the ‘Feasibility’ criteria was weighted the highest because it relates to the ‘Useful Results’ sponsor requirements and because we wanted to make sure that the experiments selected could be done within the existing lab environment and with accessible or available equipment.



			Option 1	Option 2	Option 3	Option 4	Option 5
Evaluation Criteria	**Base Line**	**Weight (1-3)**	**Normal Force Failure Experiment**	**Shear Force Failure Experiment**	**Internal Pressure Measurement (Normal and Shear)**	**Contact Area Measurement**	**Timed Attachment Test**
Feasibility	0	3	1	0	1	0	1
Time Commitment	0	1	0	-1	0	0	-1
Usefulness	0	3	1	1	1	1	1
Relevance to prior analyses	0	2	1	1	1	0	-1
Budget Consideration	0	1	1	0	0	1	1
Sponsor Input	0	2	1	0	0	1	-1
Net Score			11	4	8	6	2
Rank			**1**	3	2	4	5
Continue or Not			Continue	No	Intermediate	Intermediate	No

Figure B.2. *Pugh chart of the top rated potential experiments.* After grading all generated experiments based on each of the evaluation criteria and comparing the results, the normal force failure experiment appears to be the best.

In addition to selecting the best experimental setup, different analytical methods were also screened using a separate Pugh chart, shown in Figure B.3. After a gut check, the remaining methods were a Taguchi Design Matrix and Non-Dimensional Analysis (NDA). With the Taguchi matrix, we could create a system that incorporates both experimental iteration and evolution of the cup designs, but this would require full knowledge of the orthogonal array system to properly utilize it. In comparison, UM Professor Eric Johnsen helped us to discover that the NDA method of data analysis would allow us to create a relationship between the pressure and contact area and would allow us to maximize the pressure differential between the inside and outside of the applied suction cup using the empirically found surface tension associated with the cup. However, this more complicated method would be time consuming and does not align as closely with our sponsor needs, therefore the Taguchi matrix appears to be the best selection. Sponsor engagement and research into methods that previous students have used helped us to reach this decision.

			Option 1	Option 2
Evaluation Criteria	**Base Line**	**Weight (1-3)**	**Taguchi Matrix**	**Non-Dimensional Analysis**
Feasibility	0	3	1	1
Time Consideration	0	2	1	0
Data Value	0	1	1	1
Usefulness	0	1	1	0
Sponsor Input	0	2	1	0
Net Score			9	4
Rank			1	2
Continue or Not			Continue	No

Figure B.3. *Pugh chart of potential post-experimentation analysis methods.* The Taguchi design matrix scored positive on almost all evaluation criteria and was chosen as the prime data analysis method.

‘Feasibility’, ‘Sponsor Input’, and ‘Time Consideration’ were all weighted more heavily than other criteria because we all decided that they were depicted as the most important criteria to consider for the experimental analysis.

During our initial steps of the project, the experimental concept that came to mind was a pull test of the suction cups after attachment to a surface and a pressure test inside a vacuum chamber. The pull test relates to the normal force loading test that we chose as the best experiment from the Pugh chart, however after more research into the problem, the vacuum chamber test was marked as inefficient for collecting relevant data. As we initially expected, our chosen experiment is a good choice because it aligns with the experiments performed by previous student researchers and with the work of our sponsor, and will provide more refined results.

Appendix C. Bill of Materials & Manufacturing Plan

Table C.1. *Bill of Materials.* Materials purchased for experimentation purposes.

Bill of Materials				
Part	**Description**	**Manufacturer**	**Part Number**	**Cost**
Smooth-Sil 50: Parts A and B	Silicone Base and Hardener	Smooth-On	N/A	$40.59
20 mL Syringes	Plastic Curved Syringes for Epoxy Resin	TecUnite	N/A	$13.99
Clear Resin 1 L	Clear Resin for 3D Printing	Formlabs	N/A	$149.00
TOTAL				$203.58

Table C.2. *Manufacturing plan for suction cups.* Steps taken to manufacture and create suction cups designed by the Taguchi design matrix, with materials and tools needed.

Manufacturing Plan		
Step	**Description**	**Materials and Tools Needed**
1. Prepare workspace	Gather materials, prepare and assemble mold, and insert injection tube mechanism	Smooth-Silicone 950 Parts A and B, small mixing cup, mixing stick, screws, bolts, silicone tubing
2. Mixing Silicone	In a small cup, mix silicone and silicone thinner with a popsicle stick until completely homogenous.	Smooth-Silicone 950 Parts A and B small mixing cup, mixing stick
3. Remove air bubbles	Insert silicone mixture into vacuum chamber to remove any excess air from stirring	Vacuum chamber
4. Load silicone into syringe	Remove mixture from vacuum chamber and pour into 20 mL syringe.	20 mL syringe

Appendix D. Dry Test Results

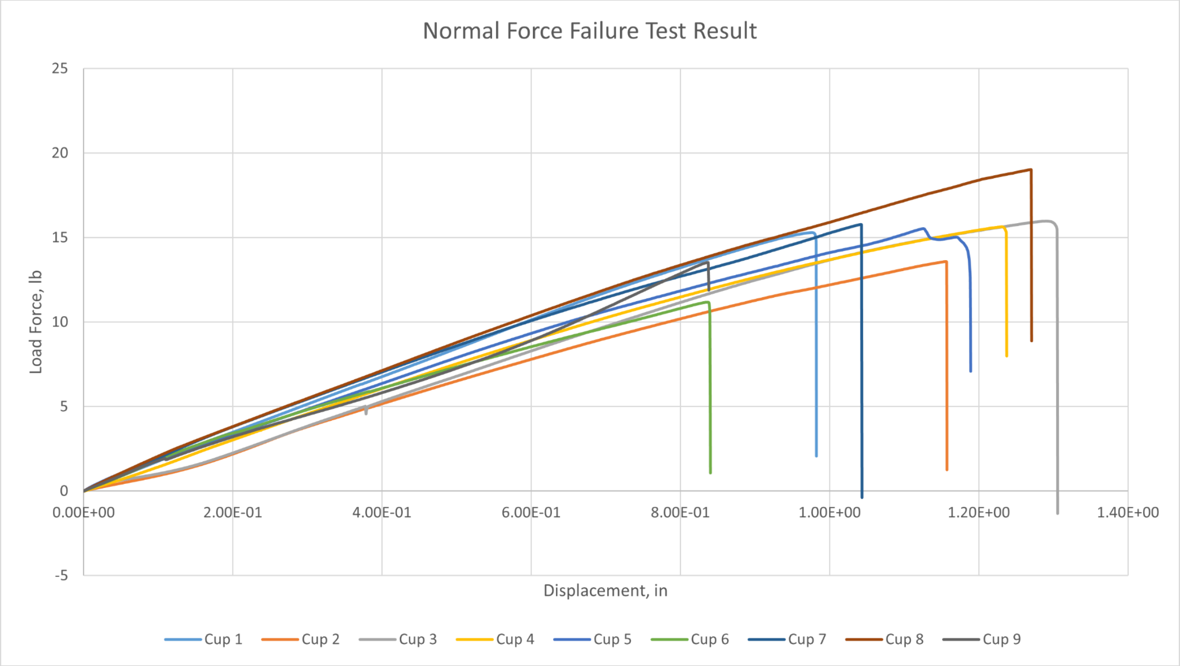
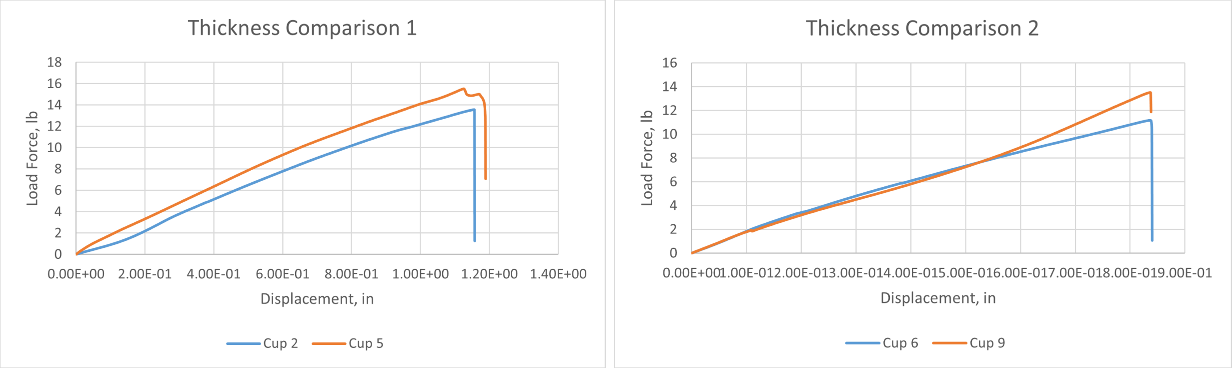


Figure D.1. *Normal force failure test under dry environment.* Cup 8 had the highest load force of 19.02 lb and corresponding top displacement of 1.27 in.



(a) (b)

Figure D.2. *Normal force failure test with thickness comparison under dry environment; cup 2 and cup 5 comparison (a); cup 6 and cup 9 comparison (b).* (a) Cup 2 and Cup 5 have different thicknesses but the same thickness ratio and width ratio. (b) Cup 6 and Cup 9 have different thickness levels but the same thickness ratio and width ratio. By comparing the recorded data directly, we evaluated the effects of varying particular key parameters on cup performance.

Table D.1 *Difference in pressure differentials of all cups under dry condition.*

Cup #	$\mathbf{P_{diff,\ dry}}$
1	6.5
2	7.4
3	7.7
4	8.5
5	9.4
6	7.2
7	8.6
8	9.3
9	8.6