2018

# NUWC Universal Undersea Gripper

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# Let It Grip!
## NUWC Universal Undersea Gripper

## Team 12


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**Company Sponsors**

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Abstract

The main objective of the ”Let it Grip” 2017-2018 NUWC Universal Undersea Gripper project was to design an effective and efficient individual gripper capable of securing a payload of various sizes, shapes, and orientations. This an important and relevant project being that the current way of securing payloads throughout the duration of a mission involves pre-installed molds that can only hold a payload of a specific size and shape. Though there were many ways to improve upon the current payload-carrying apparatus, the team decided to focus on finding the optimal shape and material of a potential universal gripper.

After conducting rigorous patent and literature searches, a more thorough understanding of how to accomplish this specific, yet challenging goal was established. In addition to increased comprehension, this research aided in further understanding of competition in terms of current devices already used in practice. Upon discovering current products, an in-depth analysis of each was conducted in order to find ways to improve and capitalize on mistakes of these current products. Through a means of preliminary concept generation, 120 possible designs were produced varying from gripper material, gripper layout, as well as the individual gripper itself. These designs varied in practicality, however, led to a plethora of truly useful and feasible ideas. With these possible concepts in mind, comprehensive QFD and engineering analyses were conducted. This process was used to aid in logical analysis in terms of specific needs required by NUWC to efficiently accomplish the goal of designing the universal gripper.

Using these analyses, the 120 possible concepts were narrowed down to a select two. The first of which was an extending, pyramid-shaped, hybrid design with a metallic base for increased strength, with an elastomer tip for increased shock absorption and coefficient of friction against the payload. The second design incorporated a hydraulically powered, conical telescopic device with a convex metallic head coated with an elastomer layer to increase shock absorption and coefficient of friction against the payload. Stress, shock, displacement, and factor of safety analyses were conducted on these two concepts using SolidWorks simulations to determine how each possible gripper design would perform under the acute stresses that will inevitably be subjected to it. After careful consideration, the conclusion was made that the hydraulically powered, conical telescopic convex-tipped gripper would be able to accomplish the goal of securing a payload of varying size, shape, and orientation in the most effective and efficient way possible.

Throughout the year, the team conducted further research and FEA analysis including internal pressure and deformation due to load testing in order to optimize the gripper design. This resulted in redesign additions such as guiding track lines to prevent unwanted gripper rotation and chamfered edges to prevent payload damage. As a result of this work, the team was able to produce a realistically modeled 3D high quality prototype and be a considerable improvement on the current apparatus in place.

# Contents

# List of Acronyms

| | | |
|---|---|---|
| CCW | - | Counter Clockwise |
| FOS | - | Factor of Safety |
| NUWC | - | Naval Undersea Warfare Center |
| OD | - | Outer Diameter |
| URI | - | The University of Rhode Island |

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# 1 Introduction

During Fall 2017, the Naval Undersea Warfare Center (NUWC) expressed interest in designing a universal undersea gripper. NUWCs representative, Dr. Peter Hardro, defined a universal undersea gripper as being compatible with the missile silo on varying submarines, as well as being able to functionally grip a payload of varying sizes, shapes, and orientations.

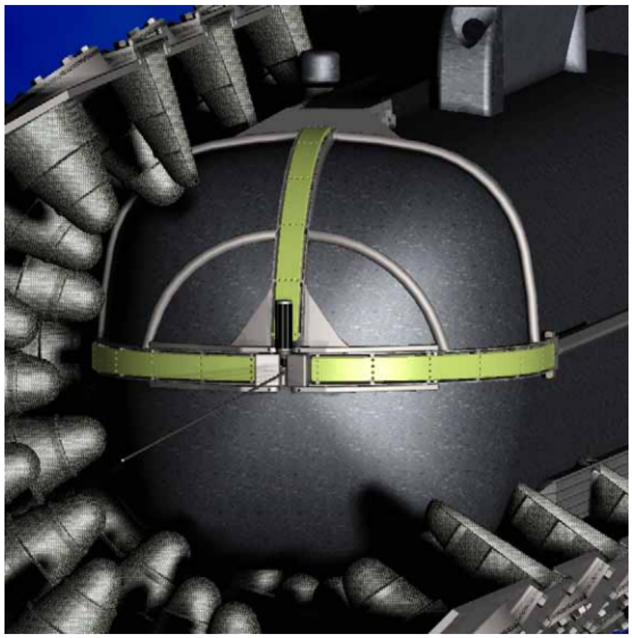
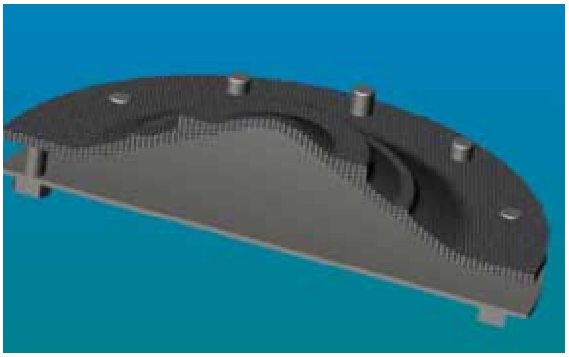


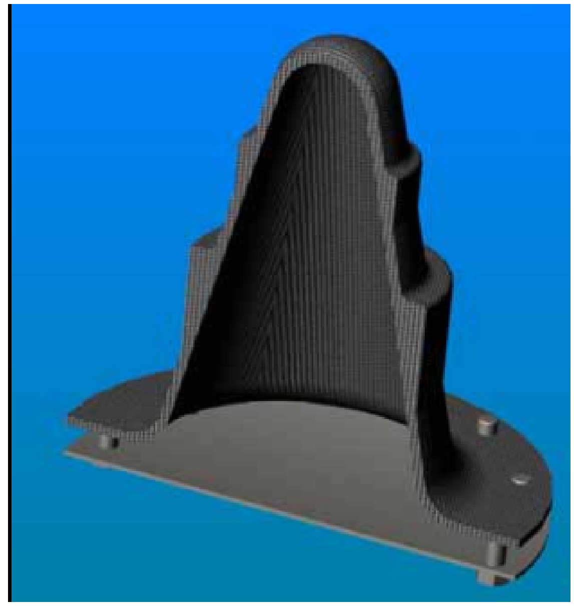
**Figure 1:** Payload being secured by an inflatable gripper system

The problem presented included current payload transportation systems, and a prior gripper design that NUWC had attempted to employ. The current system of gripping payloads consists of inserting different sized molds into the payload bay which fit to the payloads specific dimensions to complete the mission at hand. The main issue with having a mold for these payloads is that the mold sleeve itself has to be frequently changed out depending on the sizes of the payloads that are used during the mission. This is costly and time consuming as the payload molds are immense in size and require heavy machinery to change them out. That being said, changing the mold during the course of a mission is extremely inefficient, which can severely limit the scope of certain missions.

NUWC has observed the inefficiency of this method, and as a result, began the process of designing and testing new systems to grip a potential payload. NUWC's preliminary design consists of an inflatable elastomer gripper, which can inflated with air or seawater, until it has the force necessary to securely grip the payload. This preliminary design has an 18 inch diameter and uses numerous grippers evenly spread out through the inner sleeve of the silo. NUWC ultimately built a prototype of this gripper and recorded data of the gripper being inflated with air. This design was proven to work in theory, though NUWC was not certain that it was truly the most effective and efficient way to accomplish their goal.



**(a)** Gripper Deflated



**(b)** Gripper Inflated

**Figure 2:** Elastomer Gripper

NUWC gave the task of researching and designing a gripper to fit the needs and goals of their project, specifically the ability to grip a payload of varying size, shape, and orientation. After careful deliberation with Dr. Hardro and other engineers at NUWC, the scope and project definition were created to fit the Capstone course design time line as well as NUWC's goals. The project was defined as designing a universal gripper that is capable of securing a payload of any size, shape, and orientation for the duration of a 6-month mission.

Upon formation of a clear and concise problem definition, concept generation began. In order to effectively and efficiently design feasible concepts, patent searches were conducted to ensure a better understanding of the design process and observe products already on the market in this field. This ultimately led to critical design components that were incorporated in the concept designs. During patent searching, a patent owned by NUWC was found which consisted of their initial design of using inflatable grippers. Moving forward, several patents on hydraulic extenders and sensors were discovered which ultimately were incorporated into the concept generations. Using what was found in the patent searching exercise, thorough concept generation took place, compiling design specifications, and creating a QFD analysis in order to ensure that all the needs of NUWC would be met. After a total of 120 concepts were generated, it was determined that there were two designs best fit to move forward with.

The two designs were similar to the inflatable elastomer design, but instead of using an elastomer material, it was decided to use a hybrid system consisting of a metal base for increased strength and a elastomer-coated tip to ensure a high coefficient of friction, as well as shock absorption. These gripper design features a telescopic mechanism, which would be powered through means of hydraulic fluid, pushing out each consecutive section until full extension. The two designs differ in terms of the shape of the base and the tip of the gripper.

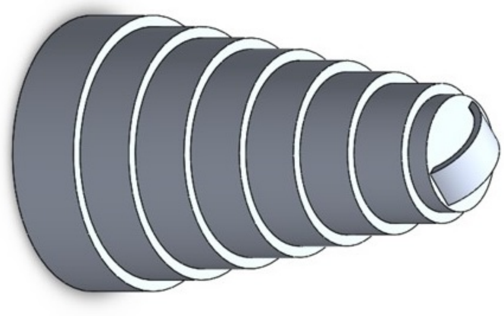


**Figure 3:** Gripper design extended

The team continued analysis on both designs. After discussions with engineers at NUWC, and research on hydrolysis and seals, the team decided to move forward with one design. The design was conical shape, similar to NUWC's first design, having a eighteen inch diameter and extending in a similar fashion. The difference was the material, as stated before, NUWC's prior design was made from elastomer material, where the teams design was metal.

The reason the team chose the conical design was mainly practicality. Having a conical design allows the gripper to extend without gaps, and allows the team to explore the option of using o-rings as a potential seal. Once the design was narrowed down, extensive finite element analysis was preformed. FEA allows the team to see if the gripper design met the specifications of NUWC, as well as potential flaws in the design.

Using the results of testing, the team began to incorporate redesigns. These redesigns included adding an extra two inches to the head, and adding guideline tracts to allow the gripper to be extended without rotation. Incorporating the redesigns lead the team to complete the final design for this Capstone project.

# 2 Project Planning

The process of designing the universal gripper began by formulating an original first semester project plan reflecting milestone dates for both the capstone course as well as the needs of NUWC. These are reflected in the project plan shown in Figure 4.

After designing a comprehensive first semester project plan, research began into how to most efficiently and effectively secure a payload of varying shapes, sizes, and orientations. The first step in accomplishing this goal was to perform patent and literature searches. Using the U.S. patent website, current designs were explored, some of which published by NUWC, that fit the needs of the project at hand. When confronted with these current designs, flaws were spotted of varying degrees.

After analyzing the problems with current payload integration systems, the process of attempting to improve and correct them began. This process included a preliminary concept design process in which 120 individual concepts were imagined, some of which were complete redesigns of current ideas, some of which sought to improve on mistakes of previous designs.

After careful analysis of each preliminary concept, the process of narrowing down the 120 concepts to a more realistic number began. This was conducted using cost and QFD analysis to determine practicality and relevance of each design. Factors such as universality and reliability were highlighted. After this rigorous process was conducted, two feasible and efficient concepts were left, both of which incorporated an extending and retracting mechanism. This aspect of the design was found to be of paramount importance due to the fact that it ensures that the gripper will be able to secure payloads of varying sizes, shapes, and orientations. The second aspect in which both concepts incorporated was an elastomer coated tip. This aspect is quite important as well because it increases the coefficient of friction to help better secure the payload. In addition, it also helps to increase shock resistance of the gripper due to high resiliency which is invaluable in a combat scenario.

When the team was confident in these two designs, in-depth engineering analysis was conducted to determine which design was most effective in gripping the payload securely. This analysis included displacement analyses for different materials, factor of safety analysis, shock analysis, and stress analysis amongst other tests. The final design was then chosen which highlighted a telescopic extending mechanism which would be powered by a hydraulic fluid and would contact the potential payload with a convex gripper head to ensure elasticity in the event of a large shock.

After this final design was chosen, additional force, pressure, and factor of safety tests were performed to optimize the angles of the arch of the convex tip as well as the wall thickness of the telescopic design. Finally, a 3-D print of the gripper head was manufactured as a proof of concept to be improved upon during the second semester.

Given the success of the first semester's proof of concept, the team was able to generate a comprehensive second semester project plan shown in Figure 5 which reflects the milestone dates for the capstone course as well as the expectations of NUWC. Research into optimal gripper material was conducted, comparing physical properties of a multitude of materials including strength, resistance to corrosion, weight, and durability. Cost was also a factor, but was not treated with the same level of importance as other factors as instructed by NUWC. The team settled on Aluminum 5083 as a result of its high strength to weight ratio as well as its resistance to corrosion which is of paramount importance in a saltwater environment.

Once this second semester project plan was generated and sufficient material research was conducted, the team began the process of 3D printing a 30% scale model of the entire gripper. This process proved to be of paramount importance due to the fact that the print was able to serve as a visual aid as to how the gripper would operate despite the fact that the 3D print was manually operated as opposed to being hydraulically powered as it would be in practice. In addition to a visual aid, a physical 3D print led the team to recognize some of the inherent problems with the design including problems with unwanted gripper rotation, sharp corners which could lead to payload damage, and gripper head size which led to issues upon initial extension of the gripper.

As a result of discovering these inherent issues with the gripper design, the team conducted a series of detailed FEA analysis to determine the best way to correct the issues. This FEA analysis included deflection testing due to gravity for each gripper ring as well as the gripper assembly as well as maximum shock and stress testing for the gripper assembly. This testing led the team to realize that certain dimensions of the gripper needed to be slightly altered in order for the gripper to function properly and to ensure that it is able to withstand the necessary forces that it would be exposed to throughout the duration of the mission.

In addition to a comprehensive redesign of gripper dimensions, certain additions to the gripper design were implemented in order to prevent the issues that the team discovered during the initial 3D print and FEA analysis. These additions included guiding track lines on each gripper ring in order to prevent unwanted gripper rotation, increased gripper head height in order to ensure proper gripper extension, and chamfered edges on each sharp corner in order to prevent damage to the payload.

After these redesigns were integrated into the design, further FEA analysis was conducted in order to ensure that these additions didn't compromise the structural integrity of the gripper design. After the team was satisfied with the results of these tests, the team 3D printed a high quality model to prove that the redesigned gripper would function as desired by NUWC. This high quality print highlighted the important aspects of the redesign process in addition to serving as a final product for NUWC to proceed with in coming years.

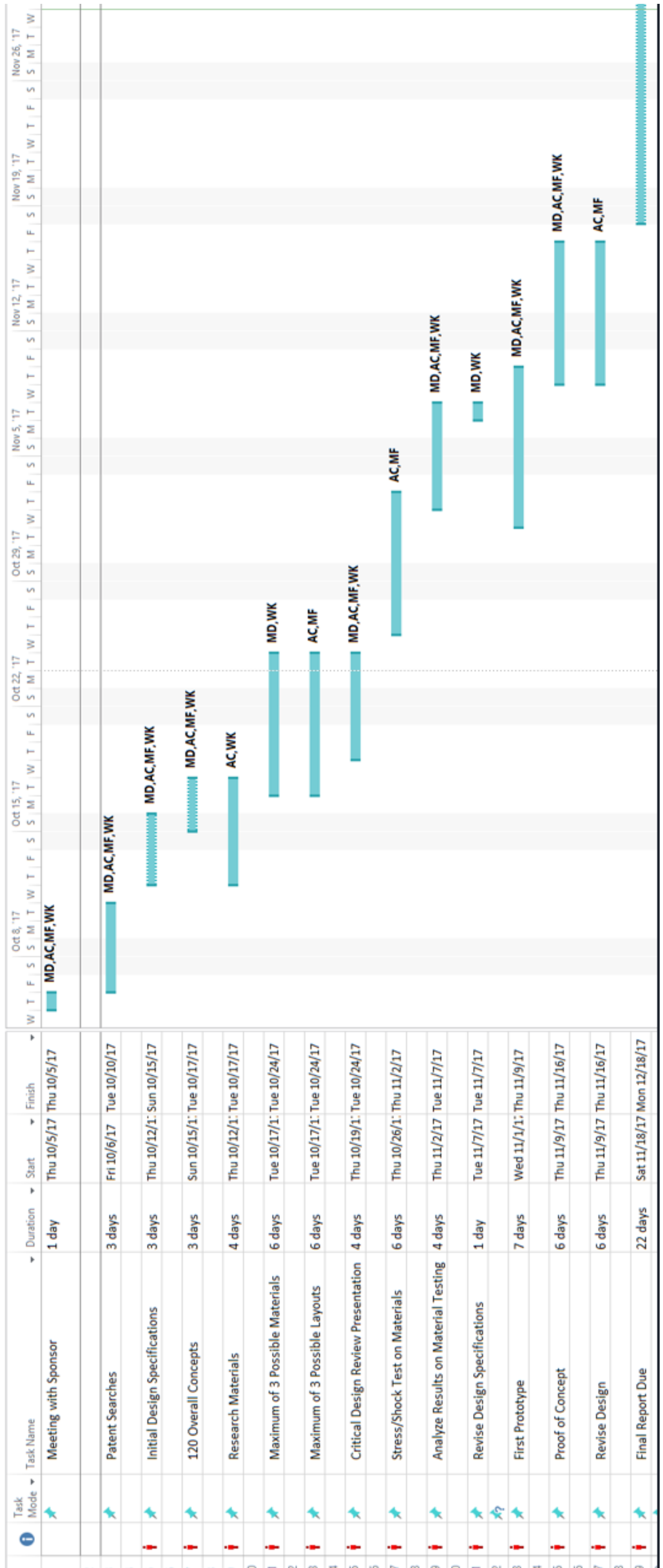



**Figure 4:** First Semester Project Plan & Gantt Chart

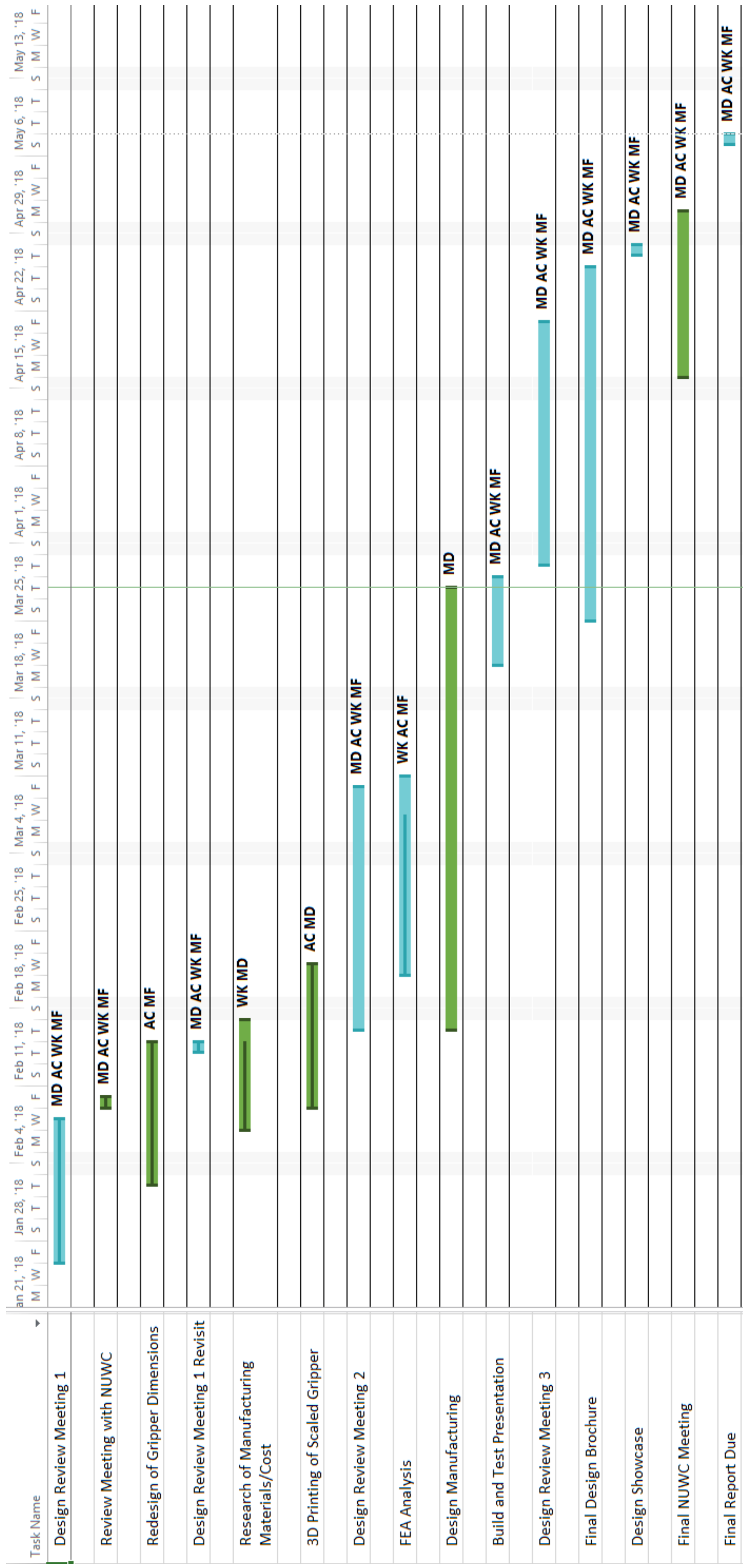



**Figure 5:** Second Semester Project Plan & Gantt Chart

# 3 Financial Analysis

## 3.1 Material Cost

**Table 1:** Cost of Metals

| Material | Price ($/lb) |
|---|---|
| Titanium | 30.00 |
| Aluminum | 0.90 |
| Nickel Aluminum Bronze | 4.00 |
| Inconel | 15-22.00 |
| Polyurethane Elastomer | 2.00 |

First semester included extensive research on materials that could potentially be incorporated into the gripper design. The team looked into four different metals, as well as conducted some research on polyurethane. These material are shown with their market value ($/lb) in Table 1, from resource [1]. Based on current market prices for the materials, the mechanical gripper will be more expensive than the current design from NUWC. The price range per gripper ranges from $49.86 to $1,662.00. This is strictly the cost of the material and does not include the manufacturing or personnel cost. On top of the material cost, the price per o-ring is approximately $ 20.00 per ring must be accounted for[2]. These prices are subject to change due to fluctuating market prices.

After discussions with NUWC, Prof. Nassersharif, and extensive research on the list of materials, the team decided to move forward with the Aluminum 5083. The strength mixed with the weight deemed best fit for this project design. Throughout the course of second semester, the team completed two 3D prints.

**Table 2:** Cost of Material

| - | Weight | Price ($/lb) | Cost |
|---|---|---|---|
| 3D Print - ABS Plastic | 2 Pounds | $2.50/pound | $5.00 |
| Aluminum 5083 | 81 Pounds | $8.33/pounds | $674.74 |
| 3D Print - High-Quality Plastic | - | - | $600.00 |
| - | - | **Total Cost:** | $1.279.73 |

Table 2 shows the cost of the two 3D prints and the material cost if the gripper were to me manufactured at full size. The plastic that is used in the 3D printers provided at Schneider Electric use ABS plastic. The 30 percent 3D print weighs two pounds and it cost $2.50 per point to print [3]. The gripper weight was determined to be 81 pounds and the cost for aluminum 5083 per pound is about $8.33 [4]. Finally the high quality plastic used with the high quality 3D printer at Schneider Electric was estimated to cost $600, per Prof. Nassersharif. The total cost for material is estimated to be $1,279.73.

## 3.2 Manufacturing Cost

The team started off the year with no budget. This made manufacturing the full size gripper infeasible. The team worked under having no budget nearly the whole two semester until Prof. Taggart reached out to Prof. Nassersharif on March 23rd, expressing he is willing to provide a budget of $3,000. This was extremely generous of Prof. Taggart, but due to time constraints the team did not have enough time to be able to have a full size model manufactured. The team did reach out to three possible manufactures for a potential quote, they have yet to get back.

## 3.3 Human Resource Allocation


**Figure 6:** Time Allocation

The total time Team 12 has spent on the project is approximately 408 hours first semester and 330 hours second semester, totaling 738 hours throughout the year. As indicated in Figure 6, most of the time was spent conducting research. Researching was immensely impotent due to the very in depth design specifications and standards set my the government. Following research. SolidWorks modeling was a very important use of time, including rigorous finite element analysis.

| - | Time Spent | Hourly Wage | Cost |
|---|---|---|---|
| **First Semester** | - | - | - |
| Team 12 | 408 hrs | $30.00 | $12,240.00 |
| Dr. Hardro | 4 hrs | $80.00 | $320.00 |
| Dr. Nassersharif | 3.5 hrs | $0.00 | $280.00 |
| **Second Semester** | - | - | - |
| Team 12 | 330 hrs | $30.00 | $9,900.00 |
| Dr. Hardro | 6 hrs | $80.00 | $480.00 |
| Dr. Nassersharif | 4 hrs | $80.00 | $320.00 |
| - | - | **Total Cost:** | $23,540.00 |

Over the course of the two semester, the team has consulted with both Dr. Nassersharif, Professor at the University of Rhode Island, and Dr. Hardro, sponsor from NUWC. Accounting for their time and Team 12, the total cost for both semesters adds up to $23,540.00.

# 4 Literature and Patent Searches

## 4.1 Literatures

Conducting research on literatures relevant to the goals and designs of the project is extremely relevant to our design process. Using the resources on similar experiments and similar materials is used to boost the total process of designing and creating the finished project. Many literatures researched for this project, include similar gripper designs, material research, and functions that can be incorporated into the design. A material analysis will be conducted on all material research in the project specific details and analysis section; the list of literatures will be shown below.

**Design and feasibility tests of a flexible gripper based on inflatable rubber pockets**

**Date:** December 5th, 2005

**Author(s):** Ho Choi & Muammer Koc; College of Engineering, University of Michigan

**Abstract:** This paper included feasibility test results of a flexible gripper design following a literature survey on various types, design and control strategies of the existing grippers. Having a flexible gripper being based on the use of compliant materials (Elastomer, rubber, ect.). Finite element analysis was conducted to test and investigate the design of a singular rubber-pocketed flexible gripper. Along with FEA, feasibility tests were performed to evaluate the limitation of the gripper device. The conclusion of this experiment was determined that objects of different shapes, weight, and types can be picked and placed without any loss of control of the object. [5]

**Relevance:** This literature is extremely relevant to the design process in which it does optimal research on elastomer gripper designs and performs experiments to test the most optimal weight, shape, and type. The conclusion of this experiment shows that choosing any factor listed can be put in place without any loss of control. This ultimately helped with choosing a shape that would best work for the designs created.

**A Positive Pressure Universal Gripper Based on Jamming of Granular Material**

**Date:** April 2nd, 2012

**Author(s):** John R. Amend Jr, Eric Brown, Nicholas Rodenberg, Meinrich M. Jaeger, & Hod Lipson; College of Engineering, Yale University

**Abstract:** This literature describes a simple passive universal gripper, consisting of a mass of granular material encased in an elastic membrane. With a combination of positive and negative pressures this gripper can rapidly grip and release a wide range of objects that are typically challenging for universal grippers. This gripper is powered by a vacuum which hardens to grip it rapidly after it passively conforms to the shape of a target object. By using both positive and negative pressure, it demonstrates performance increases of up to 85% in reliability, 25% in error tolerance. In addition, multiple objects are gripped and placed at once while maintaining their relative distance and orientation. In conclusion, this gripper successfully compares to other gripper devices and can be used universally. [6]

**Relevance:** This literature is relevant in a sense that the researchers at Yale discovered a device that can successfully detect and grip objects of multiple size, shapes, and orientation. Using this a reference is very beneficial to the design process, and was used to further the preliminary designs moving forward. The issue with this design was they use a vacuum to grip small materials, where one gripper is required. For the scope of NUWCs design, there must be many grippers to support a payload of massive proportion. This literature is a good reference, though we cant incorporate any concept into our design.

## 4.2 Patents

Patent searching is a crucial part of the design process. Knowing what is currently on the market is the first part of the designing and creating. Designing something that is currently designed and patented would be a total delay in the design process, if such patent already exists. Also viewing parents can help further a design by inspiring new ideas or possibly incorporating them into the design. Viewing patents can also show downsides of old designs, which can be used to keep the design team from making the same mistakes.

**US Patent #: 7,299,925/Flexible payload module with inflatable grippers**

**Date:** November 27th, 2007

**Inventor(s):** Ansay; Michael T. (Johnston, RI), Santiago; Mariela I. (Middletown, RI)

**Assignee:** The United States of America as represented by the Secretary of the Navy (Washington DC)

**Abstract:** A module for a payload that utilizes individual grippers in which each fill to a conical shape from an interior wall of the module toward a payload in the module. The shape of the grippers provides a holding strength on and lateral stability for the payload. The angle of the conical shape transfers the axial force of the payload into a tensional load on the gripper where it has comparatively greater strength. The conical shape of each gripper allows for more complete capture of a payload in that the grippers fill voids around the payload. Since there are more contact points with the grippers and the payload, the contact force required for an adequate capture can be spread out. [7]

**Relevance:** This patent is the design presented by NUWC at the sponsor presentation. This is the elastomer design NUWC created and tested. It expands and deflates as described in the intro. This design is used in a system to grip a payload. The goal of this project is to improve/redesign this gripper. Seeing this patent in the search shows the relevance of these searches.

**US Patent #: 9,714,057/Pneumatically actuated air control devices and methods**

**Date:** July 25th, 2017

**Inventor(s):** Smith; Jeffrey P. (Prosper, TX), Bezner; Bruce (Lindsay, TX)

**Assignee:** PACCAR Inc (Bellevue, WA)

**Abstract:** A pneumatically actuated air control device is provided. The device includes a control surface that affects the air flow along the device, and an at least one pneumatic motor configured to alter or change the configuration or orientation of the control surface or sections thereof. The device is configured such that when selective air pressure is supplied to the at least one motor, the control surface or sections thereof changes its configuration or its orientation with respect to the air flow, thereby affecting the air flow with respect to the device. [8]

**Relevance:** When constructing concept designs, the thought of incorporating a pneumatically actuated air control device is plausible. This patent is for a device that is configured such that selective air pressure is supplied to the at least one motor. This is relevant for control surfaces or sections to change its configuration though the air flow. This is beneficial if needed to affect the air flow with respect to a device in the design.

**US Patent #9,694,629/Self-repairing inflatable articles incorporating an integrated self-repair system**

**Date:** July 4th, 2017

**Inventor(s):** Dry; Carolyn M. (Winona, MN)

**Assignee:** Dry; Carolyn M. (Winona, MN)

**Abstract:** The present disclosure describes a self-repairing article comprising an inflatable component comprising one or more material layers wherein at least one material layer comprises an elastomer. It also describes a self-repairing article comprising a sealed flexible package disposed within or between material layers of the inflatable component, and a repair composition disposed in the sealed flexible package, wherein the sealed flexible package comprises a metal foil and is configured to release the repair composition upon puncture of the inflatable component. [9]

**Relevance:** This patent was relevant to the design process, in which it has to do with an inflatable component such that is relevant to NUWC's first design. This design is beneficial because it has a self-repairing article that is within or between layers of the material. If it was choosing to move forward with the elastomer design, this would be an extremely useful patent to exploit.

**US Patent #9,778,014/Method and position sensor assembly for determining a mutual position between a first object and a second object**

**Date:** October 3rd, 2017

**Inventor(s):** Hoglund; Anders (Munka Ljungby, SE)

**Assignee:** FREEVALVE AB (Angelholm, SE)

**Abstract:** A method and position sensor assembly for determining a mutual position between a first object and a second object. The position sensor assembly includes a first body, a coil, a control unit, and a sensor circuit, the first body being reciprocally displaceable in the axial direction in relation to the coil. The sensor circuit includes in turn a comparator connected to a first branch including the coil, a power switch, and a measuring resistance coupled in series with each other. [10]

**Relevance:** This patent is extremely relevant because the design ultimately incorporated hydraulics to power the extension of the gripper. This patents focus is on position sensor assembly for determining a mutual position between a first object and a second object. Ultimately the design is using fluids to extend the gripper, though sensors systems can be incorporated to improve the exactness of the design. Moving forward, a sensor is planned to be placed on the head of the gripper to stop the gripper when it comes in content with a payload.

# 5 Evaluation of the Competition

In terms of market competition, being that a universal gripper concept has never been used in the field, there are not yet any products which directly compete with this design. However, NUWC has created a preliminary design concept of their own which can be compared to the hybrid convex-tipped telescopic gripper concept design on various levels.

The NUWC design consists of an inflatable conical gripper made entirely of a semi-rigid elastomer which is inflated using a fluid to grip and secure a potential payload. The main differences between the two designs include the material, the overall strength, and the durability of the grippers.

Though both materials accomplish the specific task of securing a payload of varying size, shape, and orientation, the NUWC design is relatively inefficient in doing so. This is due to the fact that the elastomer material, though very pliable, lacks the strength and durability of the hybrid design.

The use of an anti-corrosive metal increases the strength of the design exponentially when compared to an elastomer. This is of paramount importance since stronger individual grippers can contribute towards decreasing the total number of grippers in use.

In addition to strength, a hybrid design increases overall durability of the gripper. After a number of inflations and deflations, elastomers will wear over time, deforming permanently and weakening. This can lead to more frequent servicing and replacements which can be costly and inconvenient especially during the duration of a 6-month mission. The hybrid design resolves that issue with a base made of metal. It is capable of more uses without failure due to the fact that metals have higher ultimate yield strengths when compared to elastomers.

This leads to a more fail-safe product with the use of a hybrid convex-tipped telescopic design. This is of paramount importance due to the fact that throughout a mission duration, a submarine may not have the luxury of being able to service a damaged gripper. This means that a mission could be gravely hindered in the event of a gripper failure. This being said, incorporating a hybrid design with more reliable materials greatly decreases odds of failure and therefore makes for a more efficient and optimal design.

One area where the NUWC design has an advantage over the Let It Grip design is cost. The material being used, in addition to the fact that the NUWC design is one piece, makes it more easily manufactured and cheaper. Though elastomer material isnt as strong as the metal chosen in the Let It Grip design, it is much cheaper to produce in bulk. In addition, the elastomer is easier to mold and manufacture into the desired shape which is helpful in the case of large-scale manufacturing.

Of note is the scale of production of these grippers, which will be small scale - most likely less than 100 a year. That being the case, strength and reliability outweigh cost and ease of production when it comes to this specific task of designing a universal gripper. The most important demands of this product are that it must maintain the integrity of the payload and that it must be able to secure a payload of varying sizes, shapes, and orientations. Both of these requirements are fulfilled by both designs, however, the Let It Grip design is superior in the sense that it can do so for longer, and more efficiently.

The comparison indicates a market advantage for Team 12's design despite the slight cost advantage that NUWC's design may have. For the Department of Defense, cost is not nearly as important as mission success and overall reliability of a product. This product will likely endure brutal conditions such as vast temperature and pressure fluctuations, exposure to corrosive media such as saltwater, and severe shock events throughout a duration of a mission.

# 6 Specifications Definition

A specific set of preliminary design requirements were given by NUWC to highlight what was expected when designing a universal gripper concept. The most important of these requirements was universality. This means that the gripper concept must be able to securely hold a payload of a wide range of sizes, shapes, and orientations. These ranges are specified in Table 3.

Of the most important design requirements, integrity of the payload and universality are two major requirements to meet with the main objective being universality. This is accomplished by designing a hybrid gripper incorporating both metallic and elastic components with fail-safe mechanisms to keep the gripper functioning in the event of concentrated shock during the course of a mission. Table 3 highlights the remaining design specifications.

**Table 3:** NUWC Design Specifications

| **Specification** | **Allowance** |
|---|---|
| Gripper Width/Diameter | Max 18” |
| Gripper Retraction & Extension | 7.5” - 33” |
| Total Number of Grippers in System | TBD Next Semester Upon Further Tests |
| Max Force Apploed on Each Gripper | TBD Next Semester Upon Further Tests |
| Accessibility | Hatch or Pump access to hydraulic fluid |
| Life Cycles | 100 Extensions/Retractions |
| Life Span | 6 Month Mission Duration |
| Tube Size | 419” Length, 87” Diameter |
| Use of Mechanism | Individually Controlled Grippers |
| Fluid Proofing | Gripper Must be Water-Tight |
| Budget | None (within reason) |

Once these initial design specifications were given, the convex-tipped telescopic gripper design was established and was compared to each design specification Table 4 to ensure that the concept was feasible, high-quality, and accomplished each of the design requirements given by NUWC.

**Table 4:** Design Specification Fulfillment

| Allowance | Final Design Concept |
|---|---|
| Maximum of 18” | 18” Base Diameter |
| 7.5” - 33” | 7.5” - 33.25” |
| Total Number of Grippers in System | 72 (12 rows @ 6 grippes per row) |
| Max Force Applied on Each Gripper | 458 lbs (constant) 1833 lbs (instantaneous) |
| Hatch or pump access to hydraulic fluid | Access to Fluid Pump System |
| 100 Extensions/Retractions | Specification Met |
| 6 Month Mission Duration | Specification Met |
| Individually Controlled Grippers | Specification Met |
| Fluid Proofing | Specification Met |
| No Budget (within reason) | Multiple 3-D Printed Models (Free) |

These values were derived by first analyzing the given dimensions of the tube in which the gripper would be placed. Once given these dimensions, the optimal amount of grippers were calculated using tolerances based on possible gripper diameter-to-length ratios. This amount was determined to be 72 grippers in a system, a value which would be used solely for assumptions for future calculations. This led to the optimal gripper diameter of 18 inches.

Once the gripper diameter was established, using the potential payload dimensions shown below, the maximum extension and minimum retraction of the gripper systems were determined to ensure capability of securing a payload of any of the required sizes. The extra 0.25 inches of tolerance upon full gripper extension was implemented into the design to ensure that when loading the smallest potential payload, the gripper and payload would not sustain any damage.

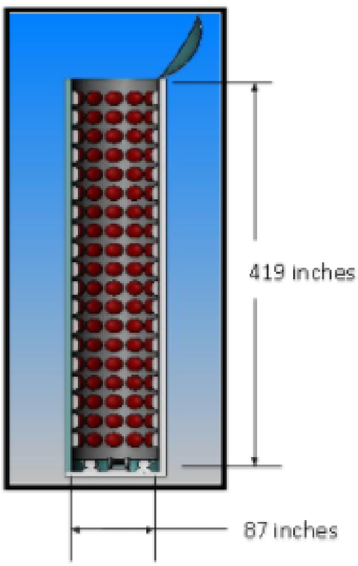
The possible weights of which a gripper may be subjected were calculated using the heaviest possible payload shown below, then distributing that value onto 72 grippers. This value led to the weight that gripper would constantly be subjected to. For the instantaneous weight that a gripper may be subjected to, the constant value was increased by a factor of 4 to simulate a shock event that a gripper may sustain throughout the duration of a mission.

In terms of the gripper extensions and retractions as well as lasting the duration of the mission, the use of the Aluminum 5083 supports the fact that the design specifications will be met. This is due to high durability and strength to weight ratio of the aluminum 5083. It is expected that the Let It Grip design will meet these design specifications using educated engineering judgment.

For fluid proofing, calculations were done using L/d ratios to ensure that when extending or retracting, the multiple gripper tiers would not bind or pinch causing a jamming of the system. In addition to these calculations, O-ring tolerances from [11] were used to determine optimal dimensions of gaskets implemented in each tier of the telescopic base. These O-rings are used to seal the design.

For budget, it is acknowledged that there is no budget. However, the gripper design must prove to be an optimal and effective solution to the problem at hand. This is under the assumption that attempts were made to be as cost effective as possible while failing to sacrifice any and all considerations to make the gripper concept meet all expected goals to accomplish the specified task.

In terms of the specific payload dimensions that a gripper may experience, due to lack of security clearances, exact dimensions could not be given. In their place, a table of different sized rectangles and cylinders were given. These shapes are chosen as they are the most likely generic shapes that a gripper may encounter throughout a mission. The table expressing potential dimensions is shown below.




| Shape | Length (in.) | Width (in.) | Height (in.) | Diameter (in.) | Weight (lbs.) Dry |
|---|---|---|---|---|---|
| Large Rectangle | 350 | 50 | 50 | | 25,000 |
| Medium Rectangle | 246 | 42 | 30 | | 7,000 |
| Small Rectangle | 36 | 36 | 36 | | 1,000 |
| Large Cylinder | 300 | | | 72 | 22,000 |
| Medium Cylinder | 200 | | | 36 | 11,000 |
| Small Cylinder | 132 | | | 21 | 3,000 |

**Figure 7:** Given Potential Payload Dimensions

# 7 Conceptual Design

In the beginning of the design process, each member of the group was tasked with the creation of Thirty unique possible design solutions. These concept ideas were documented with descriptions of the concept as well as a relevant illustration. These concepts are presented in the following sections. Each concept contains a grade on relevance to the overall Design Project.

## 7.1 Austin Cordova Concept List

Types of Metal for use in Gripper

1. Stainless Steel - Grade: 8

   Stainless Steel is strong, non-corrosive. It can be used in the construction of the gripper arm; however may cause damage to payload if used for the contact surface with payload.

2. Aluminum - Grade: 8

   There are non-corrosive alloys of aluminum. It is light and easier to manufacturer as compared with other metals, but is not as strong. It can be used for the construction of gripper/piston arm, but may cause damage to payload if used for contact surface.

3. Titanium - Grade: 6

   Very strong metal and is lighter than steel and corrosion resistant. Titanium is more expensive to manufacture. It can be used for construction of gripper/piston arm, but may cause damage to payload if used for contact surface.

4. Brass - Grade: 4

   High malleability makes it easier to construct parts out of Brass. Has strong resistance to corrosion and can be used in construction of gripper/piston assembly.

5. Cast Iron - Grade: 3

   Very easy and cheap to manufacture as well as strong. The material is very susceptible to corrosion that can weaken the material over time. Can be used for construction of gripper/piston arm, but may cause damage to payload if used for contact surface.

Types of Solid Material for use in Gripper

6. Composite Material - Grade: 8

Combination of metal matrix and high strength fiber can be specially designed to fit the needs of this project. Would require more research and development of material, and can be costly to design and manufacture.

7. High Durometer Urethane - Grade: 7

   High durometer urethane can be custom molded into shapes necessary for construction. High durometer = high strength and low deformation. Can be used for any of the assembly of the gripper system. Can be cheap or expensive depending on type of urethane and complexity of the parts.

8. Carbon Fiber - Grade: 6

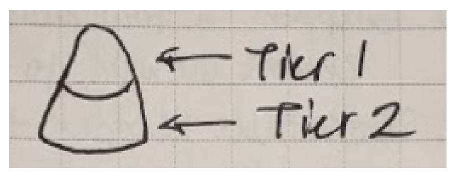
   High strength material can provide adequate support for gripper and payload. Carbon fiber can be expensive to manufacture into parts, especially more complex shapes.

9. Glass Fiber - Grade: 5

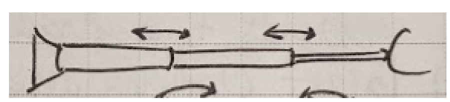
   Easy to manufacture and can be strong enough to support loads of payload. Material would be susceptible to shock damage, since the glass is strong but brittle.

Designs for Gripper

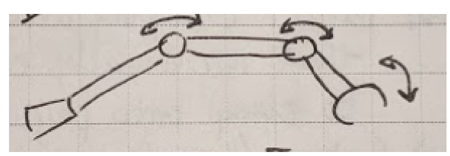
10. Extendable Conical Shape in Tiered Design - Grade: 7
    Gripper extends in conical shapes built in series, and extends until contact with payload is made. This allows gripper design to be more compact and can be filled with either air or liquid.



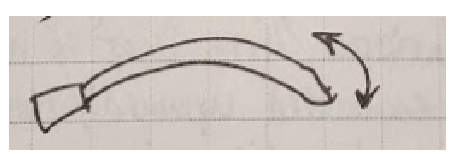

11. Extendable Arm Actuates in Tiered Design - Grade: 8
    Similar to conical design, this design works with layered actuators that extend and retract in a linear motion. This design also allows a compact gripper design that can be filled with a fluid (hydraulic design).



12. Swayable Arm Rotates into place - Grade: 5
    This design features a gripper that doesnt extend and instead rotates into place to fit the payload. This design is not compact, but may be easier to implement.

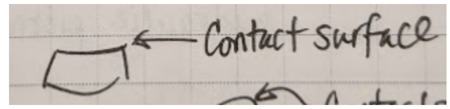


13. Curved Arm Rotates into place - Grade: 4
    Similar to (12), this design features a curved arm as opposed to members joined together in joints. The curved arm will rotate into place to meet the payload.



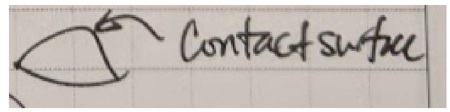
14. Flat Tipped Gripper - Grade: 8

    Tip of gripper is flat and will be composed of any material. Flat tip will be beneficial in distributing the supporting load on the payload and preventing high stress areas.



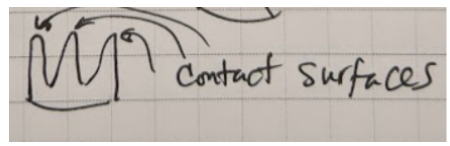

15. Round Tipped Gripper - Grade: 8

    Tip of gripper is dome/rounded outward and would be composed of a softer material/fabric to soften the load on the payload.



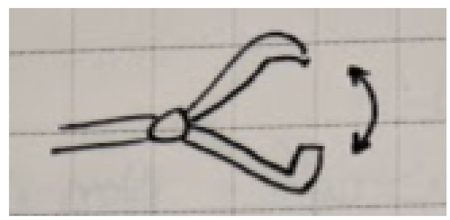
16. Branched/Finger Design of Gripper - Grade: 5

    Finger design of gripper increases the number of contact points while also distributing the supportive load. Gripper could be made of any of the materials chosen.



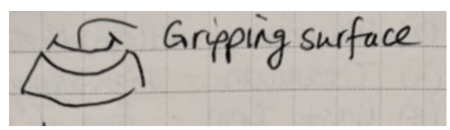

17. Clamping Tipped Gripper - Grade: 6

    Clamping device located on tip of gripper that allows for surface contact on an adjustable area. This also considers irregular shaped payload.



18. Concave Tipped Gripper - Grade: 7

    Concave tipped gripper allows for a better shaped tip for round/cylindrical payloads. This design can be made from flexible or stiff material to provide support.

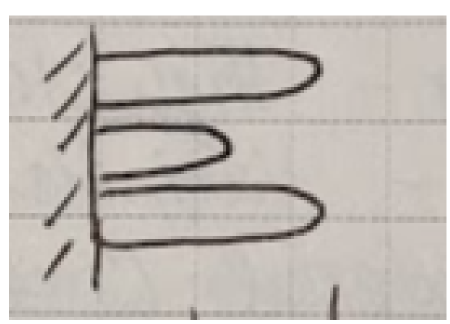



19. Angled Orientation of Grippers - Grade: 8

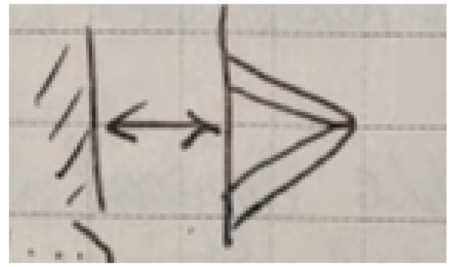
    Grippers extended at different angles to provide both horizontal and vertical support of payload. Different angled grippers also combine to provide better stability and support.


20. Tapered System of Grippers - Grade: 7

    Grippers alternate between fully extending and partially extending. Partially extended grippers would act as a supportive failsafe.

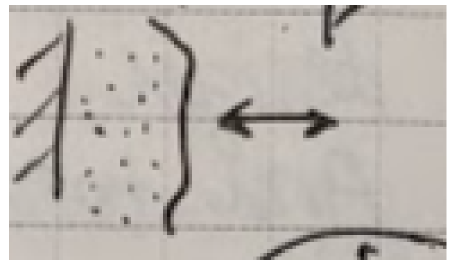


21. Extendable Grippers in Triangular Setup - Grade: 7



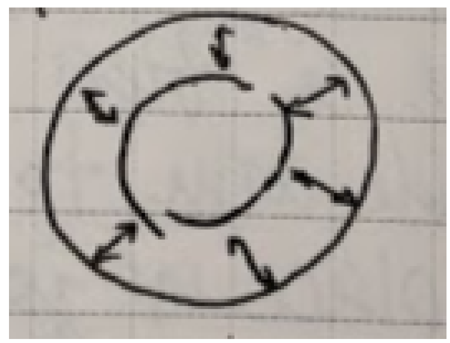
Grippers are laid out in a triangular formation and are placed on an extendable platform. This extendable platform is extended outward until contact with payload is made.

22. Inflatable Bladder Design - Grade: 6



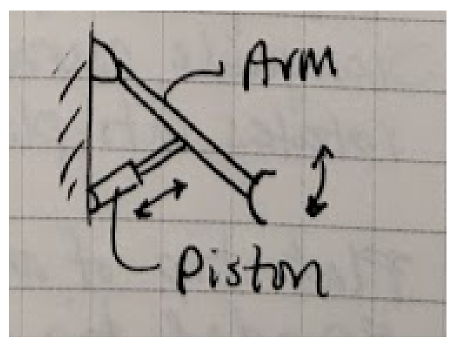
Vertical launch tube is lined with extendable bladder that is filled with fluid. Inflatable bladder is extended until contact with payload and acts as a pillow.

23. Giant Round Clamp - Grade: 4



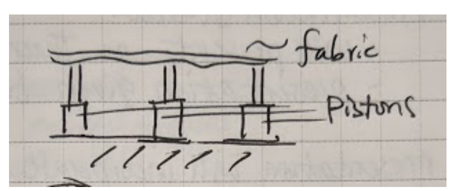
Two or Four part clamp that lines the walls of the payload tube and extends until contact with payload. Clamps are piston-powered and can be shaped to be as large/small as needed.

24. Hydraulically Extended Gripper/Arm - Grade: 7




Gripper/arm is full length and is extended by a hydraulic piston outward to meet with payload. This design is stronger than linearly extending designs, but is more robust and takes up more space.

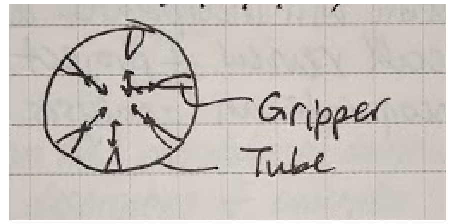
25. Soft Material Covered Piston Design - Grade: 7




Pistons lined along wall of payload tube and are covered in soft material. These pistons extend until contact with payload and the softer material that makes contact with payload helps soften and distribute the load applied.

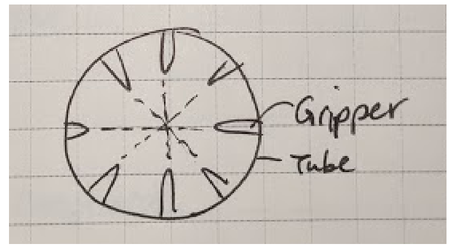
26. Six-Point Circular Gripper Array - Grade: 6

    Six grippers aligned in a circle that extend to support the payload. Six grippers dont require as much space, and will provide an adequate amount of support.



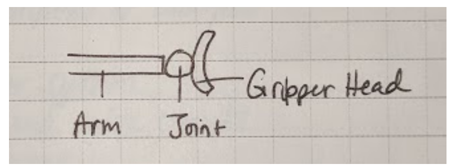

27. Eight-Point Circular Gripper Array - Grade: 8

    Eight grippers aligned in a circle that extend to support the payload. Eight grippers take up more space, however work to better apply loads in the horizontal axes, and support the payload better.



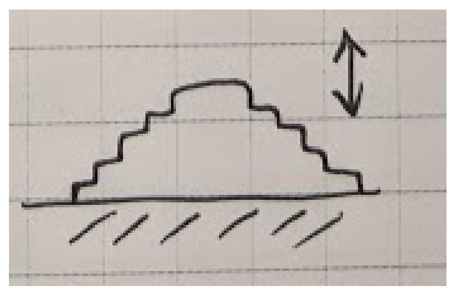

28. Rotational Gripper Head - Grade: 7

    Gripper head is attached to a rotating joint that can rotate to better fit the side of the payload. This joint helps better fit the gripper to the payload, and helps distribute supportive load.



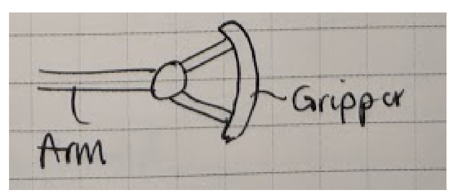

29. Extendable/Inflatable Pyramid Design - Grade: 8

    Pyramid design allows the gripper to fully collapse and then extend outward upon being filled with air/fluid. The pyramid design helps provide structural support to the gripper itself and maintain integrity of the gripper.



30. Convex Gripper Head - Grade: 7

    Solid convex gripper head acts as a supportive surface to payload, and also allows a dampening effect. This dampening effect helps support against sudden forces and shock events.

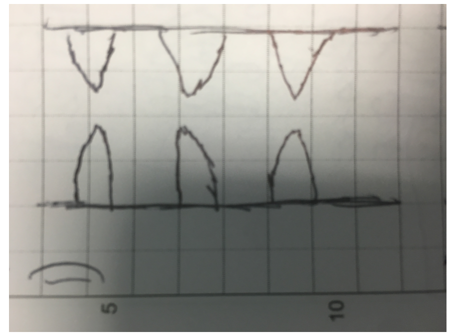



## 7.2 Matthew Delia Concept List

Designs for Gripper Layouts

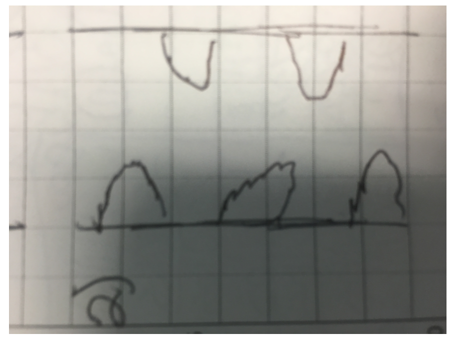
1. Uniform Layout of Conical Grippers - Grade: 10

The "Classic" layout of ring-formed grippers. This formation is beneficial since each side of the payload would be uniformly held.



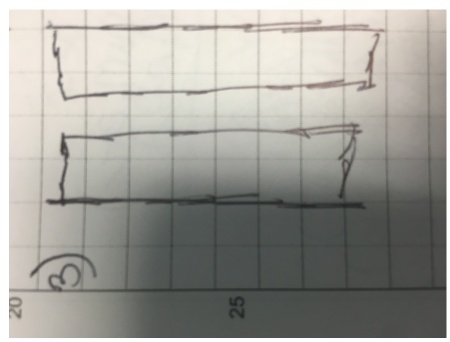

2. Staggered Layout of Conical Grippers - Grade: 10

   The staggered layout of grippers would be beneficial as abnormally shaped payloads could be help more effectively.



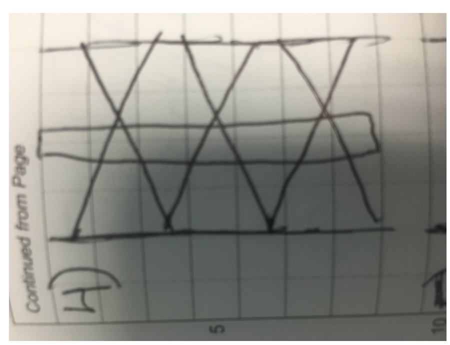
3. Singular Inflatable Membrane - Grade: 7

   Instead of individual grippers, one continuous gripper inflates and molds to a payload of any size, shape, or orientation.



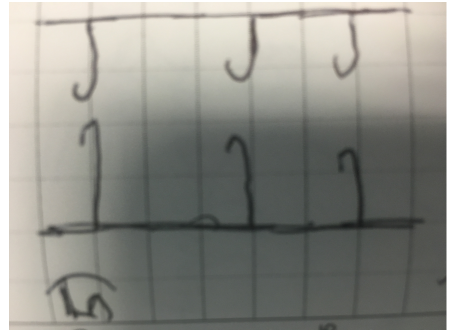

4. Elastic Resistance Bands - Grade: 4

   Elastic bands that expand and wrap around the payload to keep it stationary throughout the duration of a mission.



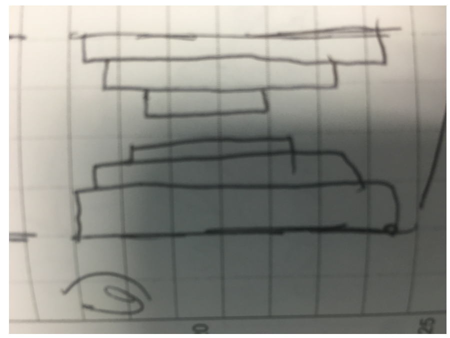

5. Hook Grippers - Grade: 3

Hooks that attach to a payload to keep payload stable during a mission. Hook loops could be attached and removed from potential payloads.



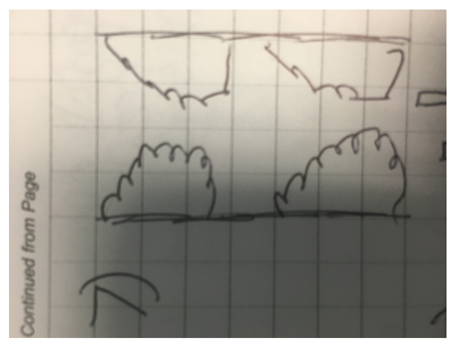
6. Retractable Walls - Grade: 3

Retractable walls that extend to hold and stabilize payload throughout a mission. The walls could be lined with soft materials.



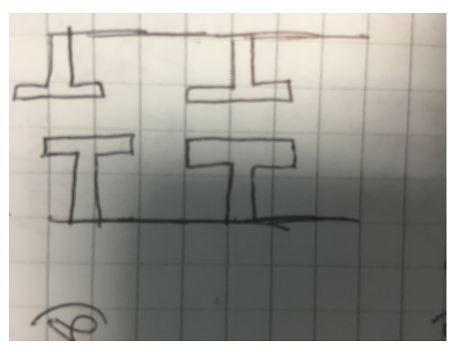
7. Air-Bag Grippers - Grade: 1

Air-Bag-like cushions deploy to hold payload in place during a mission.



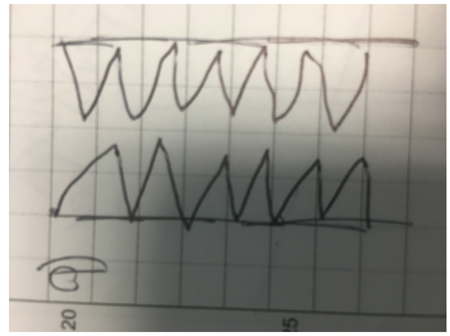

8. T-Shaped Grippers - Grade: 2

T-Shaped rods that extend to stabilize payload with higher surface area contacting a payload.



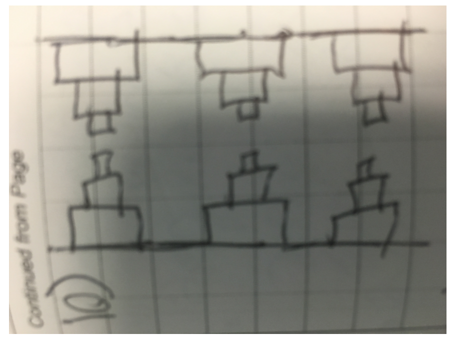

9. Pyramid Grippers - Grade: 8

Pyramid shaped inflatable grippers of varying sizes to hold payloads of abnormal shapes and sizes.



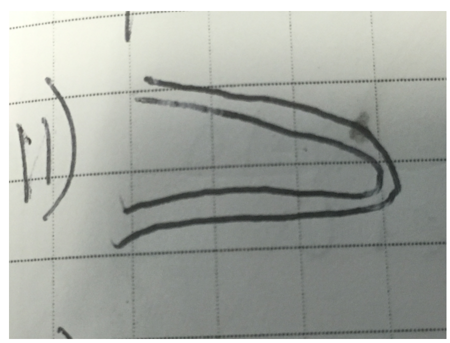
10. Retractable Metal Grippers - Grade: 9

    Retractable Metal Grippers that sense when contact with a payload is made to prevent potential damage to either payload or gripper.



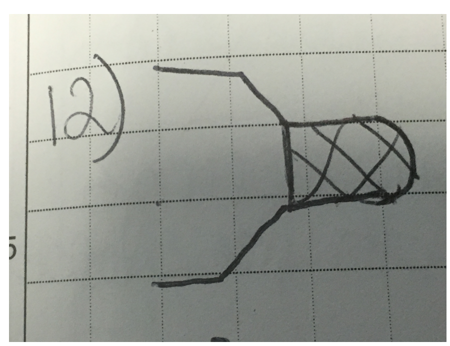

Designs for Individual Grippers

11. Inflatable Conical Grippers - Grade: 10
    Inflatable conical grippers with puncture resistant layers.



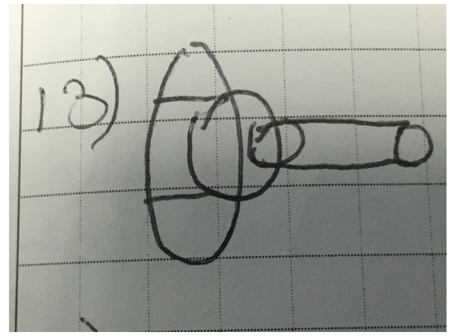

12. Retractable Metal Grippers - Grade: 10

    Metal retractable grippers with soft rubber tip to gently but firmly hold payload.



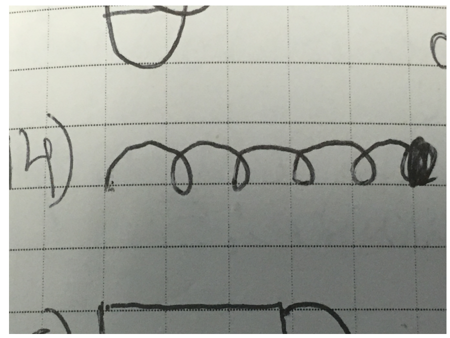

13. Extending Rods - Grade: 6

Extending rods with small tip to ensure more possible orientations and layouts can be held securely.



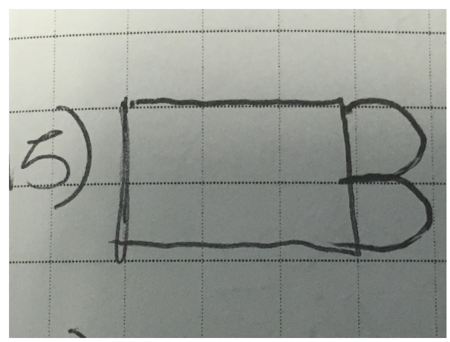

14. Retractable Spring - Grade: 6

Retractable spring to increase ability to resist possible shock events and absorb additional forces.



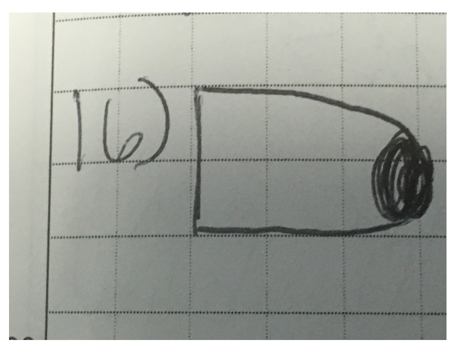

15. Multiple Gripper Heads - Grade: 5

Multiple rubber heads on one retractable metal arm to increase coefficient of friction against payload.



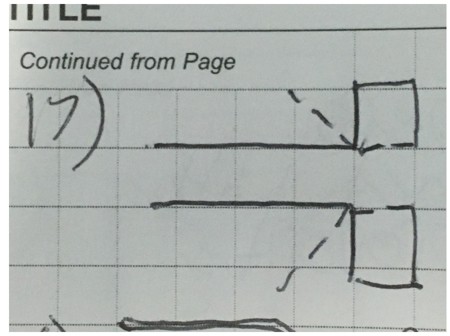
16. Pressure Sensor Gripper - Grade: 10

Gripper with pressure sensor in tip to stop inflating mechanism once contact with payload is made.



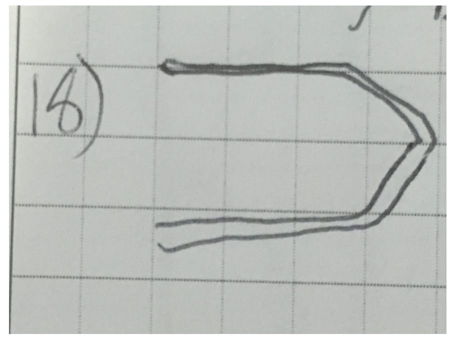

17. T-Shaped Gripper - Grade: 7

T-Shaped gripper with collapsible braces to increase possibility of payload orientation and shapes that can be held.

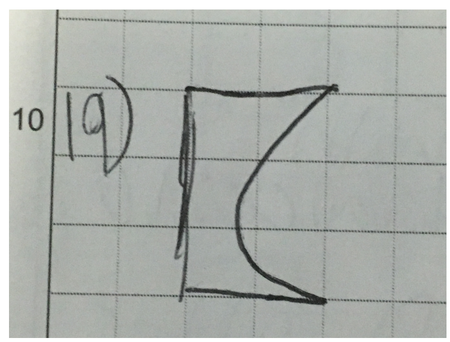



18. Coated Gripper - Grade: 8

Retractable rubber-coated gripper to increase coefficient of friction and increase shock resistance.

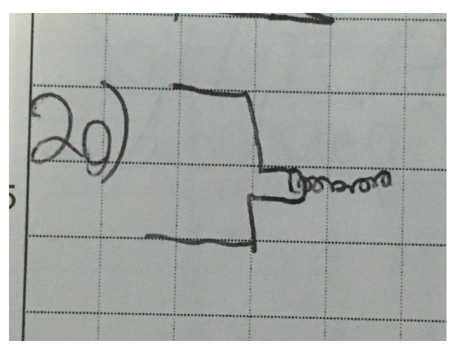



19. Concave Gripper - Grade: 6
Concave gripper designed to firmly secure rounded payloads throughout a mission.




20. Spring-Tipped Gripper - Grade: 4

Gripper with small yet firm springs on the end to increase shock resistance but are easier to control.




<u>Types of Material for use in Gripper</u>

21. Polyisoprene - Grade: 6

Cheap to manufacture, naturally occurring, wide range of hardness values.

22. Acrylic - Grade: 5

    Capable of withstanding extremely high temperatures.

23. Perfluorocarbon - Grade: 7

    Compatible with vast ranges of chemicals, oils, and water.

24. Thermoplastic Polyurethane - Grade: 8

    High abrasion resistance and impact strength. High flexibility and elasticity.

25. Aluminum Alloy - Grade: 4

    Durable, light-weight, and ductile.

26. High-Carbon Steel - Grade: 7

    High in strength and durability. Commonly used in industry for industrial-strength springs.

27. Gold-Platted Steel - Grade: 4

    High in strength and resistant to rust so longer lifespan can be expected in saltwater but very expensive.

28. Titanium - Grade: 7

    Corrosion resistant, highest strength-to-density ratio of any metallic element but very expensive and difficult to machine.

29. Stainless Steel - Grade: 8

    Especially resistant to salt water and very durable.

30. Steel with Anti-Corrosive Paint - Grade: 10

    Cheaper alternative to plating and non-corrosive metals, also very easy to maintain.

## 7.3 Michael Ferreira Concept List

Types of Metal and Systems for use in Gripper

1. Aluminum - Grade: 8

   Use more grippers with an aluminum alloy. Not as high strength as other metals but more affordable.

2. Steel - Grade: 7

   Steel is durable, high strength and not overly expensive. Some steels are corrosive so research is important.

3. Hydraulic Actuator - Grade: 8

   This system would allow the user to move a gripper in and out.

4. Titanium Alloy - Grade: 6

   Titanium is corrosion resistant but is extremely expensive. (Moderate density and high strength)

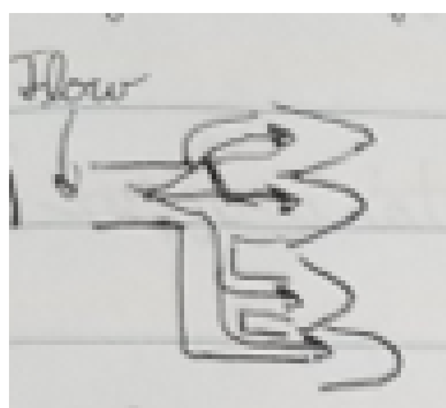
5. Inconel - Grade: 5

   Inconel is a high strength, corrosion resistant metal but is expensive. One up side would be the use of less grippers.

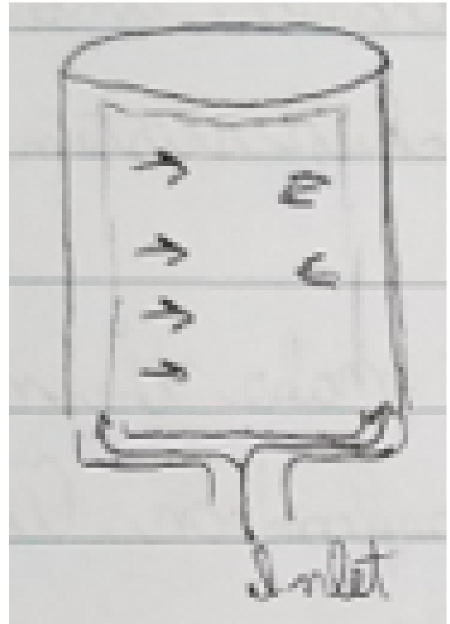
Designs for Gripper

6. Grade: 8

   A system of pipes that spreads out the inlet flow evenly to inflate each gripper evenly.

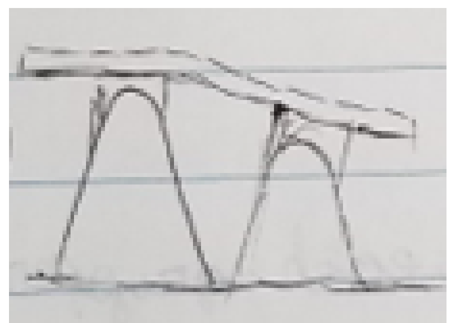


7. Grade: 3
   Have a system with fully inflatable walls. The walls would be inflated by two pipes until the payload is fully secured. Then the inlet is closed to keep the pressure constant.



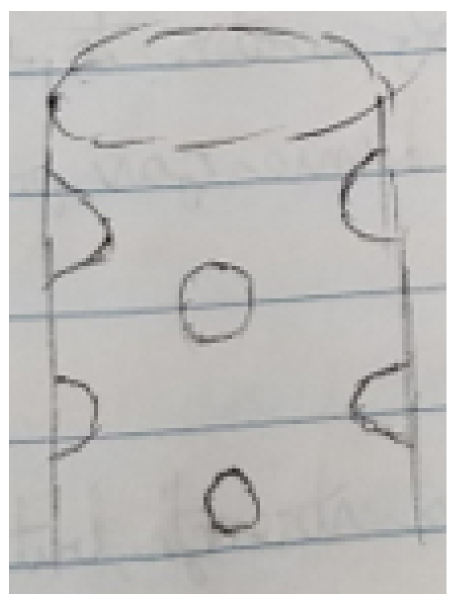

8. Grade: 6

   Add an attachment to the gripper such as a long ”blanket” that lays on top of the gripper. The material would be a form of rubber to add friction.



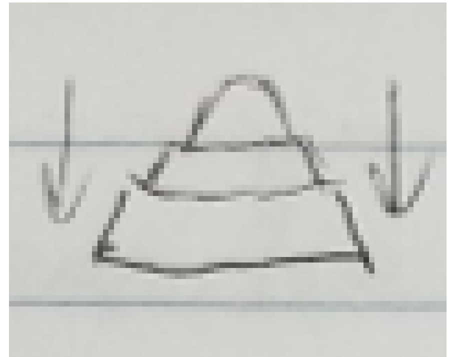
9. Grade: 6

   Use metal grippers to cut down the amount needed to hold the payload.



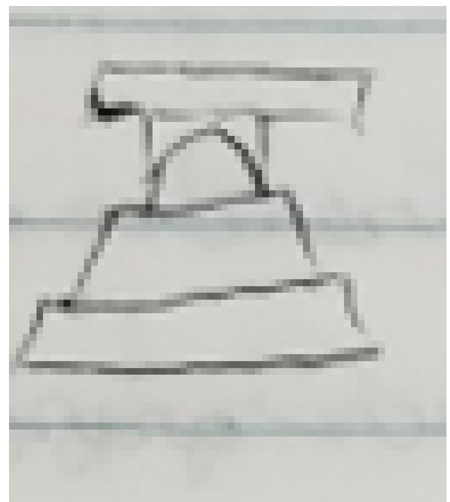
10. Grade: 7

    Use metal grippers that fold inside each other. This allows the gripper to stop at different points.



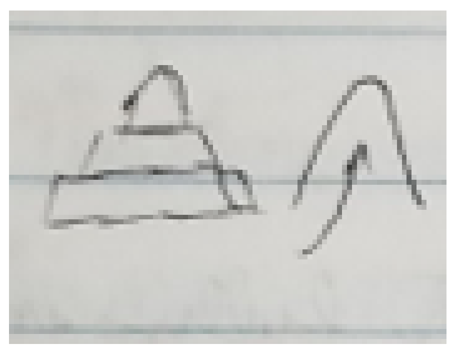
11. Grade: 9

    Use a hybrid design of the metal gripper and "blanket".



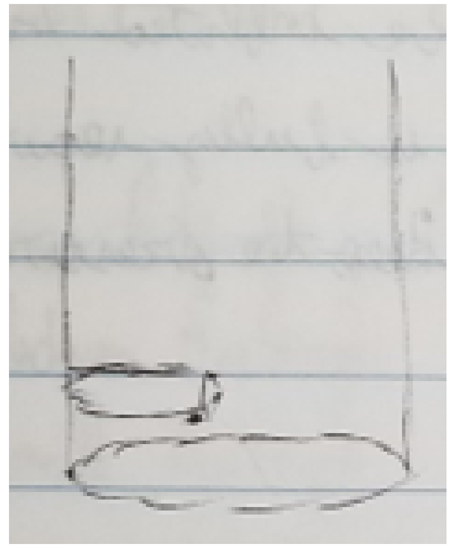
12. Grade: 7

    Alternate between mechanical and inflatable gripper as a backup system.



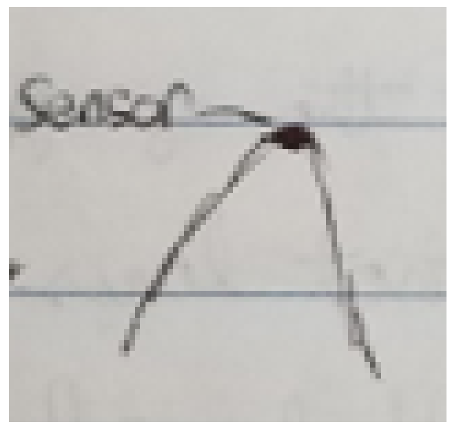
13. Grade: 2

For added support make a mechanical "table" to lay the payload on.



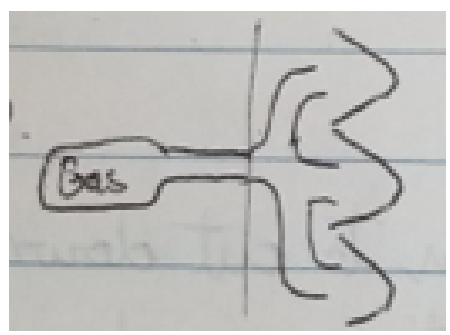
14. Grade: 8

Add a sensor to each gripper to make sure every gripper is keeping a constant force.



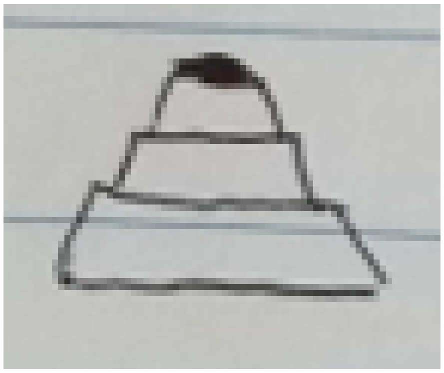

15. Grade: 5

Use a gas instead of water to inflate each gripper. (Dense gas preferred)



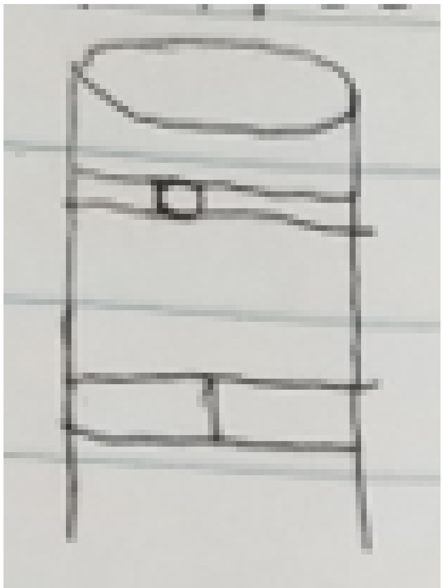

16. Grade: 9

Use a metal gripper bas for strength but have the tip be an elastomer.



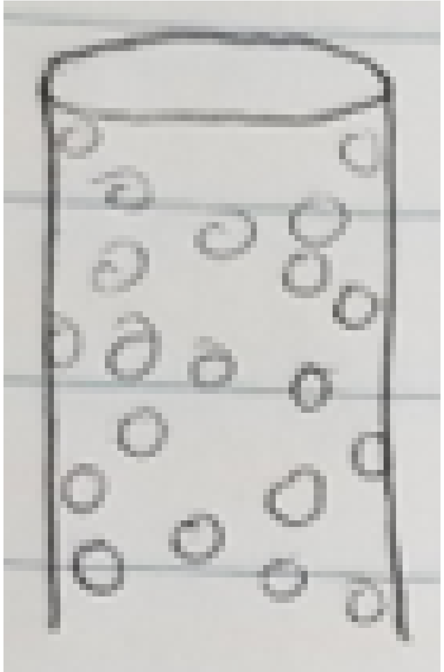
17. Grade: 2

Have metal arms that go across the whole diameter of the tube. Holds the payload between the plates.



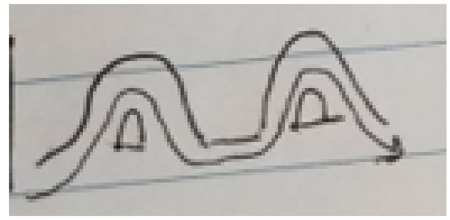
18. Grade: 6

Use a criss cross pattern for proper support. Possibly cuts down the amount of grippers needed.



19. Grade: 5

    Have a constant flow that inflates the grippers.

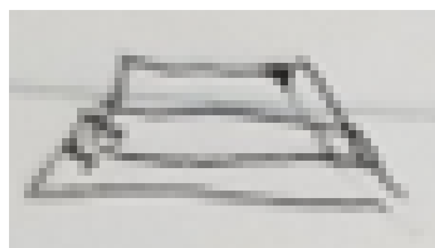


20. Grade: 6

    Small pistons come out to hold the payload.

21. Grade: 5

    Use multiple hooks in the mechanical grippers to hold everything in place.

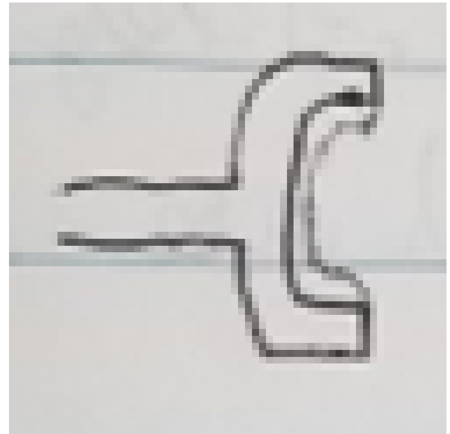


22. Grade: 4

    Use claws to grab the payload.

23. Grade: 5

Each claw has an inflatable piece to form to the payload.

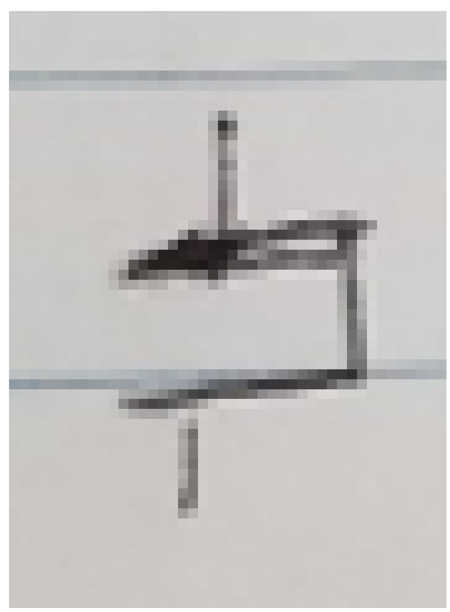


24. Grade: 3

Use a magnet at the end of each gripper to hold the payload.

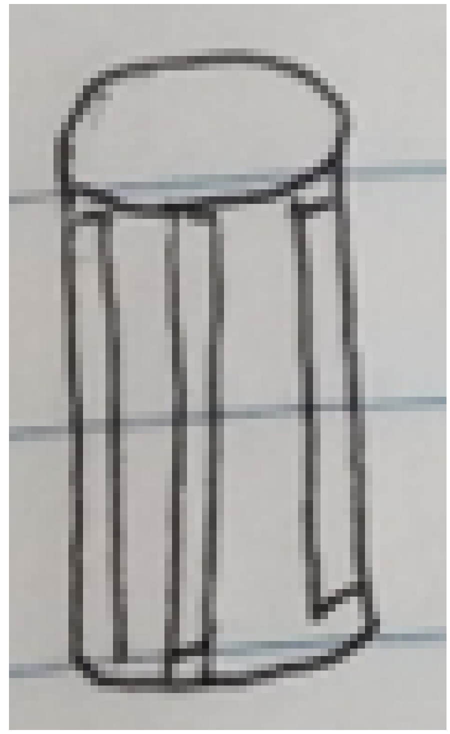
25. Grade: 2

Use a crank system to move the grippers in and out.



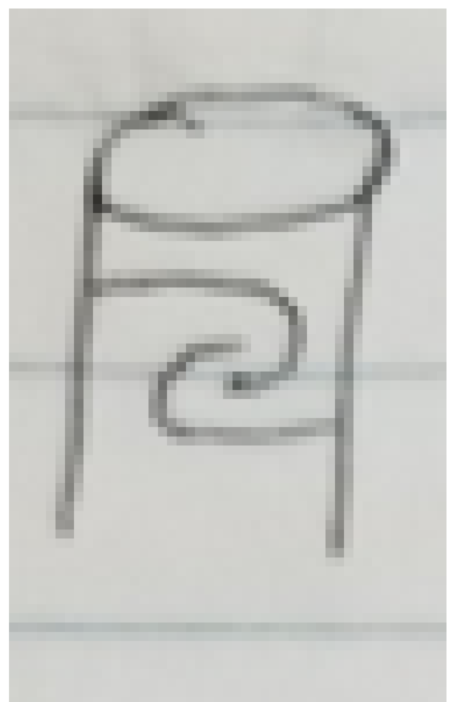
26. Grade: 4

Staggered walls come out using a hydraulic actuator.



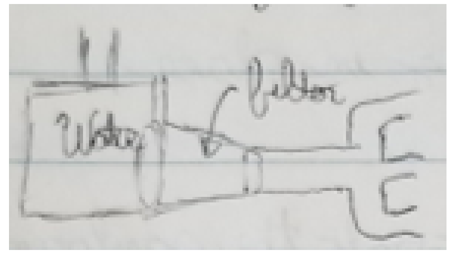
27. Grade: 3

Use hooks to grip the payload and fully secure it.

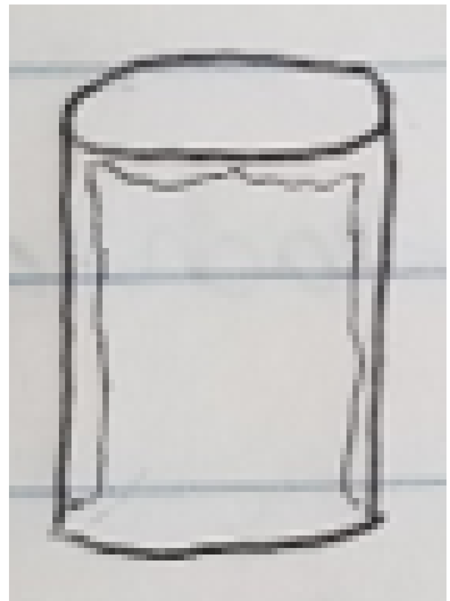


28. Grade: 5

Use a filter to purify seawater to fill the grippers.



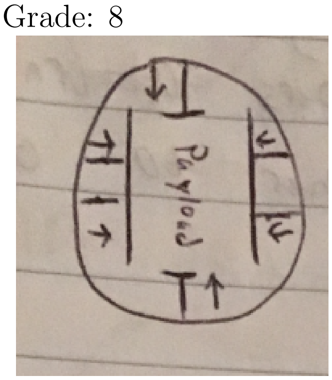

29. Grade: 1



Pad the walls for added protection in case of failure.

## 7.4 William Karabots Concept List

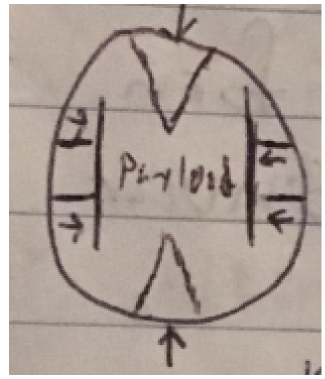
1. Four Mechanical Arms, Two Thin, Two Wide - Grade: 8




The two smaller arms secure the payload from moving in the vertical direction, while the two larger wide arms move in to secure the rest of the payload.

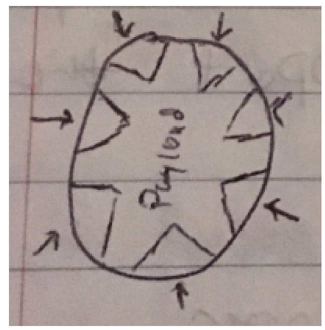
2. Two Mechanical Arms, Two Inflatable - Grade: 9

The mechanical arms and the inflatable grippers extend at the same time and secure the payload from moving.



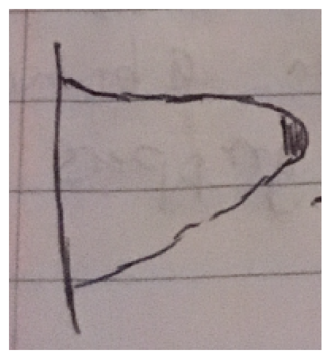

3. All Around Grippers (Inflatable) - Grade: 8

Grippers line up all along the side, which inflate to secure the payload.

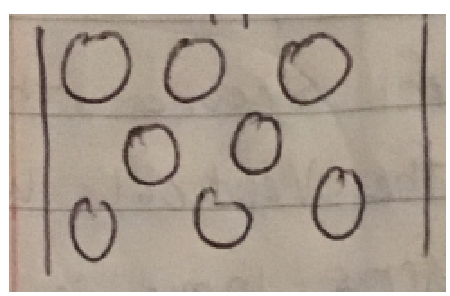



4. Sensor on the Tip og the Gripper - Grade: 10

Add a sensor to the tip of the inflatable/mechanical gripper, so when the gripper comes in contact with the payload, it stops to secure it.

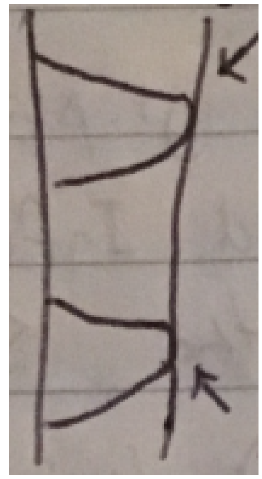


5. Grippers in Alternating arrangement - Grade: 7
   Have the grippers alternating between each other to optimize space.



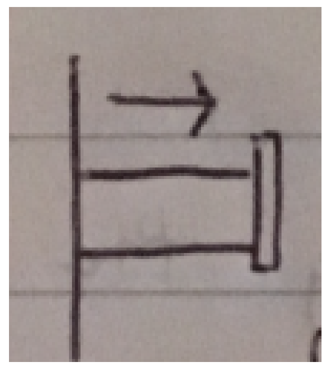
6. Rubber Sheet over Grippers - Grade: 9

Have a rubber sheet over the grippers so it can form to the payload better. Very similar to s spring matures.



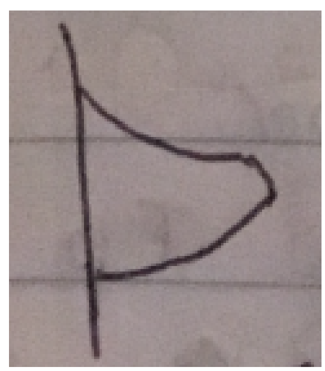
7. Hydraulic Piston as a Gripper - Grade: 7

Mechanical Piston that is powered by hydraulics to support the payload.



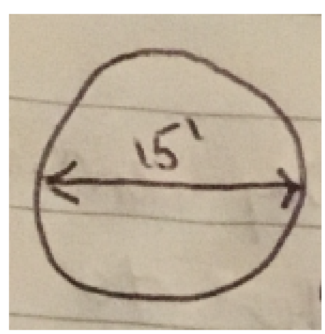
8. Use Air to Inflate Gripper - Grade: 8

Use air from the sub, which there should be an abandonment of, to inflate the grippers.



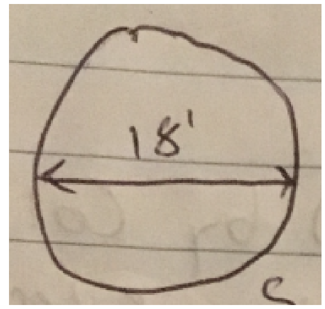
9. 15 Inch Diameter Gripper - Grade: 6

Use a 15 inch diameter gripper to optimize space and have a good amount to secure the payload.



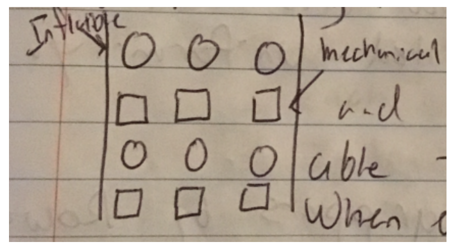

10. 18 Inch Diameter Gripper - Grade: 9

Have a 18 inch diameter gripper to have a large surface area to cover the maximum security.



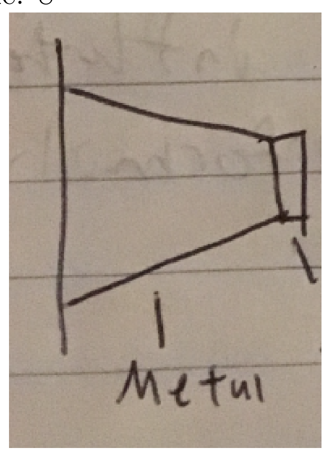

11. Alternating Mechanical and Inflatable Grippers - Grade: 10

    Have half inflatable and half mechanical to be able to have two options when gripping a payload.



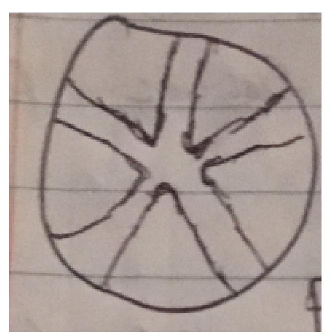

12. Rubber Padding at Tip of Metal Gripper - Grade: 8

    Add rubber pad to the end of the metal gripper. This will help secure the payload because the friction of rubber

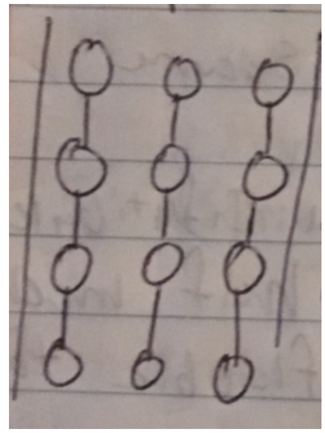



13. Inflatable Cones all the Way around - Grade: 9

    Grippers being able to expand all the way to the center in order to secure any size payload.

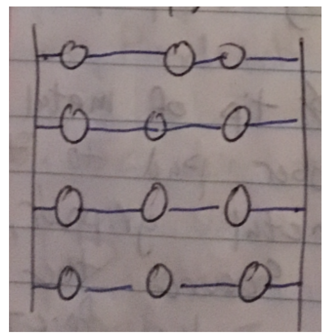


14. Fill Grippers (Inflate) by Columns - Grade: 9



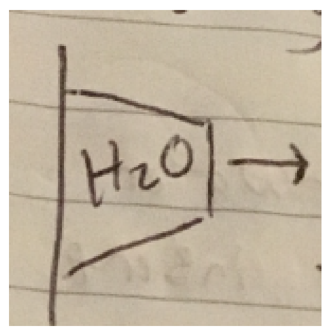
Have pipes in every column and when air is pumped into them, they are filled uniformly.

15. Fill Grippers (Inflate) by Rows - Grade: 6



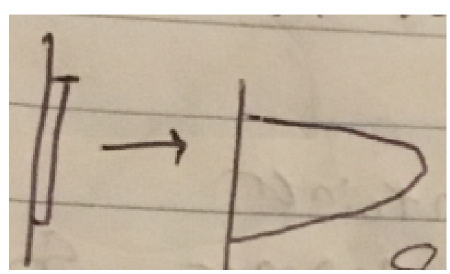
Each gripper in each row is connected by a pipe which inflates the grippers uniformly.

16. Using submersible Water Pump - Grade: 8

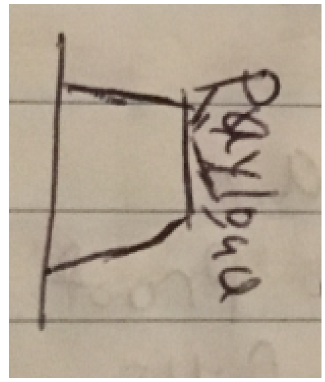



Using a water pump; when the medium is water to inflate or deflate each gripper.

17. Deflate to a Flat Shape - Grade: 10
Flexible enough to be collapsible into a flat shape such that they occupy very little volume when deflated.

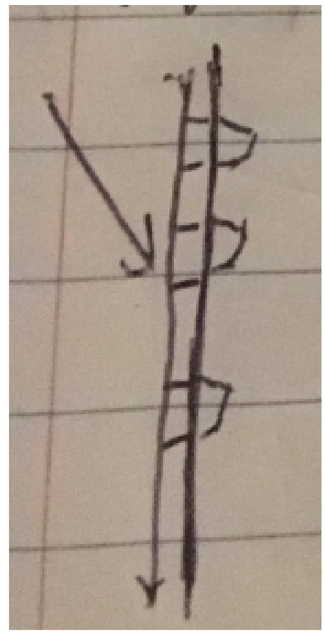


18. Pressure Controlled system - Grade: 10



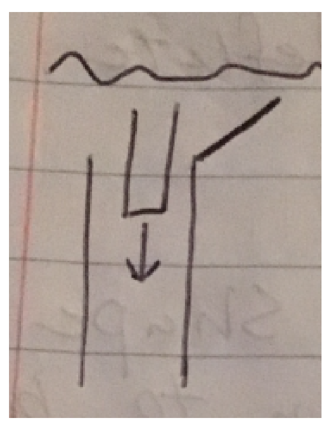

Each gripper is to be independently controlled by a pressure controlled system.

19. Inner Sleeve - Grade: 8



Several rows of flexible conical grippers attached to an inner sleeve which is located in a large pressure proof container.

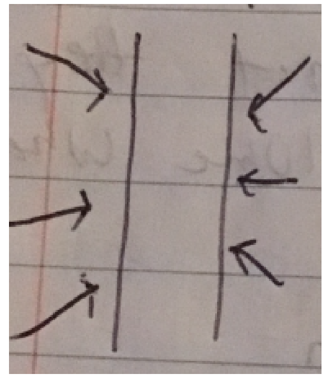
20. Payload Inserted Underwater - Grade: 9



Being able to insert the payload while the sub is submerged.

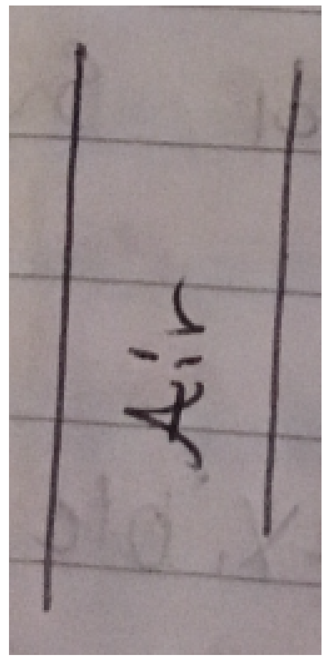
21. Pressure Proof Container - Grade: 9

The entire gripper system is contained inside a water tight and pressure proof container.



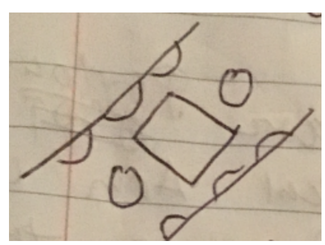
22. Fill Container with Air - Grade: 8

Because the pressure proof container is water tight, filling it with air will keep it's content dry.



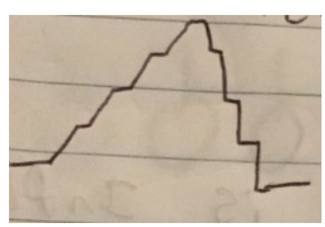

23. Access Hatch - Grade: 8

Add an access hatch for easy access when a repair or payload inspection is needed.



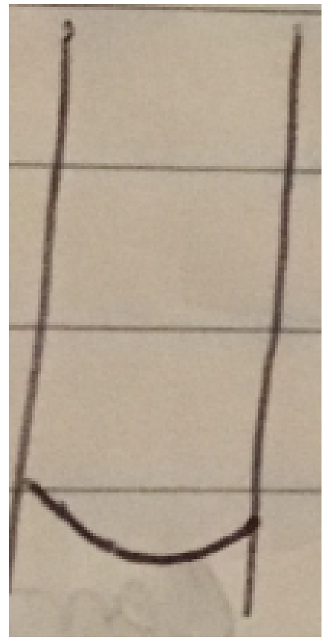
24. Conical Shape - Grade: 8

Allows gripper to collapse within itself and maximize the volume of space.

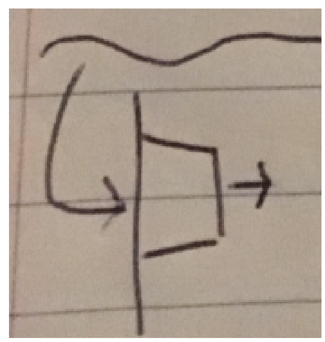


25. Sleeve at the Bottom to hold payload - Grade: 7

Have a sleeve at the bottom of the gripper so the payload is not hitting metal, if it were to slide.

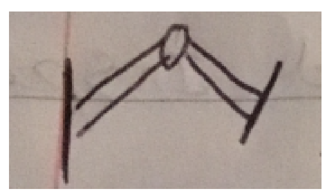


26. Use Sea Water to Inflate Gripper - Grade: 7



Because the gripper is mainly in use under water, it would be beneficial to use sea water to inflate grippers to eliminate storage.

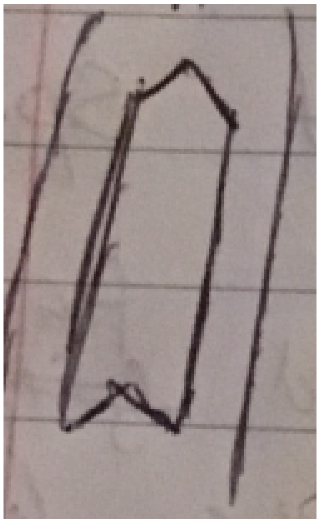
27. Mechanical Arm to Secure Payload - Grade: 6



Have a mechanical arm which extends until it reaches the payload and then it locks in place.

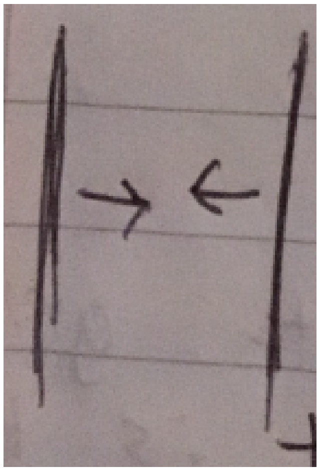
28. Mechanical Arm to Secure Payload - Grade: 5

A clamp which is inflated by air/water wraps around the payload to secure it.



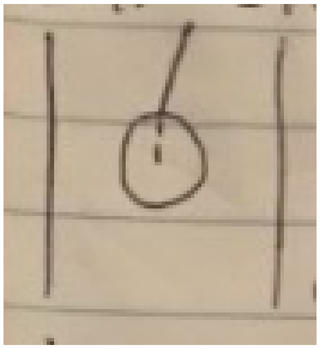
29. Mechanical Arm to Secure Payload - Grade: 7

The grippers will contain inflatable walls which will inflate until they reach and secure the payload.



30. Electric Arm - Grade: 6

Run wires down the side of the gripper and use the power of the sub to electrically move the arms to secure the payload.



# 8 QFD

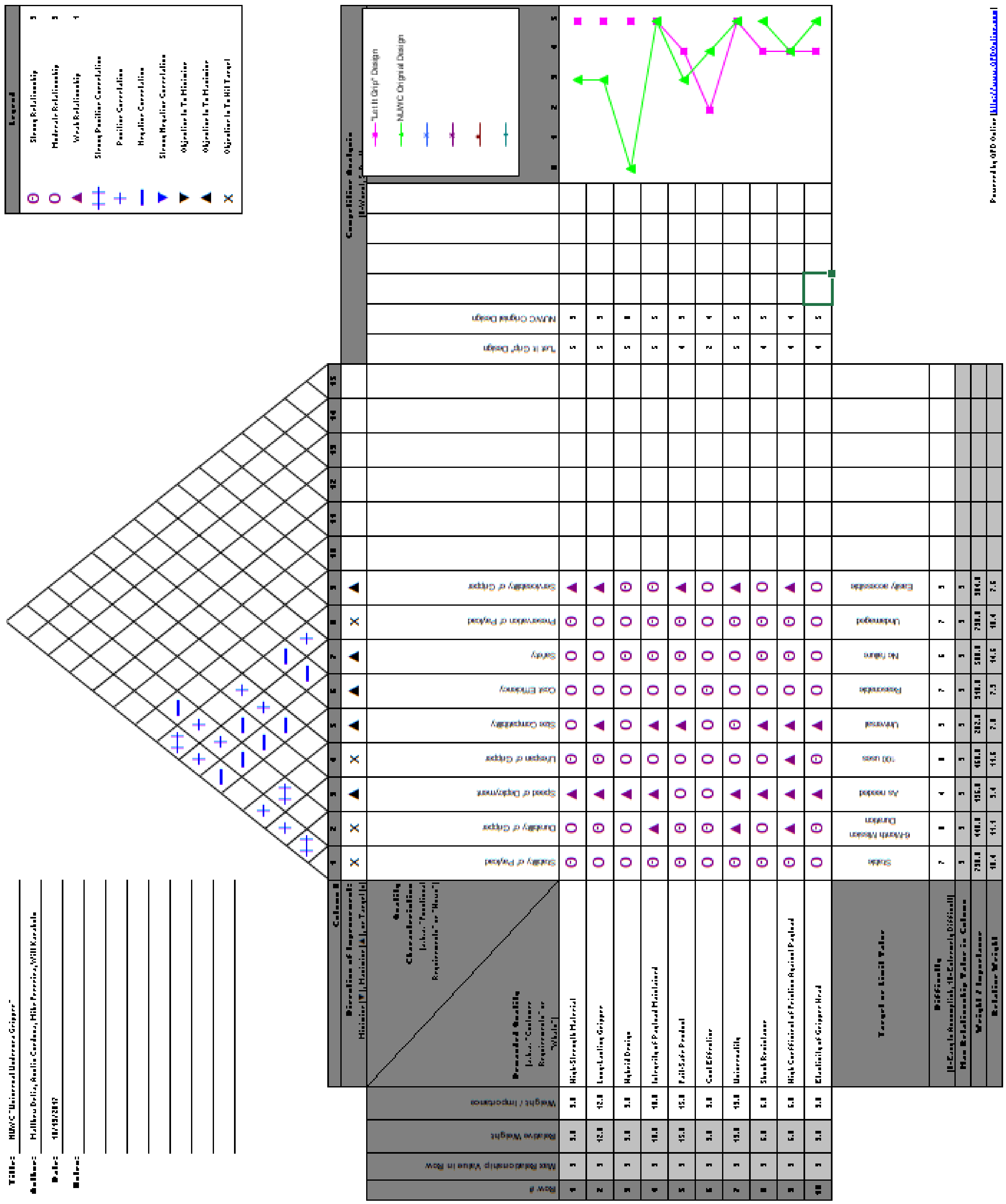


**Figure 8:** QFD and Competitive Analysis

From the QFD analysis done above there are a couple of key notes to point out. First off, since only seventy two grippers would be manufactured for the silo reliability and strength of the gripper outweigh the cost of production. The most important criteria that must be followed was to design the gripper that neither hurt itself or the payload. It is important that everything stays intact throughout the duration of the mission.

# 9 Design for X

The gripper design was first modeled in sketches in the team's design notebooks. One member designed the head and another sketched the conical extending rings. After sharing the designs with Dr. Hardro of NUWC and Prof. Nassersharif, the team worked and created the first preliminary design in SolidWorks. Once the design was finalized, the team began to run tests. Tests included gravity, stress, force, and deflection. This process were conducted in order to ensure a reliable and effective design. After the results of the tests looked promising, the team began 3D printing the the rings of the gripper at a thirty percent scale to show the ability to extend and have a strong visual of the design. The next step was to perform extensive tests to show the gripper could with-last forces during a shock event . These tests were to ensure the design was reliable and could meet the design specifications.

The team then began getting in contact with possible manufactures to get a quote on how much the gripper would cost if it would be made with aluminum 5083. The use of aluminum 5083 was chosen because cost and safety. As expressed in the financial analysis, the cost per pound of aluminum 5083 is $8.33, at current market value. That price is very cost efficient compared to other metals such as titanium and inconel. Also the safety of aluminum 5058 is optimal for this design, where it is strong and light enough to meet all of NUWC's government standards. With an increased budget from Prof. Taggart, the team, if time would allow, could potentially have enough to purchase a full scale model of the gripper. The manufacturing companies have yet to contact back.

The next plan in the design was to manufacture an extensive 3D print on the advanced 3D printer at Schneider electric. This 3D print had high accuracy and required little standing for removal of any extra material. The print is also seal proof and that would potentially allow the team to perform the test with hydraulic medium to test the durability of the design, given more time. The team would add the redesigns to the new print to ensure the gripper fully extends and retracts.

Manufacturability was an important part of the teams design. The team designed the gripper to be manufactured using basic manufacturing tactics. The team added chaffered edges to help the design, as well as to help the manufacturability of the gripper. Working on this design has had little to no effect on the environment with only use of electricity, ABS plastic, and aluminum 5058 when manufactured.

# 10 Project Specific Details & Analysis

Throughout the design process, data, specific details, and analysis were collected, compiled and used to work toward the preliminary product design. Material analysis and technology analysis were two main focuses during the design process.

## 10.1 Material Analysis

As explained, the team designed a metal gripper. The reason metal was chosen as the overall material of the gripper, was because the overall strength and durability. As seen in the design specifications, the life of these grippers must last for the duration of the ship. These ships are known to have a life of about 100 years. Using metal opposed to a elastomer design would decrease the chance of failure of a gripper.

Switching from elastomer to metal, drastically changes the price and the way gripper would be manufactured. Many factors also needed to be discussed and researched when deciding on a metal.

First, the grippers are going to be submerged in salt water for long periods of time, this forces the metal to have a very high corrosion restlessness. Next, because these grippers are going to be securing a payload of substantial weight, the material must be strong enough to hold the payload without damaging itself. This requires a high tensile strength and shear strength. Before researching any metals, the qualities needed to include cost benefits, strength, and anti corrosive traits. Preliminary research lead to aluminum as a promising metal to possibly incorporate into the design.

Exploring the different types of aluminum, two had very promising qualities (5083-O Aluminum and 6061-T6 Aluminum). After ample research on these types of aluminum, a comparison was conducted on the core qualities of the metals, given from [12], and can be seen in Table 5.

With the comparison seen in Table 5, 6061-T6 Aluminum had promising results. The much higher yield strength and higher tensile strengths are optimal for grippers used in a system in order to secure a payload.

Though 6061-T6 was promising, more metals were explored. Research on Titanium Grade 5, Inconel 718, Nickel Aluminum Bronze C95500, as well as corrosion resistance paint was conducted. Corrosion resistant paint has a very high cost benefit, with being able to use a metal such as steel. Though from a durability test; the paint will ware and need to be re coated, which could propose a problem for the life of the gripper. From [13] and [14], Titanium and Inconel have very high corrosion resistance (similar to aluminum), their tensile and yield strengths are over 150% the strengths of aluminum, but the cost is substantially more expensive.

**Table 5:** 5083-O Aluminum vs 6061-T6 Aluminum

| Material Properties (Units) | 5083-O Aluminum | 6061-T6 Aluminum |
|---|---|---|
| Elastic Modulus (GPa) | 68 | 69 |
| Fatigue Strength (MPa) | 150 | 96 |
| Poisson's Ratio | 0.33 | 0.33 |
| Shear Modulus (GPa) | 26 | 26 |
| Shear Strength (MPa) | 170 | 210 |
| Ultimate Tensile Strength (MPa) | 300 | 310 |
| Yield Tensile Strength (MPa) | 140 | 270 |
| Melting Point (Degrees Celsius) | 580 | 580 |
| Thermal Conductivity (W/m-K) | 120 | 170 |
| Thermal Expansion ($\mu$m/m-k) | 24 | 24 |
| Base Price (% Relative) | 9.6 | 9.5 |
| Density (g/m$^3$) | 2.7 | 2.7 |
| Ultimate Resilience (MJ/m$^3$) | 42 | 30 |
| Stiffness to Weight Ratio (Axial) | 14 | 14 |
| Stiffness to Weight Ratio (Bending) | 50 | 50 |
| Strength to Weight Ratio (Axial) | 31 | 31 |
| Strength to Weight Ratio (Bending) | 37 | 37 |
| Thermal Shock Resistance | 13 | 14 |

After further research and discussions with the team at NUWC, 6061-T6 aluminum was ruled out. NUWC had performed prior tests on that metal, and the results did not fall within the safety parameters. Table 6 shows a brief comparisons of the updated metals being considered.

**Table 6:** Preliminary Comparisons from [13] [14] [15]

| Material Properties (Units) | Titanium Grade 5 | Inconel 718 | C95500 |
|---|---|---|---|
| Elastic Modulus | 114 GPa | - | 110000 MPa |
| Ultimate Tensile Strength (MPa) | 1170 | 1375 | 655 |
| Yield Tensile Strength (MPa) | 1100 | 1100 | - |
| Density (kg/m$^3$) | 4430 | 8190 | 7530 |

Based on updated preliminary results titanium grade 5 looks like a promising option. NUWC expressed that cost is not a factor when backed up by qualities that prove fit to creating the most optimal design. Titanium is deemed expensive but qualities show that it could be a good match with the grippers (Individually and in a system). Moving forward, research has just begun. These metals will be explored to full extent (similar to table 5), as well as new materials will be researched. Choosing the proper material is extremely important to the success of the design. Now that the drawings are complete, material research becomes the main focus of moving forward with the design.

## 10.2 Technology Analysis

When the concepts were being narrowed down to the preliminary design, technology advancements were researched to improve the design. Many of the concepts incorporated technological advancements that would later benefit the gripper to secure a payload with the least error as possible. Concepts that seemed promising and feasible in the scope included pressure sensors, rubber/elastomer sheet connected to the system of grippers, and a potential vibration isolator. After meetings between the team, engineers at NUWC, and Professor Nassersharif, improvements using pressure sensors was considered to be the best improvement to focus time on.

The design is a system of hydraulics that extends out until it reaches the payload. The last hydraulic section is the head/the piece that comes in contact with the payload. Because the payloads are rigid bodies (not just rectangles and cylinders) each gripper will extend out different lengths. Each gripper must be individually controlled because of this. One major issue is how the gripper will stop after it comes in contact with the payload; so it does not damage the gripper or the payload. Placing a sensor at the tip of the gripper will help control when the gripper stops extending. Preliminary research has been performed on pressure sensors, and two sensors showed promising results (OPTI and OEM pressure measurement cells, as seen in figure).


**(a)** OPTI **(b)** OEM

**Figure 9:** Pressure Measurement Sensors [16]

OPTI and OEM sensors are very similar in qualities. They both have a pressure range of 2.5 MPa to 200 MPa, which is optimal for various sized payloads. They also have a

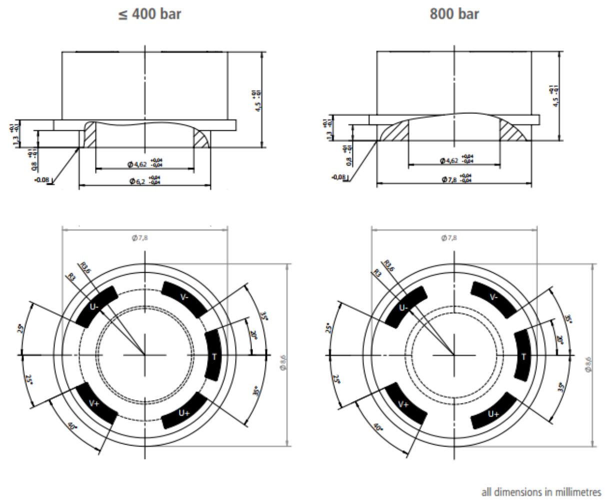



**Figure 10:** Dimensions of OEM Pressure Sensor [16]

temperature range -40+200C / (-40+392F); that is extremely important for undersea temperatures that can dip well below freezing. The OPTI and OEM pressure cells are stainless steel that are typically welded onto a stainless steel adapter. Applications for these sensors include hydraulic systems and control systems. Both these sensors look promising toward incorporation of one into the preliminary gripper design, though the electrical component could propose a challenge with wiring them through the gripper and them working properly undersea. This technology is still in early stages of research, and moving forward comparisons and new sensors will be considered while working toward reaching the most optimal design for the gripper. [16]

# 11 Detailed Product Design

During the year, the product design for this project has gone through multiple revisions, starting with the preliminary designs created in Fall 2017. After these preliminary designs, which were created in preparation for the proof of concept in December, the design was revised to allow for proper building of the design. After the initial build, and then subsequent testing on that build, another revision to the design was made and can be seen in Figure 11.

Each of these design steps will be explained further in the following pages. Each step shows the design process throughout the academic year and details the changes and revisions that were made leading to the final design.

## 11.1 Preliminary Design

During the Fall Semester, the preliminary design of the Gripper was created. In this preliminary design, the Head of the gripper and Rings one (1) through seven (7) were created. Each of these rings were designed to incorporate a single O-Ring that would seal each of the rings. These O-Rings are designed to sit in a gland that is located on the lower flange of each of the rings. These gland dimensions were taken with reference to Parker's O-Ring Handbook, [11].

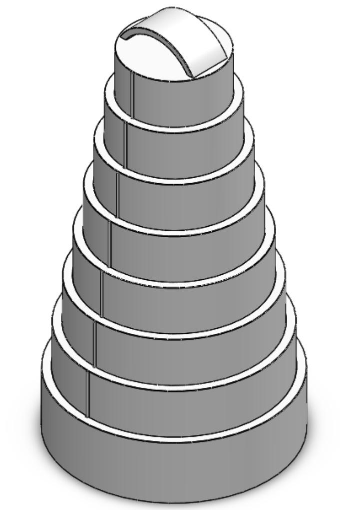
Each of the drawings can be found in **Appendix A. Preliminary Design Drawings**, and their respective figures can be referenced from Table 7.

In this preliminary design, it is important to note that the design of the gripper is entirely full-scale. The wall thicknesses for each of the rings and the head was designed at 0.25 inches with a flange height of 0.75 inches and a 0.5 inch inner lip.

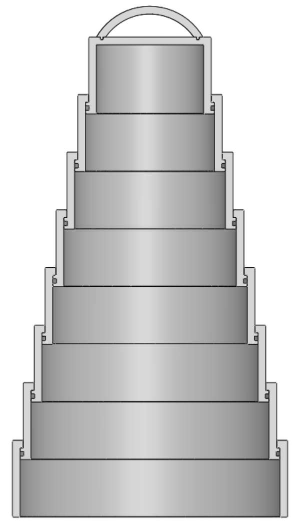
The overall dimensions of the design can be found in Table 8. This table includes the Outer Diameters of the ring walls and the subsequent flange outer diameters for those rings as well.

**Table 7:** Figure Listings for Preliminary Design Drawings

| | |
|---|---|
| Gripper Head | Figure 39 |
| Ring 1 | Figure 40 |
| Ring 2 | Figure 41 |
| Ring 3 | Figure 42 |
| Ring 4 | Figure 43 |
| Ring 5 | Figure 44 |
| Ring 6 | Figure 45 |
| Ring 7 | Figure 46 |



**(a)** Isometric View



**(b)** Cut View

**Figure 11:** Final Gripper Design

**Table 8:** Dimensions of Preliminary Design

| Ring No. | Wall OD (in) | Flange OD (in) |
|---|---|---|
| Head | 7.880 | 8.880 |
| 1 | 9.400 | 10.400 |
| 2 | 10.920 | 11.920 |
| 3 | 12.440 | 13.440 |
| 4 | 13.960 | 14.960 |
| 5 | 15.480 | 16.480 |
| 6 | 17.000 | 18.000 |
| 7 | 18.520 | - |

**Table 9:** Figure Listings for Build Design Drawings

| | |
|---|---|
| Gripper Arc | Figure 48 |
| Gripper Head | Figure 49 |
| Ring 1 | Figure 50 |
| Ring 2 | Figure 51 |
| Ring 3 | Figure 52 |
| Ring 4 | Figure 53 |
| Ring 5 | Figure 54 |
| Ring 6 | Figure 55 |
| Ring 7 | Figure 56 |

This preliminary gripper design has a full extension of 31.250 inches and the outer diameter of the assembly is 18.520 inches. Both of these dimensions initially did not meet the design specifications for this project and revisions to the design were made to account for this.

## 11.2 Build Design

At the beginning of the Spring Semester, updates and improvements were made to the gripper design in anticipation of building and testing. Due to budgeting restraints, Team 12 was unable to manufacture the gripper design out of an appropriate material and thus, a 30% scale design was created of the gripper. This 30% scale design allowed the manufacture of the gripper design at Schneider Electric with the use of 3D Printers from the Mechanical Engineering Department at the University of Rhode Island.

For purposes of presenting the overall design, the drawings created of the design are also full-scale and can be found in **Appendix B. Build Design Drawings**. Their respective figure numbers can also be referenced from Table 9.

From this redesign, the wall thicknesses were increased from 0.25 inches to 0.50 inches and the flange OD's were reduced from 0.5 inches to 0.2 inches. These changes allowed for the design to become more compact and allowed the design to meet the maximum diameter requirement of 18 inches. The dimensions of the build design can be found in Table 10. The O-Ring glands dimensions were updated to better meet the specification requirements from Parker O-Ring, [11].

## 11.3 Final design

Following the building and testing phase of the project, a redesign was completed to update the design and address issues that were discovered. This redesign produced the final design of Team 12's Universal Undersea Gripper, which can be seen in Figure 11.

**Table 10:** Dimensions of Build Design

| Ring No. | Wall OD (in) | Flange OD (in) |
|---|---|---|
| Head | 7.980 | 8.380 |
| 1 | 9.400 | 9.800 |
| 2 | 10.820 | 11.220 |
| 3 | 12.240 | 12.640 |
| 4 | 13.660 | 14.060 |
| 5 | 15.080 | 15.480 |
| 6 | 16.500 | 16.900 |
| 7 | 17.920 | - |

| | |
|---|---|
| Gripper Arc | Figure 58 |
| Gripper Head | Figure 59 |
| Ring 1 | 60 |
| Ring 2 | 61 |
| Ring 3 | 62 |
| Ring 4 | 63 |
| Ring 5 | 64 |
| Ring 6 | 65 |
| Ring 7 | 66 |

The drawings for the final design can be found in **Appendix C. Redesign Drawings** as well as the entire assembly with dimensions. Their respective figures can be referenced in Table **??**. For these drawings, it is important to note that the designs are all at 30% scale. The improvements made from the Build Design to the Final Design were done based on the 3D printed model and its dimensions.

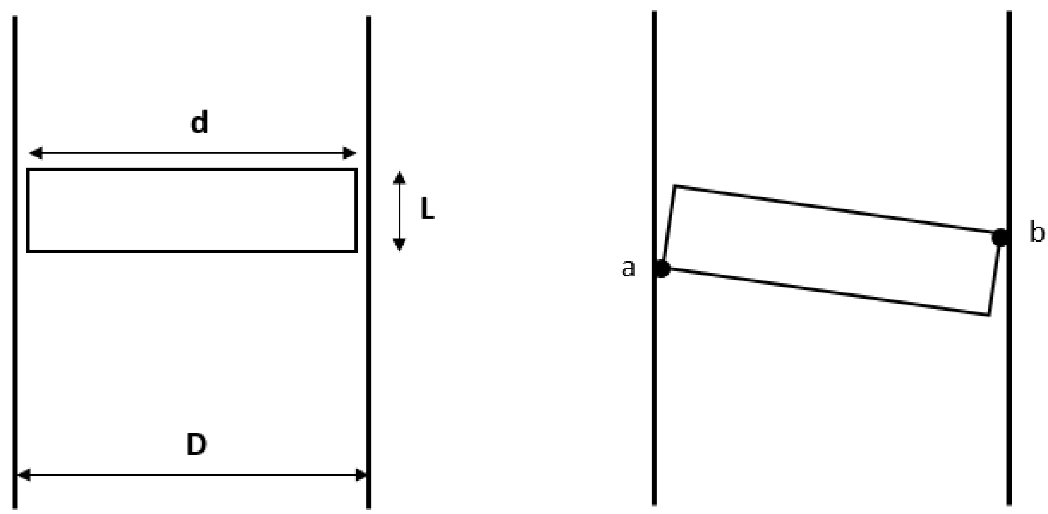
For the redesign, the previous design of the gripper was maintained. The head's height was increased to match the height of the rest of the gripper rings, and a 0.001 inch chamfer was added to all outside edges of the design. Additionally, a 0.003 inch radius guideline was added to the outside of the rings, and a 0.0045 inch groove was added to the inside lip of the rings to allow for this guideline.

These changes made to the Build Design constitute the final design of the gripper. The dimensions of the Final Design match the dimensions of the Build Design and can be referenced in Table 10. Due to the increase in height of the Head, the total extension of the design now meets the design requirement of 33 inch total extension.

## 12 Engineering Analysis

### 12.1 Length-Diameter Ratio

When a disk is sliding within cylinder, there needs to be consideration for the possibility of the disk jamming within that cylinder. In its basic form, the flanges of the rings for this design act as disks, and the wall of the outer rings act as a cylinders. For simplicity, these can modeled as shown in Figure 12, where Figure 12(b) shows the disk jamming within the cylinder.




**(a)** Dimensions of Disk and Cylinder

**(b)** Disk Jamming in Cylinder

**Figure 12:** Disk in Cylinder Representation

The Free Body Diagram of the jammed disk is given in Figure 13.

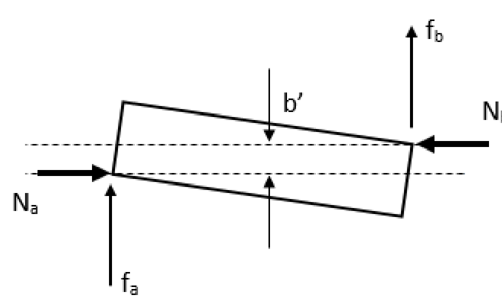



**Figure 13:** Free Body Diagram of Disk Jamming

From the geometry, the following expressions are obtained,

$$\overline{ab} = \sqrt{d^2 + L^2} \tag{1}$$

$$b' = \sqrt{\overline{ab}^2 - D^2} = \sqrt{(d^2 + L^2) - D^2} \tag{2}$$

Summing the moments about Point A (+CCW) and substituting the expression for friction and the above geometric expressions gives,

$$\Sigma M_a = f_b D + N_b b' \tag{3}$$

$$\Sigma M_a = (\mu N_b)D + N_b\sqrt{d^2 + L^2 - D^2} = 0 \tag{4}$$

When the disk jams, it can no longer rotate clockwise, and therefore, to prevent jamming, $\Sigma M_a \leq 0$. Let the clearance ratio, $c$, and the length ratio, $l$, be,

$$c = \frac{D - d}{D} \rightarrow d = D(1 - c) \tag{5}$$

$$l = \frac{L}{D} \rightarrow L = lD \tag{6}$$

Substituting (5) and (6) in (4) gives,

$$\mu D + \sqrt{d^2 + L^2 - D^2} \leq 0 \tag{7}$$

$$\mu D + \sqrt{[D(1 - c)]^2 + (lD)^2 - D^2} \leq 0 \tag{8}$$

Solving (8) for $l$,

$$l \geq \frac{\sqrt{D^2 - (\mu D)^2 - D^2(1 - c)^2}}{D} \tag{9}$$

Setting $D = 1$, gives the value of l for a unit diameter,

$$l \geq \sqrt{1 - \mu^2 - (1 - c)^2} \tag{10}$$

Using Order of Magnitude analysis, from the Parker Handbook in [11], the clearance ratios can be calculated for different O-Rings, and for this application, $c << 1$. Therefore, $(1 - c)^2 \approx 1$. This simplifies (10) to be,

$$l \geq \mu \tag{11}$$

Equation (11) poses an issue for the design of an aluminum-aluminum sliding contact. From [17], the coefficient of friction is approximately equal to 1.41 for dry sliding. Using equation (11), this would mean that the flange of the ring would have to be 1.41 times larger than the diameter of the outer ring.

However, this issue is resolved from the use of hydraulic pressure. The above calculations were completed with no external forces applied on the bodies, and therefore the ability of the design to jam is mitigated by the applied fluid pressure to extend and retract the gripper.

## 12.2 Wall Thickness

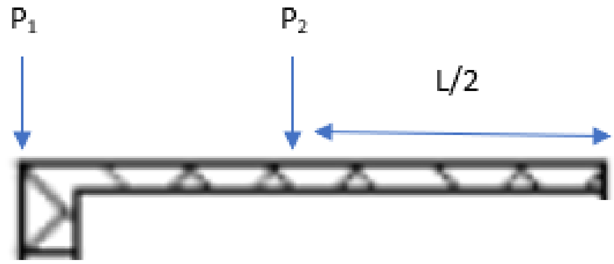



**Figure 14:** Wall of Gripper Base

**Table 11:** Al 6061-T6 Properties

| | |
|---|---|
| Density, $\rho$ | 0.0975 $\frac{lb}{in^3}$ |
| Elastic Modulus, $E$ | 10,000 ksi |
| Beam Length, $L$ | 5 in |
| Assumed Deflection, $\delta$ | 0.01 in |
| P1 | 0.366*h lbf |
| P2 | 0.061 lbf |

The purpose of this analysis is to calculate the minimum wall thickness needed to achieve a desired deflection of 0.01 in. The material properties used in the calculation are for Al 6061-T6, given in Table 11. It is also important to show that the force acting on the beam, P, is the weight of the material due to gravity.

Calculations are completed using the deflection equation,

$$\delta = \left(\frac{PL^3}{3EI}\right)_{Load1} + \left(\frac{PL^3}{3EI}\right)_{Load2} \tag{12}$$

Rearranging equation (12) for $I$ gives,

$$I = \frac{1}{\delta}\left[\left(\frac{PL^3}{3E}\right)_{Load1} + \left(\frac{PL^3}{3E}\right)_{Load2}\right] = (2.539 * 10^{-5}) * h - (1.700 * 10^{-5}) \tag{13}$$

Once this equation is solved, the results are equated to the moment of inertia of a solid beam,

$$I = \frac{bh^3}{12} \tag{14}$$

When equations (13) and (14) are equated to each other, the wall thickness, $h$ is determined to be,

$$\frac{bh^3}{12} - (2.539 * 10^{-5}) * h - (1.700 * 10^{-5}) = 0 \tag{15}$$

Solving the roots of equation (15) gives the wall thickness,

$$h = 0.061in \tag{16}$$

## 12.3 Force Concentration

To begin the analysis of the gripper, it is important to find the highest force concentration. Every calculation can be based off of the highest force load because this would be the worst case scenario. The way to find the force concentration is to divide each payload weight by the amount of grippers coming in contact with the payload. To make this calculation easier the Matlab script, Figure 38, was used.

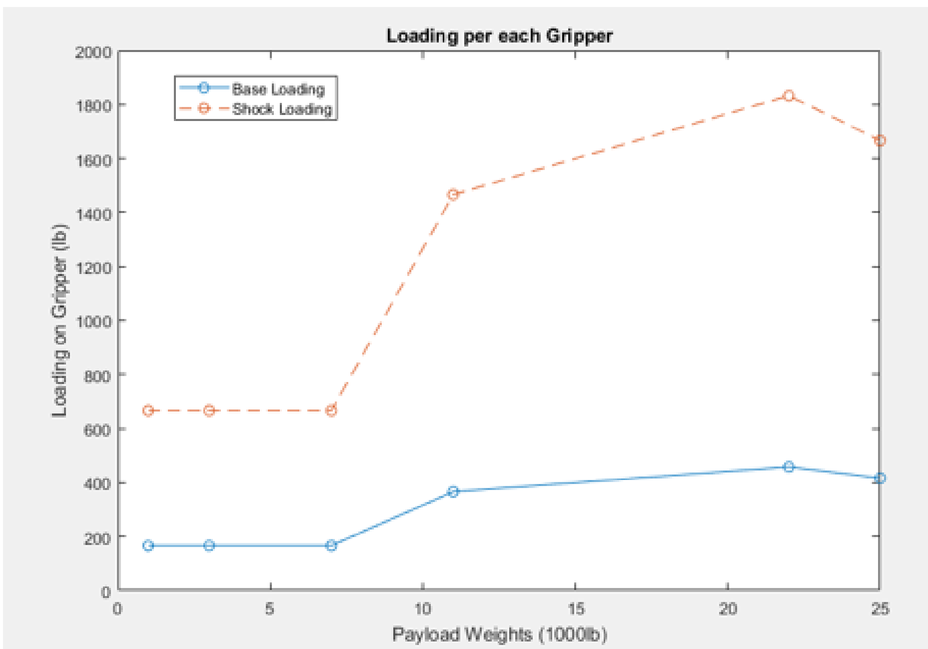
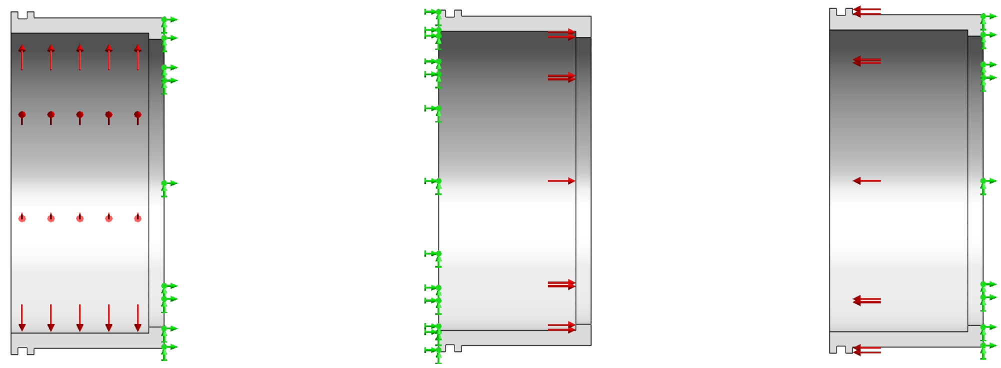



**Figure 15:** Force Concentration

Using the Matlab script gives the following data, Figure 15, which shows the highest force concentration occurs with the 22,000 lb payload. With the 22,000 lb payload the greatest normal load would be 458 lbs, and the shock load being 1,833 lb.

## 12.4 Blow Out Analysis

As seen in Figure 16 below, there are three different areas on each ring that need to be looked over. In the top portion of the figure blow out of the inner and outer lip is analyzed using a range of psi, 50 psi to 200 psi. This pressure range would account for the fluid pressure needed to extend the gripper. In addition to the lips, an analysis was performed on the wall of each ring to ensure structural integrity. The results show that the stresses experienced at these three points are well within acceptable range.



**(a)** Internal Pressure **(b)** Inside Lip **(c)** Outside Lip

**Figure 16:** Applied Pressure

# 13 Build Manufacture

When it came for the group to decide on how to manufacture a gripper, the budget for the project limited the options. For the majority of the semester, the budget for the project was minimal, which is not enough to make neither a full size metallic gripper nor a scaled down model. After manufacturing a metallic version of the gripper it was decided to manufacture a, plastic, 3-D print using the printers provided by the University of Rhode Island. The reason why a 3-D print is a viable option is because they are able to accommodate the tight tolerances of the rings. The process to print a gripper began with scaling down the Solidworks models to thirty percent. Next, to speed up production time, every other ring would be printed within each other allowing two to three rings to be made at a time. The printing process would take approximately two days to be completed and assembly would then take two hours, Figure 17. So, the final production time for one scaled print would take slightly longer than two days. If the total amount of grippers needed, seventy-two, were manufactured it would take about 180 days. For the scope of the project though, one gripper would suffice. If the project were to be continued, it is advised to manufacture a full size metallic gripper to preform tests.

**Figure 17:** Gripper Assembled

# 14 Testing

For the testing phase of this project, the design of the gripper underwent both Physical Testing using the 3D Printed model as well as FEA Testing using Solidworks to analyze the design. These tests allowed the team to see areas where improvement was needed, and the changes made from the testing of the design were used to produce the Final Design.

## 14.1 Physical Testing

Following the completion of the Build Design, the entire gripper design and assembly was built using the 3D Printers available at the University of Rhode Island at Schneider Electric. These printers aided in creating the design of the gripper, and allowed the testing of the extension of the gripper. This 3D print can be referenced in Figure 18.

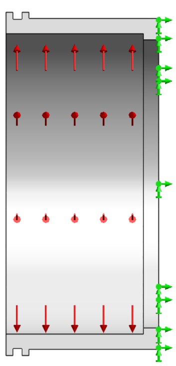
The 3D Print allowed the testing of the extension of the gripper. Due to the tolerances of the printer, some material needed to be removed to allow for the rings to fit within each other. After this, the rings were able to fit and slide properly.

As part of the physical testing of the design, the team was able to discover the difficulty of the head to extend outward from the fully retracted position. Once the head extended up to Ring 1, the edge of the head would catch the inside of Ring 1 and fail to extend outward. Additionally, the team was able to observe the ease of the design to rotate unexpectedly. This rotation allowed for the failure of the gripper tip of the gripper to make proper contact

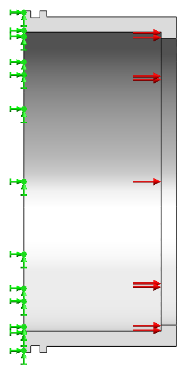
(a) Extended

(b) Retracted

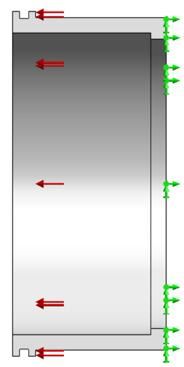
**Figure 18:** First Build of Gripper Design



(a) Internal Pressure



(b) Inside Lip



(c) Outside Lip

**Figure 19:** FEA Testing Setup of Individual Rings

with the payload.

## 14.2 FEA Testing

In addition to physical testing of the 3D print, extensive FEA testing was completed to analyze the design for its ability to withstand pressures. This FEA testing was completed on each of the rings as well as the entire assembly. This testing consisted of applied pressures on each ring and overall deflection testing of the design. The testing setups can be seen in Figure 19 and Figure 26.

### 14.2.1 Stress and Deflection Testing for Each Ring

For this FEA analysis of the design, different pressures were applied at the areas indicated by the red arrows in Figure 19. These pressures were 50, 100, 150, and 200 psi. The green

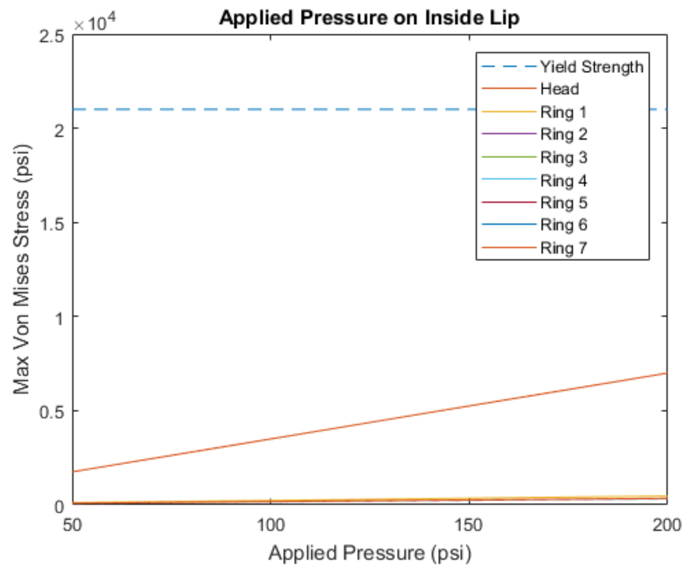



**Figure 20:** Inside Lip Pressure Stresses

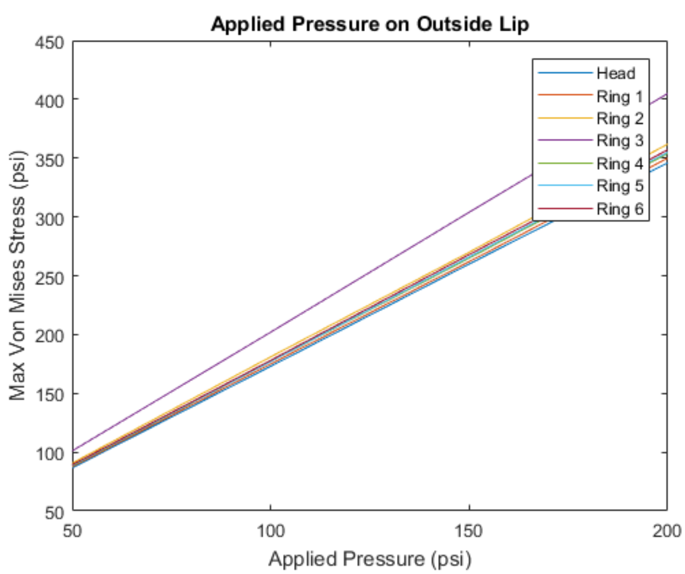



**Figure 21:** Outside Lip Pressure Stresses

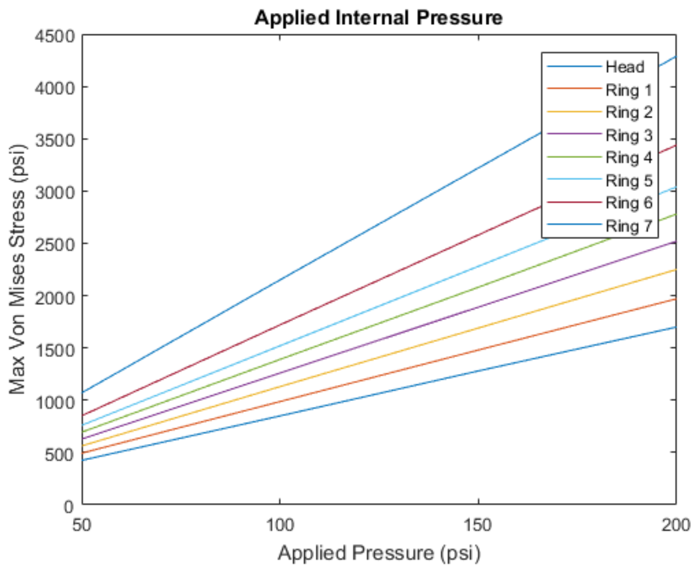



**Figure 22:** Internal Pressure Stresses

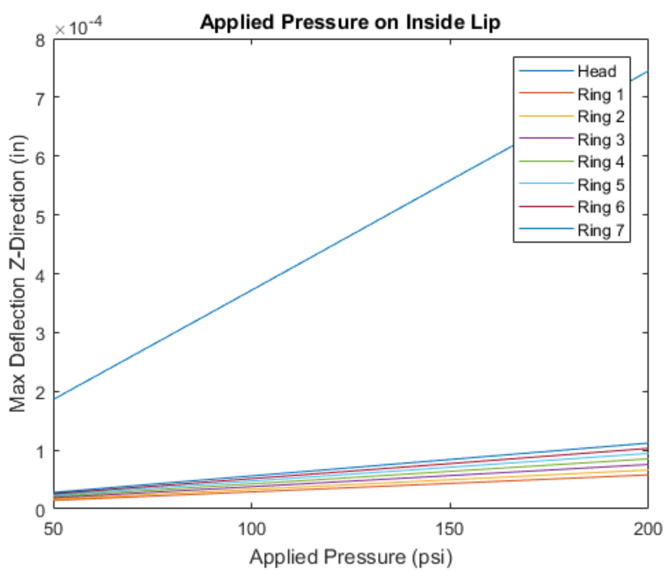



**Figure 23:** Inside Lip Pressure Deflections

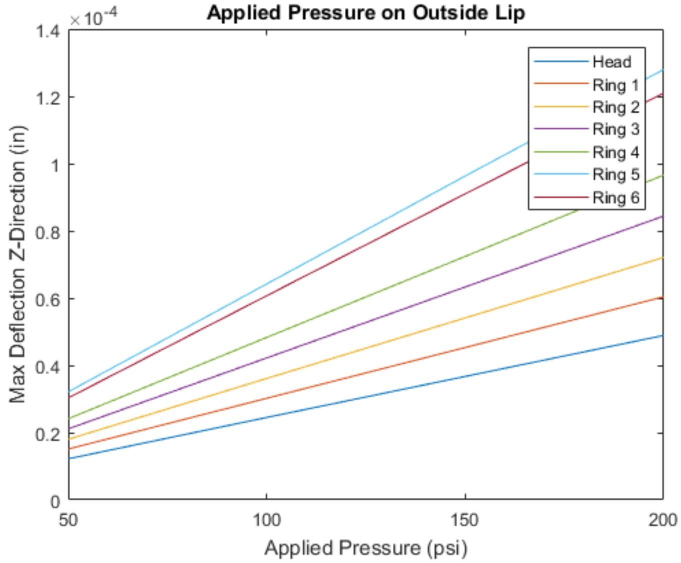



**Figure 24:** Outside Lip Pressure Deflections

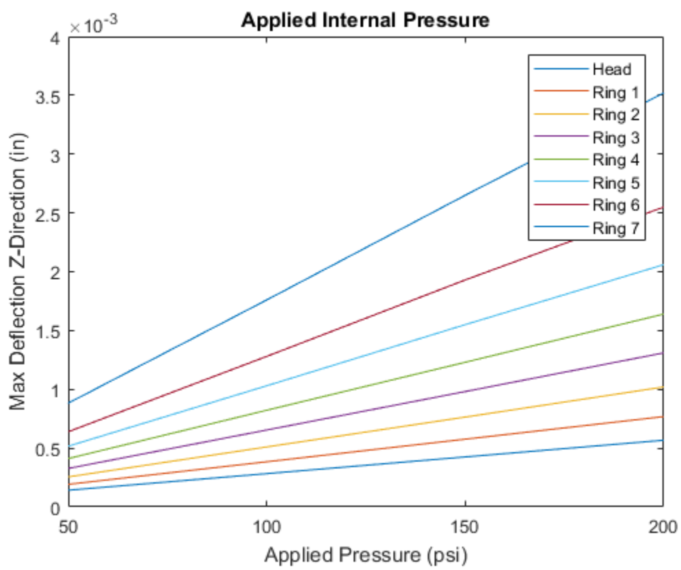



**Figure 25:** Internal Pressure Deflections

arrows indicate where the rings were secured in the tests.

During testing, the maximum Von Mises Stress and Z-Direction deflection from each of the tests was recorded. These results were then plotted on two graphs - Stress vs. Pressure and Deflection vs. Pressure. These plots are presented in Figures 20, 21, 22, 23, 24, 25.

From the results of the testing, all tests were well below the material's yield strength of 21000 psi. The test that had the lowest factor of safety was the applied pressures on inside lip testing, where the maximum Von Mises stress for Ring 7 at 200 psi had an approximate 2.5 FOS.

Additionally, Z-Direction deflection tests were recorded due to the notion that excessive deflection would lead to a blow out causing the inside ring to push through the outside ring. From the FEA testing of these deflections, it was determined that the maximum deflection came from applied internal pressure. The maximum Z-Dir deflection came from Ring 7 and had a value of approximately 3.5E-03 inches. Although this was the largest deflection, this value did not cause a need for updates to the design.

#### 14.2.2 Testing for Entire Assembly

When testing the assembly there were three tests that were performed to ensure structural integrity. Figure 27 shows an FEA test with the force of the water and gravity on a fully extended gripper. This is needed to ensure that the gripper is strong enough to work without an external force from the payload. The test shows that the maximum stress occurring is only 185 psi which is acceptable. To further show the gripper is safe, it is seen in Figure 28 that the maximum deflection is negligible at -2.453E-04 in. Finally to ensure that the gripper meets the standard, a shock test was performed. The reason why only a shock test is needed to ensure the gripper is acceptable is because this would be the worst case scenario that can occur. Using the highest force concentration, 1,833 lbs, a test was ran on Solidworks. From Figure 26 it is seen that the max stress the gripper would experience is 7,903 psi, well within the material strength of 21,000 psi. With this data the factor of safety is calculated at approximately 2.65.

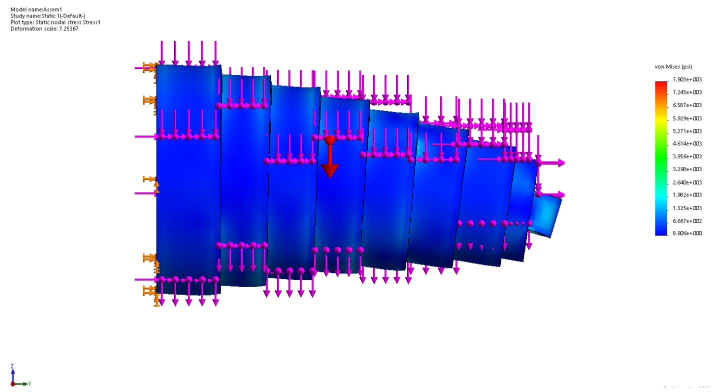



**Figure 26:** FEA Testing of Assembly with Applied Forces

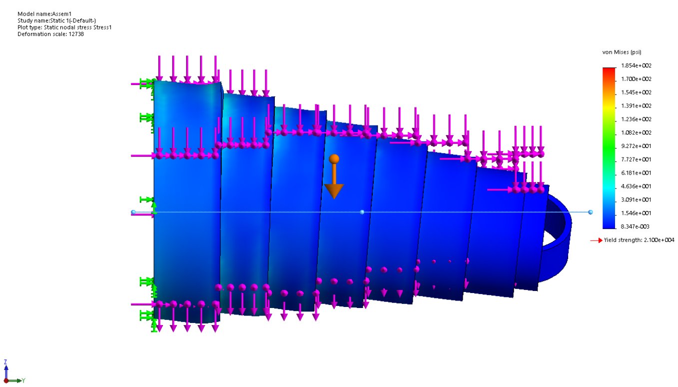



**Figure 27:** FEA Testing of Assembly with Applied Water Forces

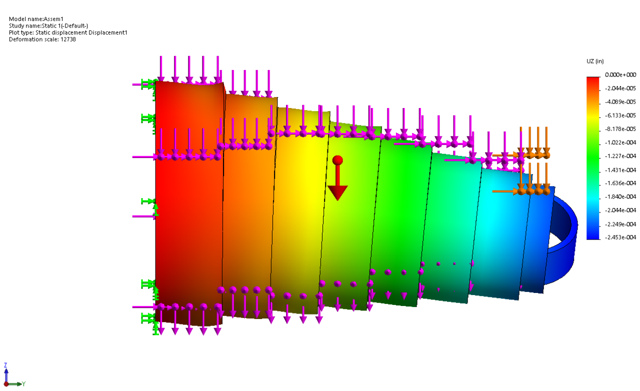



**Figure 28:** FEA Testing of Assembly Deflection

# 15 Redesign

When the team initially printed a 3D model of the initial gripper design and conducted an array of FEA analysis, a multitude of potential issues became clear. The first of this issues was that upon extension, the gripper was free to rotate both clockwise and counter clockwise depending on the forces that were subjected on it. This presents a problem because it prohibits one from knowing exactly how a gripper would come in contact with a payload and subsequently prevents one from being able to understand how a gripper would react under the forces it would be subjected to. This essentially meant that the gripper could potentially fail if it was subjected to forces in such an orientation that it was not designed for. Once the team became aware of this potentially catastrophic issue, the process of re-designing the gripper began. To solve this issue, the team implemented two guiding track lines separated by 180 degrees on each side of each gripper ring and the gripper head. These guiding track lines, shown in figure 29 appear on both the inside and outside of each gripper ring incorporating a male and female track to ensure that the gripper would still be able to extend and retract with ease without the possibility of unwanted rotation. As a result, the team was able to guarantee that the gripper would be able to withstand the forces subjected to it in the orientation that the gripper was designed for.

The team then moved on to another potentially catastrophic issue that had been over-looked in the original design. This issue came in the form of sharp edges on each corner of the gripper. The team recognized this as an issue because unwanted or unforeseen payload contact with the gripper's sharp edges could lead to severe payload damage, especially in the case of a shock event. To combat this issue, the team implemented a chamfer of 0.013 inches on all sharp corners of the gripper design. In addition to a greatly decreased risk of payload damage as a result of gripper contact, the chamfered edges also greatly decrease the cost and time necessary for manufacturing due to the fact that sharp corners are relatively difficult to machine. These chamfered edges can be seen in figure 30.

Following the successful correction of both the gripper rotation and sharp edges, the team moved on to another potential issue revealed after initial testing and printing. This issue had to do with the length of the gripper head, which was initially designed to be shorter than the rest of the gripper rings to allow for a wider range of potential payload sizes, but this design led to an issue when the gripper was initially extending. Being that the gripper head was shorter than the other rings, during full gripper retraction the gripper head rested below the lip of the outer rings. This led to the gripper head potentially becoming caught on the outer ring's lip which would potentially lead to jamming and subsequently the inability for the gripper to extend. This quickly became clear to the team as a major issue, but was an easy fix as the gripper head was simply extended to the same 5 inches length that the rest of the gripper rings were designed at. The initial extra 2 inches of clearance was sacrificed, but it was necessary to ensure that the gripper was fail-safe which was deemed much more important. The modified gripper head can be seen in figure 31.

It is worth noting that the team explored decreasing the wall thickness of each gripper ring to cut down on both cost and weight of the design. However, as a result of FEA analysis, the

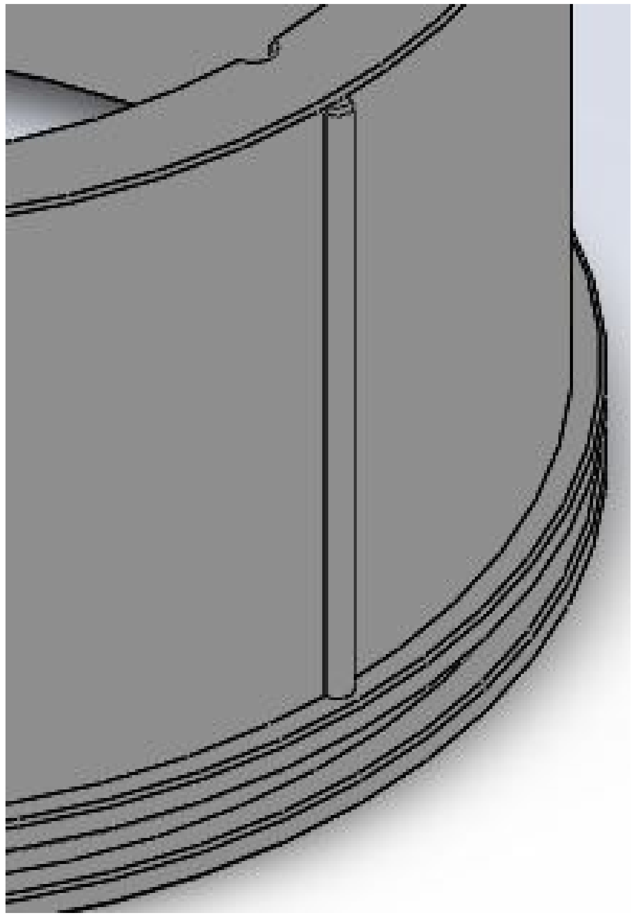


**Figure 29:** Guiding Track lines

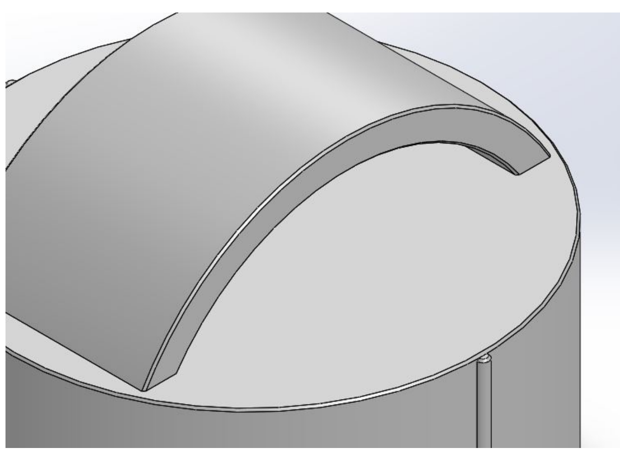


**Figure 30:** Chamfered Edges

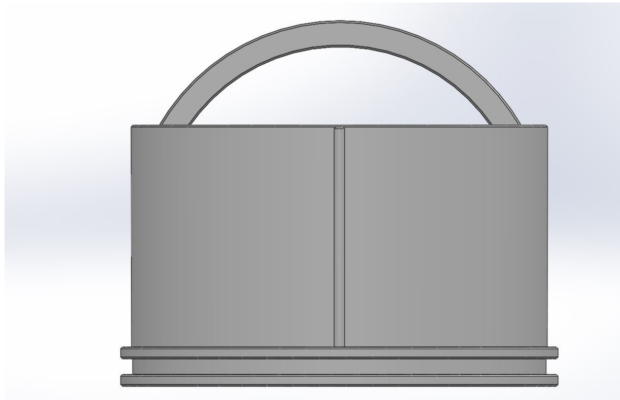


**Figure 31:** Modified Gripper Head

team came to the conclusion that decreasing the wall thickness could potentially compromise the structural integrity of the design when subjected to maximum instantaneous forces and the pursuit of this particular redesign element was deemed to not be worth the potential risk.

# 16 Operation

The most important design requirement given by NUWC in the beginning of the year was that the gripper must be "universal," meaning that it must be able to secure a payload of varying sizes, shapes, and orientations. As a result of this design specification, the team came to the conclusion that the best way to accomplish this goal was to allow for each of the 72 grippers in the system to be controlled individually. This conclusion was made with the thought that payloads of asymmetric and abnormal shapes would not be able to be securely held if the system operated as a whole rather than individually. Though, due to project scope and time constraints, the team never explored how to integrate this specific requirement. The team operated under the assumption when designing the gripper that each one would be able to controlled individually. In theory, a payload would be inserted into the gripper system via a wench located at the bottom of the payload bay. The operator would then extend each gripper using saltwater acquired from outside the submarine individually from the operating room on the submarine. This saltwater would be collected from the outside of the submarine and streamlined to each gripper using a series of piping and automated control valves to ensure that each gripper is only extended to the desire of the operator.

In order to ensure that the operator does not overextend a gripper, which could potentially result in damage to both the payload and the gripper, pressure sensors would be integrated into the base of each gripper which would be triggered once the force of contact with the payload is felt by the gripper. Once the operator has extended the necessary grippers to secure the payload, this sensor would alert the operator to stop extending. Once the payload was fully secure, the operator need only monitor these pressure sensors to ensure that the force on one gripper never becomes too great. Once the payload is ready to leave the payload bay, the operator simply slowly retracts the grippers fully to ensure that no damage is done to either the payload or the gripper system upon leaving the payload bay. Though no manuals were physically made, this basic assumption of how the gripper system would operate was used when implementing each aspect of the design.

It is important to note that due to the fact that there is no manual extension or retraction of a gripper, the only potential operation hazard comes in the form of overextending the gripper and thus potentially catastrophically damaging the payload. Being that the payload has the potential to be an explosive, the team made sure to implement aspects of the design to make sure that this never happens such as the pressure sensors and convex elastomer coated gripper tip.

In addition to safety, the team also kept in mind both repair and assembly when designing a gripper. Being that each gripper is comprised of seven concentric rings and a gripper head, the gripper would have to be assembled from the top down, meaning the head would be manufactured first followed by the first ring, then the second ring, and so on. The gripper head would act as the initial base, then each following ring would be placed on top of the head thus ensuring that each ring can only move in the desired direction of the operator. Each gripper would be installed individually once fully put together and operated individually as well as discussed above. In regards to repair, being that each gripper is both operated and installed individually, the system as a whole need not be shut down as a result of a single damaged gripper or gripper ring. The operator would simply closed the automated control valve for the damaged gripper, climb into the payload bay, and replace the damaged gripper. Being that each gripper is comprised of the same amount of rings that fit concentrically within each other, in the event that a single ring is damaged, the entire gripper need not be replaced, just the damaged ring. This design is cost effective in this regard being that one damaged part does not result in having to replace the entire system or potentially, even an entire gripper. The repairman would simply remove the gripper with the damaged ring, disassemble the gripper until the damaged ring could be reached, replace the damaged ring, reassemble the gripper, and reinstall the gripper. Throughout this entire process, the undamaged remainder of the gripper system would be fully operational.

# 17 Maintenance

When designing the gripper, the team was very careful to ensure that the gripper system would not be compromised as a result of a few damaged grippers. Being that each gripper is controlled individually via a system of piping and automated control valves, a damaged gripper could simply have its valve shut leaving it available for maintenance while the rest of the system continues to operate as required. In the event of a damaged gripper, the operator would shut that particular gripper's valve, climb into the payload bay via the access hatch required by the design specifications, remove the damaged gripper, and replace with a new one if necessary. Being that each gripper is a collection of seven concentric rings and a gripper head, it is likely that an entire gripper would never be damaged. Rather, only a ring or possibly the head. In the much more likely event that this happens, the operator would simply close the valve of the damaged gripper, climb into the payload bay via the access hatch, remove the gripper with the damaged ring, disassemble the gripper until the damaged ring could be reached, replace the damaged ring, reassemble the gripper, and reinstall the gripper, then reopen that gripper's particular valve. As a result of this design aspect, grippers are easily maintained both during a mission and when the submarine is docked. This saves a considerable amount of money as well being that the submarine would not need to come in for gripper maintenance during a mission being that it can be serviced at sea.

NUWC requires each gripper to be able to be extended and retracted up to 100 times and be able to last the duration of a six-month mission. As a result of material choice of Aluminum 5083, the gripper would have no problem meeting these requirements due to its high strength to weight ratio and resistance to corrosion. However, when the time does come for a gripper to be replaced Aluminum 5083 is recyclable. That being said, there is little to no environmental effect on disposing of these grippers because a large portion of the material can be reused possibly even to manufacture new grippers. The only aspects of the design that would need to be permanently disposed of are the elastomer coating on the gripper head as well as the o-rings which encircle each gripper ring and the head to ensure a seal of the fluid media used to power the extension of each gripper. These elastomer materials would contribute the the rest of the waste accumulated on the submarine throughout a mission and would be disposed of in the same manner. Being that the gripper is largely recyclable, it can be concluded that the gripper design is quite efficient in regards to waste.

# 18 Additional Considerations

There were a variety of additional considerations that the team had in mind when designing a universal gripper. The first of which was the economic impact that the design would have, specifically in terms of cost. Being that the gripper is designed to be easily maintained, the submarine does not need to stop in port in order to replace or repair damaged grippers. This saves a considerable amount of money not only in terms of fuel required to make a unscheduled stop, but also in terms of the time saved in being able to repair the gripper while out to sea. This time saved is invaluable in military application as submarines in operation are extremely limited and therefore time spent on maintenance stops is extremely wasteful. In addition to time saving, material choice was also affected by economic considerations. The material Aluminum 5083, which was the teams final choice for gripper material, only costs $8.33 per pound, which when compared to other potential materials such as inconel or titanium is incredibly cost effective. Being that the gripper weight is roughly 81 lbs and a system consists of 72 grippers, this cost per pound adds up incredibly quick and becomes extremely relevant when accounting for cost in the design.

In addition to economic impact, the team made sure to consider environmental impact as well when developing the universal gripper design. In choosing Aluminum 5083 as the gripper manufacturing material, the team was able to greatly reduce the amount of waste produced by grippers upon disposal being that Aluminum 5083 is recyclable. Being that the vast majority of the gripper is made from this recyclable material, the amount of waste accumulated when disposing of grippers that have reached the end of their life-span is negligible. The only true waste that the universal gripper design concedes is the elastomer coating on the gripper tip as well as the o-rings that each gripper ring and head has to ensure sealing of the hydraulic fluid used to power the extension of the gripper. This waste would be collected with the rest of the waste accumulated on the submarine throughout the duration of the mission and would be disposed of in the same manner. In addition to the recyclable aluminum 5083 saving money, it also ensures a more sustainable design being that the gripper material is readily available and easily manufactured and maintained.

The group also made sure to consider societal impact when designing the universal gripper, however it was determined that there was no additional impact to be considered for this design due to its incredibly specific application.

Political and ethical considerations were made when designing the universal gripper to ensure that the design did not leave the Navy at any additional risk than they already face on a daily basis. Being that the gripper is designed to grip payloads that could be explosive, fail-safe design aspects needed to be installed to ensure that there was no possibility of catastrophic system failure. Sailors lives would be directly at risk if the design were to fail and therefore a considerable amount of consideration was put into how to ensure safe operation of the grippers. The first consideration taken to ensure a fail-safe design is to coat the gripper tip with an elastomer. In addition to the chamfered edges of the gripper, this elastomer coating ensures no sharp edges would ever come in contact with the payload which could potentially damage the payload. In addition, pressure sensors were implemented into the design to ensure that the operator wouldn't over-extend a gripper which could lead to payload damage as well. Endangering lives of any person is extremely unethical, but the political ramifications of potentially harming members of the military as a result of negligence led the team to ensure that the design would be fail-safe and work properly in all conditions. These health and safety considerations were of paramount importance when designing the universal gripper.

# 19 Conclusions

Team Let it Grip was tasked with designing a gripper system to be compatible with the missile silo, as well as be able to functionally grip a payload of varying universal size, shape, and orientation. NUWC wants a system that can successfully grip with as little maintenances and error as possible. The team directed their focus to designing and devolving a singular gripper that is independently operated and has the strength to support the weight and stress of a payload. NUWC was unable to provide the exact dimensions of various payloads because lack of security clearances, but they did provide specifications that closely resembled shapes that the gripper will be used to secure (expressed in the design specification). With the dimensions supplied, the team began narrowing down their 120 concept generations. After discussions with NUWC, it was decided to move forward with designing a gripper made of metal. NUWC had previously designed and prototyped an elastomer gripper, which was been presented to the team at the start of the year. Their design was a gripper system that inflated with air being pumped in. NUWC expressed that if the team believed that elastomer was the most optimal design; it should be moved forward with and the development of an inflatable elastomer gripper should not be discouraged even though they have preformed tests on a similar design. With the full support of NUWC, the team performed research and comparisons and determined that metal would be a more optimal material for the security of a payload of varying size and shape. After eliminating all elastomer designs from the concept generations, the team decided to move froward with two generated designs.

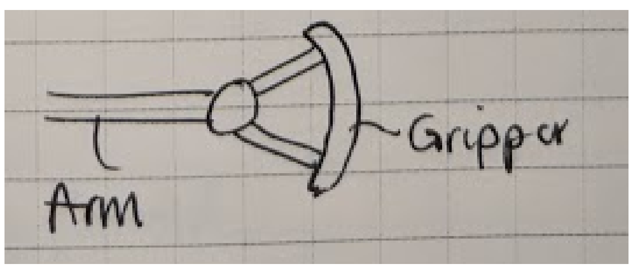



**Figure 32:** Concept Generation 1

The first concept, can be seen in Austin Cordova's concept generations. It is a solid convex gripper that acts as a supportive surface for the payload, as well as allows a dampening effect. This dampening effect helps support against sudden forces and shock events. This head was promising to moving forward in the design process but it needed to be connected to a extension device that could comply with the specifications of the missile silo.

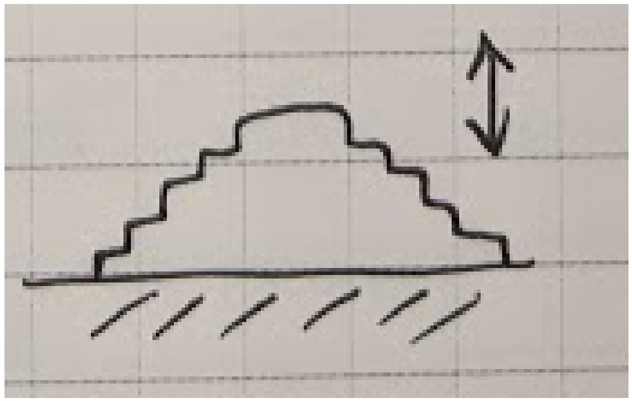
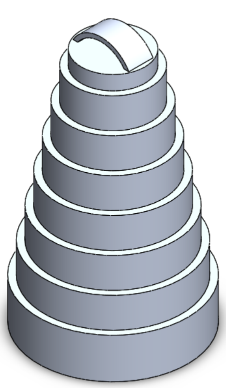


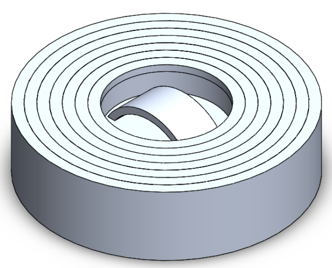
**Figure 33:** Concept Generation 2

This next concept generation is similar to the design that was presented by NUWC. It is a pyramid design that allows the gripper to fully collapse and expand outward using fluid. This design is promising because it allows the gripper to expand and collapse to specific dimensions of the missile silo. This design will be powered by hydraulics and will be made of metal.

Moving forward with both designs, concept generation 2 was modeled in SolidWorks. The team also worked on creating an extension system that worked with concept generation 1. After performing research and creating models in SolidWorks, the two concepts were combined. The convex head was added to the collapsible, metal, hydraulic powered extension system. As research and updates continued, the shape changed from a pyramid to a cylindrical design that uses o-rings to seal each section as the hydraulics pushed out each ring expanding toward the payload. The last piece is the convex head that works as a dampener once it comes in content with the payload. In order to provide more security and eliminate chance of damage for both the payload and the gripper, a rubber layer was added along the arch of the convex head. The updated design was modeled in SolidWorks and can be fully seen in the project design section.



**(a)** Gripper Extended



**(b)** Gripper Retracted

**Figure 34:** Design Modeled in SolidWorks

When this first model is compared to the design specifications, most requirements were meet. The base has a diameter of 18 inches, and if made using any one of the metals researched, the allowance for life and extensions/retractions are easily met. The allowance for retraction and extension is not fully met. The allowance for minimum retraction is 7.5 inches, where the design exceeds the allowance at 5.5 inches. The extension allowance is 33 inches; this is where the first design falls short. The gripper design only extends 31.25 inches, 1.75 inches short.

Second semester, the focus was to meet every design specification. Though the team wanted to fix the the lack of extension as soon as possible, it was important to follow the design process. The next step in the design process was to build it. The importance of building it is to see any flaws before testing and redesigns. As expressed in prior sections, the teams budget was non-existent. Because of this, the team began to use the resources provided to them. The build include doing a thirty percent scale 3D print on a printer at Schneider Electric. The print was a good visual of the extension and retraction.

**(a)** Gripper Extended

**(b)** Gripper Retracted

**Figure 35:** First 3D Print

Once the build was complete, the team moved on to testing. Testing was extremely important to the design of the gripper because it would show if the gripper would be able to withstand the the many forces of securing a payload. Using finite element analysis the team tested, the grippers ability to extend, deflection of single ring due to gravity, deflection and Stresses of Gripper assembly due to gravity, deflection and Stresses of Gripper O-Ring Lip due to applied forces, and deflection and Stresses of single ring due to applied pressures. the results for testing can be seen in the analysis and testing section. The tests went extremely well and showed the grippers are structurally sound to government standards.

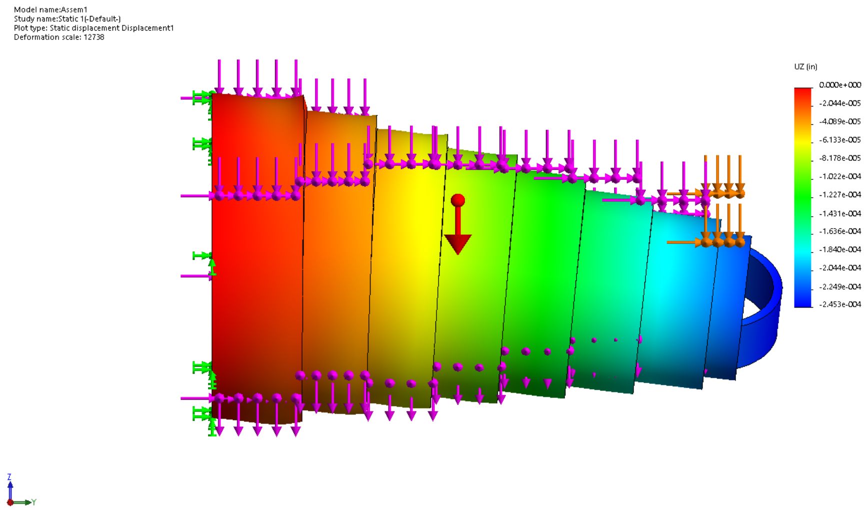
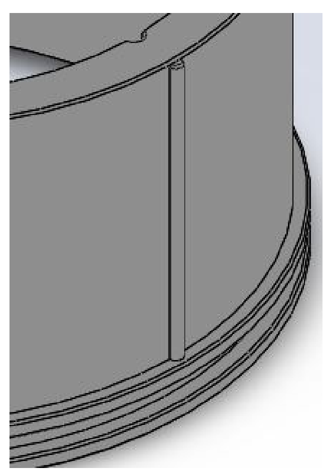



**Figure 36:** Assembly Deflection: z-Direction with Water

Once testing was completed, the team used results from the build and testing to incorporate redesign. The first redesign was to meet the extraction specification of 33 inches. The team added two more inches to the head to meet this specification. The addition of the two inches also added stability to the design when it is retracted, making the head and every ring the same height. The next redesign was proposed after the build. The team added guideline tracks along the rings and head, so the gripper would not rotate during extension. Finally the team incorporated chamfered edges to remove all sharp edges and optimize manufacturability. All redesigns were incorporated in the improved 3D print.

**(a)** Updated 3D print



**(b)** Guided Track Lines

**Figure 37:** Redesign

In conclusion, a gripper system that is compatible with the missile silo, as well as able to functionally grip a payload of varying universal size, shape, and orientation was designed and tested, with two scale models 3D printed. The gripper system functions to all specifications and abilities that NUWC required.

The Let it Grip team would like to extend a special thanks to Dr. Peter Hardro, and the engineering team at NUWC for their help and support through the semester and with the design process, and to Professor Nassersharif for his advice and guidance throughout this semester which lead to a successful product design.

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# Appendices

# Appendix A Script Used for Force Concentration

```
% URI CAPSTONE, MCE 401/2
%
% Team 12 - NUWC, Universal Undersea Gripper

% Determining Maximum Concentrated Load on Gripper

Bay_D = 87; % in
Bay_Circ = 2*pi*Bay_D/2; % in

Pay_D = Bay_D - 33*2; %Smallest Dia. of Ext. Grippers
Pay_Circ = 2*pi*Pay_D/2; % in

GripRing = 6; % 6 Grippers in a ring
GripColumn = 12; % 11 Grippers in a column
GripSpace = 419/GripColumn; % Amount of space covered b/w each gripper

GripNum = GripRing*GripColumn; % Total Number of Grippers

Weights = [1 3 7 11 22 25]; % Payload Weights X1000 lb
Grip = [1 3 7 5 8 10];   % Nu. of Rings providing support on payload
Grip_Tot = Grip.*GripRing; % Nu. of Grippers providing support on payload

Loading = Weights./Grip_Tot*1000; % 1000lb/Gripper
Shock_Loading = Loading*4; % Shock Values on Grippers

plot(Weights, Loading, '-o', Weights, Shock_Loading, '--o');
title('Loading per each Gripper'); xlabel('Payload Weights (1000lb)');
ylabel('Loading on Gripper (lb)');
legend('Base Loading','Shock Loading');
```

**Figure 38:** Force Concentration Script

# Appendix B Preliminary Design Drawings

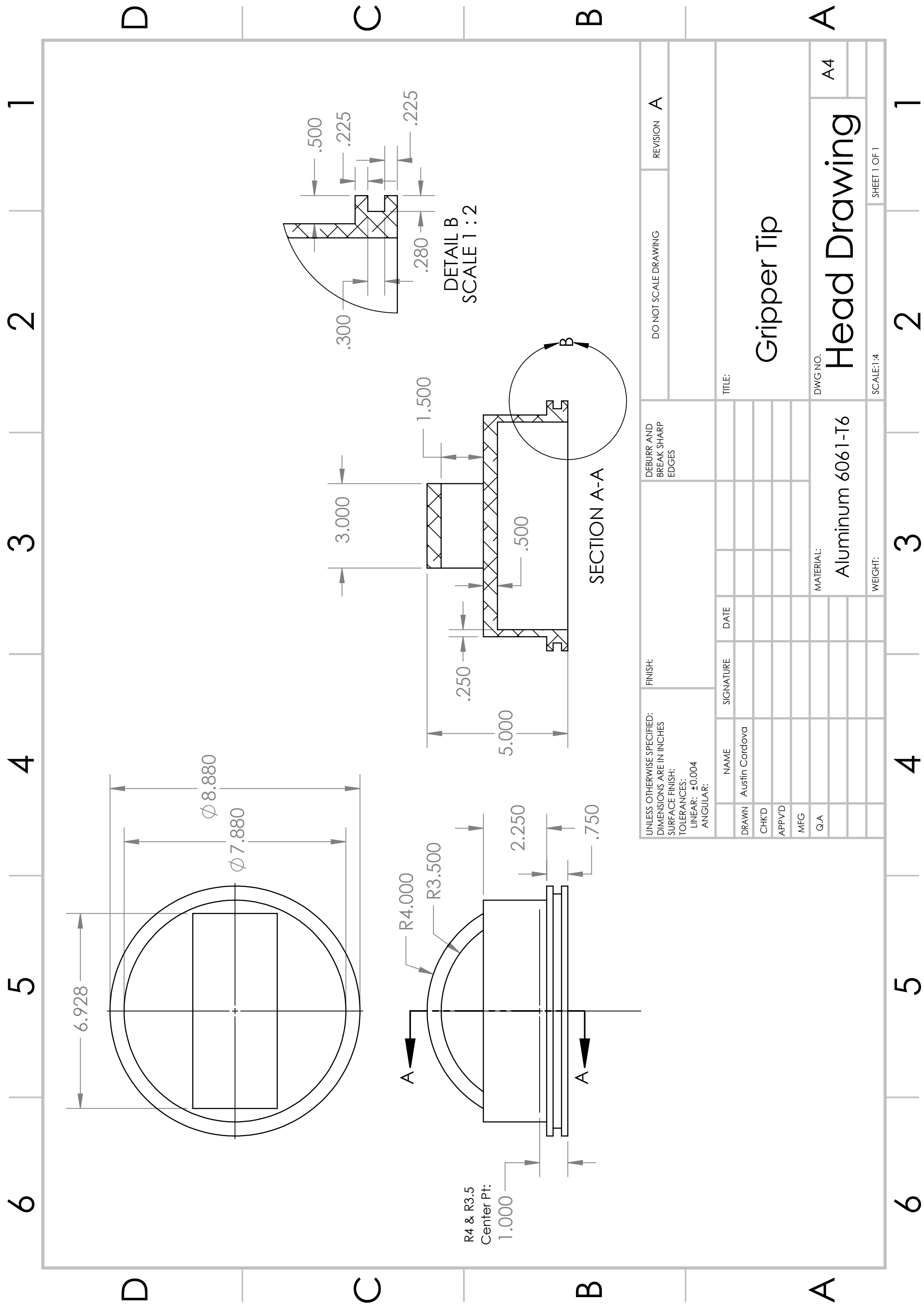


**Figure 39:** Gripper Head Drawing

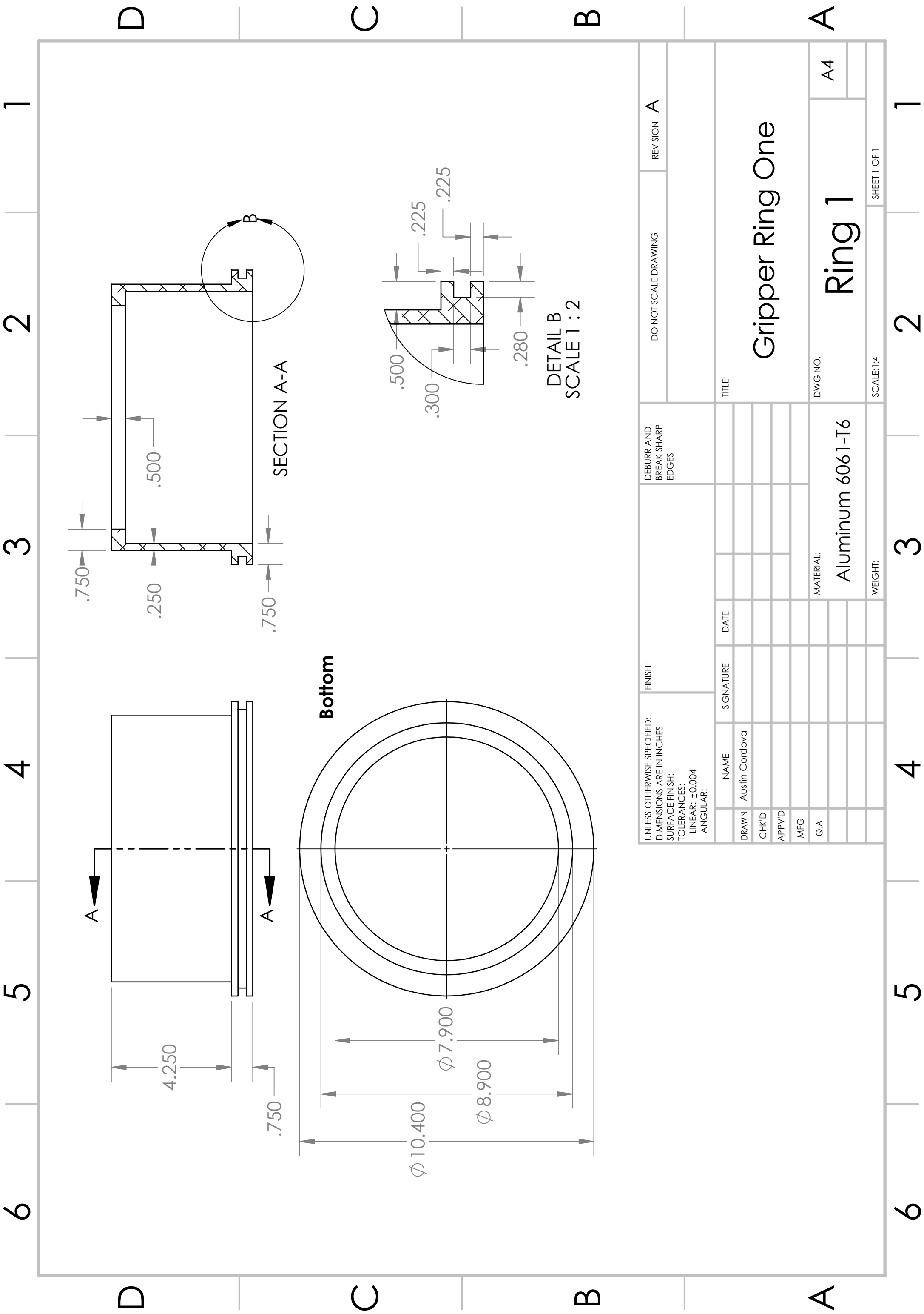


**Figure 40:** Ring 1 Drawing

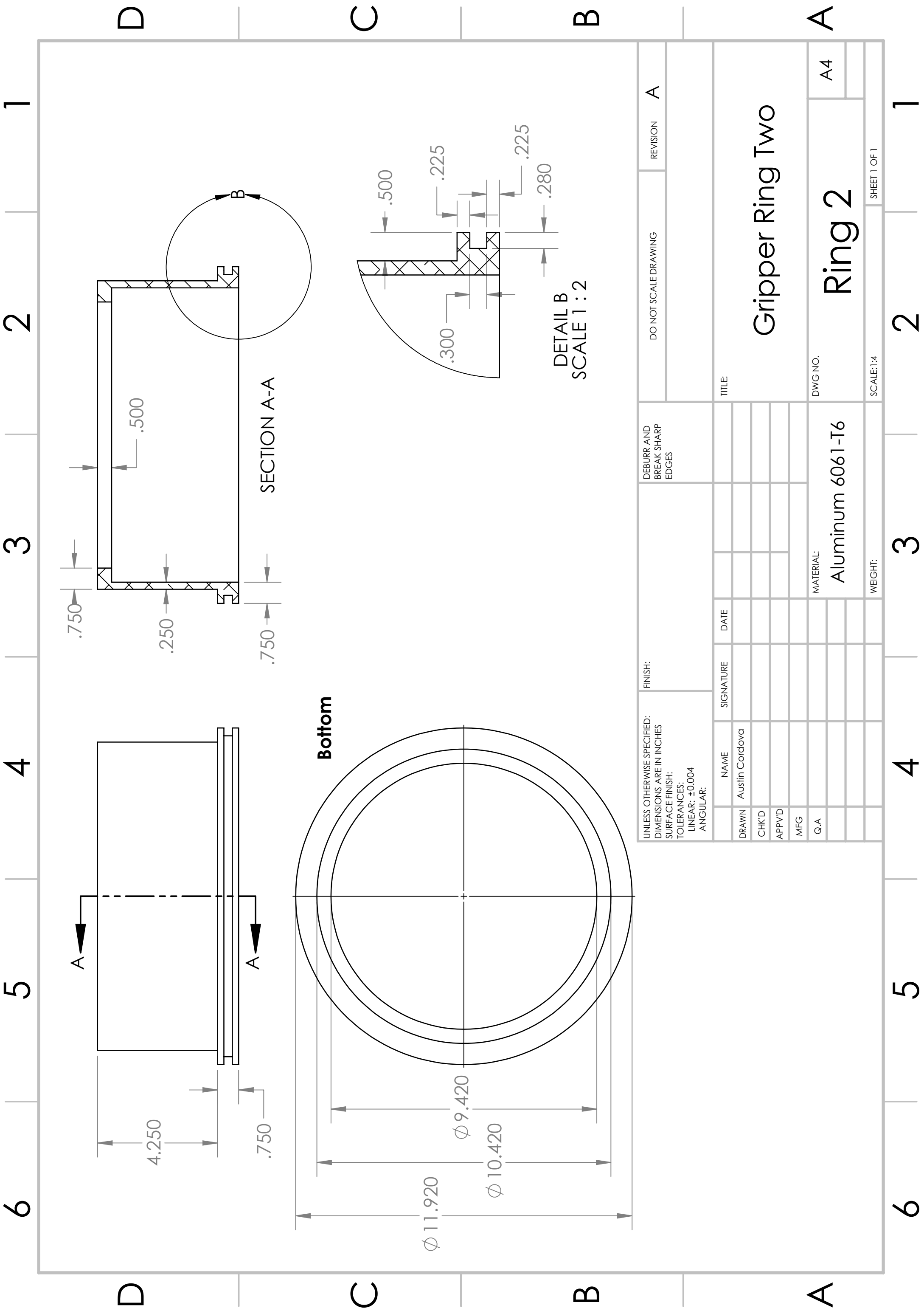


**Figure 41:** Ring 2 Drawing

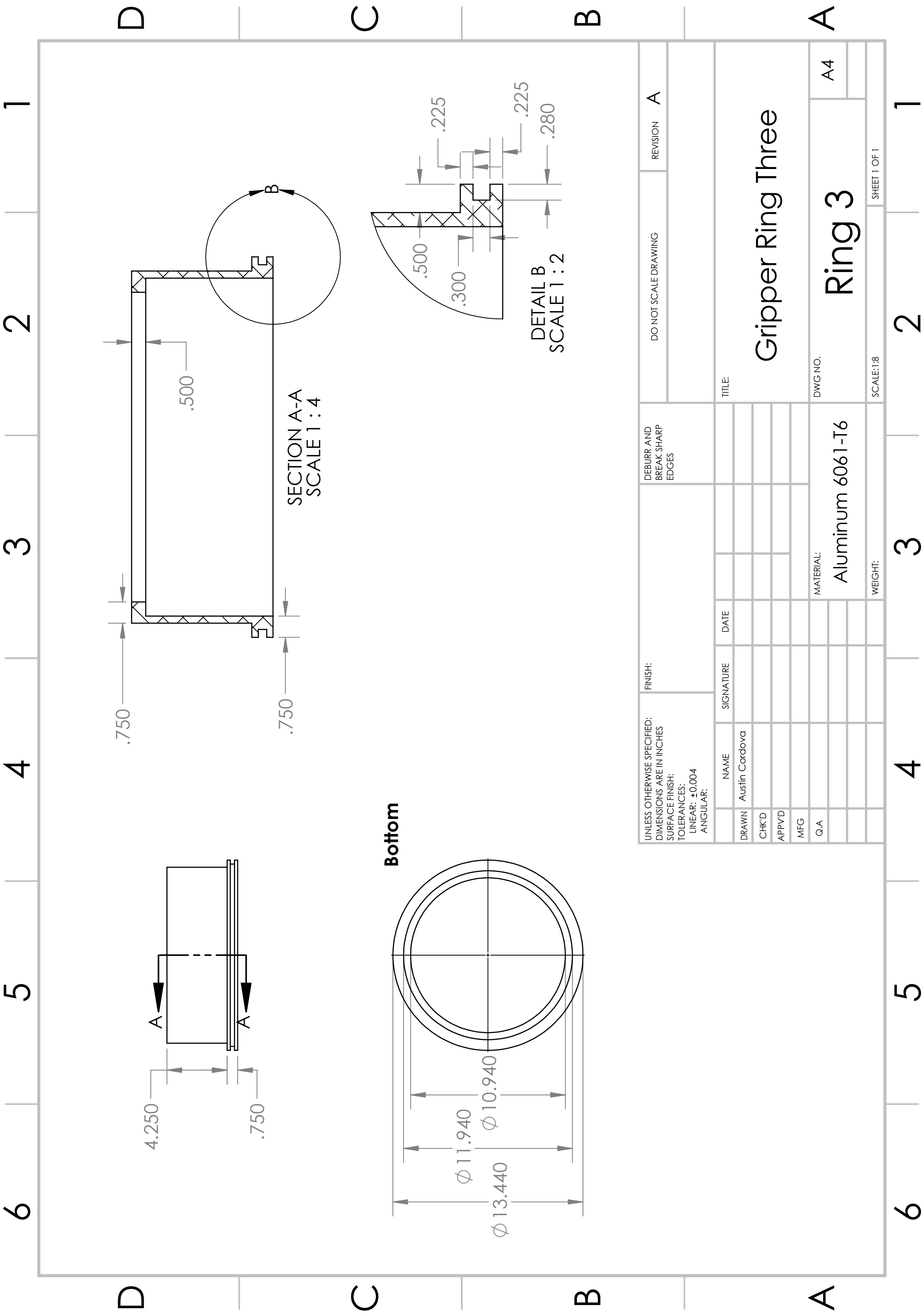


**Figure 42:** Ring 3 Drawing

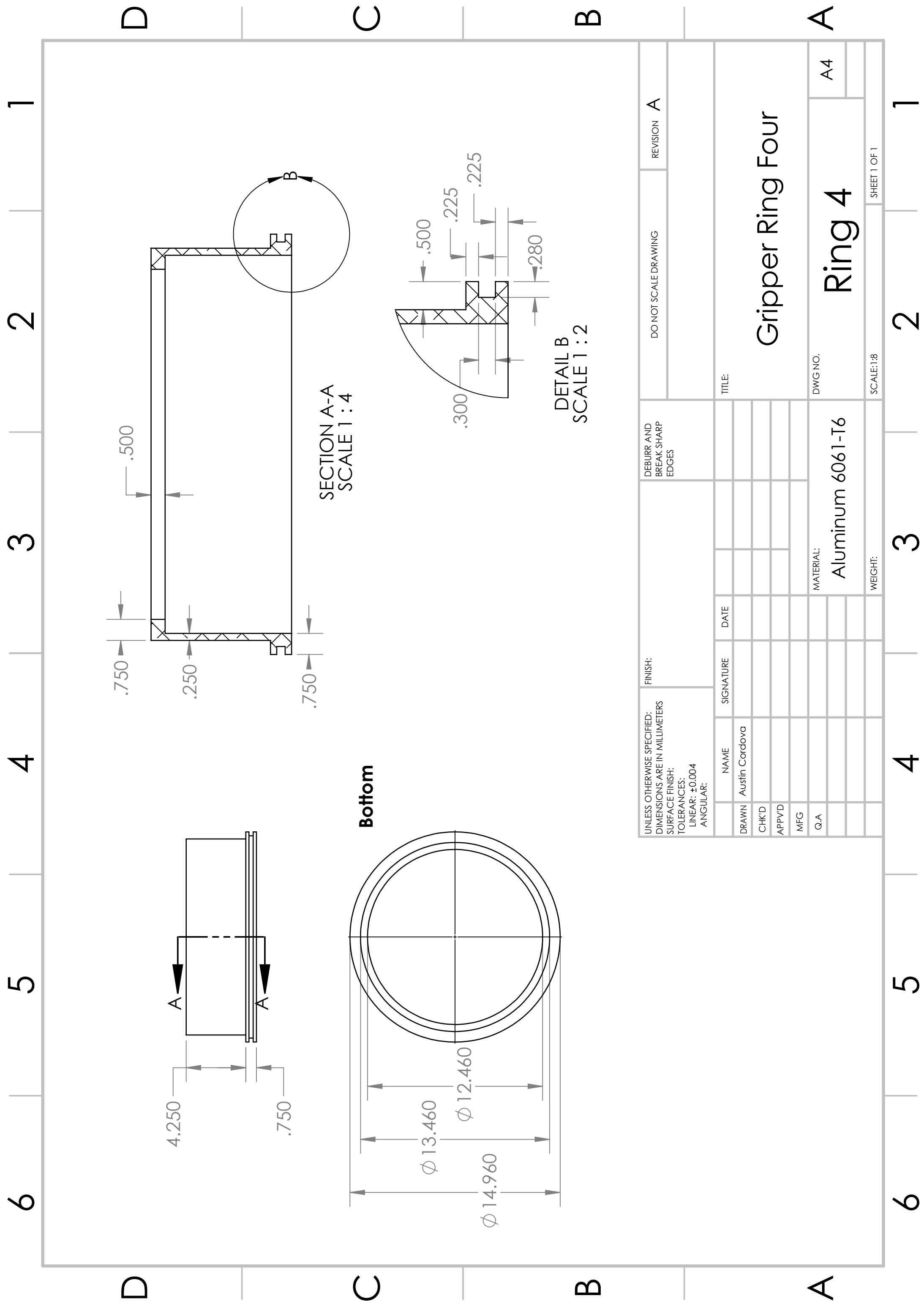


**Figure 43:** Ring 4 Drawing

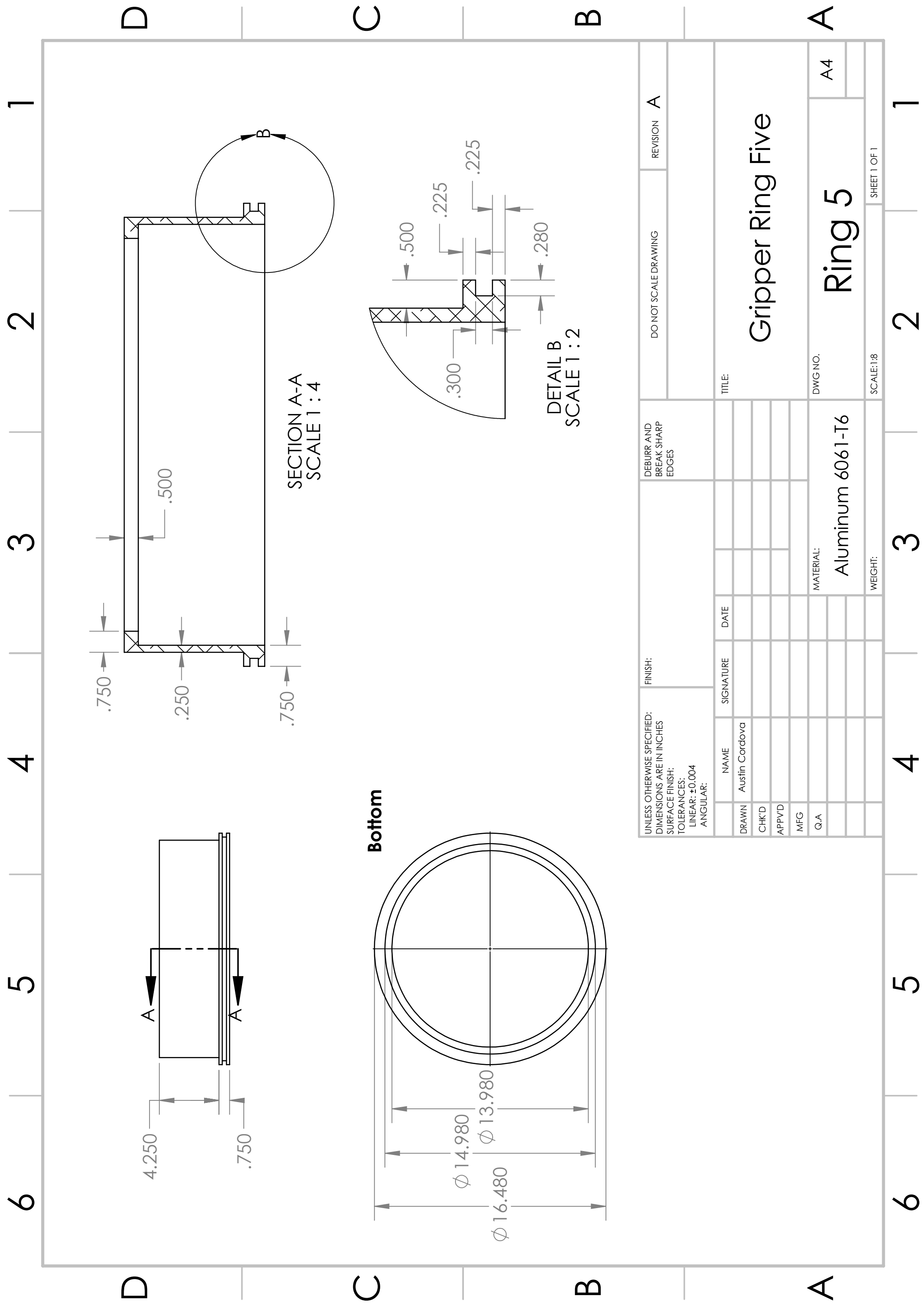


**Figure 44:** Ring 5 Drawing

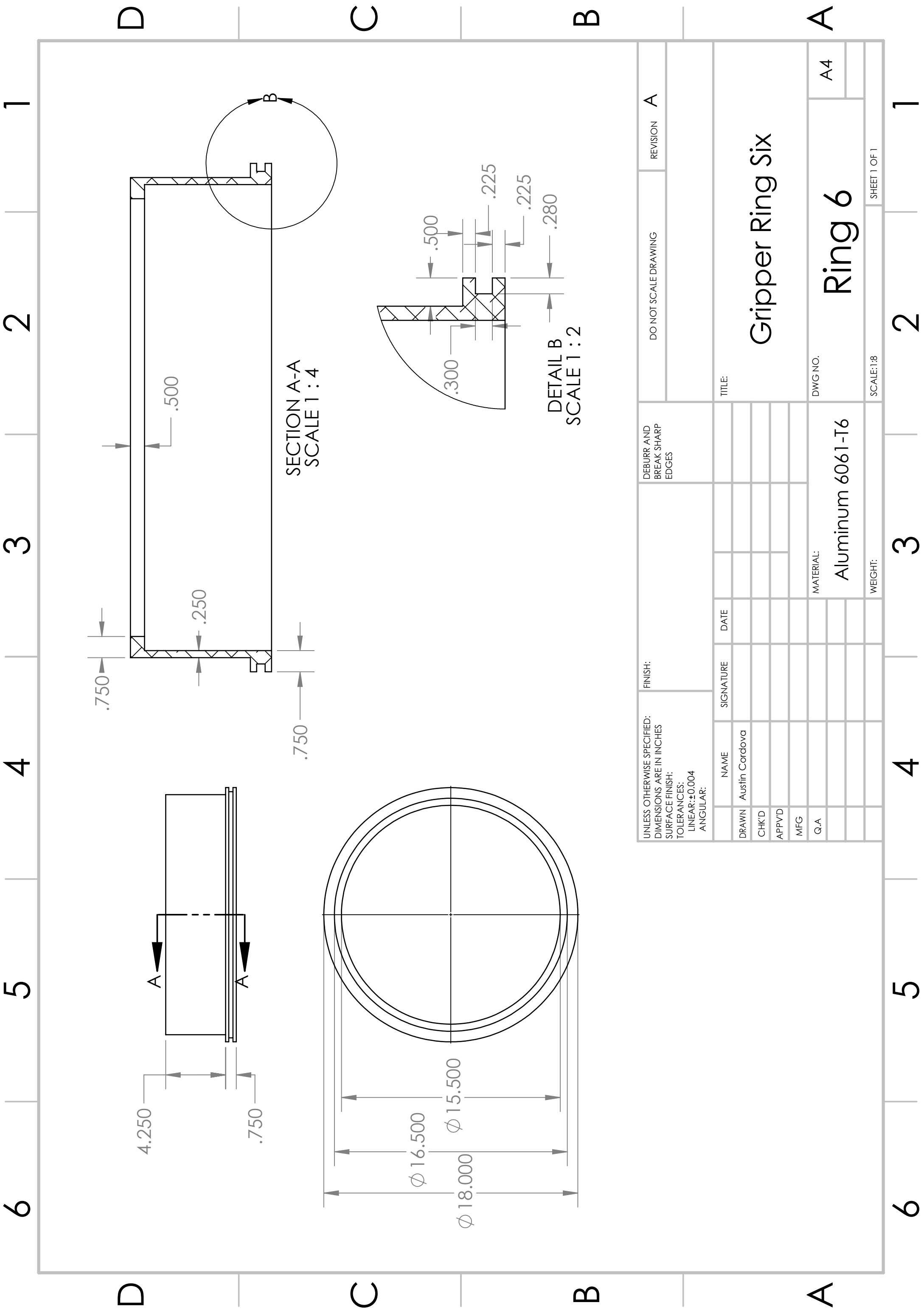


**Figure 45:** Ring 6 Drawing

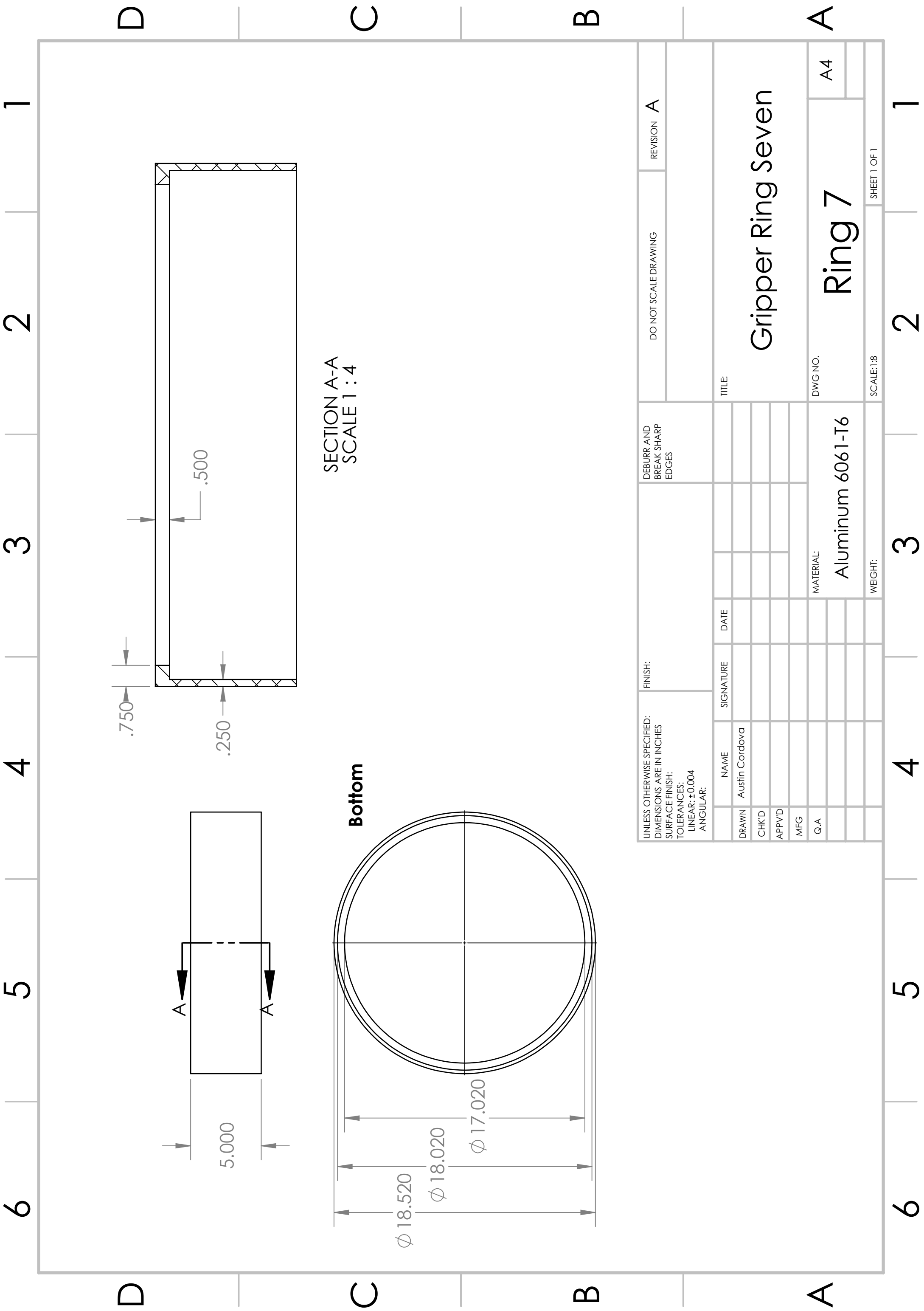


**Figure 46:** Ring 7 Drawing

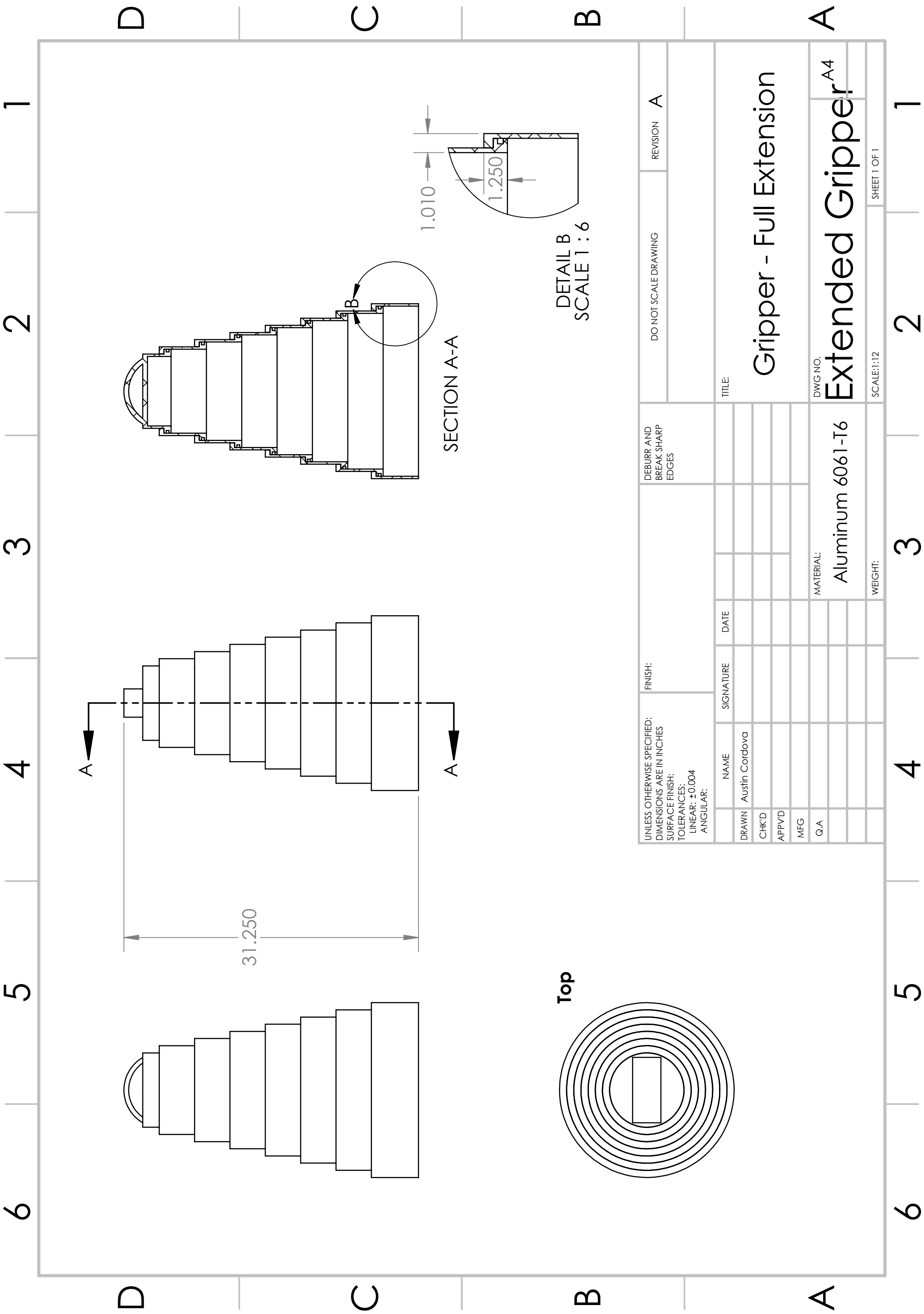


**Figure 47:** Preliminary Design Full Assembly Extension

# Appendix C Build Design Drawings

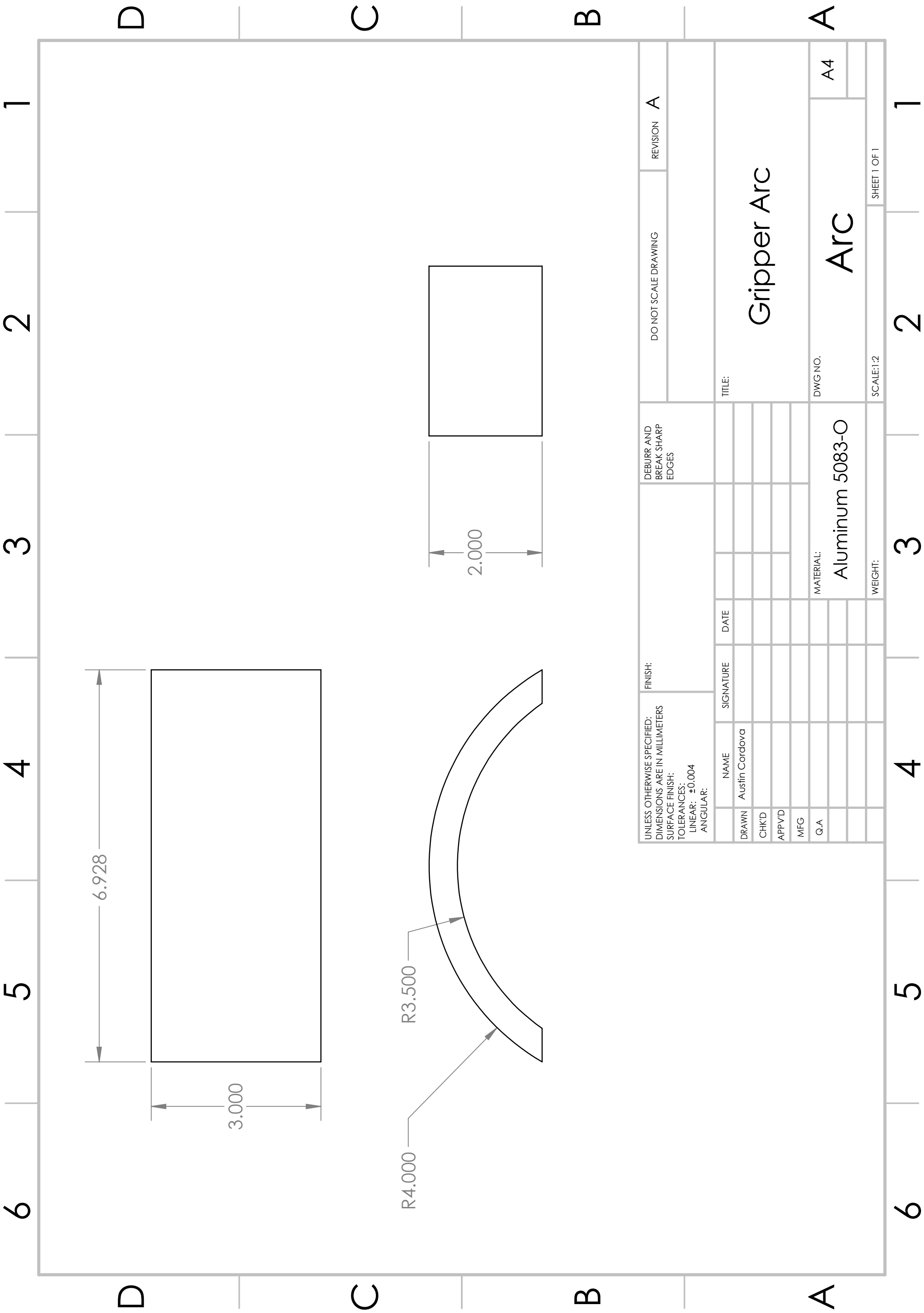


**Figure 48:** Arc Drawing

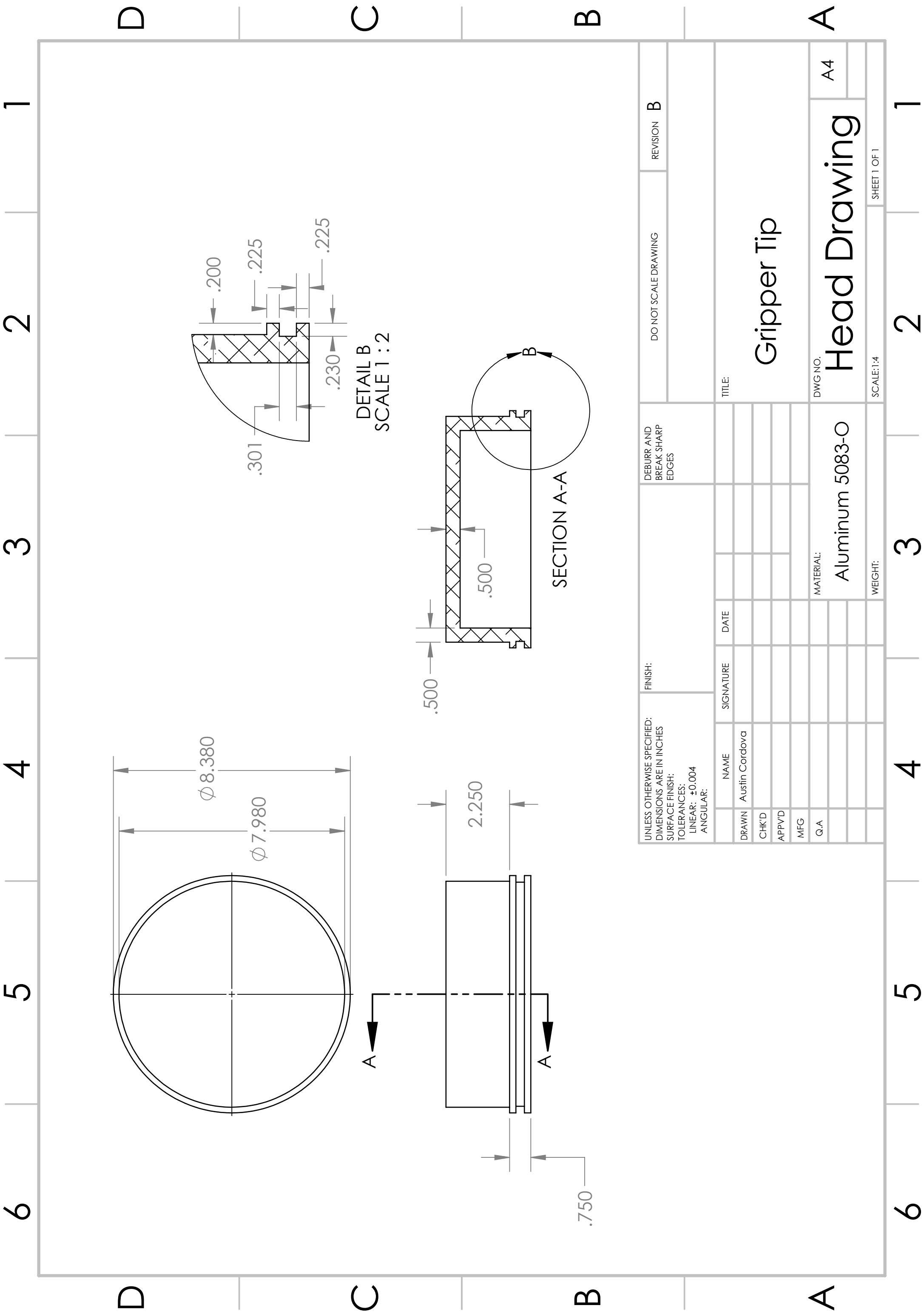


**Figure 49:** Head Drawing

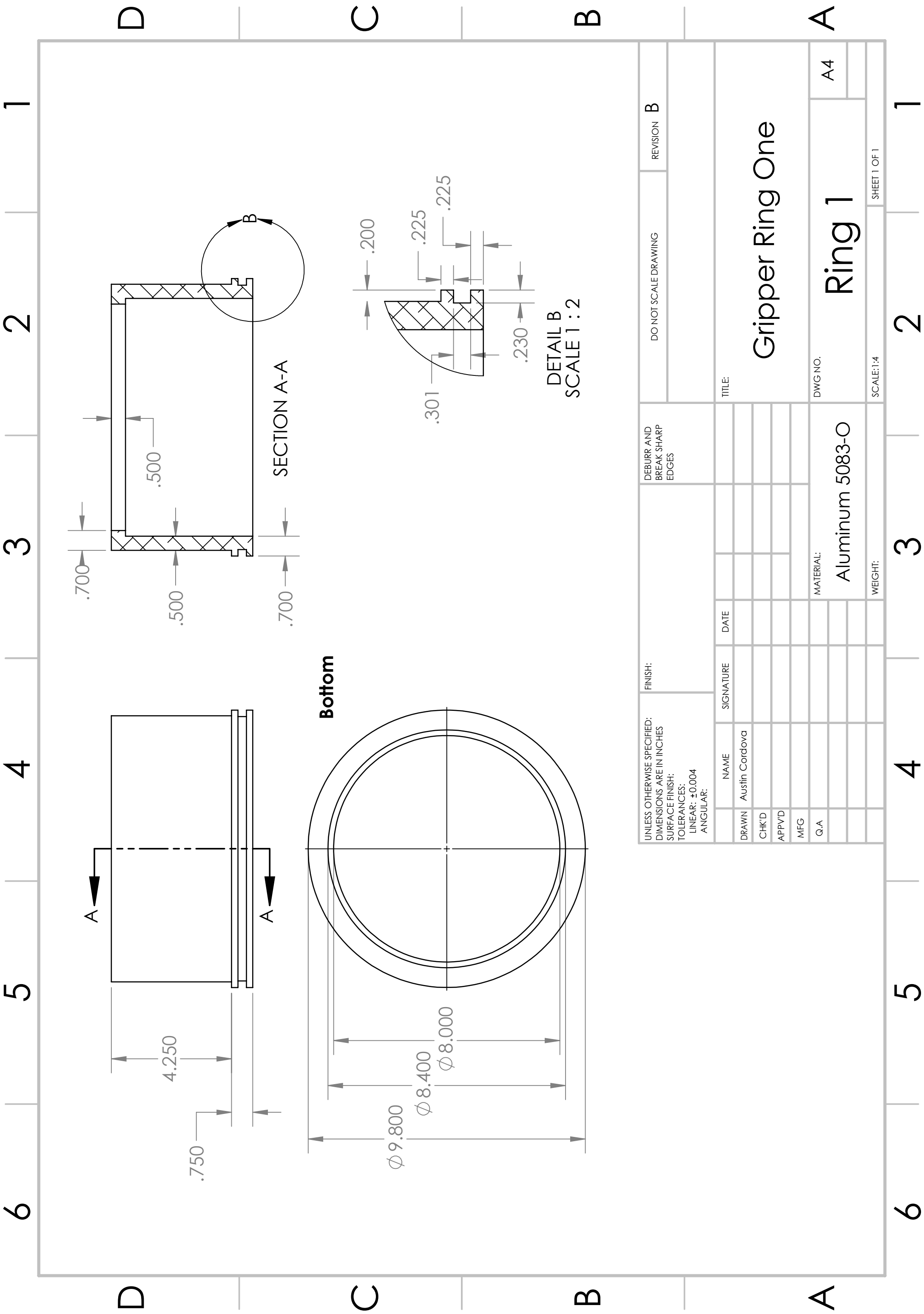


**Figure 50:** Ring 1 Drawing

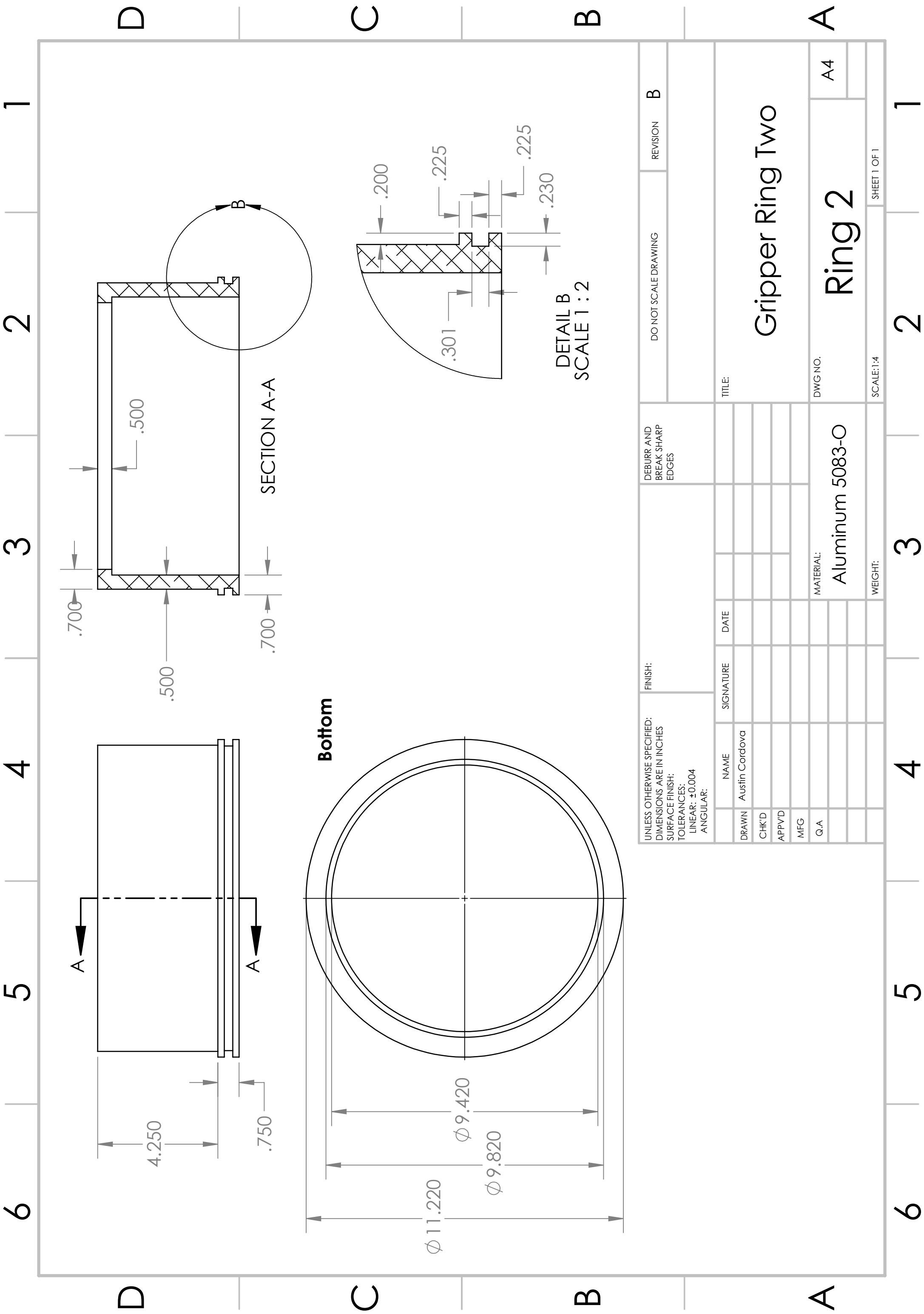


**Figure 51:** Ring 2 Drawing

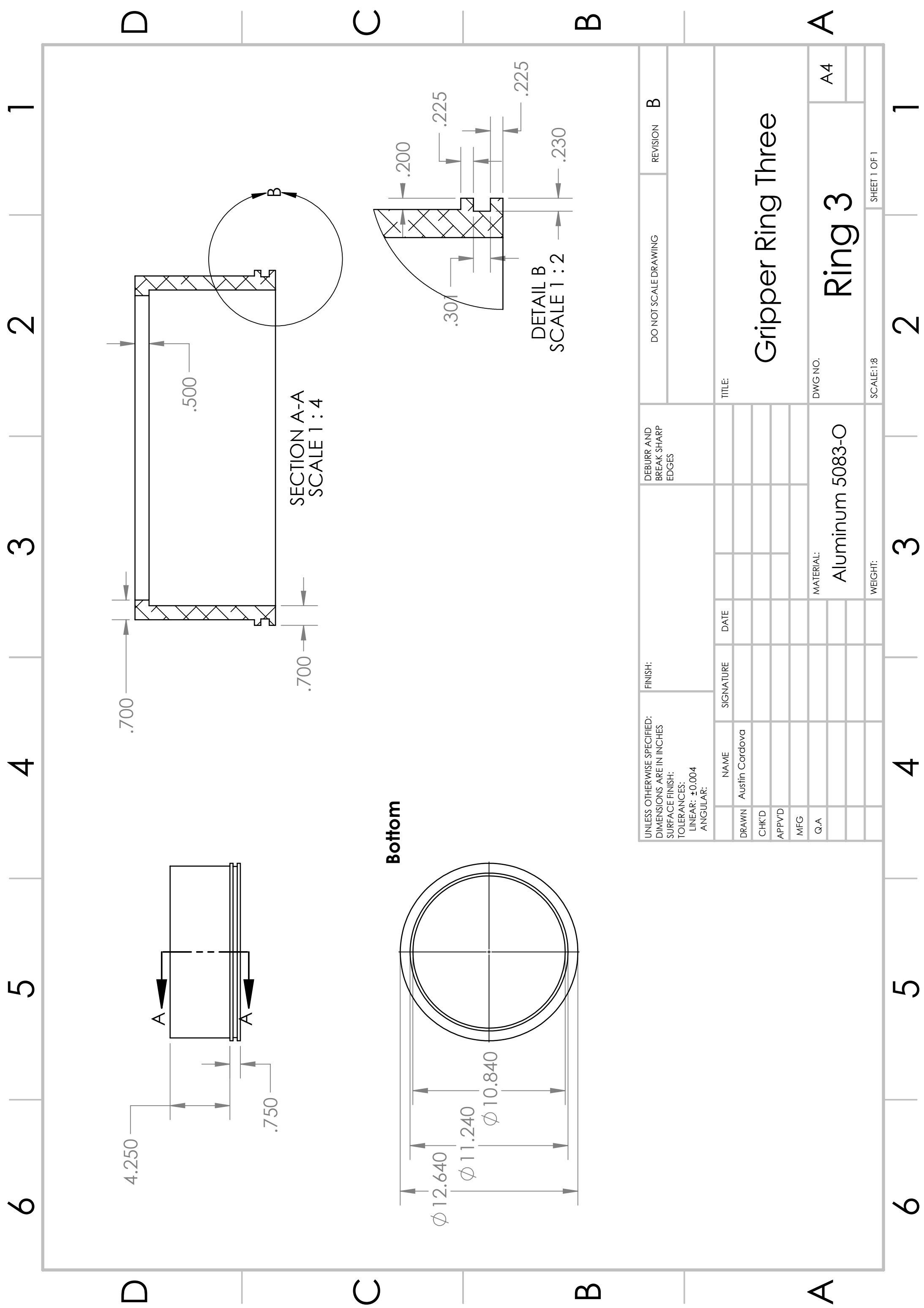


**Figure 52:** Ring 3 Drawing

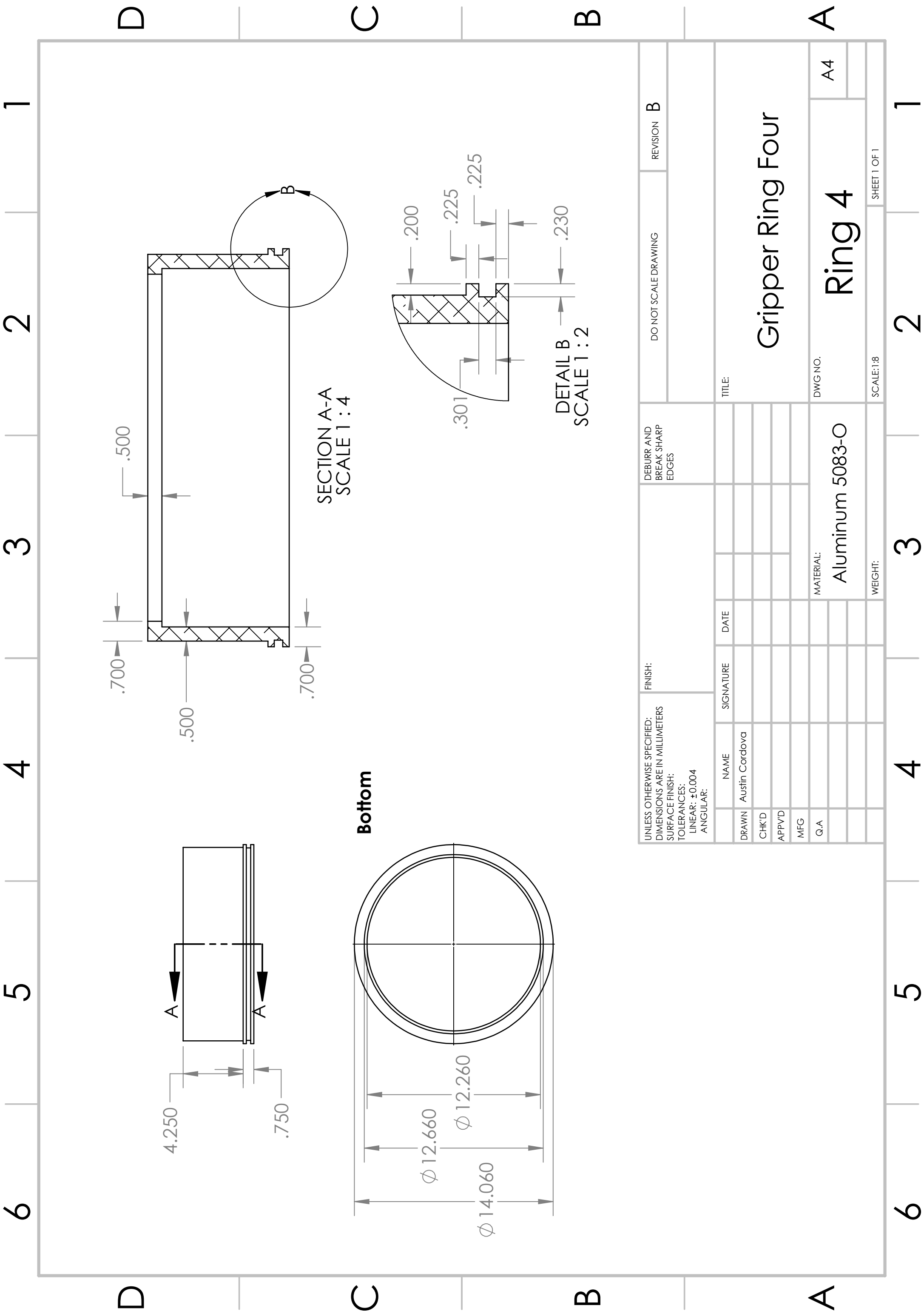


**Figure 53:** Ring 4 Drawing

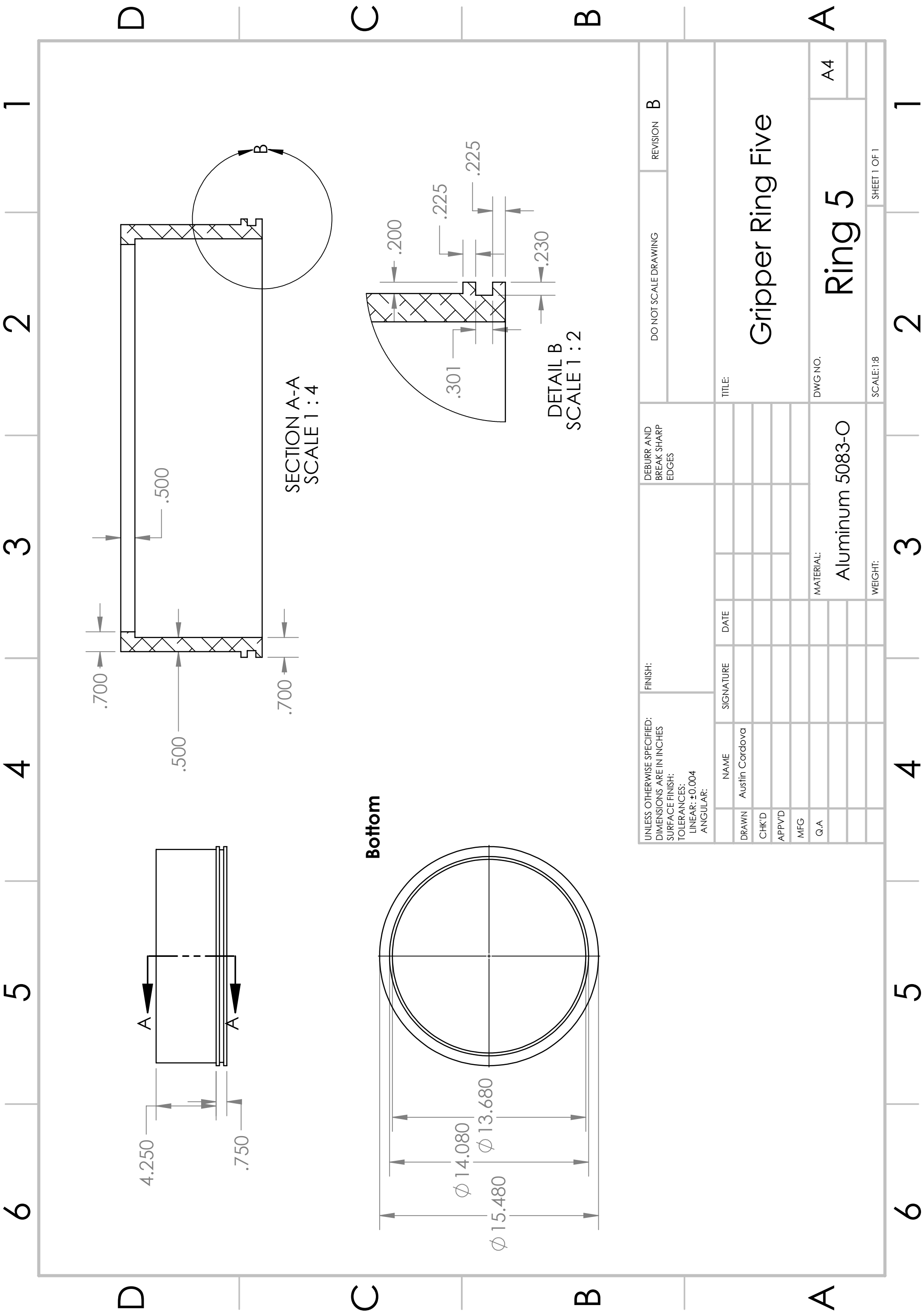


**Figure 54:** Ring 5 Drawing

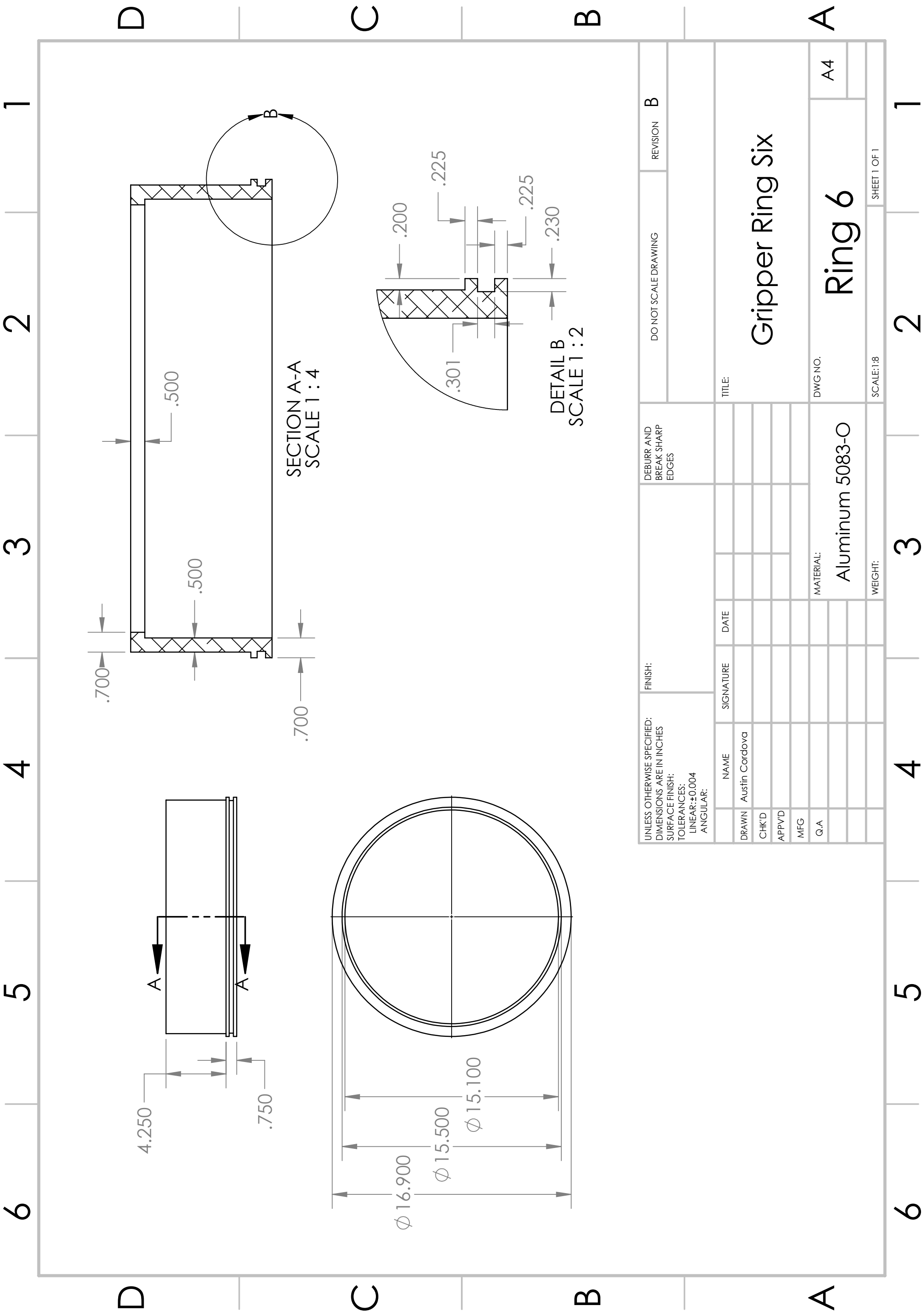


**Figure 55:** Ring 6 Drawing

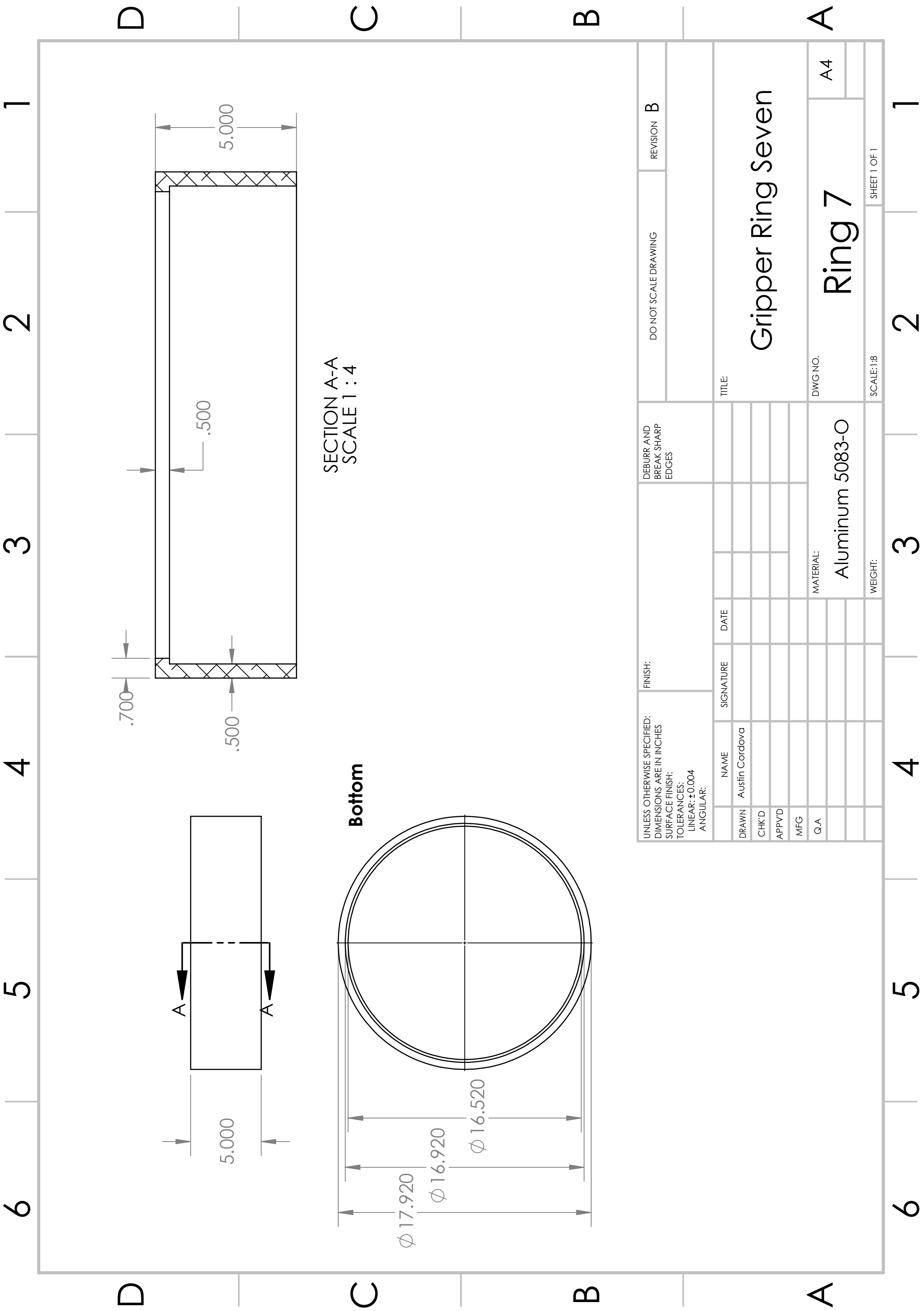


**Figure 56:** Ring 7 Drawing

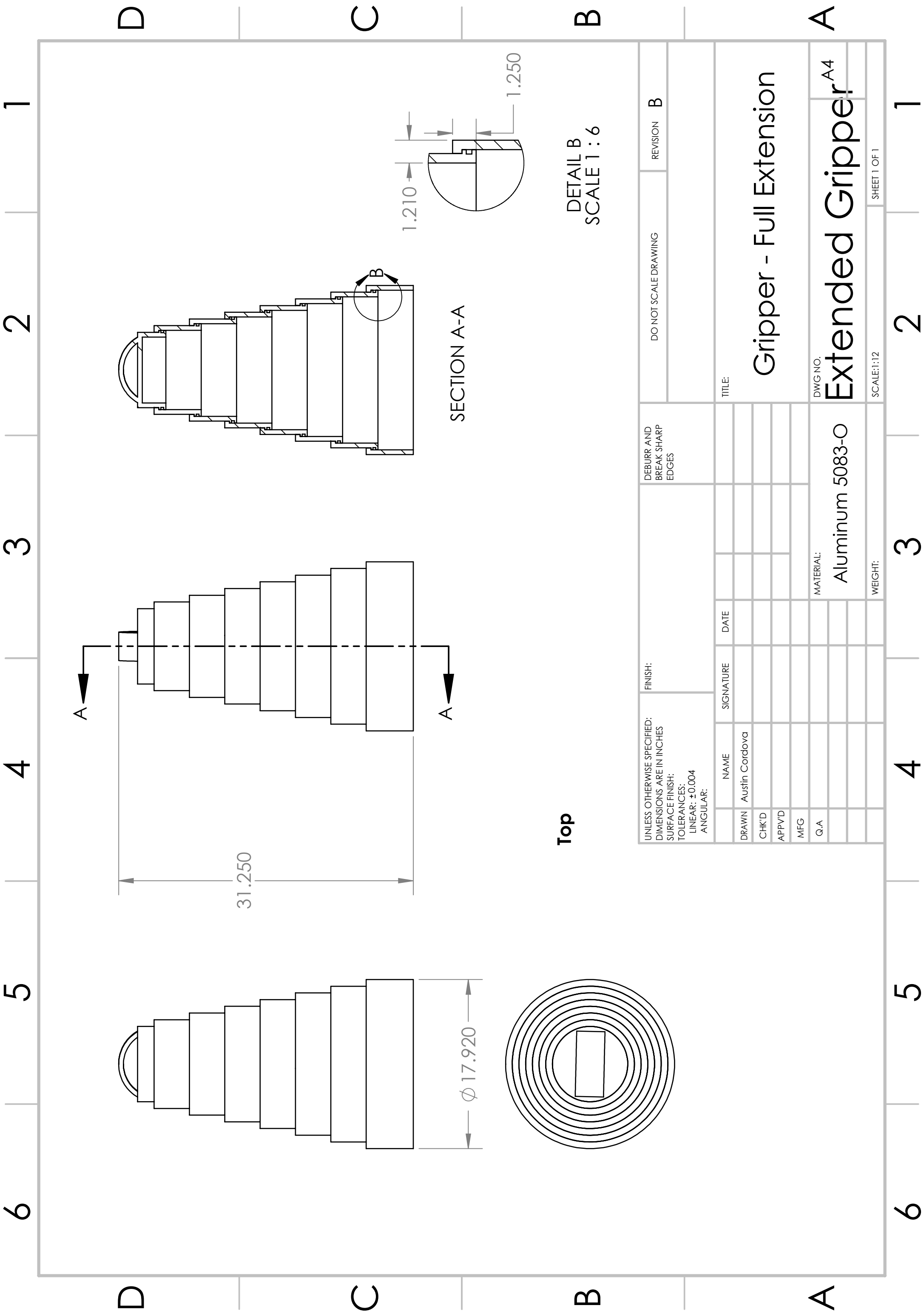


**Figure 57:** Build Design Full Assembly Extension

# Appendix D Redesign Drawings

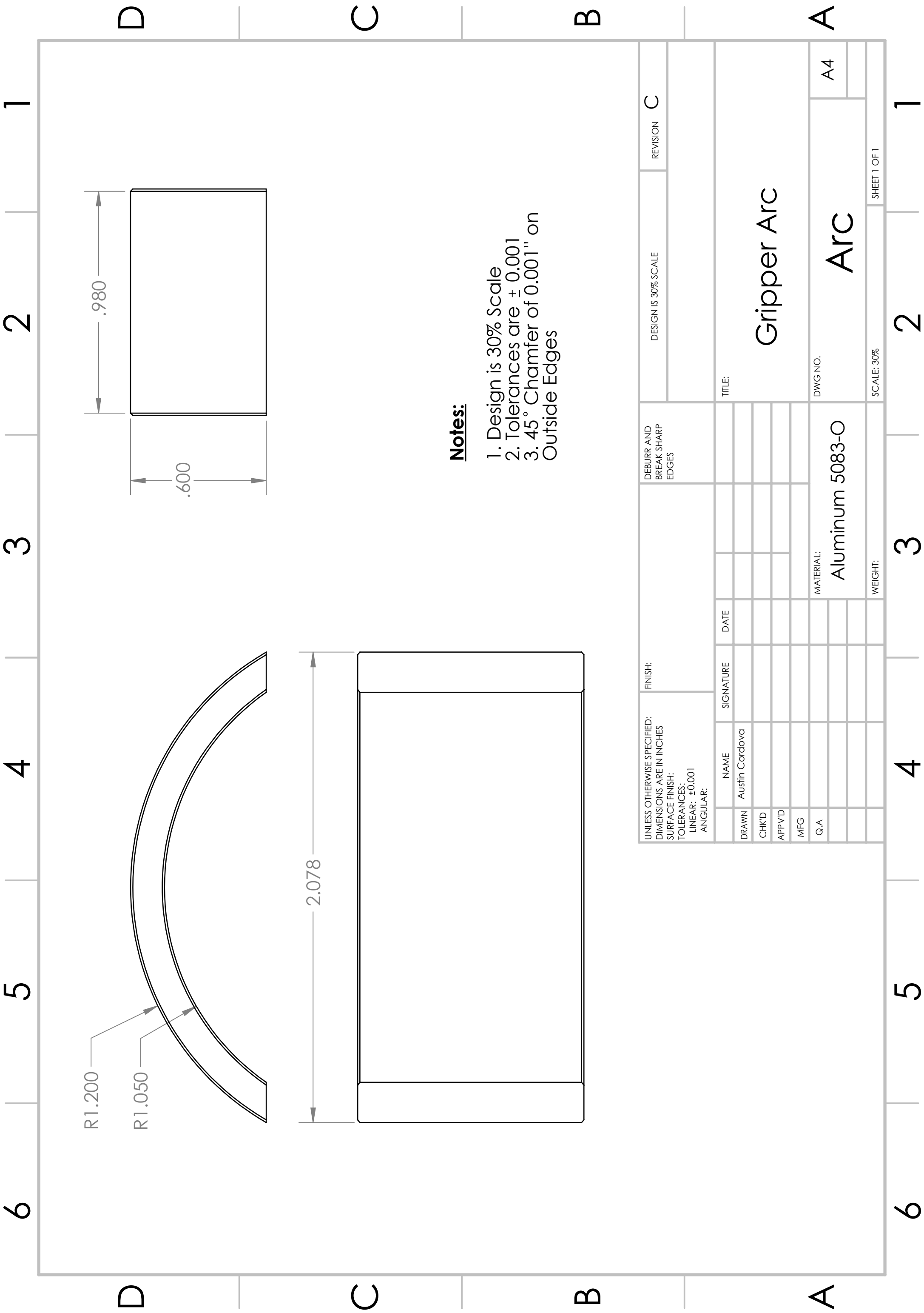


**Figure 58:** Arc Drawing

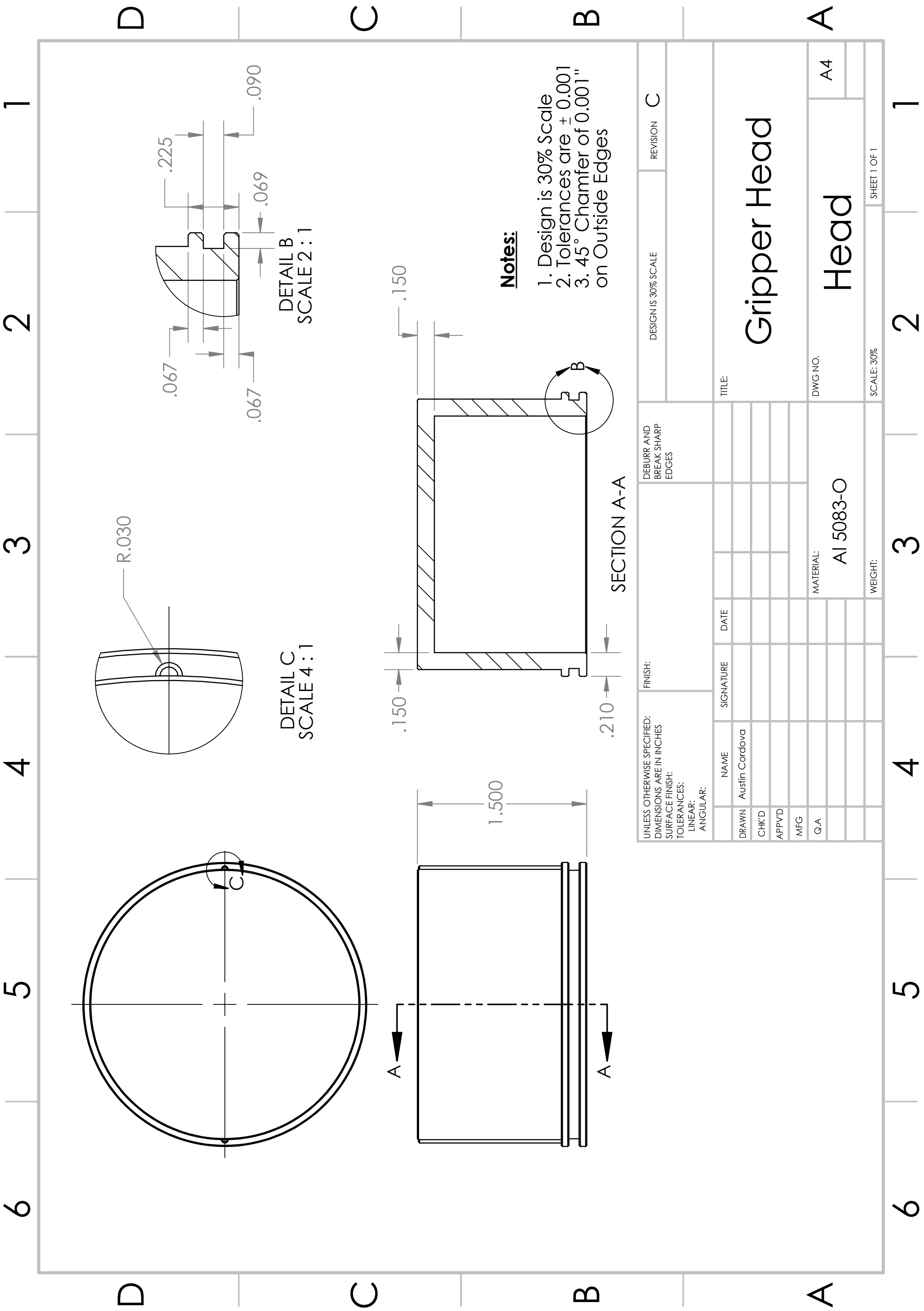


**Figure 59:** Head Drawing

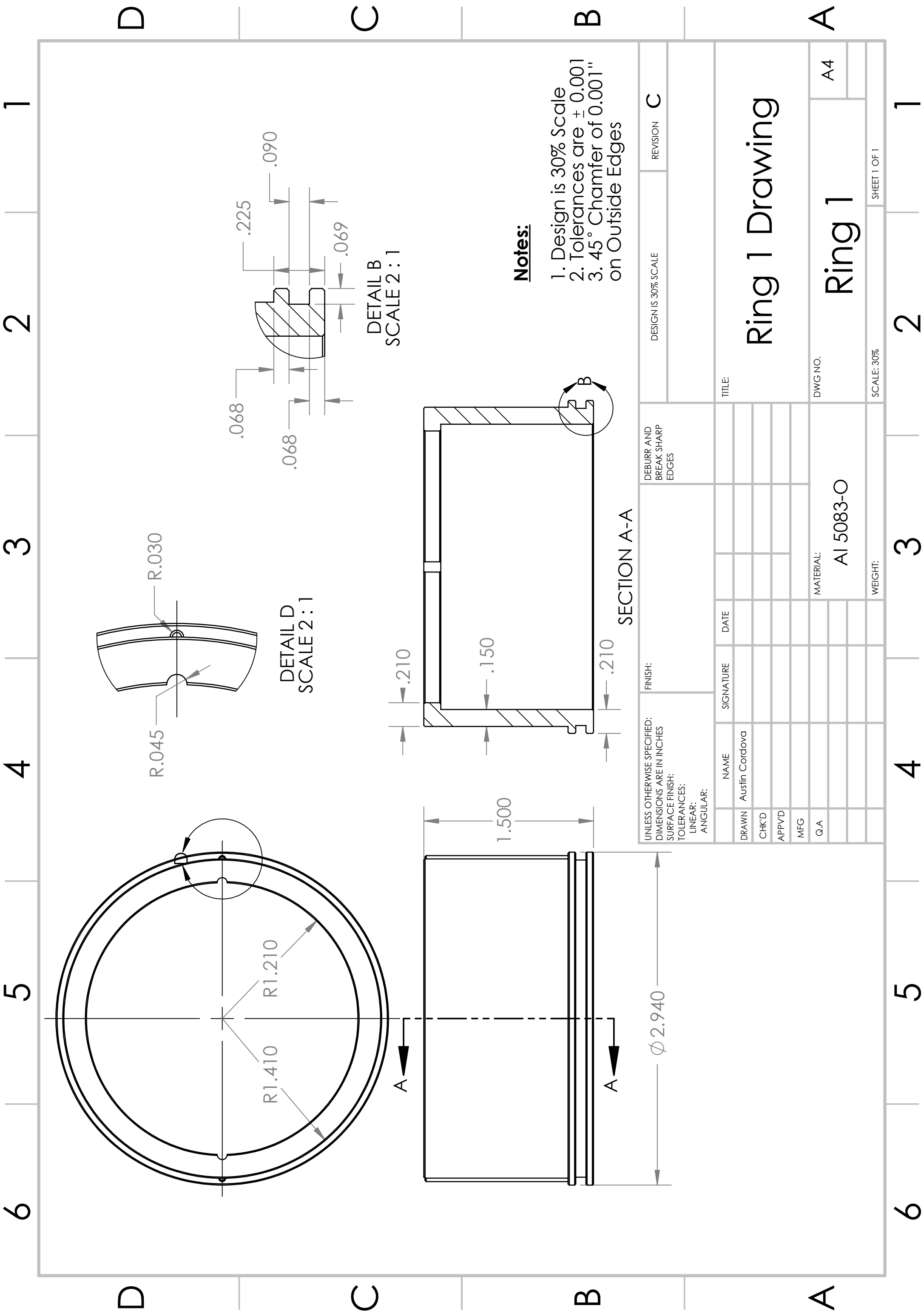


**Figure 60:** Ring 1 Drawing

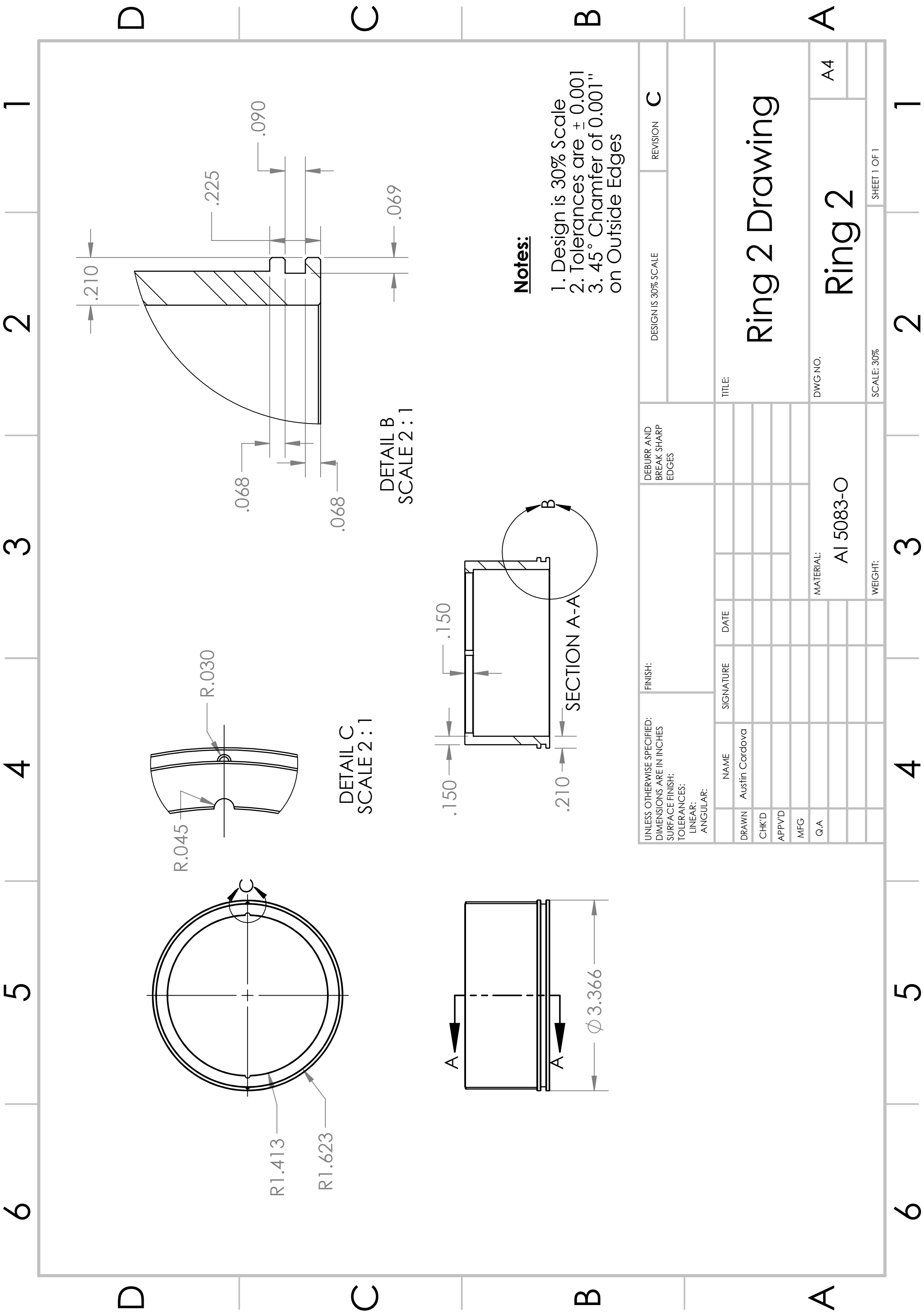


**Figure 61:** Ring 2 Drawing

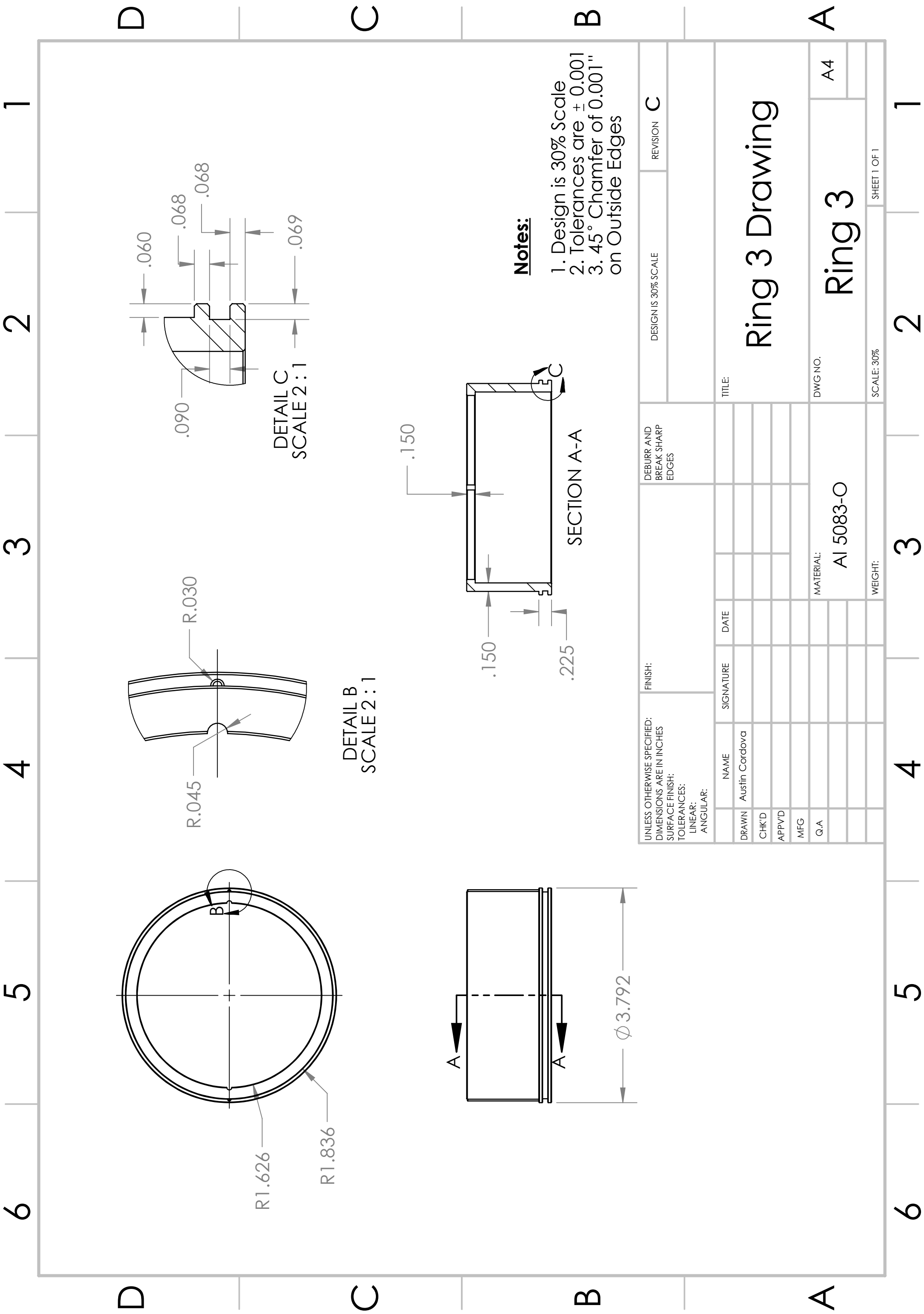


**Figure 62:** Ring 3 Drawing

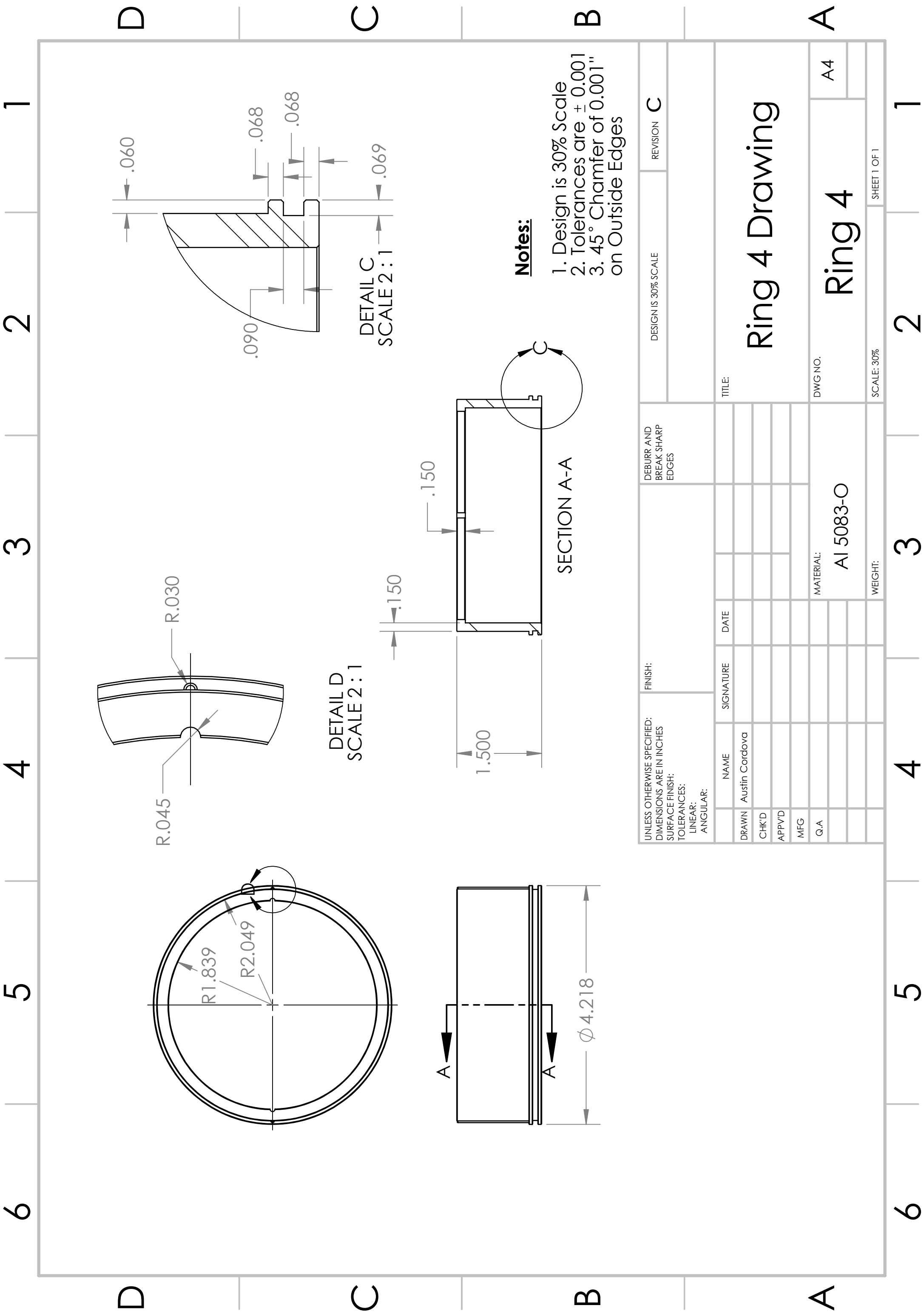


**Figure 63:** Ring 4 Drawing

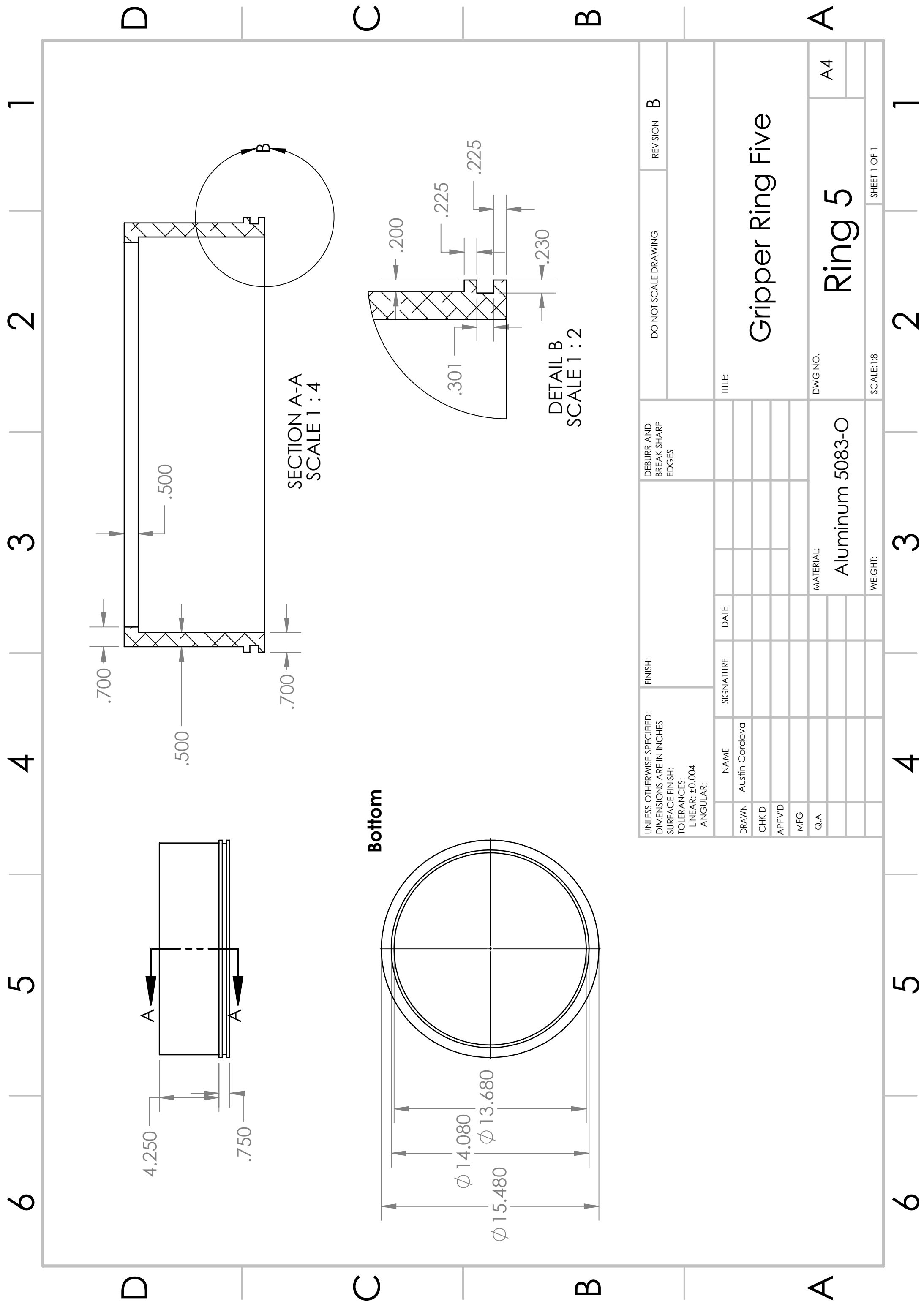


**Figure 64:** Ring 5 Drawing

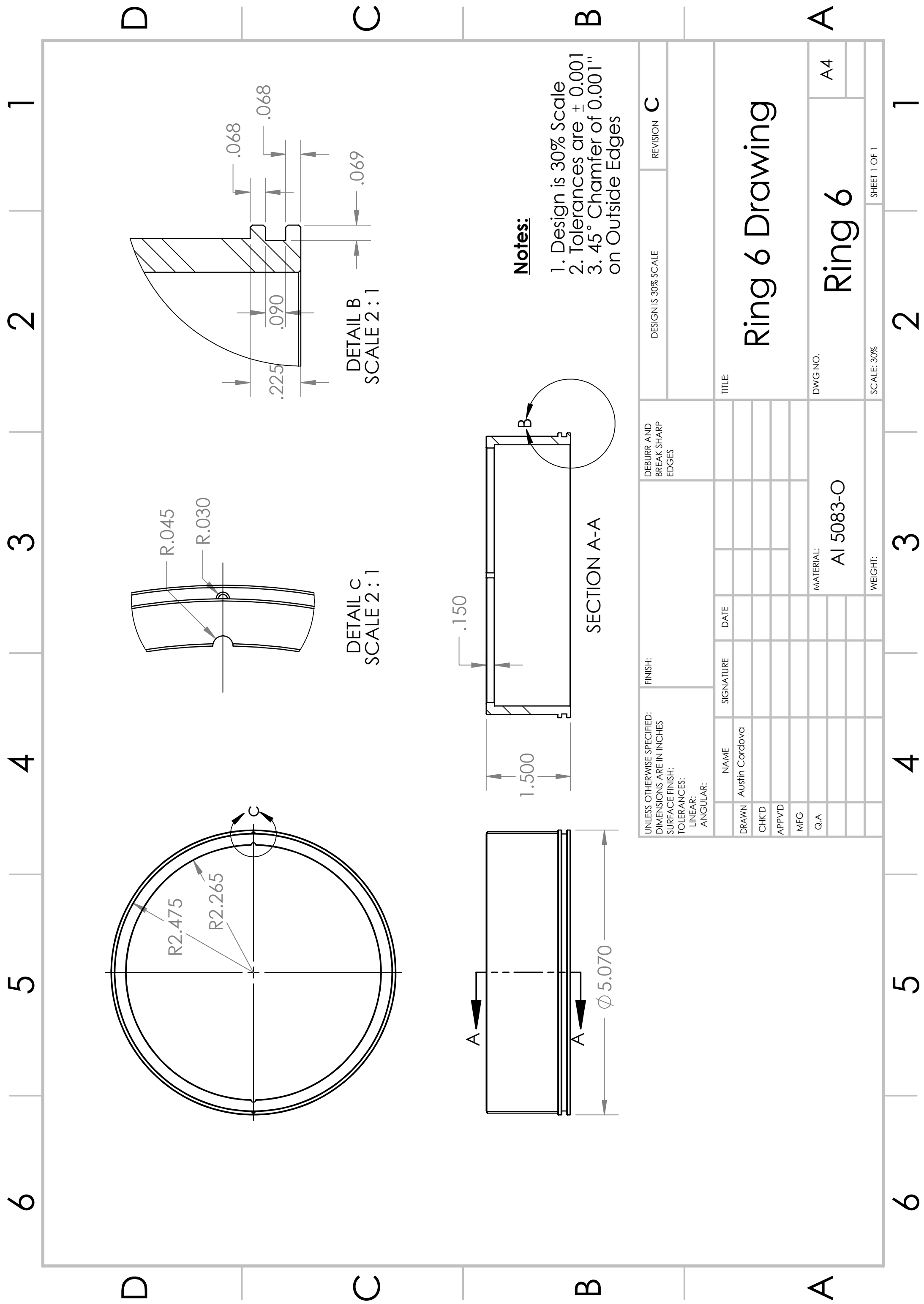


**Figure 65:** Ring 6 Drawing

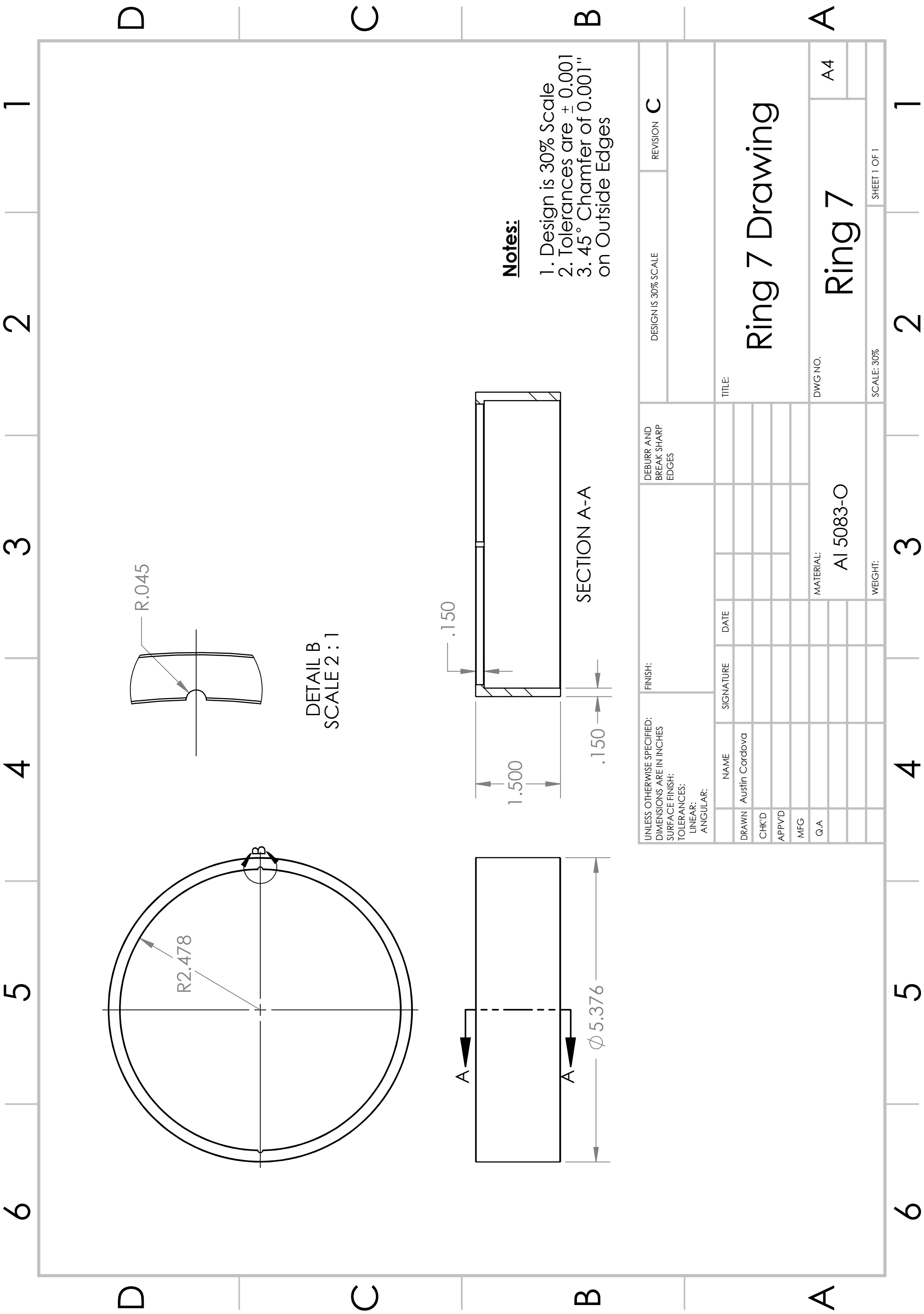


**Figure 66:** Ring 7 Drawing

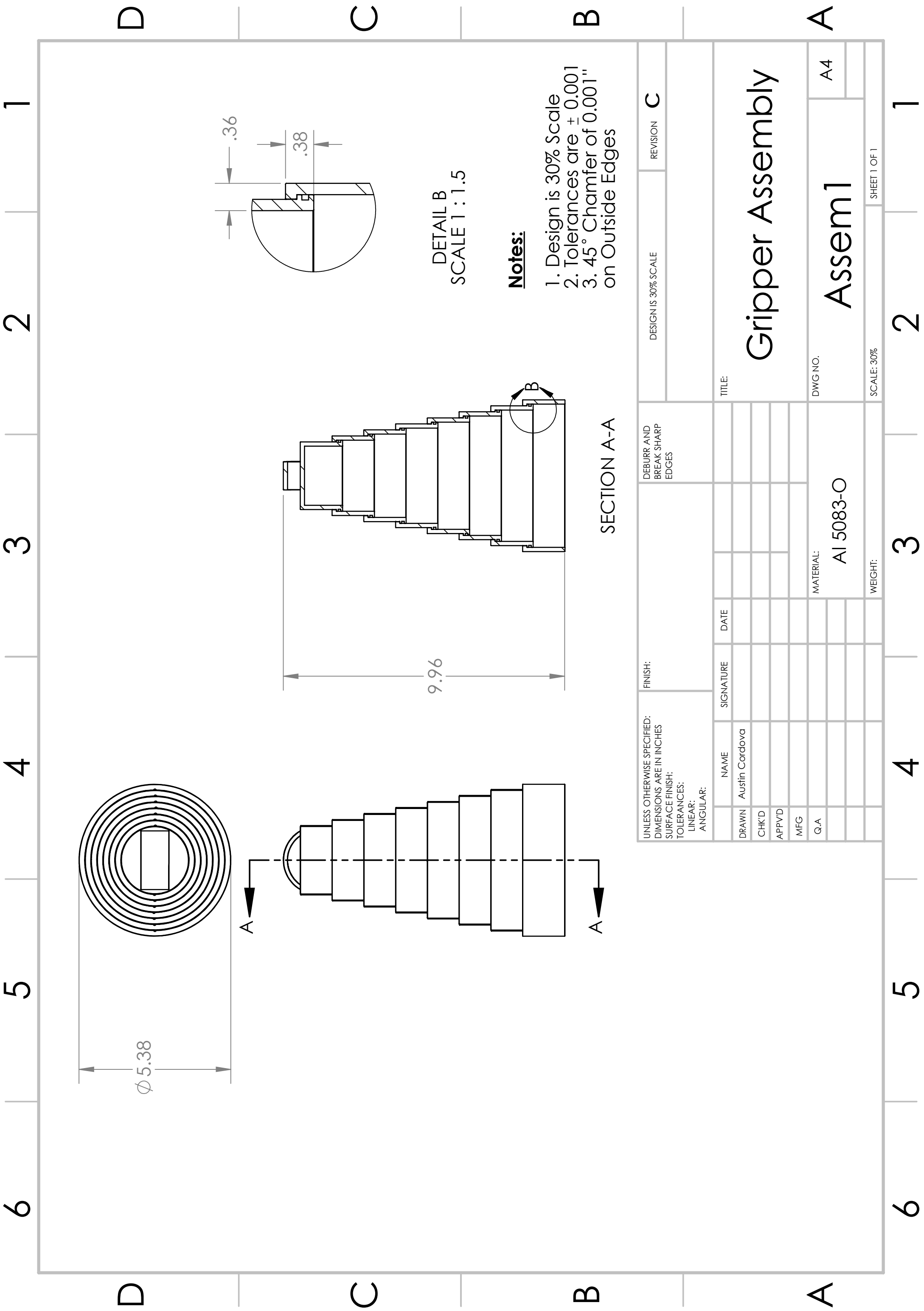


**Figure 67:** Redesign Full Assembly Extension