Final Project: Novel Arm-Wrestle Training Gym Machine

Section No: 001

Athish Ram Das

Will Tse

Ruhan Yang

MCEN 5045: Design for Manufacturability

Instructor: Dan Riffell

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EXECUTIVE SUMMARY

This report entails the objective and description of the final project in designing a novel Arm-Wrestling Gym Machine for MCEN 5045: Design for Manufacturability, instructed by Professor Dan Riffell. The goal of this project is to understand the all the separate steps involved in the design process of creating a product from its initial conceptualization.

This process will revisit all of the processes involved in the Reverse Engineering portion of the course, being: modifying an existing product (in this case, our initial design) to improve either functionality, manufacturing processes, assembly processes, or overall consumer satisfaction.

Separate from the Reverse Engineering process, this final project process will have heavier influence on the manufacturing processes involved in making the product, as well as considerations that justify these processes: such as Initial Market Analysis (why the product is pragmatic in terms of being an actual manufactured item), FEA Analysis and more in-depth Material and Process selection. It will also include the processes involved in creating an initial design, detailing the project scope and its objectives. Another major difference is the fact that we will not be working with an actual product, so the physical documentation of disassembly is not necessary, although the figurative disassembly and its processes such as the Design for Assembly Analysis still applies.

The team is comprised of three people whose names and contact information are in Table 1.

Name	Email	Phone
Athish Das	athish.das@colorado.edu	720-651-2509
William Tse	william.tse@colorado.edu	720-633-2868
Ruhan Yang	ruhan.yang@colorado.edu	720-539-4180

Table 1: Contact Information of the team

Figure 1. Arm-Wrestle Training Gym Machine (isometric view) next to a 5’8” tall human, for scale.

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I. INTRODUCTION

The objective of this project combines both Design for Manufacturing (DFM) and Design for Analysis (DFA) processes together into a novel product: The Arm-Wrestle Training Gym Machine. The product is novel in a multitude of ways, there doesn’t exist a standardized gym machine or equipment specifically customized to the sport of arm-wrestling, although some training devices do exist, but only have very small modifications to the arm-wrestling table itself, and none exist in the gym environment. Besides never being done before, it is also novel in the fact that it is not a product we will be actually manufacturing, as it would be outside the scope the course. However, the report below would justify and highlight its manufacturability.

The integration of arm-wrestling to a gym setting (see figure 2). is compatible in that they both train the arm, and for lack of a better phrase, both “hit arm day”. Professional arm-wrestlers, namely in the World Armwrestling League (WAL), have the biggest arms and biceps in the world, which forms a perfect marriage with the gym, if an individual wanted to train his biceps for that particular workout. Furthermore, friendly arm-wrestling matches can be done with the table, as it has the same dimensions, pads, and pegs as a traditional arm-wrestling table, which adds to the marketability and appeal of the product (especially in the case that the individual using the machine had a workout partner with them).

Figure 2: Final Design of the Arm-Wrestling Training Gym Machine in a gym setting

The final design will have the capability in training all the main areas of arm-wrestling, being pronation, supination, rising (radial and ulnar deviation), and cupping (flexion and extension) (seen in figure 3)[1]. These areas focus on the wrist and forearm directional movements, as the muscles in the forearm are directly related to the wrist position. Strengthening these positions form the basis of professional arm-wrestling training (ref. ResearchGate).

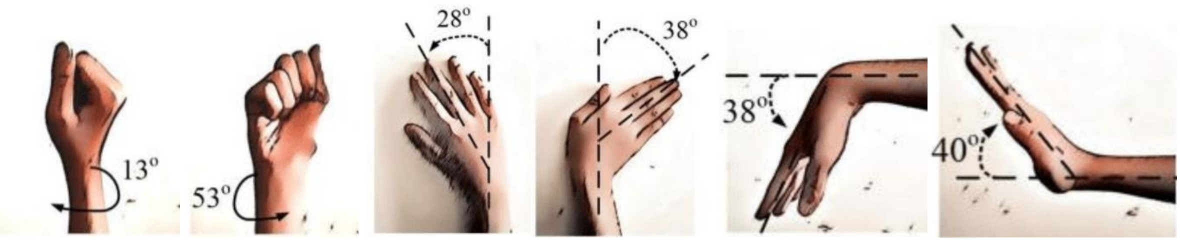


Figure 3: Left to right - Pronation, Supination, Radial Deviation, Ulnar Deviation, Flexion, Extension

The sport of arm-wrestling is more so “hand-fighting”, with the forearm and bicep muscles being the engine, or where the power comes from. Therefore, the machine trains all of the aforementioned wrist motions with the following subsystems (figure 4):

- Cupping Subsystem (dark blue)
- Cable Subsystem (light blue)
- Arm Anchor Subsystem (yellow, Preacher Pad is transparent)
- Pulley Subsystem (green)
- Weight Subsystem (red)
- Table Subsystem (black)

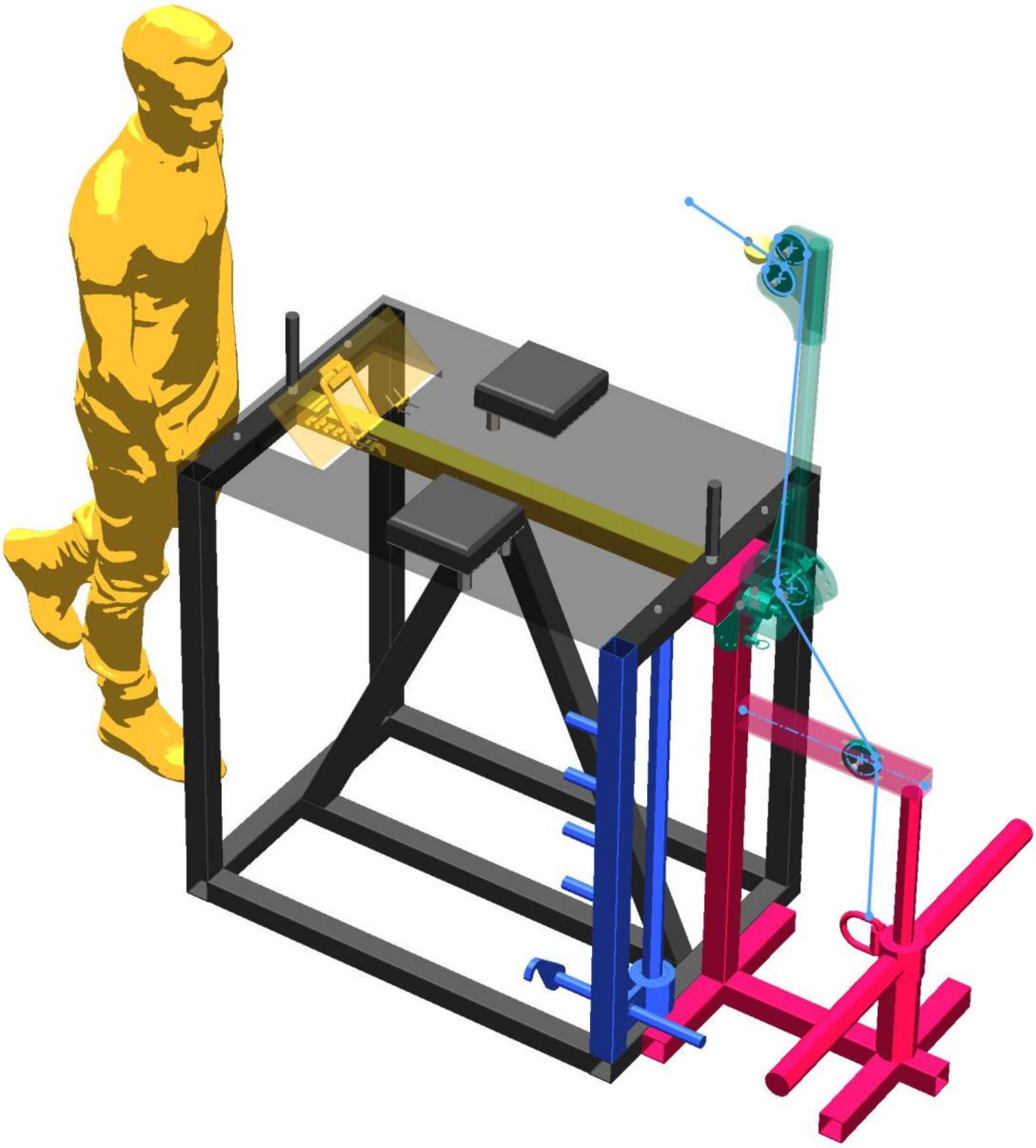


Figure 4: Sub-assemblies marked by differentiating colours: Cupping (dark blue), Cable (light blue), Arm Anchor (yellow), Pulley (green), Weight (red), Table (black).

More in-depth analysis on the sub-assemblies itself will appear in the Final Design section of the report. For this introduction, we first look at the Cupping Subsystem, and as the name suggests, it trains the arm muscles for cupping (flexion and tension), as the horizontal rod is raised up by a cupped hand, or rather, palm. In arm-wrestling terms, this prevents the wrist from “breaking” by strengthening those muscles in that fixed position, with a load acting opposite of it, as the horizontal rod can be plate-loaded by standard gym weight plates.

The Arm-Anchor Subsystem is similar to the standard preacher curl machine seen in commercial gyms today, allowing for the arm rest at an angle, impeding the elbow from moving in the y-direction, isolating stress onto the arm, rather than other parts of the body such as the shoulders and back.. In this position, the user can train pronation, supination, and rising (radial and ulnar deviation) my mimicking arm-wrestling movements with adjustable angles (whether it be their top-roll, hooking, and other arm-wrestling techniques).

II. INITIAL MARKET ANALYSIS

From a financial and numerical standpoint, there is a promising market for the team’s arm-wrestling gym machine, as it is designed to be a standardized equipment found in commercial gyms. Arm-wrestling has been around since the 1960s, but not until recently has it started to become a sport that attracts both competitors and viewers, expanding its potential market. Of the professional arm-wrestlers in the World Armwreslting League (WAL), one of the greatest arm-wrestlers of all time, Devon Larratt, has been a great advocate for the sport: promoting it on his YouTube channel, documenting trips to other regions of the world in search of other great arm-wrestlers, and collaborating with other notable social media influencers, including a bodybuilder, Jujimufu, showing the practicability of a gym and arm-wrestling crossover (figure 5).

Figure 5**:** Jujimufu (left) and Devon Larratt (right) in a YouTube video, introducing the sport of arm-wrestling to bodybuilding.

From the information collected from Google trends, it was inferred that the sport of arm-wrestling has a high popularity in regions of United States (US), Canada, Australia, and parts of Europe (figure 6).

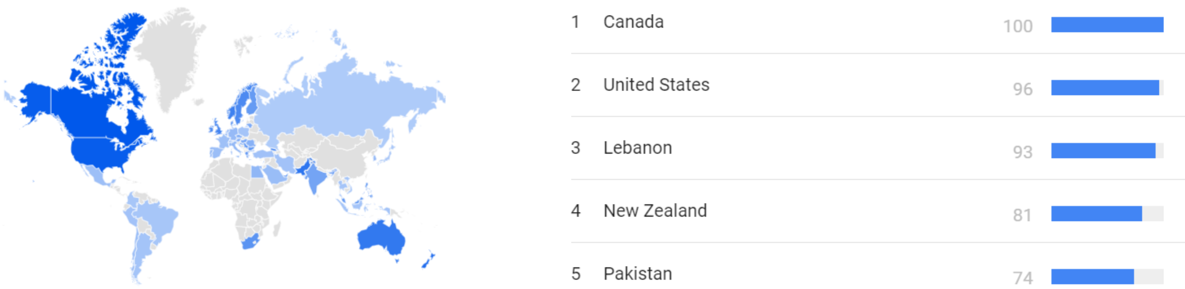


Figure 6: Google trends search data for the term 'Arm wrestling'

In addition, a search for current models of arms wrestling training equipment was made, and it was observed that a handful of other sophisticated equipment was released in the US market years ago. None of these sophisticated designs, however, have made it into a commercialized gym, or grossed a large amount of sales, assuming their sophistication isn't compatible to manufacturing processes. Observing Devon's social media activity, professional arm-wrestlers and bodybuilders interested in the sport, such as Jujimufu, train arm-wrestling simply by way of challenging other individuals, or using variations of

bicep and forearm exercises at the gym, or custom-made equipment to target the various wrist angles needed for arm-wrestling (Tom Juji youtube channel, 2019). This shows the rising market of the sport of arm-wrestling, and commercialized gyms can be a very advantageous platform in which a standardized machine, targeting arm-wrestling and "arm-building", can exist.

III. PROJECT SCOPE AND GOALS

Scope

The scope of the project goes over two iteration of the design, even though the goal, later mentioned, has a vision beyond the scope. In theory, with all the brainstorming, and other hand drawings, the design has gone through many more iterations of design, but this report specifically entails the initial design (based on all of those hand sketches) and the final design (done in SolidWorks). In reality, the design process of this product would go through many more iterations of changes, beyond a two-month period, with a larger team of three.

In addition, most of the current design is based on personal knowledge of a group member, Will Tse, who has spent some considerable time at the gym working out and watching videos on arm-wrestling and bodybuilding, so no exclusive research has been on any specific standards that gym equipment needs to make in order to be suitable in a commercial gym. For example, the part does not include stickers for safety warnings and instructional equipment steps, seen on all standard gym equipment, and the designs for the stickers are not present in the final design. Other research could have also been done in order to garner some statistical data due to the recent global pandemic, Coronavirus (COVID-19), as a live experiment with an arm-wrestling at a gym could have been conducted (taking the count of how many gym patrons would arm-wrestle on the table as oppose to those who pass it by, in a given amount of time). The research and more in-depth analysis into the marketability of the product are generally out of the scope of the course, as it has more analysis as the actual manufacturing processes involved in making the novel product.

Goals

The objective of the project is: to design a gym machine that incorporates the training methods of arm-wrestlers, justify its design through extensive manufacturing and assembly analysis, make a case for its marketability in a cost analysis, and conclude a pragmatic assessment to the product's overall merits and its ability to integrate the sport of arm-wrestling to bodybuilding.

The main obstacles that the design faces are: the scarcity of similar designs to work off from, utilizing similar components from other gym equipment to aid the function of the design itself, and as mentioned before, having enough research to support its proof-of-concept. Going into more detail with utilizing similar gym components, the final design repurposes similar designs from a Smith Machine and its locking system, seen in the Cupping Sub-system. In addition, the initial design features a cable system very similar to the one that can be seen in a commercial machine, but the final design excludes this cable machine, as later detailed in the report.
In terms of the scarcity of similar designs of standard arm-wrestling gym machines, there are none that exist in commercial gyms. However, there are custom designs made by professional arm-wrestlers like Devon Larratt have used in his training (figure 7). This machine is very custom to Devon Larratt, using

towels as grips, duct tape over the table for extra support, and other various rudimentary components. Other professionals such as John Brzenk have been featured on custom training devices, but none of the training devices target all the six main directional movements that arm-wrestlers focus on: supination, pronation, radial and ulnar deviation, flexion, and extension, while having the option to arm-wrestle on the device. The product, in it's actualization, will be designed to provide a solution to this discontinuity.

Figure 7: Devon Larratt training at a custom arm-wrestling training device in his home.

IV. ECONOMIC GOALS

The best way to set an economic goal for any product is to compare with similar products as a benchmark. But as the arm-wrestling sport is in a growing stage, there aren't many commercially released products in the market. The ones which are available in the market have received poor customer reviews, as they do not deliver the requirements of a normal arm-wrestling training routine. Due to this, the aspirants of the sport build equipment in-house, customized to their specific training. So, there is no legitimate product in the market for the team to benchmark with. As an alternative approach, the team set the economic target in a way it divides the product into independent sub-assemblies, those economy of those sub-assemblies are then totalled. Looking at the available products we have in the market, our product can be divided into a functional trainer and a table. Current prices for both were checked (Fitkit) and is summarized in Table 2.

Sl No	Description		Price ($)
1	Functional Trainer		1300
2	Adjustable Table		769
		Total	2069

Table 2**:** Prices of sub-assemblies in benchmark products

It was acknowledged that the complete functionality of a functional trainer is not used in our product. So, after analysing the prices of these products, it was inferred that the price of Arm-wrestling training equipment would have to below an amount of **$2069.**

V. SCHEDULE AND GANTT CHART

To streamline and complete the project within the anticipated completion date, a Gantt chart was prepared, and work was divided among the team members. Given in figure 8, the team's Gantt Chart is shown for the novel project

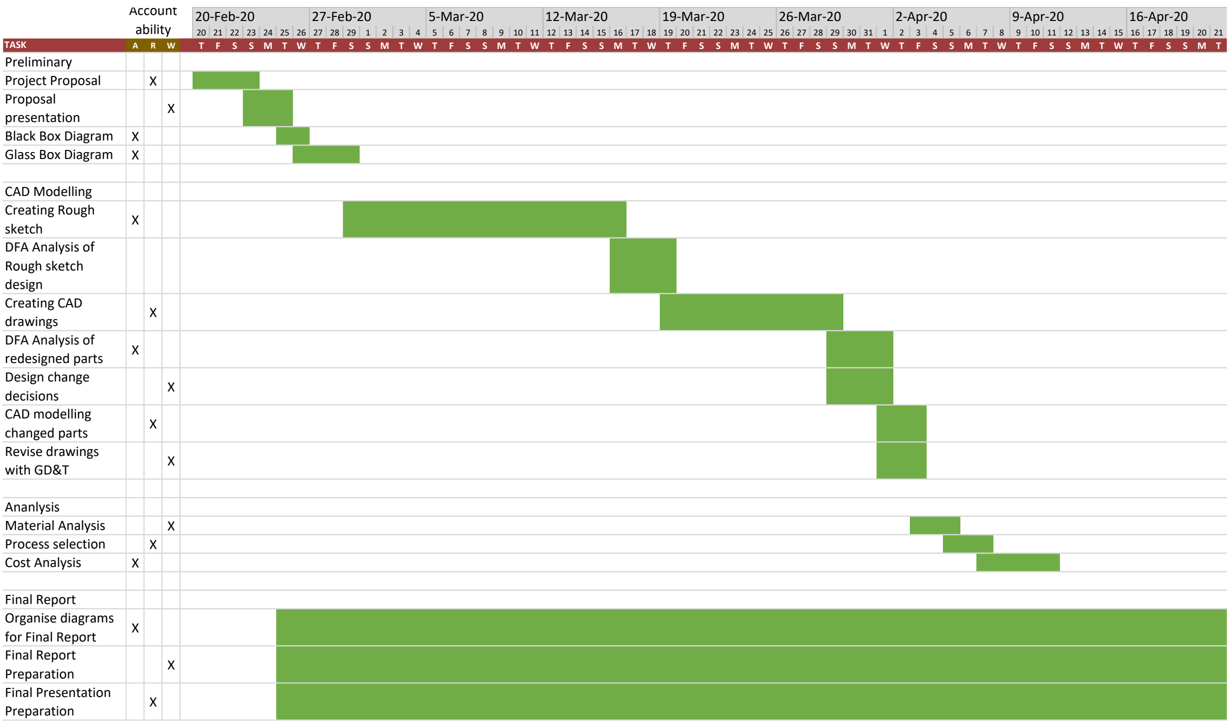


Figure 8: Gantt Chart

VI. BLACK BOX DIAGRAM

To comprehend the basic understanding of the machine and the overall system's inputs and outputs, a black box diagram was prepared (Figure 9).

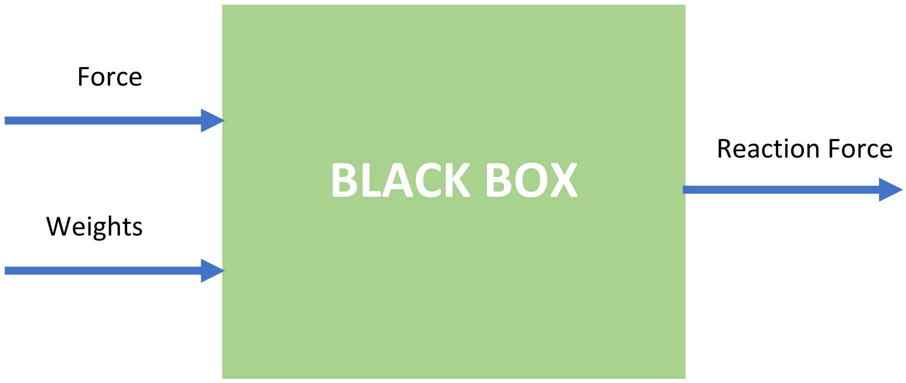


Figure 9: Black Box Diagram

The inputs that go into the system were found to be the force that the user apply to the machine and the weight adjustment that the user choose to train himself. It is to be acknowledged that: the higher the weight chosen for training, the higher challenging the training progresses. The output from the machine must be the reactionary force, that the machine needs to provide, to challenge the force applied by the user.

VII. GLASS BOX DIAGRAM

Before deciding the subsystems of the machine, a glass box diagram was prepared to synthesize a mechanism to make the system work. It had to include every innovative or pre-existing mechanism, all synchronized to make up the system (Figure 10).

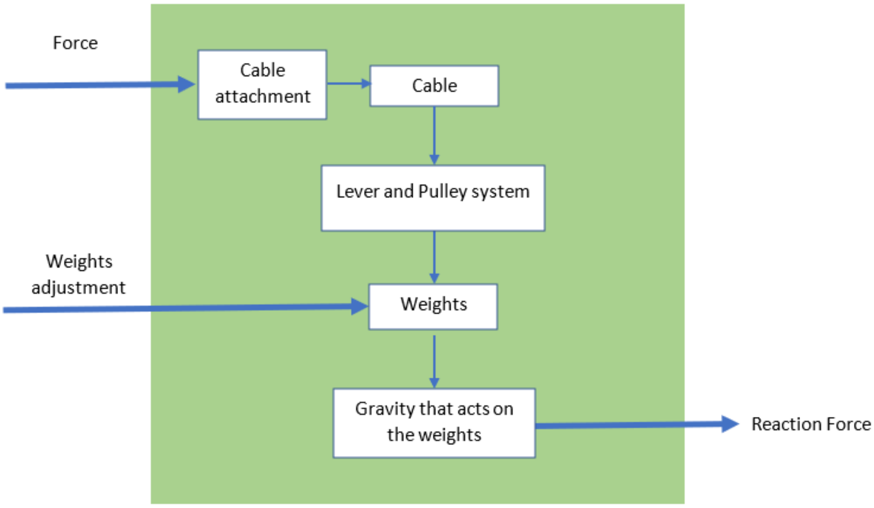


Figure 10**:** Glass Box Diagram

It can be inferred from the glass box diagram that the force applied by the user will be transmitted to the stacked weights through a cable and lever and pulley system, which pulls the weights upward. The gravitational force then acts on the raised weights, providing the reactionary force to the hand grip that the user holds. The individual sub-assemblies will be further detailed in the Fishbone diagram.

VIII. FISHBONE DIAGRAM

To organise all our thoughts and preliminary ideas of the individual components, a fishbone diagram was prepared (Figure 11). As indicated by the diagram, the system primarily consists of four initial sub-systems, being: the Cable, Table, Pulley and Lever, and the Weights.

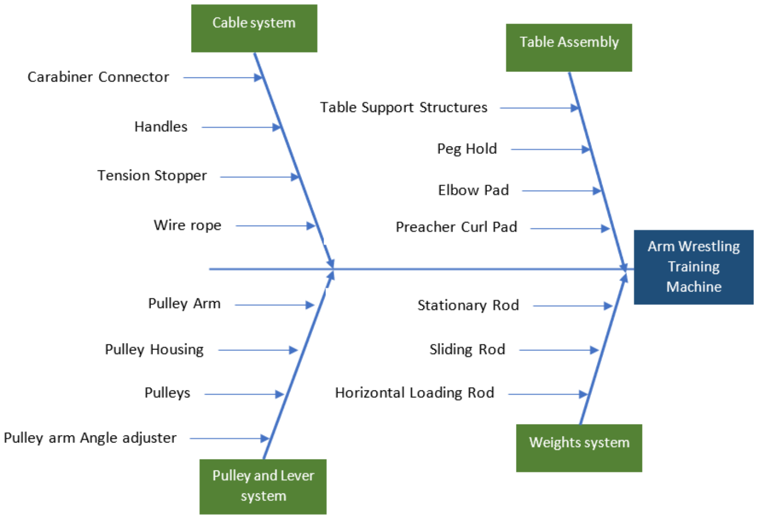


Figure 11**:** Fishbone Diagram

The individual subsystems are later discussed as sub-assemblies in the initial design section, later found in this report, as this design process is documented chronologically. The Pulley and Lever System is renamed as the Pulley Arm Sub-Assembly, in said section. Before initial drawings and in-depth analysis of these sub-assemblies were made, a patent search was needed to help mitigate design infringement and further the team's design motivation.

IX. PATENT SEARCH

To know about the developments of arm training apparatus through the years, a patent search was performed. When surfed through the patents we found out that the apparatus had history of design improvements since 1909. It was found that, from 1909 through 2016, the design had 71 instances of development. Moreover, this exercise clarified our doubts on the development of certain subassemblies in the machine. This report describes three major instances of design development of the apparatus:

US911925, Feb 09, 1909

The design developed by Victor M Del Valley Zeno on May 13, 1908 (Figure 12), describes itself to be an apparatus to develop the forearm and wrist muscle. Although this model does not present itself to be an arm-wrestling training machine, it is considered to be the pioneer and the reference to all the subsequent design variants of arm-wrestling training machines developed later.

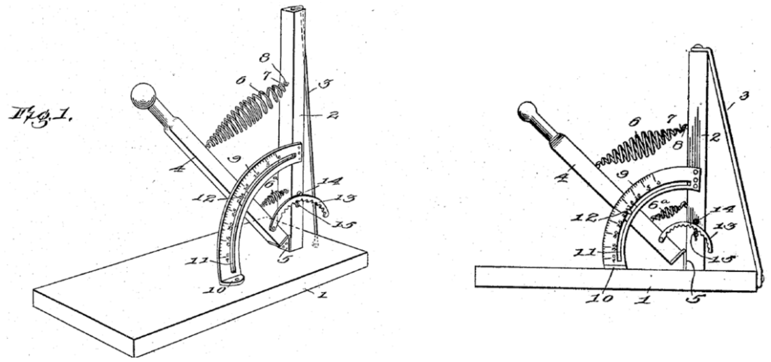


Figure 12: Patent US911925

The design comes with an oscillating handle lever which is mounted to swing about a longitudinal axis to the front of the standard. One or more contractile springs are secured in a detachable manner in order to indicate the development of the muscles. To test the strength of the forearm, a scale bar is secured at one end to one side of the standard.

US 4129297 December 12, 1978

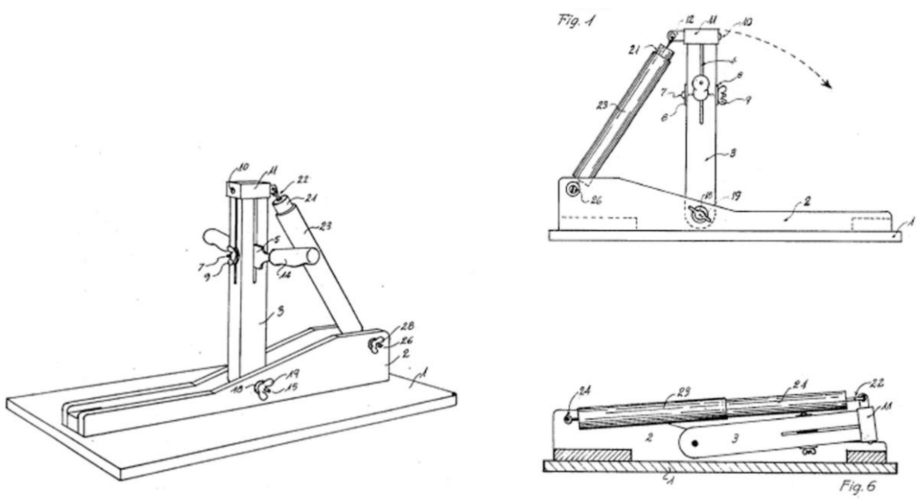


Figure 13: Patent US 4129297

John W Dolan’s model developed on June 14, 1976 (Figure 13) came with the label of “Arm Wrestling Training Machine”. Unlike the initial models of arm-wrestling training modules, the springs in this model came inside a retractably extensible cylinder. The advantage that came with it was that it countered the retraction of the spring in the event of sudden release of the grip by the user by the damping force of the damper in the cylinder.

US 9314657 B2 April 19, 2016

The latest patent in the field of arm-wrestling training equipment was filed by Antonio M. Martinez on June 2, 2014, patent approved on April 19, 2016. This design is used widely now to develop new models of the machine.

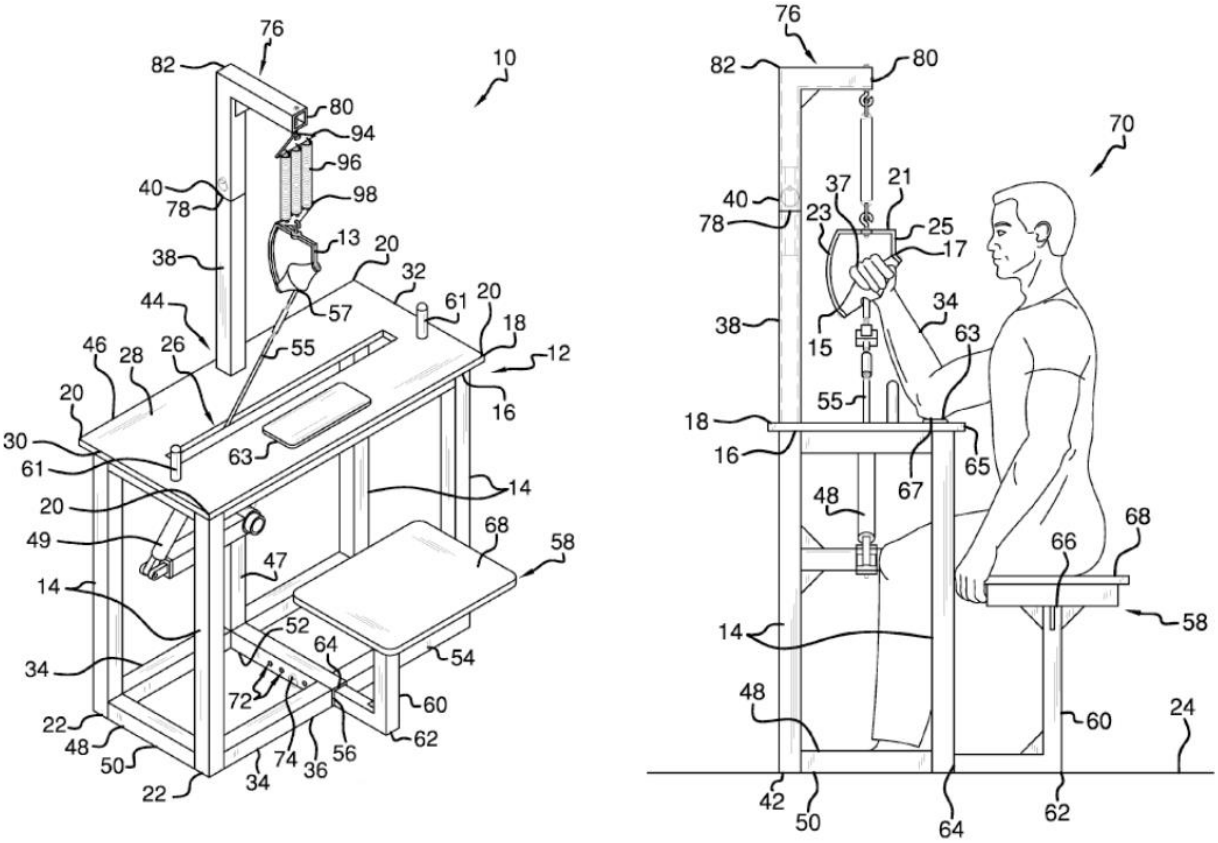


Figure 14: Patent US 9314657 B2

As indicated by figure 14, the design consists of a table positioned on a support surface. A support arm is coupled and is extended upwardly from the table. The handle coupled with the spring biasing member provides for the reaction for that the training requires when the user applies the arm-wrestling training repetitions.

A major drawback consistently found in these designs and the other patent searches like it, was that the fact that they were all lacking user-friendliness. All these designs did not have the user-ability of adjusting strength levels. For example, a user that wants to progress his training with a more weight would have to add additional spring attachments to the handle, which is quite inconvenient.

X. INITIAL DESIGN PROCESS

The initial design process included: multiple brainstorming sessions, hand-sketches, and a final hand-sketch of the initial design. After conversing over the Black and Glass Box diagrams, as well as the initial patent searches, the team compiled the following set of designs:

Leading up to the final hand-sketch, many brainstorming ideas were considered, to cover all the different angles needed for arm-wrestling training, manufacturability, and assembly, later taken into consideration in the final hand-sketch as well as the final design as follows:

Table with Cupping Rod Rack

This initial brainstorming design formed the base for the final hand-sketch. It is largely inspired by the rudimentary design that Devon Larratt trains on in his home. One issue that the team was concerned with was including a mechanism that trained cupping, to strengthen the wrist and forearm. The cylinder on top of the rack (Figure 15) resembles this cupping mechanism, with a large diameter, so the full palm of the hand would wrap around the cylinder, engaging the entire wrist and forearm. The main issue with this mechanism is that the load on the rod would need to act directly down, while the load acts at an angle if the user cupped the rod vertically up. This design also does not provide the dual function of arm-wrestling another individual as one of the sides is framed off.

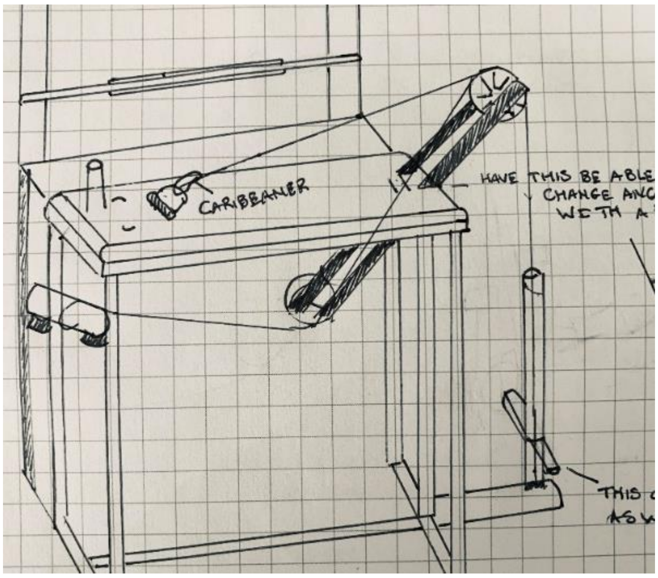


Figure 15. Table with Cupping Rod Rack

Hemispherical Table with Rotating Pulley Arm

This initial design focuses on the directional movement that the pulley arm should have (Figure 16). The rotational element of the pulley arm was later addressed in the final design later detailed, with all the degrees of freedom in the x, y, and z directions in the final pulley arm design (resembling an actual opposing arm). The main issues with this initial design is the lack of sport integration.

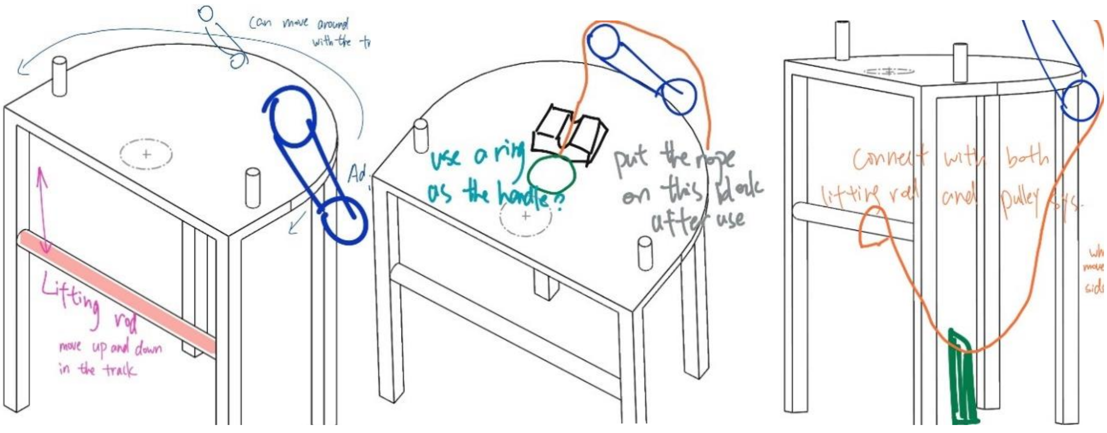


Figure 16: Hemispherical Table with Rotating Pulley Arm

After considering the initial brainstorming ideas, the team agreed upon a final initial hand-sketch design (figure 17).

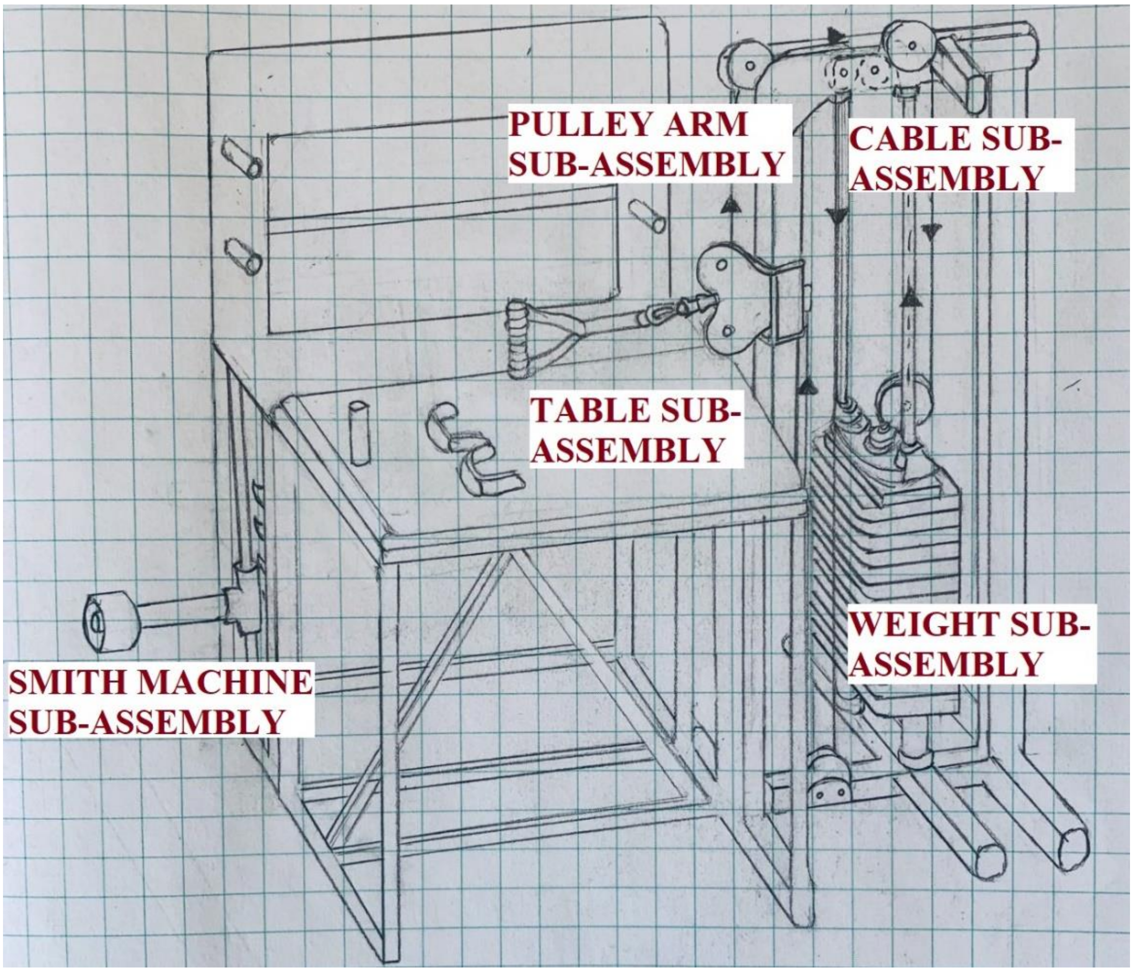


Figure 17**:** Final hand-sketch of initial design, which will be improved upon with the final CAD.

The initial design includes the following sub-assemblies and their respective purposes, keeping in mind the project scope and its objectives:

- Table Sub-Assembly
- Smith Machine Sub-Assembly
- Cable Sub-Assembly
- Weight Sub-Assembly
- Pulley Arm Sub-Assembly

Initial Table Sub-Assembly

The initial table sub-assembly features the same dimensions as a standard arm-wrestling table (length 38”, width 26”, height 40”), with a foam pad attached directly over the top face of the table, excluding the area purposed for the raised hand holds seen in figure 17. The initial design also has a back compartment attached to it, having a Back Frame with pegs to place resistance bands, wide grips, and other accessory items onto. In addition, the Back Frame has a polyvinyl chloride (PVC) pipe that is capable of rotation, giving consumers the option to attach resistance bands onto, to increase the tension when training. The Back Frame also allows room for the Smith Machine Sub-Assembly directly below it. The removal of this Back Frame is later detailed in the Final Design and Design Changes sections of this report.

Smith Machine Sub-Assembly

The Smith Machine Sub-Assembly takes into account the current merits of a pre-existing gym machine called, as expected, the “Smith Machine”, which traditionally has a horizontal plate-loaded peg that can be moved upwards through a stationary vertical rod. The vertical and horizontal rods interface through a housing that has a linear bearing, aiding the movement in the y-direction. The housing also traditionally has a hook (not clearly depicted in the initial, but later detailed and considered in the final design) that can rest the horizontal rod onto the spaced prongs attached to the leg frame adjacent to it. The smith machine targets the cupping movement of the wrist that arm-wrestlers are looking to train, as the horizontal rod can be cupped and pulled upwards, completely vertical, isolating the forearm muscles as the elbow is unbent.

Cable Sub-Assembly

The Cable Sub-Assembly is quite complex in the initial drawing, the direction of the cable is marked by the black arrows shown in figure 18. The Cable Sub-Assembly travels through seven different pulleys completely linearly, translating the load from the weight accurately as gravity acts down onto it. The initial design of the Cable-Sub Assembly is also driven by current designs in a traditional standard gym cable machine, and is eventually modified, or rather, removed, to prevent design infringement, further detailed in the Final Design section of the report.

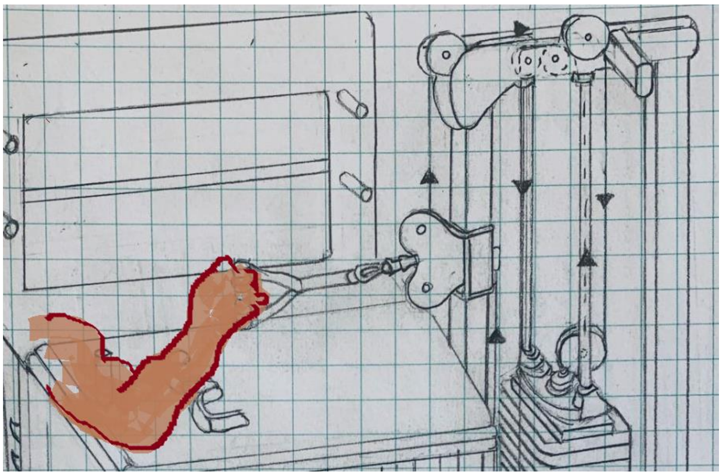


Figure 18**:** Initial Design with arm demonstrating the pulling direction of the Cable Sub-Assembly

Weight Sub-Assembly

The weight stack is your traditional weight stack you see in commercial gyms, the first plate is marked ten pounds (or 4.5 kg), and the subsequent stacks increase by fifteen pounds (Figure 19). A pin can be placed inside a pin hole located in the middle of each weighted stack, and the weight housing located attached to the first weight stack isolates the stack to the desired weight.

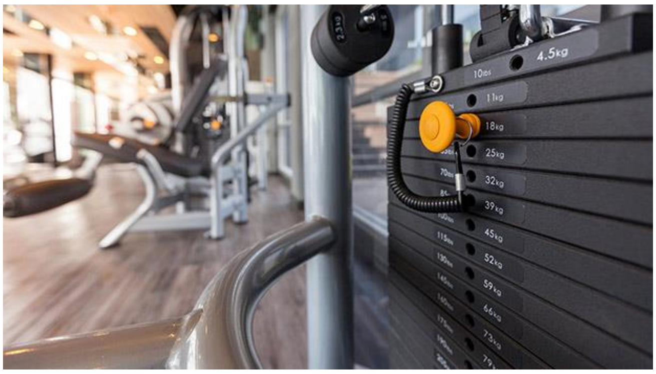


Figure 19: Traditional Gym Weight Stack

Pulley Arm Sub-Assembly

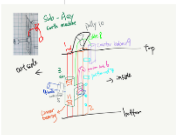
Finally, the Pulley Arm Sub-Assembly features seven different pulleys, and the exit housing has two pulleys guiding the movement of the cable.

To conclude the initial design, it highlights design inspirations from traditional gym machines such as the Smith Machine and a standard cable machine, for initial proof of concept, and to ultimately improve upon these designs in our final CAD iteration of the project, as they are modified to exclude the product from design infringement, as well as improving overall simplicity, as later seen, from the initial to the final DFA analysis.

XI. INITIAL DFA ANALYSIS

The Initial Design for Assembly (DFA) analysis is done for the final hand sketch detailed in the previous section. The DFA table used will combine the Pulley Arm Sub-Assembly, Weight Sub-Assembly and Cable-Sub Assembly into one Sub-Assembly named: "Cable-Machine Sub-Assembly for simplicity. The Cable Machine Sub-Assembly will then be separated into its major structural subsystems and the subsequent hardware needed for such a complex sub-assembly. The three sub-assemblies are separated in Tables 3-5 as: The Smith Machine, the Main Body, and the Weight System.

The Smith Machine Sub-assembly



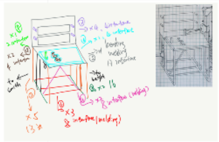
Part		DFA Complexity		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
Part Number	Part Name	Number of Parts (N_p)	Number of Interfaces (N_I)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
1000	Smith Machine - ASSY																				
1001	Rod	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1002	Veritcal Bar	1	7	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
1003	Slider	1	3	1	0	L	1	0	1	0	0	0	0	0	1	0	0	1	1	1	0
1004	Handle	1	3	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0
1005	Handle Cylinder	1	1	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1
1006	Position Hook	1	2	0	0	L	1	0	1	0	0	0	1	0	0	0	0	0	1	1	1
1007	Position Rod	5	6	0	0	L	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1
1008	Cable	1	3	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1009	Counter Balance	1	1	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1010	Pully	1	2	1	1	M	1	0	0	0	0	0	1	0	0	1	0	0	1	1	1
1011	Linear Bearing	2	4	0	1	M	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1
	Totals	16	36	8	2	0	10	0	3	0	0	0	4	0	2	2	0	1	9	8	5
	Design for Assembly Metrics	24		50.0%	←Theor. Effy. Pract. Effy.→		62.5%	0.38		0.00			1.00				2.88				

Table 3: Initial design DFA analysis of the Smith Machine Sub-assembly

For the Smith Machine, there are eleven total components. Standardized parts are not being used, besides the Linear Bearing and the Pulley. With the components listed, the team noticed that there was still room for improvement, in terms of reducing the design's components, while retaining functionality. In some respects, part reduction was not ideal – for example, there was a possibility that the Position Hook and the Handle could be made from the same steel pipe, but it would be too cumbersome to process. Likewise, the Position Rods could be made from the same steel tubing of the vertical stand, but it would be harder to process.

In the assembly process, the Slider can be assembled in either direction, as we want the angle to be adjustable. In addition, during the assembly, a linear bearing will be press fitted in between the Handle Rod and the Slider, having a rotational functionality to it, so the Position Hook can be placed onto the Position Rods. Another issue in the assembly arises as the Position Rods may not be perfectly aligned; Therefore, marks will be added on the vertical stand to help locate them. Overall, this sub assembly contains more components than the team would like and would encounter difficulties in assembly, if not addressed in the final design.

The Main Body Sub-Assembly



Part		DFA Complexity		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
Part Number	Part Name	Number of Parts (N_p)	Number of Interfaces (N_i)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
2000	Main Body - ASSY																				
2001	Horizontal Bar - Length	3	8	1	0	L	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0
2002	Horizontal Bar - Width	3	16	1	0	L	1	1	0	0	0	0	1	0	0	0	0	0	1	1	0
2003	Vertical Bar - Height	6	13	1	0	L	1	1	0	0	0	0	1	0	0	0	0	0	1	1	0
2004	Diagonal Bar	2	8	1	0	L	1	0	1	0	1	0	1	0	0	0	0	0	1	1	1
2005	Tabletop	1	17	1	0	M	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
2006	Foam Sheet	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2007	Shelf Rod	4	4	1	1	L	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0
2008	Gripping Peg	1	2	1	1	L	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0
2009	Handle	2	4	0	1	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	Totals	23	76	8	3	0	9	3	1	0	1	0	6	0	0	0	0	0	8	7	2
	Design for Assembly Metrics	41.80908992		34.8%	←Theor. Effy. Pract. Effy.→		39.1%	0.50		0.13			0.75				2.13				

Table 4: Initial design DFA analysis of the Main Body Sub-assembly

In the Main Body, there are nine different components and 23 total parts. The number of parts has been minimized for basic functions. Possible problems with assembly arise as all table frame bars can be easily mistaken, and the diagonal bars may be assembled in the wrong direction. To add, all the bars have sharp edges on the end which would need be deburred. And finally, everything is welded onto the table, presenting problems with precise locate of welds. In the final design, these problems will be addressed, the material of the Tabletop will be changed, and additional components will be added to the table for improved functionality to meet our project objectives, later discussed.

The Weight Sub-Assembly

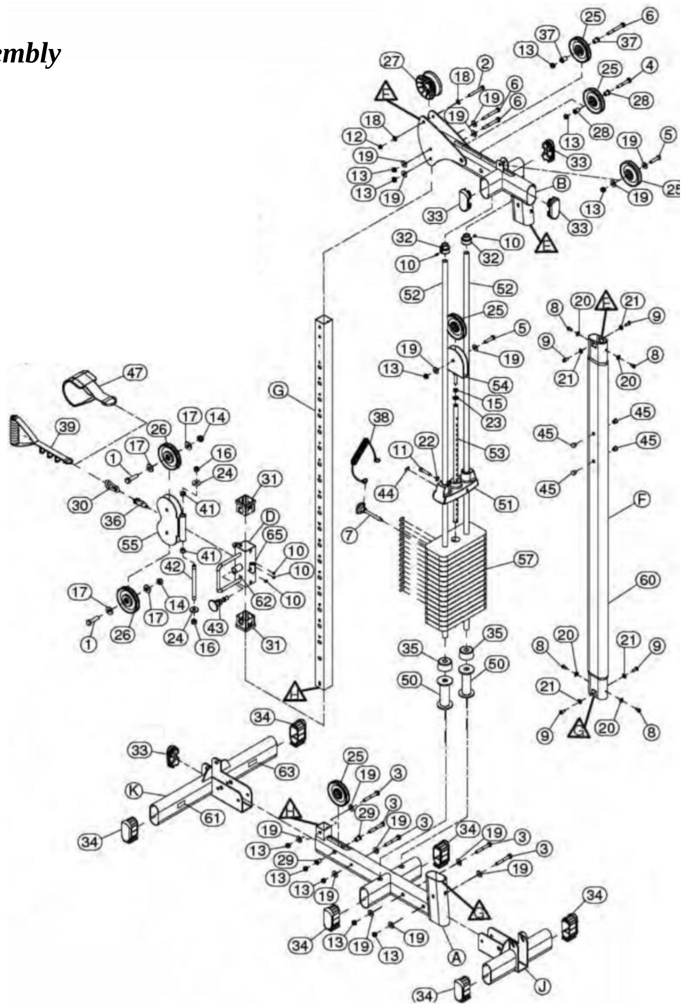


Figure 20: Picture of the Sub-Assembly is included separate from the DFA table, being so large.

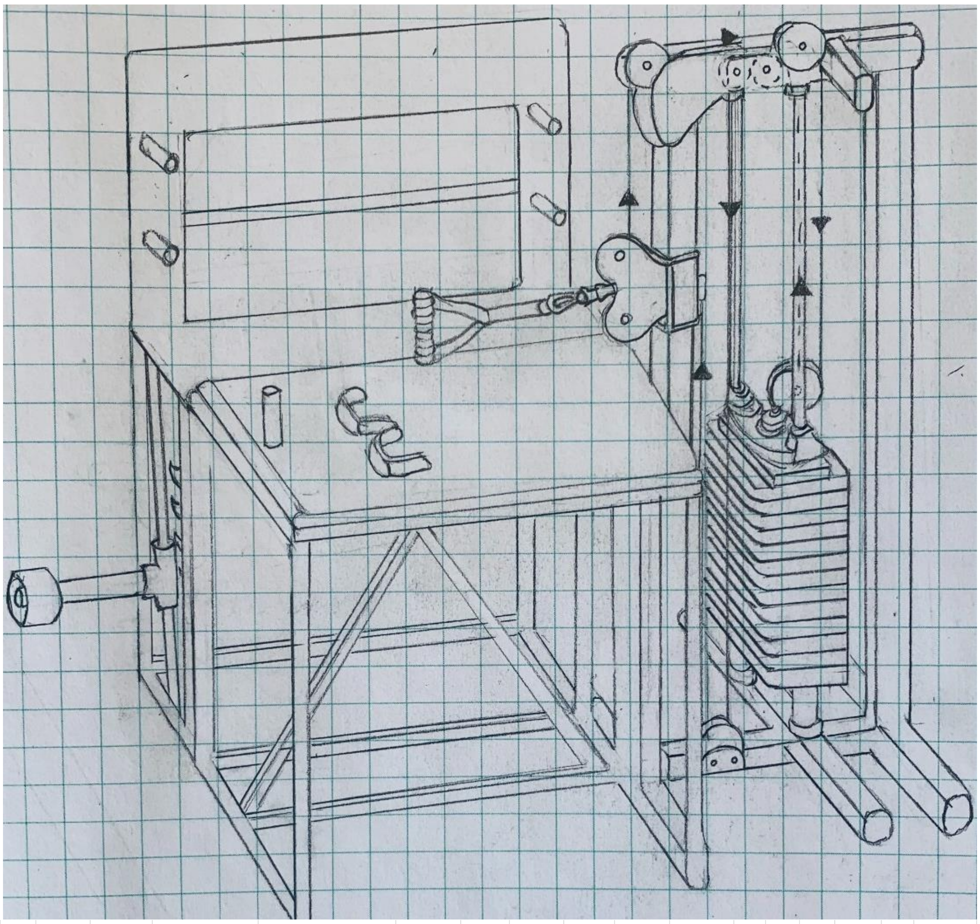
3000- Weight System SubAssy														Team: RPS				Date: 04/23/20			
the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a numbe																					
Part		DFA Comp.		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
#	Name	Number of Parts (N_p)	Number of Interfaces (N)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
	Cable Subsytem: Base Frame																				
A1	BASE LONG ARM	1	18	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
A2	BASE SHORT ARM	2	6	0	0	L	0	0	1	0	0	0	1	1	0	0	0	0	1	1	0
A3	BASE UPRIGHT ARM	1	6	0	0	L	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0
A4	BASE CUBE CONNECTOR	1	6	0	0	L	0	0	1	0	0	0	1	1	0	0	0	0	1	1	0
	Cable Subsystem: Top Frame																				
B1	TOP LONG ARM	1	12	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
B2	TOP SHORT ARM	2	12	0	0	L	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0
B3	TOP DOWNRIGHT ARM	1	5	0	0	L	0	0	1	0	0	0	1	1	0	0	0	0	1	1	0
B4	TOP PULLEY HOUSING	2	16	1	1	L	1	0	1	0	0	0	0	0	0	0	0	0	1	1	0
	Cable Subsystem: Handle Adjuster																				
C1	ADJUSTER GRIP	1	2	0	0	L	0	0	1	0	0	0	1	0	0	0	0	0	1	1	0
C2	ADJUSTER BODY	1	12	1	1	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
C3	ADJUSTOR PIN HOLD	1	2	0	1	L	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0
C4	ADJUSTER TAB CONNECTORS	2	4	0	1	L	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0
	Cable Subsystem: Upright Frame																				
F1	UPRIGHT FRAME	1	8	1	1	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
F2	Housing	1	13	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	Cable Subsystem: Guide Post																				
G1	GUIDE POST	1	7	1	0	M	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cable Subsystem: Large Stabilizer																				
K1	L-STABILIZER ARM	1	7	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
K2	L-STABILIZER BODY	1	24	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
K3	L-STABILIZER SUPPORT	2	4	0	0	L	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	Cable Subsystem: Small Stabilizer																				
J1	S-STABILIZER ARM	2	8	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
J2	S-STABILIZER BODY	1	24	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
J3	S-STABILIZER SUPPORT	2	4	0	0	L	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	Cable Subsystem: Hardware (63)																				
1	HEX HEAD BOLT 1/2” x 50 mm	2	12	1	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
2	HEX HEAD BOLT 3/8” x 3”	1	6	1	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
3	HEX HEAD BOLT M10x75	7	42	0	1	L	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0
4	HEX HEAD BOLT M10x65	1	7	0	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
5	HEX HEAD BOLT M10x45	2	14	0	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
6	HEX HEAD BOLT M10x85	3	21	1	1	L	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
7	WEIGHT STACK PIN	1	2	1	1	L	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0
8	HEX HEAD BOLT M8x15	4	12	0	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
9	HEX HEAD BOLT M8x20	4	12	1	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
10	ALLEN SCREW M8x8	5	10	0	1	L	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
11	ALLEN HEAD BOLT 3/8” x 1 3/4”	1	3	1	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
12	NYLON NUT 3/8”	1	2	1	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
13	NYLON NUT M10	#	22	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
14	NYLON NUT 1/2”	2	4	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
15	NUT 1/2” x 13 mm	1	2	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
16	NYLON NUT M12	2	4	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
17	WASHER 1/2” ID	4	12	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
18	WASHER 3/8” ID	2	6	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
19	WASHER M10 ID	#	48	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
20	ARC WASHER M8	4	12	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
21	WASHER M8 ID	4	12	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
22	SPRING WASHER 3/8”	1	3	0	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
23	SPRING WASHER 1/2”	1	3	1	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
24	WASHER M12	2	3	1	1	L	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
25	PULLEY Φ110	5	15	1	1	M	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0
26	PULLEY Φ 4 ½	2	6	0	1	M	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0
27	PULLEY Φ109	1	3	0	1	M	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0
28	STEEL BUSHING Φ16 x Φ10 x 16.5L	2	6	1	0	L	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0

Table 5: Initial design DFA analysis of the weight system sub assembly

3000- Weight System SubAssy													Team: RPS						Date: 04/23/20		
If the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a number.																					
Part		DFA Comp.		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
#	Name	Number of Parts (N_p)	Number of Interfaces (N)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
29	STEEL BUSHING Φ20 x Φ10 x 21.5L	2	6	0	0	L	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
30	SNAP LINK Φ8	1	2	1	0	L	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
31	NYLON BUSHING	2	6	1	0	L	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
32	SHAFT COLLAR	2	6	1	0	L	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
33	END CAP	4	4	1	0	L	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
34	FOOT CAP	6	6	0	0	L	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
35	RUBBER DONUT	2	4	0	0	L	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
36	STEEL CABLE	1	3	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1
37	STEEL BUSHING	2	4	1	0	L	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
38	WEIGHT STACK PIN LANYARD	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	HANDLE	1	2	1	0	L	1	0	1	0	0	0	0	0	1	0	0	0	1	0	0
41	OILITE BUSHING	2	6	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	SHAFT COLLAR	1	7	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	FLAT POP PIN	1	3	1	0	L	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
44	WEIGHT STACK STICKERS	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
45	ROUND CAP	4	8	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	ANKLE STRAP	1	1	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	POSTER CLIPS	1	2	0	1	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	WEIGHT STACK RISER	2	8	1	1	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	TOP PLATE	1	1	0	0	L	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0
52	GUIDE ROD	2	16	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
53	SELECTOR BAR	1	5	0	1	L	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
54	PULLEY HOLDER	1	3	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	DOUBLE PULLEY HOLDER	1	3	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	WEIGHT STACK	1	6	1	0	H	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	FOAM GRIP	2	4	0	0	L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	ROUND END CAP	2	4	0	0	L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	PINCH POINTS STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
61	WARNING STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
62	POP PIN STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
63	GENERAL WARNING STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
64	BODYSOLID PLATE	1	1	0	0	L	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0
65	CARBLE WARNING STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
66	BODYSOLID LOGO	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
67	WARNING STICKER	1	1	0	0	L	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
	Totals	176	635	35	35	0	58	43	27	8	0	0	7	4	13	0	0	23	32	33	1
	Design for Assembly Metrics	334.305		19.9%	Effy. Pract. Effy.→		33.0%	2.00		0.23			0.69				2.54				

Table 6: Initial design DFA analysis of the weight system sub assembly (Cont.)

For the initial weight system, the team, in large part, re-purposed an existing design of a cable machine, for its proof of concept, and also for purposes of extracting the type of assembly that takes place in such a standard gym machine. Furthermore, the cable machine has been a common gym machine that professional arm-wrestling athletes have attached to a standard arm-wrestling table to train certain techniques. After the DFA analysis, the team concluded that the design had many areas of improvement, as the usual cost of these cable machines range around \$2,000 - \$4,000, and the DFA justifies that price. Designing something with the same function, but ultimately having a smaller overall selling price could appeal towards commercial gyms. Overall, the initial design has too many parts, and while it maintains the same functions, the number of parts can be reduced significantly, as well as some becoming standardized.



Part	Comp.		Functional Analysis / Redesign Opportunity				Proofing		Handling			Insertion				Secondary Operations				
#	Number of Parts (N_p)	Number of Interfaces (N_i)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
Totals	215	747	51	40	0	77	46	31	8	1	0	17	4	15	2	0	24	49	48	8
DFA Metrics	400.756		23.7%	←Theor. Effy. Pract. Effy.→		35.8%	1.51		0.18			0.75				2.53				

Table 7: Total Initial Design DFA Metrics of the initial design

Totalling all the sub-assemblies gives the team an initial design with 215 parts and 747 interfaces, scoring a complexity of 400. Overall, our initial design did not perform very well in this DFA analysis. There are too many parts. Most of them are not been minimized, which led to a low efficacy. Many parts cannot be standardized, or haven't been standardized yet, which highly increase the processing cost. The metric for the complexity is extremely high for this design, the error proofing metric and the secondary operations metric are also quite expensive. The final design and DFA will address these metrics and seek to improve them.

XII. FINAL DESIGN DESCRIPTION AND ANALYSIS

The final design has some very major changes in comparison to the initial design (Figure 21). For the purposes of comparison, a hand-sketch of the final design is shown to help better display the significant changes in design, that will later be seen in the changes from the initial DFA analysis to the final DFA analysis.

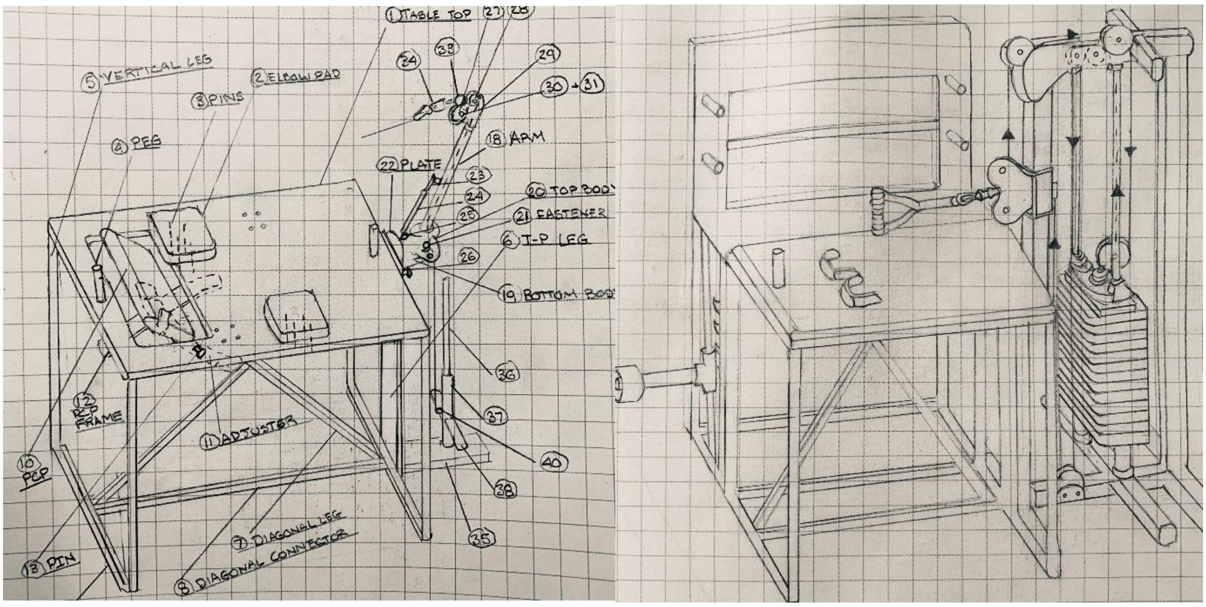


Figure 21: Final design preliminary hand sketch (left) and initial design final hand sketch (right)

The preliminary hand sketch for the final design was utilized to streamline the vision of the final product across the team, to help aid the process in compiling all the individual components that make up the Final CAD Assembly (Figure 22).

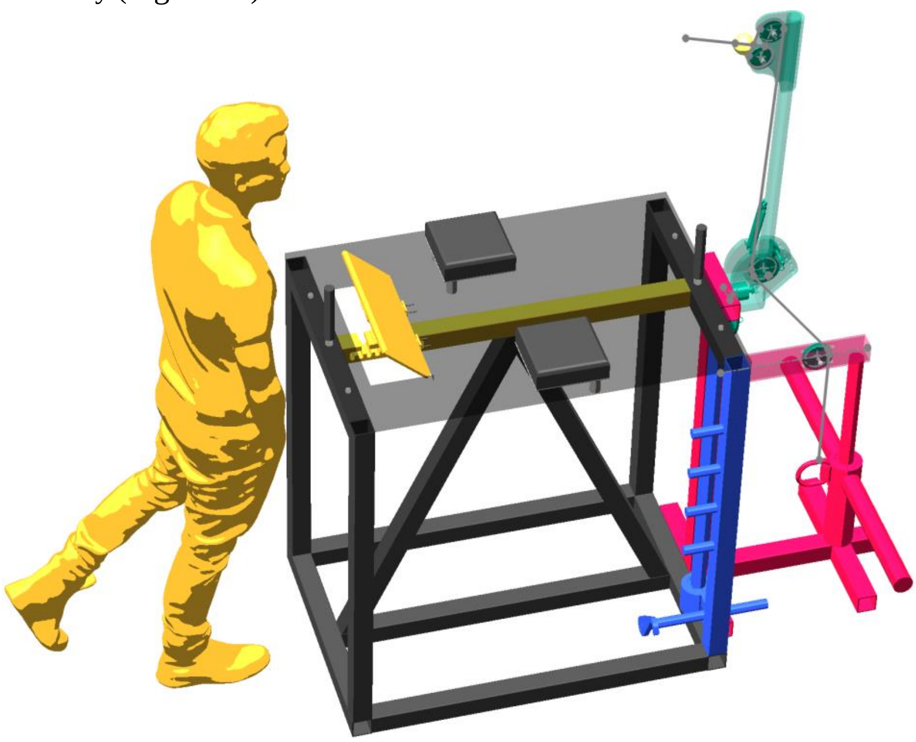


Figure 22: Final CAD of the Assembly, oriented in the same position of the final design hand sketch.

FINAL BILL OF MATERIALS

The Final Assembly is comprised of the following parts in the Bill of Materials (Table 8) and will be of reference as to the description of each subsystem. There are 60 total parts in three sub-assemblies (labelled in the BOM), in which there are six total subsystems (Later discussed under each sub-assembly section). Comparing to the initial design, the Bill of Materials sees a drastic decrease in the number of parts, as it was concluded to be excessive, in regard to the number of parts and fasteners the initial cable system needed.

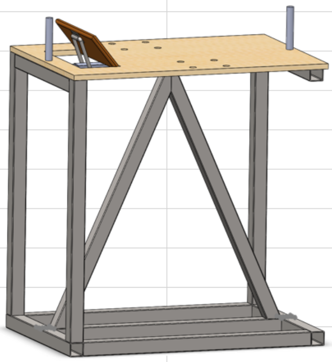
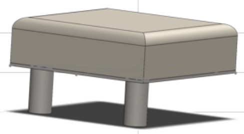
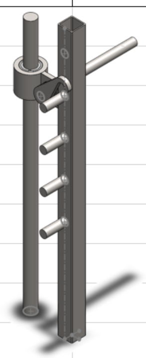
Item #	Part #	Qty	Name	Material	Visual
	6660		**Main Body Sub-assembly**		
1	6677	1	Tabletop	Teak	
2	6661	2	Horizontal Bar Width	Sheet Metal	
3	6662	3	Horizontal Bar Length	Sheet Metal	
4	6663	3	Vertical Bar Length	Sheet Metal	
5	6664	2	Gripping Peg	304 Steel	
6	6665	2	Diagonal Bar	Sheet Metal	
7	6667	1	Preacher Curl Pad (PCP)	Teak	
8	6668	2	Upper Horizontal Bar	Sheet Metal	
9	1060	2	Screw For Handle	SS Socket Head	
10	1061	4	Screw For Tabletop	Black Oxide Alloy S.	
11	1062	2	Hinge For PCP	304 Steel	
12	1063	8	Screw For PCP	Alloy Steel	
13	6669	1	Upper Horizontal Bar	Sheet Metal	
14	6670	1	PCP Adjuster Connecter	Low Carbon Steel	
15	6671	1	PCP Adjuster	304 Steel	
16	1064	4	Screw For PCP Adjuster	Zinc Plated Steel	
17	6001	2	Elbow Pad Board	Low Carbon Steel	
18	6002	4	Elbow Pad Pin	Low Carbon Steel	
19	6003	2	Elbow Pad Foam	Polyurethane Foam	
	6606		**Smith Machine Sub-assembly**		
20	6616	1	Vertical Rod	Sheet Metal	
21	6626	4	Position Rod	Low Carbon Steel	
22	6636	1	Rod	304 Steel	
23	1006	1	Linear Bearing	Delrin	
24	6656	1	Slider	304 Steel	
25	6676	1	Slider Block	Low Carbon Steel	
26	1016	1	Ball Bearing	6048 Steel	
27	6686	1	Handle	304 Steel	
28	6696	1	Position Hook	304 Steel	
	6066		**Weight System Sub-assembly**		
29	6166	1	Vertical Bar	Sheet Metal	
30	6266	5	Horizontal Bar	Sheet Metal	
31	6366	1	Ground Bar	Low Carbon Steel	
32	6466	1	Adjustment Rod	Low Carbon Steel	
33	1066	1	Sleeve Bearing	6061 Aluminum	
34	6566	2	Adjuster Plate	Cast Carbon Steel	

Table 8: Final Bill of Materials

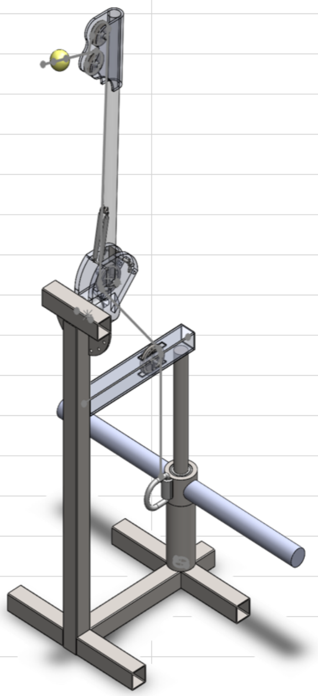
Item #	Part #	Qty	Name	Material	Visual
34	6566	2	Adjuster Plate	Cast Carbon Steel	
35	6766	1	Adjuster	Cast Carbon Steel	
36	1166	2	Lower Pulley	Cast Carbon Steel	
37	1266	1	Screw For Adjuster	Zinc Plated Steel	
38	1366	1	Spring Pin	Stainless Steel	
39	1466	2	Upper Pulley	Cast Carbon Steel	
40	1566	1	Hitch Pin For Pulley Arm	Zinc Plated Steel	
41	1766	1	Bolt For Pulley On Adjuster	Stainless Steel	
42	1866	2	Locknut	High Strength Steel	
43	1966	2	Gas Spring	Various	
44	2066	1	Pin for Gas Spring	Stainless Steel	
45	6866	1	Vertical Stationary Rod	304 Steel	
46	2166	1	Linear Bearing	Delrin	
47	6966	1	Vertical Sliding Rod	304 Steel	
48	7066	2	Horizontal Loading Rod	304 Steel	
49	2266	1	Ring for Rope	Stainless Steel	
50	7166	1	Pulley Arm	304 Steel	
51	7266	1	Pulley Housing	Sheet Metal	
52	2366	2	Pin For Upper Pulley	Low Carbon Steel	
53	7366	2	Gas Spring Connecter	Low Carbon Steel	
54	7466	1	Upper Bar	Low Carbon Steel	
55	2466	1	Screw For Lower Pulley	Zinc Plated Steel	
56	2566	1	Pin For Gas Spring	Stainless Steel	
57	7566	1	Pin Connecter	Low Carbon Steel	
58	7666	1	Rope Stopper	ABS	
59	7766	1	Vertical Stationary Rod Tube	304 Steel	
60	7767	1	Rope	Nylon Core SS	

Table 8: Final Bill of Materials (Cont.)

Each of the sub-assemblies will now be addressed in more depth entailing the components, function and user-ability, as well as the assembly consideration (manufacturing processes will be later discussed in Process Selection:

MAIN BODY SUB-ASSEMBLY

The Main Body Sub-Assembly has two subsystems: ***Arm Anchor*** and ***Table***.

Arm Anchor Subsystem (Yellow)

<u>Components</u>

In comparison to the initial design, this subsystem is an entirely new addition. The subsystem comprises of the Preacher Curl Pad (PCP), Hinge for PCP, Screw for PCP, Upper Horizontal Bar, PCP Adjuster Connector, PCP Adjuster, and the Screw for PCP Adjuster (Figure 23).

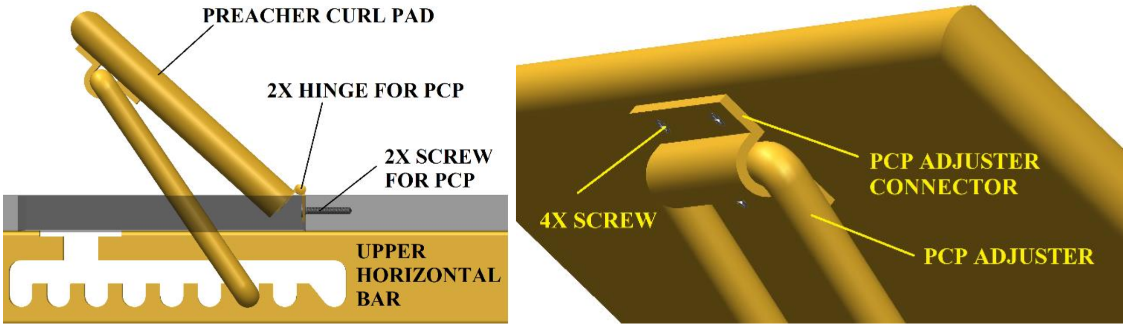


Figure 23: Side view and isometric bottom view of Arm Anchor Subsystem

Function and User-ability

Briefly mentioned in the introduction, the Arm Anchor Subsystem allows for the user to fix their elbow position in various different angles while they train with the Pulley Arm, directly adjacent to the Preacher Curl Pad (PCP). The angle can be changed by the Upper Horizontal Bar and the PCP Adjuster, from zero degrees (parallel to the Tabletop) to eighty degrees, by pulling the PCP adjuster by forward or backwards along the bar. Pronation, supination, and rising (radial and ulnar deviation) can be trained from this fixed elbow position, practicing your arm-wrestling techniques with a firm elbow position. A strong elbow position is important as the actual elbow pad, on top of standard arm-wrestling tables. is an area in which your elbow cannot move outside of, or a elbow foul is counted in the sport and in WAL In terms of bodybuilding, this PCP resembles an angled pad you could use at the gym to do your curls, isolating stress on your bicep and forearm muscles (depending the angles you pull in), as it takes the shoulder and back movements away from the exercise.

Assembly

Alloy steel fasteners were chosen to secure the PCP Adjuster Connector onto the PCP with the PCP Adjuster enclosed within it. Black Oxide Alloy Steel Screws were also chosen to secure the Hinge for PCP onto the Tabletop. This is done manually at the end of the assembly line, first the hinge is secured to the table top, and then the PCP Adjuster onto the PCP, making sure to fit the PCP Adjuster in between the two beforehand. This is then placed into the Upper Horizontal Bar manually as well for the complete integration of the Arm Anchor Subsystem to the Table Subsystem.

Table Subsystem (Black)

Components

The Table Subsystem includes: The Tabletop, Horizontal Bar Width, Horizontal Bar Length, Vertical Bar Height, Gripping Peg, Diagonal Bar, and the Screw for Handle (Figure 24).

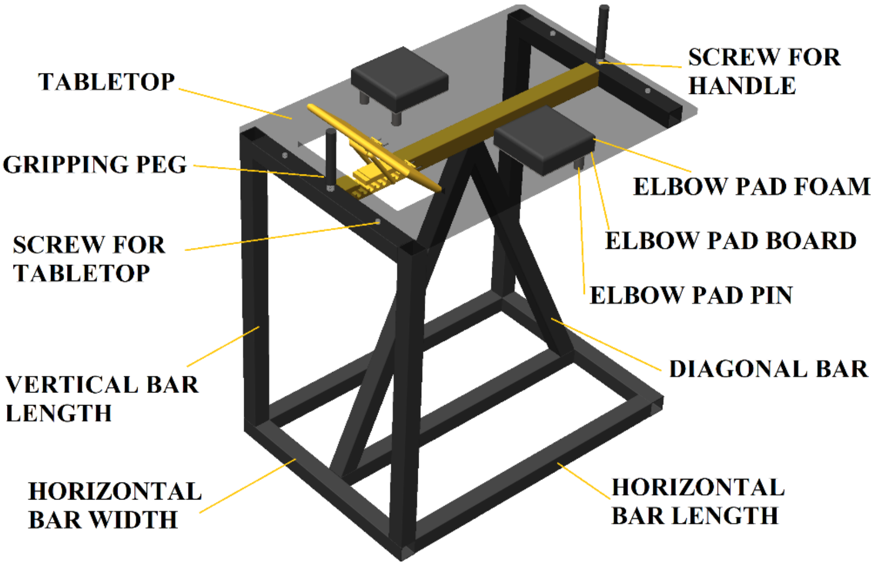


Figure 24: Tabletop Subsystem isolated isometric view (in black), Tabletop is transparent for viewing.

Function and User-ability

The Final Table Subsystem differs from the initial design, as it sees the removal of the Back Frame and the top pad. Removal of the Back Frame allows for the final design to have a duality to the product: integrating the sport of arm-wrestling to bodybuilding by allowing users to arm-wrestle directly at the machine. In previous, the Back Frame blocked the entirety of the long backside of the table, removing this function. With the final design, the elbow pads are present instead of the singular top pad, so arm-wrestling matches can occur with standard arm-wrestling rules.

Assembly Considerations

The assembly of the Table Subsystem will undergo an automated assembly line to perform the necessary welds that connects the Diagonal, Vertical, and Horizontal Length and Width Bars. The Elbow pads are will be packaged separately as they can be installed by the user.

SMITH MACHINE SUB-ASSEMBLY (DARK BLUE)

Components

The components of the Smith Machine are as follows: Vertical Rod, Position Rod, Rod, Linear Bearing, Slider, Slider Block, Ball Bearing, Handle, and the Position Hook (Figure 25). The Rod is tentatively labelled as so, to prevent confusion with the Table Sub-assembly's Vertical Bar, even though it does not resemble a rod.

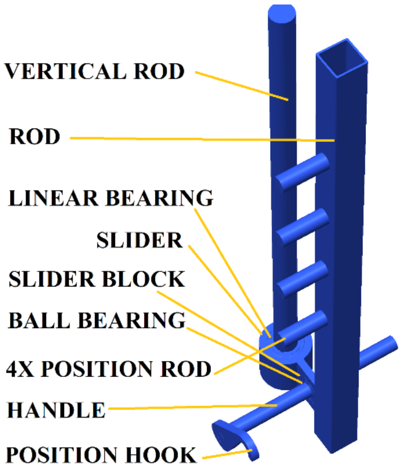


Figure 25: Isometric View of Smith Machine Sub-Assembly

Function and User-ability

The Smith Machine saw some improvements from the initial design with the addition of a Delrin Linear Bearing placed in between the Vertical Rod and the Slider. There is also a Ball Bearing in between the Handle and the Slider Block, which is attached to the Slider. The Slider translates the motion between the Vertical Rod and the Handle, as the user pulls vertically upward with a cupped hand around the handle, to train forearm muscles in flexion or extension (cupping). The Ball Bearing allows for the Handle to be rotated, and in turn, rotates the Position Hook onto one of four stationary Position Rods These position rods lets users rest the load at a desired height, before repeating their next exercise repetition.

Assembly Considerations

The Smith Machine Subsystem will involve a series of machine welds and press fits for the bearings. The Rod will be welded to the Slider Block, and then welded to the Slider. The Ball Bearing is then press-fitted into the Slider Block and the Linear Bearing along with the Vertical Rod are both press-fitted into the Slider. The Handle is welded onto the Position Hook and fitted through the Ball Bearing. All of the processes involved above happen in chronological order in an automated assembly line.

WEIGHT SUB-ASSEMBLY

Components

The Weight Sub-assembly includes the remaining thirty-one parts, seen in the BOM. This sub-assembly can be broken down into three main subsystems: Pulley Subsystem, Cable Subsystem, and Weight Subsystem. Although the Sub-Assembly has half of the remaining parts, it still sees a drastic improvement from the seventy parts that made up the Weight Subsystem.

Pulley Subsystem (Green) and Cable Subsystem (Light Blue)

Components

The Pulley Subsystem is made up of twenty different components, and the Cable Subsystem has two components (Figure 26). Figure 26 displays both the assembly into two halves, the upper half (adjusts the z and y-direction) and the lower half (adjusts the x-direction) of the Pulley Subsystem.

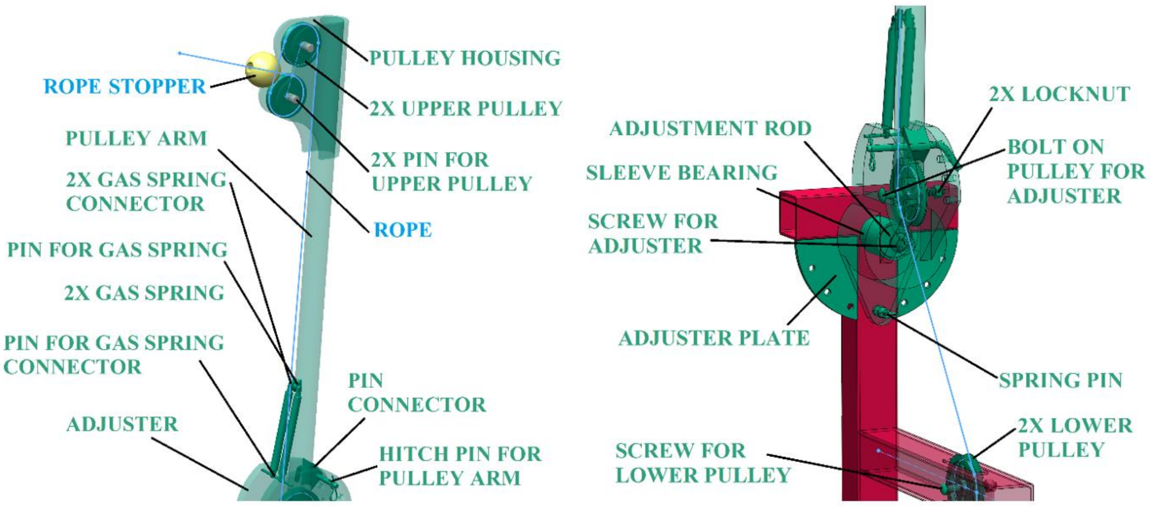


Figure 26: Pulley and cable subsystem

Function and User-ability

The Pulley Subsystem as mentioned previously can control all three degrees of freedom to mimic the movement of a human arm, at various angles. This allows users to train at certain compromising positions, which they can strengthen in their training with the machine. The upper half of the Pulley Subsystem (Figure 26, left), controls the y and z-direction of the Pulley Arm. The adjustment is made by releasing the Hitch Pin, adjusting the arm to the desired height, and inserting the Hitch Pin through one of three holes in the Adjuster. In doing this, the Gas Spring attached to the Pulley Arm pulls the arm inwards or outwards depending on the height that is chosen.

Similarly, for the lower half of the Pulley Subsystem, the adjustment is done through the Spring Pin, by way of releasing and inserting through a chosen hole for a desired angle. This movement is aided with a Sleeve Bearing over the Adjustment Rod.

Finally, the Cable Subsystem is simply two parts: the rope and the rope stopper. The Rope Stopper prevents the Rope from losing its tension when the Rope is not in use. The Rope Stopper fits nicely in between the two Upper Pulleys to keep the Rope from retracting to the floor, as the rope is secured within the Rope Stopper.

Assembly Considerations

The Adjuster Plate and the Adjuster Rod will be machine welded onto the Weight Subsystem components, detailed in the following section. The Pin Connector and Gas Spring Connector also gets machine welded to the Adjuster. All of the pins except for the Hinge Pin and Spring Pin are dowel pins that need to pressed into their interfaces The Spring and Hinge Pin arrive in a separate package as they are adjustable by nature. The Screws for the Lower Pulley, Screw for Adjuster, and Bolt and Locknut will manually be fastened, at the end of this assembly process, as the Lower Pulley interacts with the Weight Subsystem.

Weight Subsystem (Red)

<u>Components</u>

The remaining ten components are in the Weight Subsystem, of the Weight Sub-assembly (some naming confusion that could be a learning lesson in future projects, the team realizes). The components are shown in Figure 27 to be: Horizontal Bar, Vertical Bar, Ring For Rope, Upper Bar, Vertical Stationary Rod, Weight Linear Bearing, Vertical Sliding Rod, horizontal Loading Rod, Vertical Stationary Tube, and the Ground Bar.

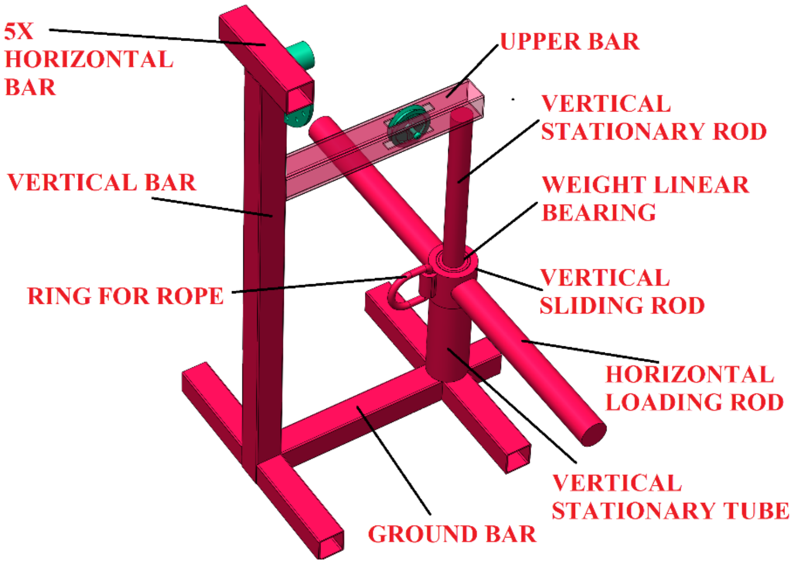


Figure 27: Weight Subsystem (red)

<u>Function and User-Ability</u>

Comparing this weight system to the initial design, the team opted to go for a plate loaded system rather than a weight stack loaded system due to the major reduction in overall parts this change allowed for. The Horizontal Loading Rods are compatible to your standard commercial gym weight plates, having the slightly smaller diameter, so the weights can slide into the rod accordingly. The overall structure of the system allows for the rope to travel in straight paths, making sure the weight translated to the end of the pulley arm is equivalent to the weight that is loaded onto the rod. Lastly, there is a Linear Bearing in between the Vertical Sliding Rod and Vertical Stationary Rod, so the load can move upwards with minimal friction.

<u>Assembly Considerations</u>

The Horizontal Bars (5X), will all be machine-welded with the Ground Bar, Vertical Bar, and Vertical Stationary Tube. Then, the Vertical Station Rod is press fit into the Vertical Stationary Rod. The Ring Rope are then machine welded to the Horizontal Loading Rods, in which the Linear Bearing is press fit in between the hold for the weight load and the Vertical Stationary Rod. Finally, the Upper Bar is Welded to both the Vertical Bar and Vertical Stationary Rod. This process is performed in chronological order as explained in an assembly line. The green shown simply shows where the Pulley and Cable Subsystems connect with the Weight Subsystem to form the Weight Subassembly.

XIII. FINAL DFA ANALYSIS

Our Final Design of the Arm-wrestling Training Gym Machine is divided into four Sub-assemblies: the Main Body Sub-assembly, the Smith Machine Sub-assembly, the Weight System Sub-assembly, and the Elbow Pad Sub-assembly (Although in previous, this Elbow Pad Sub-assembly was combined with the Main Body Sub-assembly for convenience, as it only had three separate components). The following will describe as a separate sub-assembly as it was designed that way in SolidWorks.

DFA Analysis Worksheet																					
Assembly Name: Arm-wrestling Training Gym Machine									Team: RPS									Date: 04/20/2020			
If the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a number.																					
Part		DFA Comp.		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
 Part Number	 Part Name	Number of Parts (N_p)	Number of Interfaces (N_i)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
6660	MAIN BODY SUBASSEMBLY																				
6677	TABLETOP	1	28	1	0	M	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0
6661	HORIZONTAL BAR WIDTH	2	14	1	0	L	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0
6662	HORIZONTAL BAR LENGTH	3	8	0	0	L	1	1	0	0	0	0	1	0	0	0	0	0	1	1	0
 6663	VERTICAL BAR HEIGHT	3	9	0	0	L	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0
6664	GRIPPING PEG	2	4	1	0	L	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0
6665	DIAGONAL BAR	2	6	1	0	L	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0
6667	PREACHER CURL PAD (PCP)	1	12	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6668	UPPER HORIZONTAL BAR WIDTH	2	12	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1060	SCREW FOR HANDLE	2	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1061	SCREW FOR TABLETOP	4	8	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1062	HINGE FOR PCP	2	12	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1063	SCREW FOR PCP	8	16	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6669	UPPER HORIZONTAL BAR	1	6	1	0	M	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0
6670	PCP ADJUSTER CONNECTOR	1	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6671	PCP ADJUSTER	1	3	1	0	L	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0
1064	SCREW FOR PCP ADJUSTER	4	8	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Totals	39	158	12	0	0	16	3	1	0	1	0	3	1	0	0	0	2	3	11	0
	Design for Assembly Metrics	78.498		30.8%	←Theor. Effy. Pract. Effy.→		41.0%	0.33		0.08			0.33				1.33				
	DFA Metrics for the Initial Design	41.809		34.8%	←Theor. Effy. Pract. Effy.→		39.1%	0.50		0.13			0.75				2.00				
	Delta	36.689		4.0%	←Theor. Effy. Pract. Effy.→		1.9%	0.17		0.04			0.42				0.67				

Table 9: Final Design DFA Metrics of the Main Body sub assembly

For the Main Body Sub-assembly, there are total of sixteen different parts, including five standardized parts that can directly buy from the market. All the bars in the frame are cut from the standardized metal bar. In theory, these bars can all be simplified into a few curved frames, but that would, in turn, increase the processing cost, outweighing its value. When assembling, these bars may be mistaken because they only differ in length. In the future, stickers can be added with numbers to help separate them. Besides the bars, the only part that may be assembled with error would be the adjuster, although it will have a large impact, even if it were to be assembled wrong. The middle frames, being the two diagonal bars and two horizontal bars, could present some problems, as they are hard to locate. We can add features such as the welding markers to help distinguish the difference. Also, all the wood and metal parts manufactured will be painted to prevent rust and any other exterior damage.

Part	DFA Comp.	Functional Analysis / Redesign Opportunity			Error Proofing	Handling	Insertion	Secondary Operations
Design for Assembly Metrics	78.498	30.8%	←Theor. Effy. Pract. Effy.→	41.0%	0.33	0.08	0.33	1.33
DFA Metrics for the Initial Design	41.809	34.8%	←Theor. Effy. Pract. Effy.→	39.1%	0.50	0.13	0.75	2.00
Delta	36.689	4.0%	←Theor. Effy. Pract. Effy.→	1.9%	0.17	0.04	0.42	0.67

Table 10: DFA Metrics comparison of the Main Body sub assembly

If we compare the DFA metrics of the Main Body Sub-assembly from the initial design to the final design, we will find some interesting changes. The complexity actually increases, as we added an entire subsystem to the table itself: The Arm Anchor Subsystem. Although the theoretical efficiency has been decreased, the actual efficiency has increased. This can be explained by an increase in processing difficulties and expenses. Besides this discrepancy, all other DFA metrics dropped significantly.

DFA Analysis Worksheet

Assembly Name: Arm-wrestling Training Gym Machine **Team:** RPS **Date:** 04/20/2020

If the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a number.

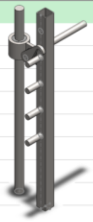
Part		DFA Comp.		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
 Part Number	Part Name	Number of Parts (N_p)	Number of Interfaces (N_i)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
6606	SMITH MACHINE SUBASSEMBLY																				
 6616	VERITICAL BAR	1	7	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6626	POSITION ROD	4	5	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6636	ROD	1	3	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1006	LINEAR BEARING	1	2	1	0	M	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
6656	SLIDER	1	2	1	0	L	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0
6676	SLIDER BLOCK	1	2	0	0	L	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0
1016	BALL BEARING	1	2	1	0	M	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
6686	HANDLE	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6696	POSITION HOOK	1	2	1	0	L	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0
	Totals	12	27	7	0	0	9	0	1	0	0	0	0	0	4	0	0	0	0	6	0
	Design for Assembly Metrics	18		58.3%	←Theor. Effy. Pract. Effy.→		75.0%	0.14		0.00			0.57				0.86				
	DFA Metrics for the Initial Design	24		50.0%	←Theor. Effy. Pract. Effy.→		62.5%	0.38		0.00			1.00				3.00				
	Delta	6		8.3%	←Theor. Effy. Pract. Effy.→		12.5%	0.23		0.00			0.43				2.14				

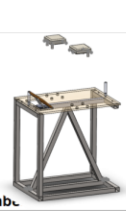
Table 11: Final design DFA Metrics of the Smith Machine sub assembly

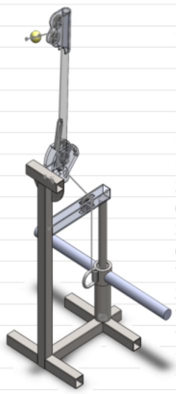
For the Smith Machine Sub-assembly, there are nine components, including two bearings that can be bought directly from the market. All other parts are made from standardized metal bar and sheet. Although the position rods can be made from the vertical bar, it will reduce the maximum force load capacity, so we kept them as separate parts. The Slider and Slider Block can also be made as one part with a bending metal sheet but requires very high processing accuracy, ultimately increasing the production cost. We didn’t use a standardized Position Hook, since we have simplified this Smith Machine, which in turn modifies more complex standard Smith Machine components. Currently, the Position Hook could be assembled the wrong way around, so the component would benefit from a sticker marking its direction. All the bearings are press fitted, so there will be resistance to insertion. And finally, all components, besides the bearings and the Rod, will be painted.

Part	DFA Comp.	Functional Analysis / Redesign Opportunity			Error Proofing	Handling	Insertion	Secondary Operations
Design for Assembly Metrics	18	58.3%	←Theor. Effy. Pract. Effy.→	75.0%	0.14	0.00	0.57	0.86
DFA Metrics for the Initial Design	24	50.0%	←Theor. Effy. Pract. Effy.→	62.5%	0.38	0.00	1.00	3.00
Delta	6	8.3%	←Theor. Effy. Pract. Effy.→	12.5%	0.23	0.00	0.43	2.14

Table 12: DFA Metrics comparison of the Smith Machine sub assembly

Comparing the final design of the Smith Machine Sub-assembly to the initial design, the DFA complexity has decreased, while the efficacy has been increased. One significant change can be noted in secondary operations, which dropped from 3.00 to 0.86. This is due to part reduction from the initial design, requiring an excessive amount of welding, deemed unnecessary by the team.





DFA Analysis Worksheet																					
Assembly Name: Arm-wrestling Training Gym Machine		Team: RPS															Date: 04/20/2020				
Part		DFA Comp.		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
Part Numbe	Part Name	Number of Parts (N_p)	Number of Interfaces (N_i)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
6066	WEIGHT SYSTEM SUBASSEMBLY																				
6166	VERTICAL BAR	1	13	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6266	HORIZONTAL BAR	5	18	0	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
6366	GROUND BAR	1	5	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6466	ADJUSTMENT ROD	1	3	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
1066	SLEEVE BEARING	1	3	1	0	M	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6566	ADJUSTER PLATE	2	8	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6766	ADJUSTER	1	15	1	0	M	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1166	LOWER PULLEY	2	4	1	0	M	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
1266	SCREW FOR ADJUSTER	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1366	SPRING PIN	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1466	UPPER PULLEY	2	4	1	0	M	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
1566	HITCH PIN FOR PULLEY ARM	1	3	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1766	BOLT FOR PULLEY ON ADJUSTER	1	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1866	LOCKNUT	2	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1966	GAS SPRING	2	6	0	0	M	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2066	PIN FOR GAS SPRING	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6866	VERTICAL STATIONARY ROD	1	4	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
2166	LINEAR BEARING	1	2	1	0	M	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6966	VERTICAL SLIDING ROD	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
7066	HORIZONTAL LOADING ROD	2	2	0	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
2266	RING FOR ROPE	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
7166	PULLEY ARM	1	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0
7266	PULLEY HOUSING	1	5	1	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
?366	PIN FOR UPPER PULLEY	2	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7366	GAS SPRING CONNECTOR	2	6	0	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
7466	UPPER BAR	1	4	1	0	L	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0
2466	SCREW FOR LOWER PULLEY	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2566	PIN FOR GAS SPRING	1	4	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7566	PIN CONNECTOR	1	2	0	0	L	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
7666	ROPE STOPPER	1	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7766	VERTICAL STATIONARY ROD TUBE	1	5	0	0	L	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0
7767	ROPE	1	6	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Totals	44	164	25	0	0	32	0	0	0	0	0	8	0	1	2	0	2	15	0	1
	Design for Assembly Metrics	84.947		56.8%	Pract. Effy.→		72.7%	0.00		0.00			0.44				0.72				
	DFA Metrics for the Initial Design	334.31		19.9%	Pract. Effy.→		33.0%	2.00		0.23			1.00				2.54				
	Delta	249.36		36.9%	Pract. Effy.→		39.7%	2.00		0.23			0.56				1.82				

Table 13: Final design DFA Metrics of the Weight System sub assembly

The Weight System Sub-assembly has the largest complexity of our final product. There are thirty-one different components, including fifteen components from the market. Although this design is the best we can propose, as of now, there is always room for improvement, as further components can be reduced. Given more time, the team would improve the way in which the subassemblies were conjoined, by reducing the use of the bars for the table frame. Also, there are existing standardized components for the Pulley Arm and its Adjustment Plate, which could be another possibility. However, the current design reaches a practical minimum number of parts, within the scope and initial objectives of this project. During the assembly process, all parts have clear and distinguishable features that determine their direction, except for the frame bars and rods. To address this, welding markers will be included. As for the Pulley assembly, there might be some difficulty in aligning the dowel pins for press fitting, but it will not be a large issue. Lastly, the majority of metal parts will be machine-welded and painted.

Part	DFA Comp.	Functional Analysis / Redesign Opportunity			Error Proofing	Handling	Insertion	Secondary Operations
Design for Assembly Metrics	84.947	56.8%	Pract. Effy.→	72.7%	0.00	0.00	0.44	0.72
DFA Metrics for the Initial Design	334.31	19.9%	Pract. Effy.→	33.0%	2.00	0.23	1.00	2.54
Delta	249.36	36.9%	Pract. Effy.→	39.7%	2.00	0.23	0.56	1.82

Table 14: DFA Metrics comparison of the Weight System Sub-assembly

Comparing to the initial DFA analysis, we see the largest improvements in the Weight System Sub-assembly, with a complexity reduction from 334 to 85, with a large improvement in efficacy. To add, final assembly will require less processes and there will be no need for error proofing.

DFA Analysis Worksheet

Assembly Name: Arm-wrestling Training Gym Machine — Team: RPS — Date: 04/20/2020

If the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a number.

Part Number	Part Name	DFA Comp.: Number of Parts (N_p)	DFA Comp.: Number of Interfaces (N_I)	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
6000	ELBOW PAD SUBASSEMBLY																				
6001	ELBOW PAD BOARD	2	8	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6002	ELBOW PAD PIN	4	8	1	0	L	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0
6003	ELBOW PAD FOAM	2	2	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Totals	8	18	3	0	0	3	0	0	0	0	0	1	1	0	0	0	0	3	0	0
	Design for Assembly Metrics	12		37.5%	←Theor. Effy. Pract. Effy.→		37.5%	0.00		0.00			0.67				1.00				
	Targets																				

Table 15: Final design DFA Metrics of the Elbow Pad sub assembly

In the Elbow Pad Sub-assembly, all the parts will be standardized. Both the Elbow Pad Pins and the Elbow Pad Boards will be cut from standardized metal rods and sheets, and the Elbow Pad Foam will be bought from the market. The pins and boards will be welded together and the foam secured onto the board by an adhesive. Alignment of the pins will be considered but the accuracy will not be entirely crucial to the design, as the holes can have slight freedom in its diameter as the pad is meant to be taken out by the user, each time, when arm-wrestlers decide to switch hands for their matches. In either case, added features such as the welding markers can help locate this alignment.

DFA Analysis Worksheet

ARMWRESTLING TRAINING GYM MACHINE — Team: RPS — Date: 4/20/20

Part	DFA Comp.	Functional Analysis / Redesign Opportunity			Error Proofing	Handling	Insertion	Secondary Operations
DFA Metrics	194.425	45.6%	←Theor. Effy. Pract. Effy.→	58.3%	0.11	0.02	0.45	0.91
DFA Initial Design	400.756	23.7%	←Theor. Effy. Pract. Effy.→	35.8%	1.51	0.18	1.00	2.53
Delta	206.331	21.9%	←Theor. Effy. Pract. Effy.→	22.5%	1.40	0.15	0.55	1.62

Table 16: Final DFA Metrics

Comparing our final design DFA metrics to our initial design DFA metrics, the improvement in design is obvious. For each category, the DFA metrics of the final design is significantly better than the initial design. The complexity was reduced from 400 to 194. Although a complexity of 194 is still quite large, it is a drastic improvement for such a complex system with multiple sub-assemblies and subsystems. Finally, the efficacy of the final product design is also promising, as total parts have been minimized or standardized, an issue that was largely present in the initial design.

XIV. MATERIAL SELECTION

Due to high load that the components are under, careful consideration is required in choosing the material it was constructed from. The three components under some of the highest stresses in the system are as follows:

- Pulleys
- Wrestling Table
- Table Support Structures

Material analysis helps to decide the best material for a component based on its operational constraints. Figure 28 shows the various steps that are followed by the material analysis (Ashby, 2005).

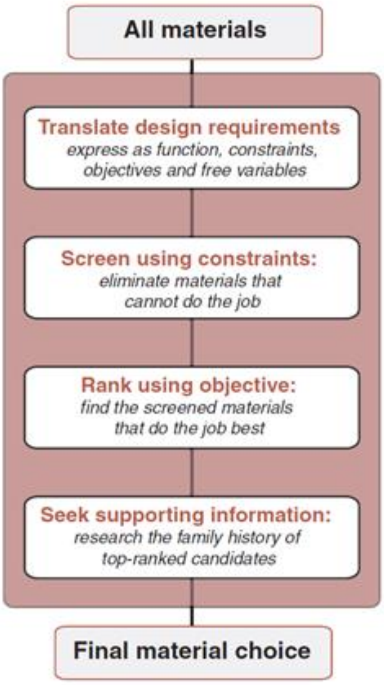


Figure 28 : Steps of Material Analysis

These steps were performed on the components under consideration. Analysis done for each component is shown below

XIV.1. Pulleys

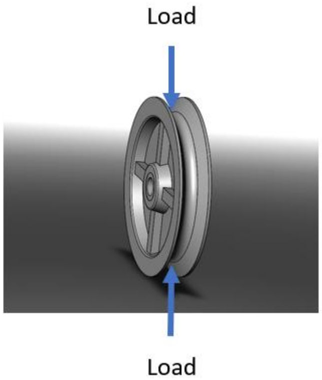


Figure 29: Loading condition of Pulley

1. Translate design requirements

Constraints

- Must have high strength
- Must be cost effective
- Low RPM
- Wear resistant
- Low friction

2. Screen using constraints

One of the methods of screening the material is screening by material performance index. Material indices for various loading conditions are given in the following table:

Design Objective: Minimum Weight for Different Shapes and Loadings	**To Maximize Strength**	**To Maximize Stiffness**
Bar in tension: load, stiffness, length are fixed; section area is variable	σ_f/ρ	E/ρ
Torsion bar: torque, stiffness, length are fixed; section area is variable	$\sigma_f^{2/3}/\rho$	$G^{1/2}/\rho$
Beam in bending: loaded with external forces or self-weight; stiffness, length fixed; section area free	$\sigma_f^{2/3}/\rho$	$E^{1/2}/\rho$
Plate in bending: loaded by external forces or self-weight; stiffness, length, width fixed; thickness free	$\sigma_f^{1/2}/\rho$	$E^{1/3}/\rho$
Cylindrical vessel with internal pressure: elastic distortion, pressure, and radius fixed; wall thickness free	σ_f/ρ	E/ρ
Other design objectives, as stated below		
Thermal insulation: minimize heat flux at steady state; thickness given	$1/k$	
Thermal insulation: minimum temperature after specified time; thickness given	$C_p\rho/k$	
Minimize thermal distortion	k/α	
Maximize thermal shock resistance	$\sigma_f/E\alpha$	

α_f = failure strength (yield or fracture stress as appropriate to problem); E = Young's modulus; G = shear modulus; ρ = density; C_p = specific heat capacity; α = thermal expansion coefficient; k = thermal conductivity.

Table 17: Material Performance Indices under various loading

From Figure 29, we can see that the component under consideration is under the loading condition of a material under compression. The major constraint of the component is that the component should not fail under higher loads. So, the material must have high strength.

To maximize strength, the material performance index,

$$M = \frac{\sigma_f}{\rho}$$

From the Ashby chart in Figure 30, we can infer that soft metals elastomers and foam material can be eliminated as they are at a lower side for minimum mass design.

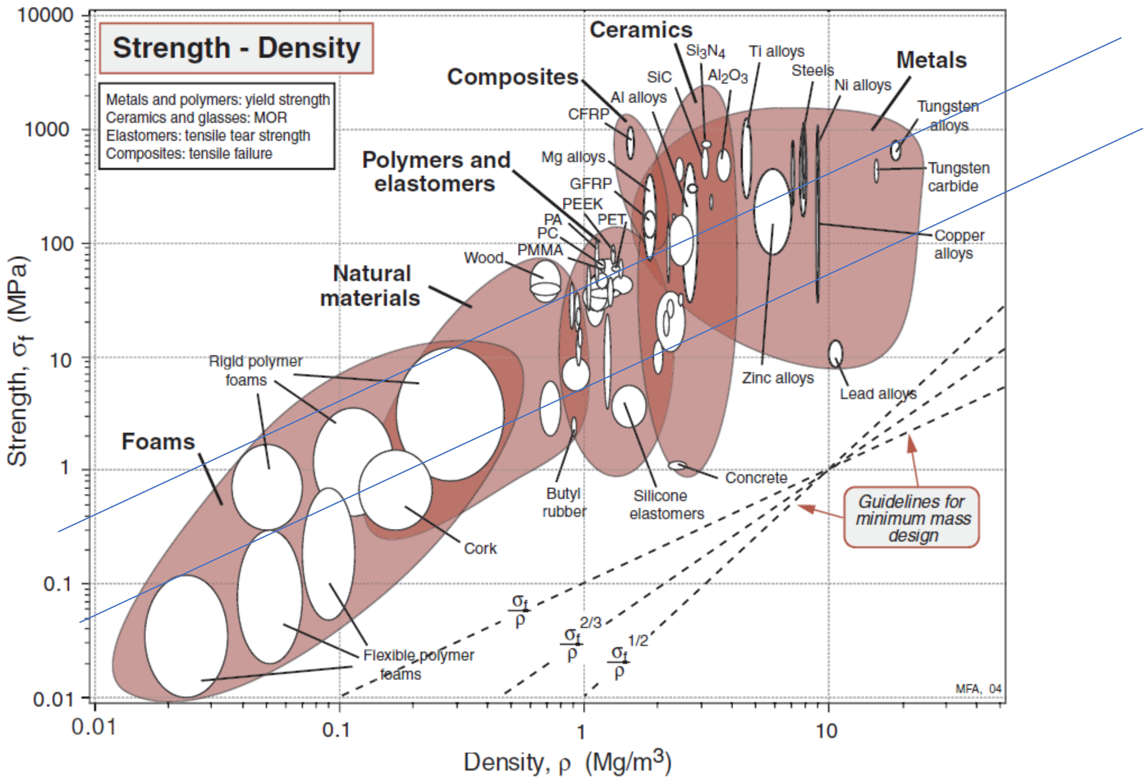


Figure 30: Ashby Chart: Strength vs. Density

From the Ashby's chart, the following material were selected:

- Wood
- Nylatron PA6
- Steel
- Cast Iron
- Silicon carbide
- CFRP
- Titanium alloys

3. Rank using objectives

1. CFRP
2. Silicon Carbide
3. Steel
4. Cast Iron
5. Titanium alloy
6. Wood
7. Nylatron PA6

4. Seek supporting info

From the shortlisted material, factors such as wear resistance and cost were considered in selecting the final material. From the Figure 31, we can see that CFRP, Silicon carbide and Titanium alloys are high cost material and so can be eliminated. Now, wood has high performance index, but there is a concern of wear over the years in wood and safety is a major concern in these high load members. So, wood can also be eliminated. With a factor of safety for the component to not fail, steel and cast iron can be easily considered over polymers.

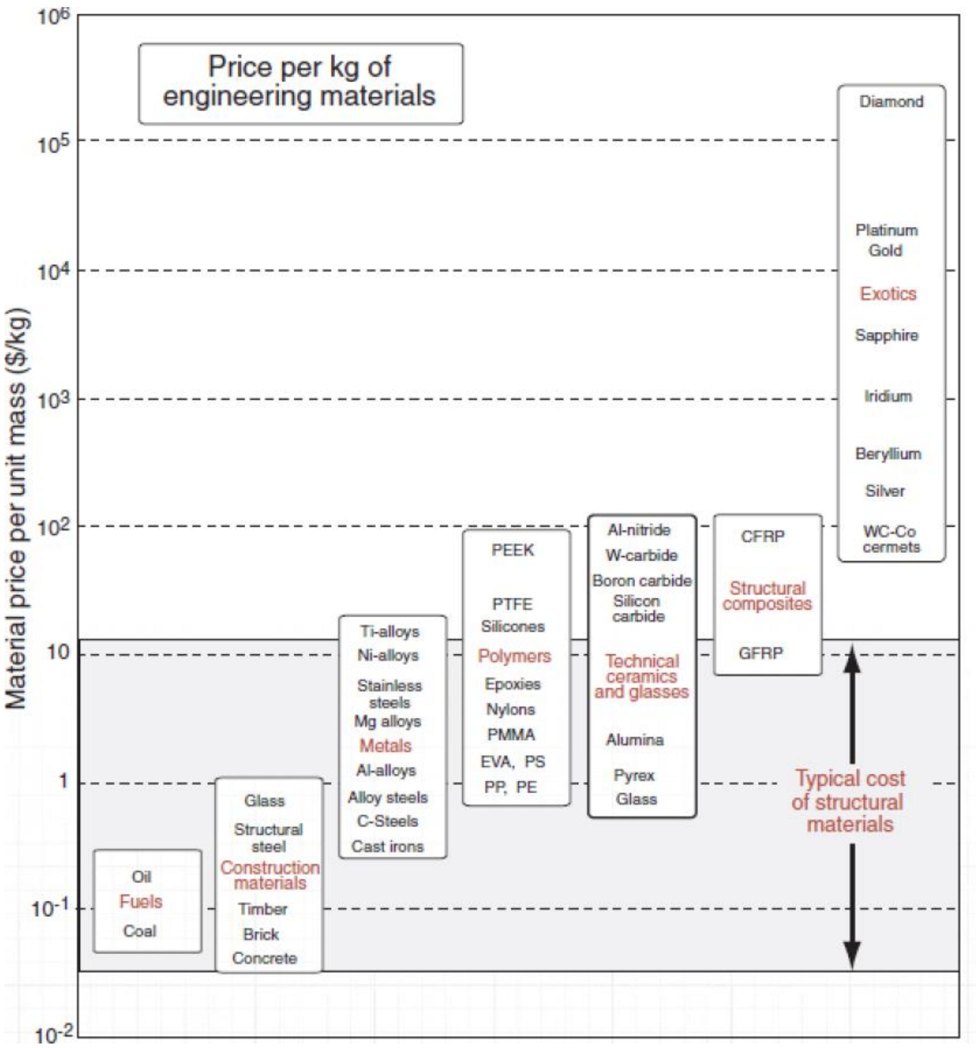


Figure 31: Price/kg of Engineering Materials

Furthermore, the part would need to be machined to get the required tolerance in its shaft and also for the wire rope travelling over it. Machinability of cast iron is more than that of steel. So, the material selection for the pulley can be cast iron.

5. Final material selected: cast carbon steel

XIV.2. Wrestling Table

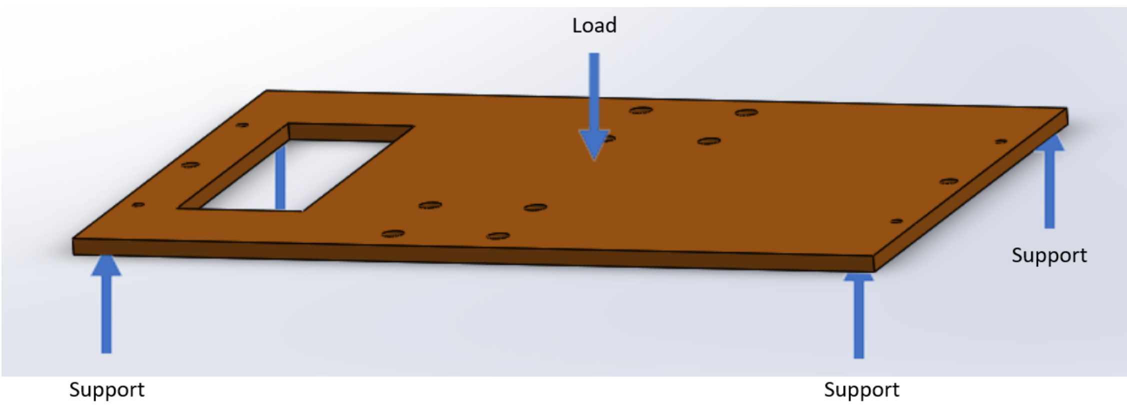


Figure 32: Loading condition of Table Top

1. Translate design requirements

Constraints

- Must have high stiffness
- Must be light weight
- Low cost
- Should not be brittle

2. Screen using constraints

Again, the screening of material is done with the help of material performance index. From the Figure 32, we can see that the material under consideration is plate in bending. Looking at Table 17, we can see that for the current loading condition of the part, to maximize stiffness, the material performance index is

$$M = \frac{\sqrt[3]{E}}{\rho}$$

Ashby chart of Density against Youngs modulus is shown in Figure 33.

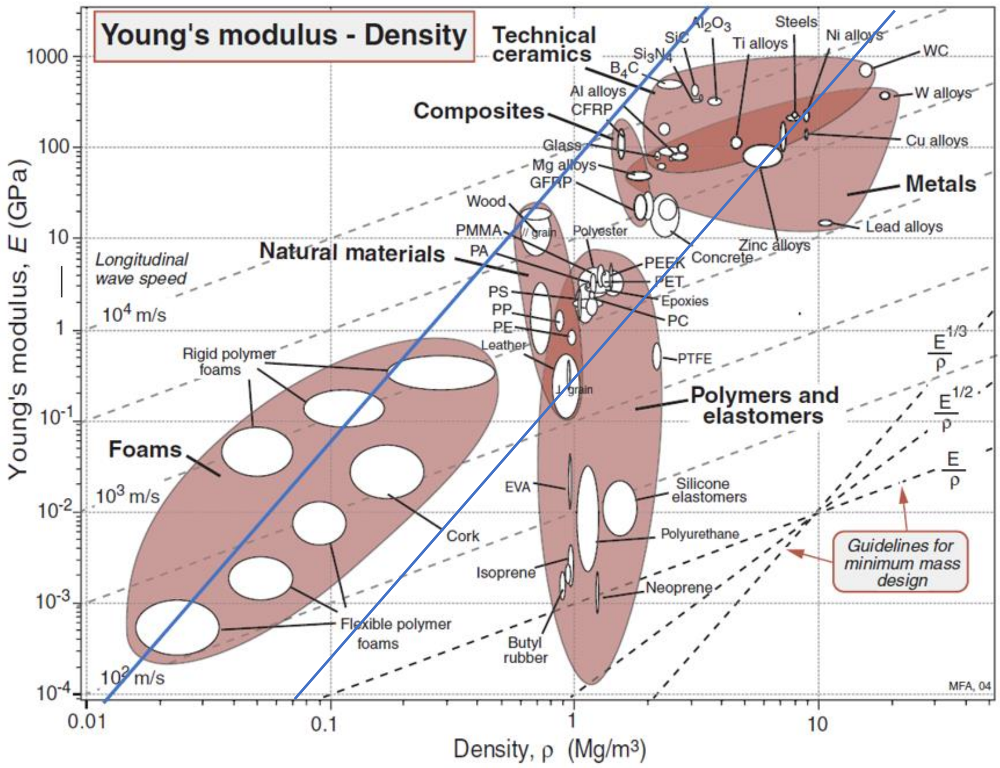


Figure 33: Ashby's Chart: Youngs modulus vs Density

From the pool of material found in Ashby's chart, Foams can be eliminated as they have very low young's modulus. A minimum strength is required for the material to bear the strength that is put on the table by the user. Polymers and elastomers can also be eliminated for the same reason. We can see that low-density metals, like lead, stays lower in material performance index. Most of the natural materials can be eliminated due to its brittleness. The following materials can be shortlisted from the chart.

- Steel
- Aluminium
- High Density Polyethylene (HDPE)
- Ultra-High Molecular Weight Polyethylene (UHMW)
- Wood

3. Rank using objectives

Based on material performance index and other factors like manufacturability, the shortlisted materials were ranked as given below.

1. Wood
2. HDPE
3. UHMW
4. Aluminium
5. Steel

4. Seek supporting info

The material which are shortlisted were identified for making the top surface of the table. But other supporting information also need to be collected to select the final material. From the Figure 31, we can see that the prices of polymers are higher compared to steel or wood. Aluminium alloys are costlier than wood. Wood can be a better option as it doesn't deliver any other problems in its manufacturing and assembling too. So, the material for producing top part of the table was selected to be wood.

5. Final Material Selected: Wood

XIV.3. Table Support Structures

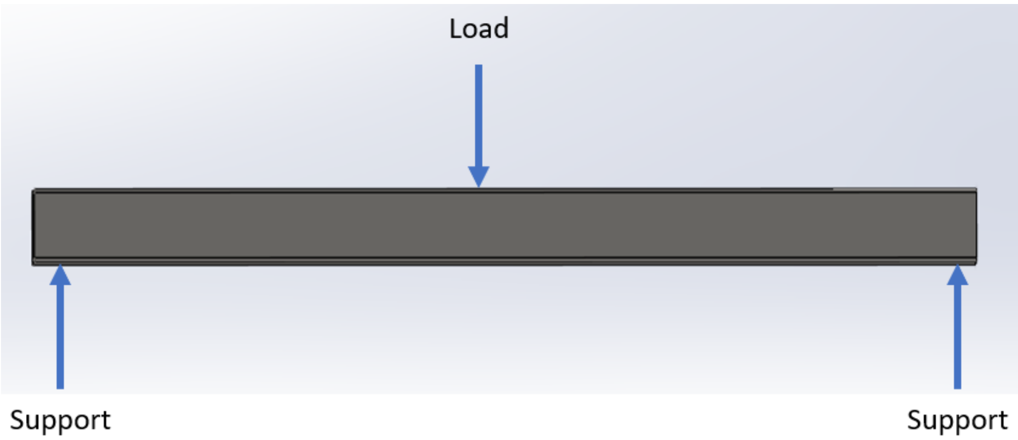


Figure 34: Loading condition of table support structures

From the Figure 34, we can see that the loading condition is beam under bending.

1. Translate design requirements

Constraints

- Must have high stiffness
- Must be light weight
- Must be cost effective
- Ease of manufacturing and assembling

2. Screen using constraints

As indicated earlier, we can see that the material is a beam under loading. So, by referring to Table 17 we can see that the material performance index for the condition for stiffness is

$$M = \frac{\sqrt{E}}{\rho}$$

From Figure 35, we can eliminate a pool of material such as low-density metals, foams, ceramics, polymers and elastomers which doesn't compare to commonly used material such as wood and steel in performance index. From the Ashby's chart, we can see that the following material can be used as a feasible material of construction of the table supports:

- Steel
- Aluminium alloys
- Titanium Alloys
- CFRP
- Wood

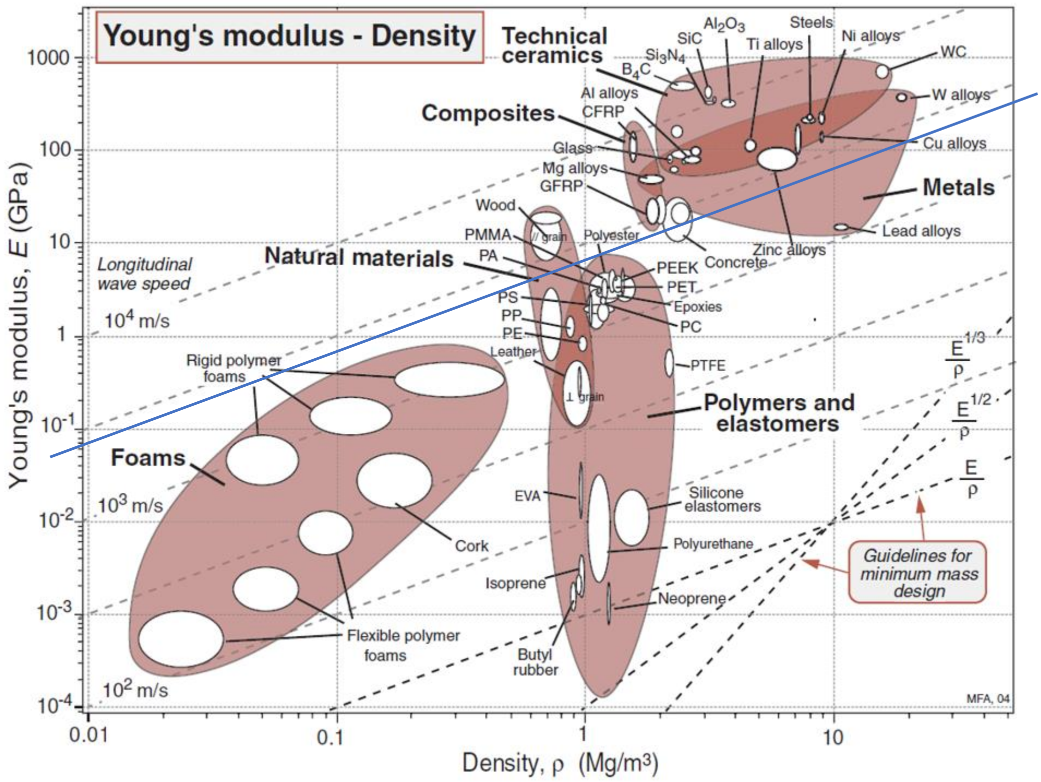


Figure 35: Ashby's Chart: Youngs modulus vs Density

3. Rank using objectives

Based on performance index, the material can be ranked as follows,

1. CFRP
2. Wood
3. Steel
4. Titanium alloy
5. Aluminium alloy

4. Seek supporting info

Referring the Figure 31, we can eliminate expensive material such as CFRP, Titanium alloys and Aluminium alloys. As the table has several support structures, we need to consider the ease of assembling as well to reduce cost and time of the product. Automation in assembling wood has limitations and are less common. But, with steel, assembling of components can be automated and will reduce cost of manufacturing. Hence, steel can be used for table support structures.

5. Final Material Selected: Steel

XIV.4. Pulley Arm

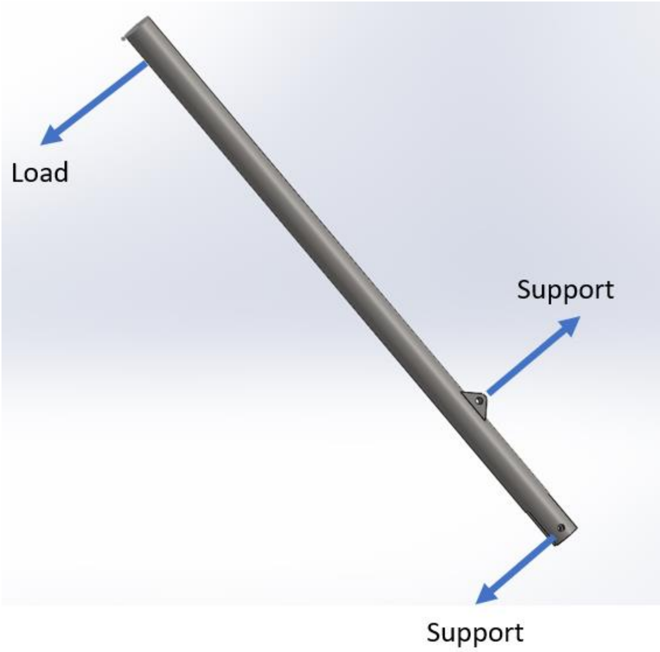


Figure 36: Loading condition of pulley arm

From the Figure 36, we can see that the member is a beam under bending.

1. **Translate Design Requirements**

Constraints

- High Stiffness
- Light weight
- Cost effective
- Ductile (For manufacturing)

2. **Screen using constraints**

For stiffness, the material performance index of a beam under loading is (Table 17),

$$M = \sqrt{E}/\rho$$

From Figure 33, we can see that the possible material the constraints would be,

- Low carbon steel
- Cast carbon steel
- CFRP
- Silicon carbide
- Aluminum

3. **Rank using objectives**
    1. CFRP
    2. Silicon Carbide
    3. Low carbon steel
    4. Cast carbon steel
    5. Aluminum
4. **Seek supporting info**

With the cost constraints, costly material like silicon carbide and CFRP can be avoided. The material has to be bent to make the component. So, all the brittle materials have to be avoided. High stiffness requirement eliminates aluminum. So, Low carbon steel can be used to fulfil the constraints.

5. Final material selected: Low Carbon Steel

After analysing the critical parts, the material for each component was decided. Material selection of all components are shown in Table 18.

Part No.	Part Description	Material	Part No.	Part Description	Material
6677	MAIN BODY TABLETOP	Teak	6366	WEIGHT GROUND BAR	Low Carbon Steel
6661	MAIN BODY HORIZONTAL BAR WIDTH	Sheet Metal	6466	WEIGHT ADJUSTMENT ROD	Low Carbon Steel
6662	MAIN BODY HORIZONTAL BAR LENGTH	Sheet Metal	6566	WEIGHT ADJUSTER PLATE	Cast Carbon Steel
6663	MAIN BODY VERTICAL BAR HEIGHT	Sheet Metal	6766	WEIGHT ADJUSTER	Cast Carbon Steel
6664	MAIN BODY GRIPPING PEG	304 Steel	1166	WEIGHT LOWER PULLEY	Cast Carbon Steel
6665	MAIN BODY DIAGONAL BAR	Sheet Metal	1466	WEIGHT UPPER PULLEY	Cast Carbon Steel
6667	MAIN BODY PREACHER CURL PAD (PCP)	Teak	6866	WEIGHT VERTICAL STATIONARY ROD	304 Steel
6668	MAIN BODY UPPER HORIZONTAL BAR WIDTH	Sheet Metal	6966	WEIGHT VERTICAL SLIDING ROD	304 Steel
6669	MAIN BODY UPPER HORIZONTAL BAR	Sheet Metal	7066	WEIGHT HORIZONTAL LOADING ROD	304 Steel
6670	MAIN BODY PCP ADJUSTER CONNECTOR	Low Carbon Steel	7166	WEIGHT PULLEY ARM	304 Steel
6671	MAIN BODY PCP ADJUSTER	304 Steel	7266	WEIGHT PULLEY HOUSING	Sheet Metal
6616	SMITH MACHINE VERITAL BAR	Sheet Metal	7366	WEIGHT GAS SPRING CONNECTOR	Low Carbon Steel
6626	SMITH MACHINE POSITION ROD	Low Carbon Steel	7466	WEIGHT UPPER BAR	Low Carbon Steel
6636	SMITH MACHINE ROD	304 Steel	7566	WEIGHT PIN CONNECTOR	Low Carbon Steel
6656	SMITH MACHINE SLIDER	304 Steel	7666	WEIGHT ROPE STOPPER	ABS
6676	SMITH MACHINE SLIDER BLOCK	Low Carbon Steel	7766	WEIGHT VERTICAL STATIONARY ROD TUBE	304 Steel
6686	SMITH MACHINE HANDLE	304 Steel	6001	ELBOW PAD BOARD	Low Carbon Steel
6696	SMITH MACHINE POSITION HOOK	Low Carbon Steel	6002	ELBOW PAD PIN	Low Carbon Steel
6166	WEIGHT VERTICAL BAR	Sheet Metal	6003	ELBOW PAD FOAM	Polyurethane Foam Rigid
6266	WEIGHT HORIZONTAL BAR	Sheet Metal			

Table 18: Material of construction of all parts

XV. PROCESS SELECTION

As the material of construction of all components were analysed, it is now required to decide the manufacturing process through which the part will be made.

XV.1. Table frames

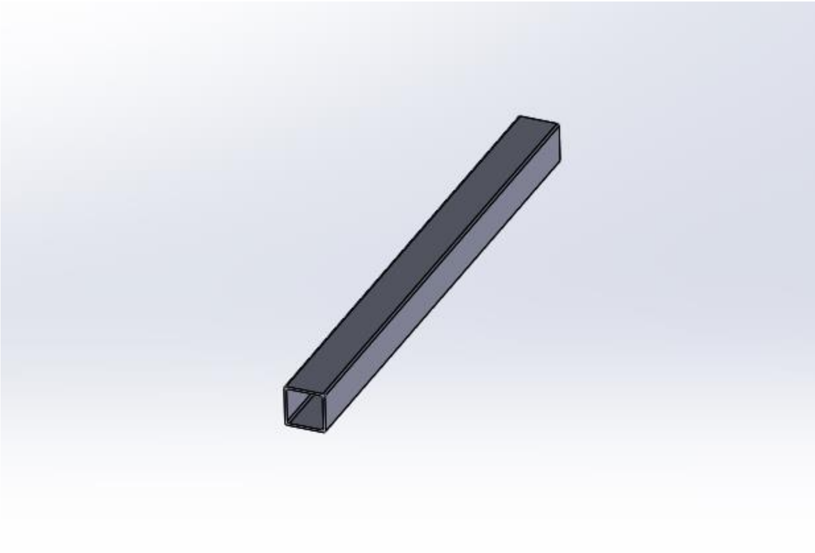


Figure 37: Table frame to be manufactured

The spatial complexity of the part was found from Table 19.

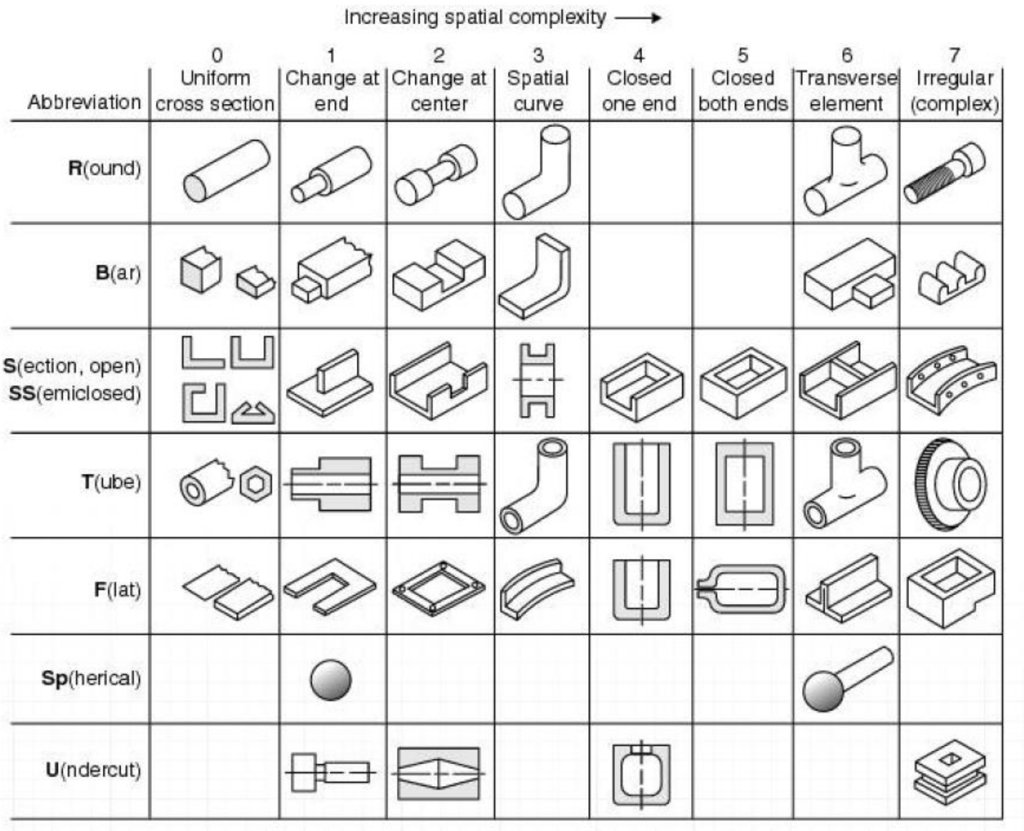


Table 19: Spatial complexity table

From the table, it was found that spatial complexity of the part was T0. Now, the possible manufacturing processes for T0 was found from Table 20.

Ability of Manufacturing Processes to Produce Shapes

Process	Capability for Producing Shapes
Casting processes	
Sand casting	Can make all shapes
Plaster casting	Can make all shapes
Investment casting	Can make all shapes
Permanent mold	Can make all shapes except T3, T5; F5; U2, U4, U7
Die casting	Same as permanent mold casting
Deformation processes	
Open-die forging	Best for R0 to R3; all B shapes; T1; F0; Sp6
Hot impression die forging	Best for all R, B, and S shapes; T1, T2; Sp
Hot extrusion	All 0 shapes
Cold forging/cold extrusion	Same as hot die forging or extrusion
Shape drawing	All 0 shapes
Shape rolling	All 0 shapes
Sheet-metal working processes	
Blanking	F0 to F2; T7
Bending	R3; B3; S0, S3, S7; T3; F3, F6,
Stretching	F4; S7
Deep drawing	T4; F4, F7
Spinning	T1, T2, T4, T6; F4, F5
Polymer processes	
Extrusion	All 0 shapes
Injection molding	Can make all shapes with proper coring
Compression molding	All shapes except T3, T5, T6, F5, U4
Sheet thermoforming	T4, F4, F7, S5
Powder metallurgy processes	
Cold press and sinter	All shapes except S3, T2, T3, T5, T6, F3, F5, all U shapes
Hot isostatic pressing	All shapes except T5 and F5
Powder injection molding	All shapes except T5, F5, U1, U4
PM forging	Same shape restrictions as cold press and sinter
Machining processes	
Lathe turning	R0, R1, R2, R7; T0, T1, T2; Sp1, Sp6; U1, U2
Drilling	T0, T6
Milling	All B, S, SS shapes; F0 to F4; F6, F7, U7
Grinding	Same as turning and milling
Honing, lapping	R0 to R2; B0 to B2; B7; T0 to T2, T4 to T7; F0 to F2; Sp

Table 20: Ability of manufacturing processes to produce shapes

From the table it was found out that the possible processes included,

- Sand casting
- Plaster casting
- Investment casting

- Die casting
- Hot extrusion
- Cold forging/Cold extrusion
- Shape drawing
- Permanent mold
- Shape rolling
- Lathe turning
- Honing, lapping

Compatibility of carbon steel was checked against the possible manufacturing processes from Figure 38.

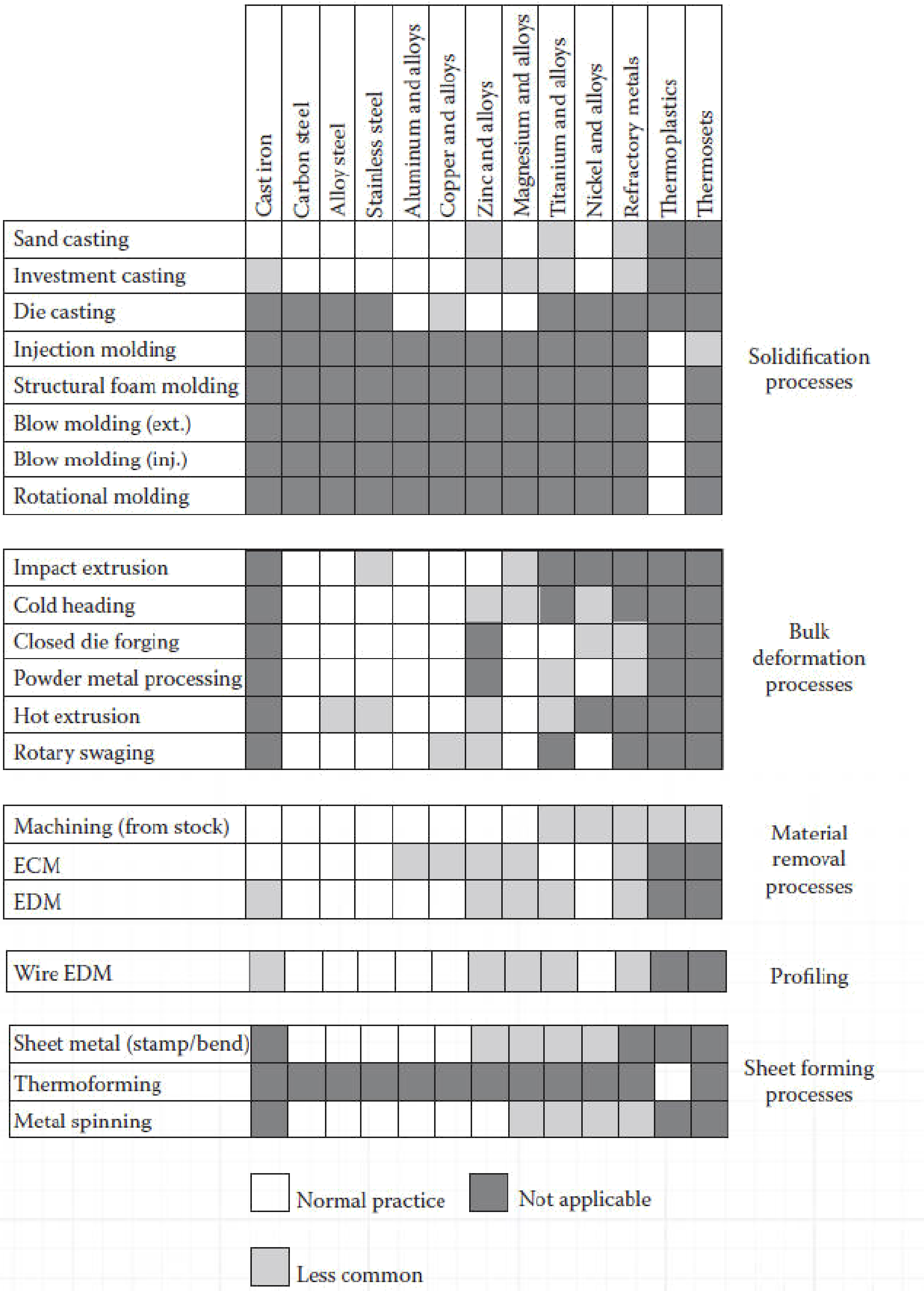


Figure 38: Compatibility between processes and materials

With reference to the above table, an initial screening of manufacturing processes was made. Table 21 summarised the screening process.

Process	Carbon Steel Yes or No	Reject?	Reason for Elimination
Sand casting	Y	R	Section thickness of 3mm cannot be obtained
Plaster casting	Y	R	Not economical for higher batch sizes
Investment casting	Y	R	Not economical for higher batch sizes
Permanent mold	Y		
Die casting	N		
Hot extrusion	Y		
Cold forging/Cold extrusion	Y		
Shape drawing	Y		
Shape rolling	Y		
Lathe turning	Y	R	Not suitable for square hollow bars
Honing, lapping	Y	R	Not suitable for square hollow bars

Table 21: Initial screening of candidate processes

From the initial screening, the following manufacturing processes were selected,

- Permanent mold
- Hot extrusion
- Cold forging
- Shape drawing
- Shape rolling

Second screening was done on the listed processes based on cycle time, process flexibility, material utilisation, quality, and equipment tooling cost. Screening process shown in Table 22.

Process	Cycle Time	Process Flexibility	Material Utilisation	Quality	Equipment Tooling	Total
Permanent mold	4	2	2	3	2	**13**
Hot extrusion	5	3	4	3	2	**17**
Cold forging	3	4	3	2	2	**14**
Shape drawing	3	3	4	3	3	**16**
Shape rolling	5	3	4	3	2	**17**

Table 22: Second screening of possible manufacturing processes (Table frame)

From the second screening, it was inferred that shape rolling and Hot extrusion can be possible processes. But, the overhead cost for hot extrusion is much higher than shape rolling. So, the process selected is **shape rolling.**

Process

The part will be made of sheet metal of thickness 0.12 inches and then shape rolled and welded by ERW. The manufacturing of the part is illustrated in Figure 39.

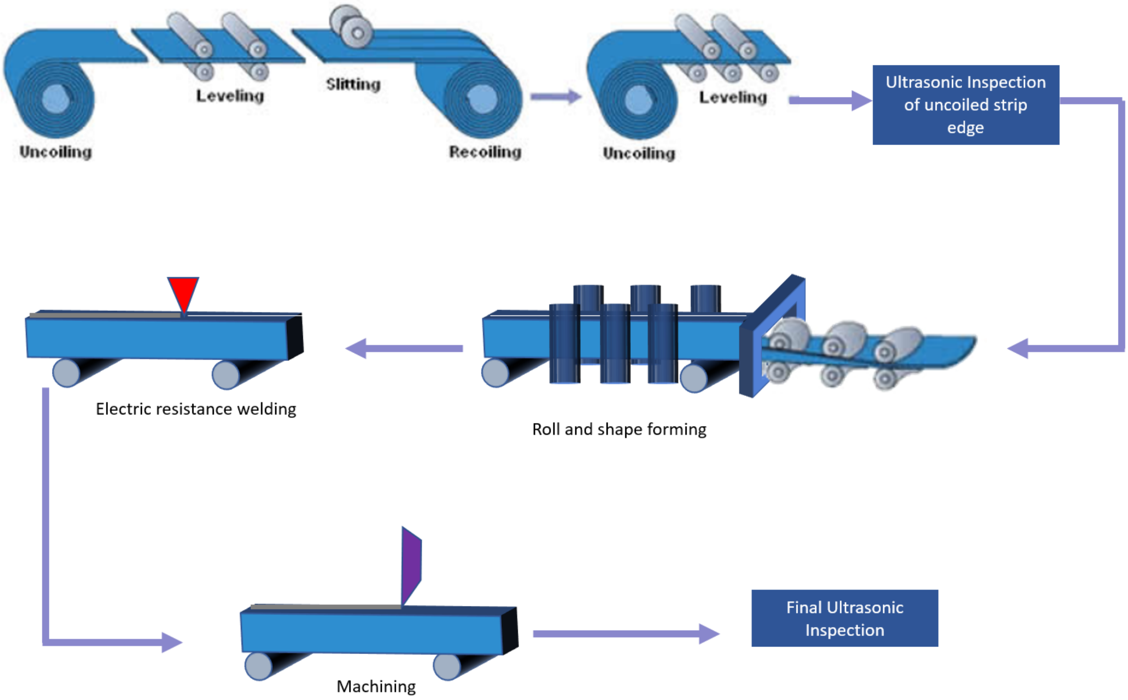


Figure 39: Square frames manufacturing process

Tolerance for parts are included in the part drawing in appendix.

XV.2. Pulleys

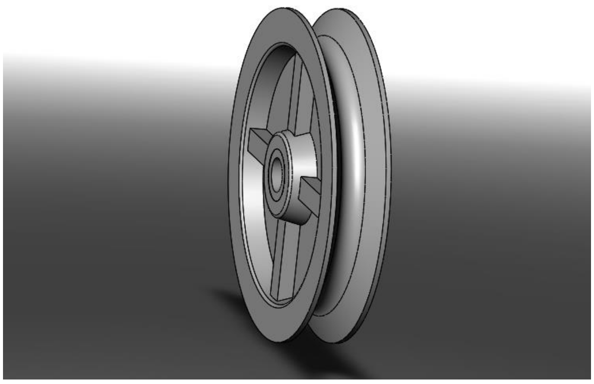


Figure 40: Pulley to be manufactured

Apart from the central grove, there are several undercuts provided in the design to provide structural support. The spatial complexity of the part from Table 19 was found to be U7. From Table 20: Ability of manufacturing processes to produce shapes, the possible manufacturing processes were found to be:

- Sand casting
- Plaster casting
- Investment casting
- Cold press and Sinter
- Hot isostatic pressing
- Powder injection molding
- PM Forging

The part is made of Cast iron. Initial screening was done by referring Table 20: Ability of manufacturing processes to produce shapes. Screening process is summarized in the following table:

Process	**Cast Iron Yes or No**	**Reject?**	**Reason for Elimination**
Sand casting	Y		
Plaster casting	Y		
Investment casting	Y		
Cold press and sinter	N		
Hot isostatic pressing	N		
Powder injection molding	Y		
PM Forging	N		

Table 23: Initial screening of candidate processes (Pulleys)

Second screening was done on the listed processes and summarised in Table 24.

Process	**Cycle Time**	**Process Flexibility**	**Material Utilisation**	**Quality**	**Equipment Tooling cost**	**Total**
Sand casting	2	5	2	2	1	**12**
Plaster casting	2	5	2	3	1	**13**
Investment casting	2	4	4	4	3	**17**
Powder injection molding	4	1	4	3	1	**13**

Table 24: Second screening of possible manufacturing processes (Pulley)

From the second screening, it was inferred that the pulleys can be made from **investment casting.**

Process

The manufacturing process is illustrated in Figure 41.

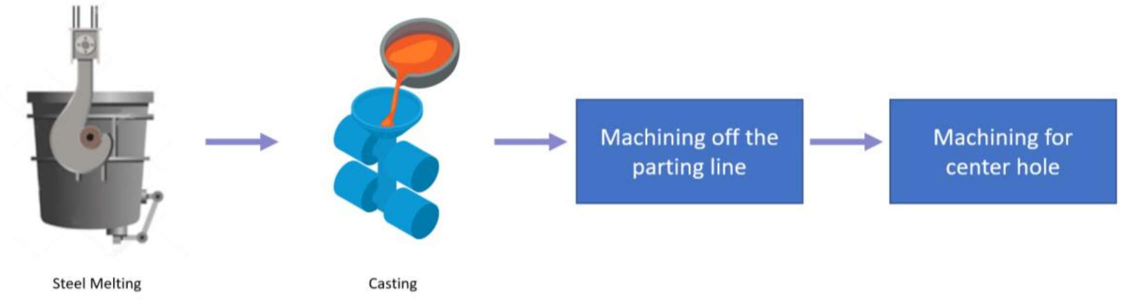


Figure 41: Pulley manufacturing process

XV.3. Pulley Housing

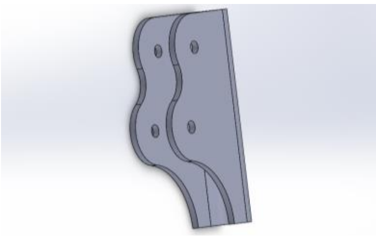


Figure 42: Round bar to be manufactured

The spatial complexity was determined from Table 19, and was found out to be S0. Possible manufacturing process for S0 shapes are:

- Sand casting
- Plaster casting
- Investment casting
- Permanent mold casting
- Die casting
- Hot extrusion
- Cold forging
- Shape drawing
- Shape rolling
- Bending
- Cold press and sinter
- Hot isostatic pressing
- Powder injection molding
- PM forging
- Milling

Round bars are made of Low carbon steel. So initial screening was done based on material compatibility and summarised in Table 25.

Process	**Low Carbon Steel (Yes/No)**	**Reject?**	**Reason for Elimination**
Sand casting	Y	R	Not economical for higher batch sizes
Plaster casting	Y	R	Not economical for higher batch sizes
Investment casting	Y	R	Not economical for higher batch sizes
Permanent mold casting	Y		
Die casting	N		
Hot extrusion	Y	R	Suitable for parts with uniform cross section
Cold forging	Y	R	Not suitable for low section thickness
Shape drawing	Y	R	Suitable for parts with uniform cross section
Shape rolling	Y	R	Suitable for parts with uniform cross section
Bending	Y		
Cold press and sinter	Y	R	Not suitable for low section thickness
Hot isostatic pressing	Y	R	High equipment cost
Powder injection molding	Y		
PM forging	Y		
Milling	Y		

Table 25: Initial screening of candidate processes (Pulley Housing)

From the initial screening, the following manufacturing processes were selected,

- Permanent mold casting
- Bending
- Powder injection molding
- PM forging
- Milling

Second screening was done on the listed processes based on cycle time, process flexibility, material utilisation, quality, and equipment tooling cost.

Process	**Cycle time**	**Process flexibility**	**Material utilisation**	**Quality**	**Equipment tooling cost**	**Total**
Permanent mold casting	4	2	2	3	2	13
Bending	5	2	4	3	5	19
Powder injection molding	4	2	4	4	1	15
PM forging	3	3	4	4	2	16
Milling	2	5	1	5	4	17

Table 26: Second screening of possible manufacturing processes (Pulley housing)

After second screening, it was decided to adopt **bending** to manufacture the part.

Process

The part will be made of sheet metal, cut with waterjet cutting, and then bent to the specific shape. Figure 43 illustrates the process.

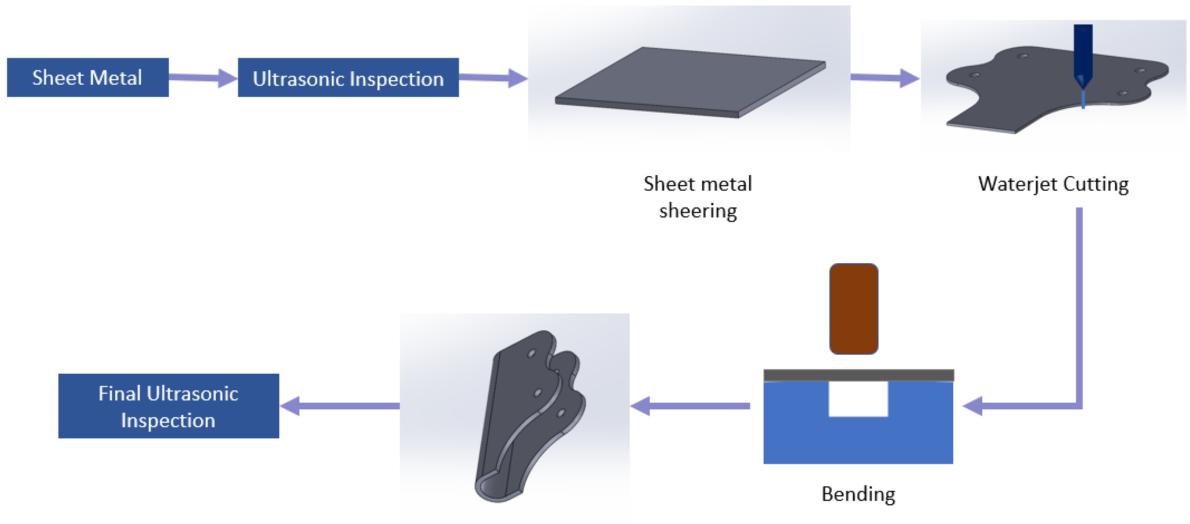


Figure 43: Pulley Housing manufacturing process

After process analysis for critical shapes, manufacturing methods for all non-OTS parts were decided. The processes for all parts are summarised in Table 27.

Part	Description	Process	Part	Description	Process
6677	MAIN BODY TABLETOP	Cutting and Finishing	6366	WEIGHT GROUND BAR	ERW
6661	MAIN BODY HORIZONTAL BAR WIDTH	ERW	6466	WEIGHT ADJUSTMENT ROD	Cutting
6662	MAIN BODY HORIZONTAL BAR LENGTH	ERW	6566	WEIGHT ADJUSTER PLATE	Waterjet cutting
6663	MAIN BODY VERTICAL BAR HEIGHT	ERW	6766	WEIGHT ADJUSTER	Casting & Machining
6664	MAIN BODY GRIPPING PEG	Cutting & Machining	1166	WEIGHT LOWER PULLEY	Casting & Machining
6665	MAIN BODY DIAGONAL BAR	ERW	1466	WEIGHT UPPER PULLEY	Casting & Machining
6667	MAIN BODY PREACHER CURL PAD (PCP)	Cutting and Finishing	6866	WEIGHT VERTICAL STATIONARY ROD	Cutting
6668	MAIN BODY UPPER HORIZONTAL BAR WIDTH	ERW	6966	WEIGHT VERTICAL SLIDING ROD	Hot extrusion & Machining
6669	MAIN BODY UPPER HORIZONTAL BAR	ERW	7066	WEIGHT HORIZONTAL LOADING ROD	Machining
6670	MAIN BODY PCP ADJUSTER CONNECTOR	Cutting & Bending	7166	WEIGHT PULLEY ARM	Cutting & Machining
6671	MAIN BODY PCP ADJUSTER	Cutting & Bending	7266	WEIGHT PULLEY HOUSING	Waterjet cutting & Bending
6616	SMITH MACHINE VERITAL BAR	ERW	7366	WEIGHT GAS SPRING CONNECTOR	Casting & Machining
6626	SMITH MACHINE POSITION ROD	Cutting	7466	WEIGHT UPPER BAR	ERW
6636	SMITH MACHINE ROD	Cutting	7566	WEIGHT PIN CONNECTOR	Casting & Machining
6656	SMITH MACHINE SLIDER	Hot extrusion & Machining	7666	WEIGHT ROPE STOPPER	Injection Molding
6676	SMITH MACHINE SLIDER BLOCK	Waterjet cutting	7766	WEIGHT VERTICAL STATIONARY ROD TUBE	Hot extrusion & Machining
6686	SMITH MACHINE HANDLE	Cutting	6001	ELBOW PAD BOARD	Waterjet Cutting
6696	SMITH MACHINE POSITION HOOK	Waterjet cutting	6002	ELBOW PAD PIN	Cutting
6166	WEIGHT VERTICAL BAR	ERW	6003	ELBOW PAD FOAM	Foam Casting
6266	WEIGHT HORIZONTAL BAR	ERW			

Table 27: Manufacturing processes for components

XVI. FINITE ELEMENT ANALYSIS

The design involves lifting heavy loads. So, due consideration must be given while designing load bearing members. The wire rope sling used is a ½” nylon core wire rope which has a safe working load (SWL) capacity of 2 tons. Now, the critical members also need to be analysed for its SWL limits. One of the most critical parts was the pulley arm (Figure 44).

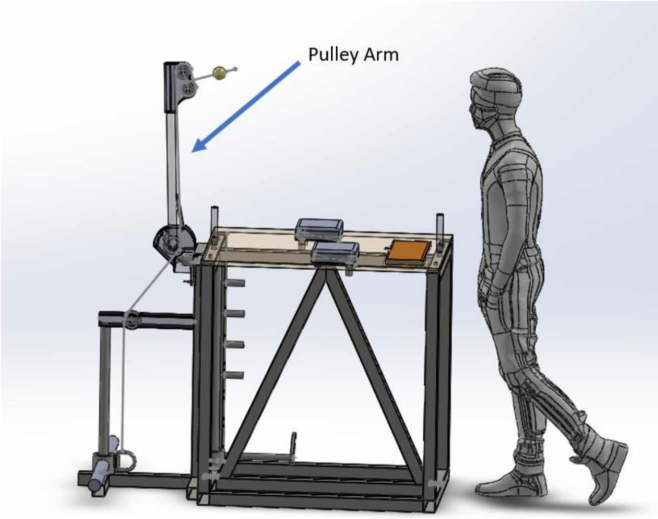


Figure 44: Part to be analysed for structural integrity (Pulley Arm)

Finite element analysis was done to determine the maximum equivalent (Von mises) stress that the part will undergo upon application of an assumed perpendicular force that the member will be provided. The analysis is done with a force of 300 lbf acting on the member, which is a safe value to assume as the equipment will not be undergoing a force of more than 180 lbf in its operation. The analysis was done on several iteration of the design and the criteria for acceptance was that the maximum stress must be below 75% of the yield stress of Low carbon steel. The FEA output of the equivalent stresses is shown in Figure 45.

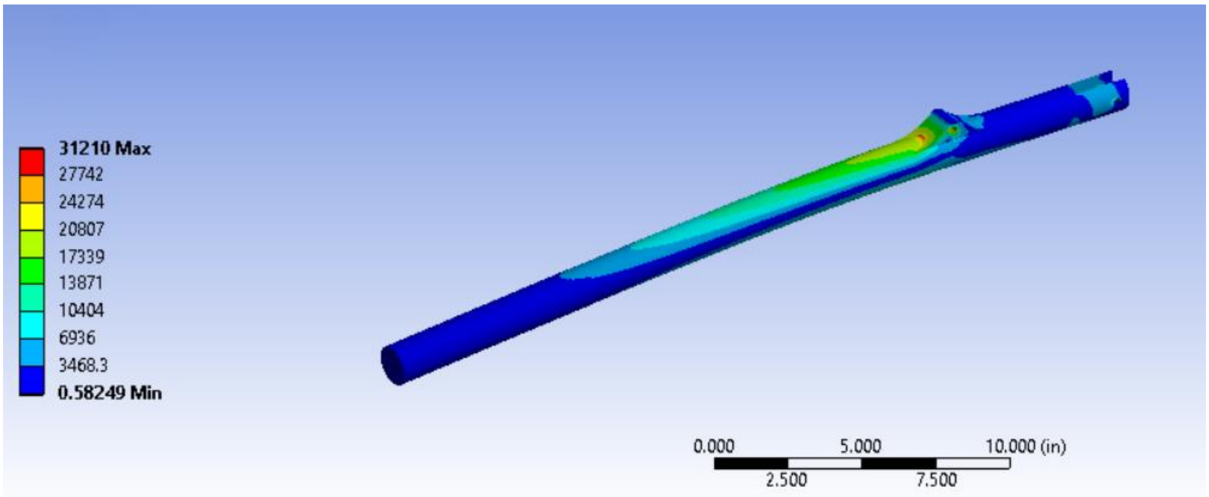


Figure 45: FEA output for von mises stress

From the figure, the maximum equivalent stress acting on the member is 31210 psi whereas the yield stress of Low carbon steel is 53700 psi. It implies that the maximum stress is 58% of the yield stress of the material. So, the design was accepted.

XVII. COST ANALYSIS

Cost analysis was done to make sure that the manufacturing cost of all components constricted to the initial economic goals that were set for the product for it to be commercially viable. Several cost estimation methods were adopted in this report to compare and errorproof the results.

XVII.1. Order of Magnitude Estimate (OME)

OME cost estimation was used to roughly calculate the manufacturing and selling cost of each component. The OME estimate works on the thumb rule of 1:3:9. That is, if the material cost of a component is ‘x’, then

Manufacturing cost = 3*x

Price = 9*x

The material weight of non OTS components were determined from the CAD files of each component and was put for estimate. Table 28 shows the order of magnitude estimate that was done on the components.

Part No.	Part Description	Material	Qty	Mass (lb)	Material Rate ($/lb)	Material Cost ($)	Mfg Cost	Price
6677	TABLETOP	Teak	1	15.2	0.53	8.056	24.168	72.50
6661	HORIZONTAL BAR WIDTH	Sheet Metal	2	13.4	0.32	4.288	12.864	38.59
6662	HORIZONTAL BAR LENGTH	Sheet Metal	3	26.28	0.32	8.4096	25.228 8	75.69
6663	VERTICAL BAR HEIGHT	Sheet Metal	3	28.59	0.32	9.1488	27.446 4	82.34
6664	GRIPPING PEG	304 Steel	2	2.38	1.07	2.5466	7.6398	22.92
6665	DIAGONAL BAR	Sheet Metal	2	19.32	0.32	6.1824	18.547 2	55.64
6667	PREACHER CURL PAD (PCP)	Teak	1	1.45	0.53	0.7685	2.3055	6.92
6668	UPPER HORIZONTAL BAR WIDTH	Sheet Metal	2	11.04	0.32	3.5328	10.598 4	31.80
6669	UPPER HORIZONTAL BAR	Sheet Metal	1	13.16	0.32	4.2112	12.633 6	37.90
6670	PCP ADJUSTER CONNECTOR	LCS	1	0.21	0.24	0.0504	0.1512	0.45
6671	PCP ADJUSTER	304 Steel	1	0.92	1.07	0.9844	2.9532	8.86
6616	SMITH MACHINE VERITAL ROD	Sheet Metal	1	9.53	0.32	3.0496	9.1488	27.45
6626	SMITH MACHINE POSITION ROD	Low Carbon Steel	4	2.68	0.24	0.6432	1.9296	5.79
6636	SMITH MACHINE ROD	304 Steel	1	17.88	1.07	19.1316	57.394 8	172.18
6656	SMITH MACHINE SLIDER	304 Steel	1	3.92	1.07	4.1944	12.583 2	37.75
6676	SMITH MACHINE SLIDER BLOCK	LCS	1	0.62	0.24	0.1488	0.4464	1.34

Table 28: OME of components (contd. in next page)

Part No.	Part Description	Material	Qty	Mass (lb)	Material Rate ($/lb)	Material Cost ($)	Mfg Cost	Price
6686	HANDLE	304 Steel	1	2.95	1.07	3.1565	9.469	28.41
6696	POSITION HOOK	LCS	1	0.93	0.24	0.2232	0.669	2.01
6166	WEIGHT VERTICAL BAR	Sheet Metal	1	9.53	0.32	3.0496	9.148	27.45
6266	WEIGHT HORIZONTAL BAR	Sheet Metal	5	10.3	0.32	3.296	9.888	29.66
6366	GROUND BAR	LCS	1	4.64	0.24	1.1136	3.340	10.02
6466	WEIGHT ADJUSTMENT ROD	LCS	1	0.92	0.24	0.2208	0.662	1.99
6566	WEIGHT ADJUSTER PLATE	LCS	2	1.18	0.3	0.354	1.062	3.19
6766	WEIGHT ADJUSTER	LCS	1	17.57	0.3	5.271	15.813	47.44
1166	LOWER PULLEY	LCS	2	1.014	0.3	0.3042	0.912	2.74
1466	UPPER PULLEY	LCS	2	1.08	0.3	0.324	0.972	2.92
6866	VERTICAL STATIONARY ROD	304 Steel	1	12.26	1.07	13.1182	39.354	118.06
6966	VERTICAL SLIDING ROD	304 Steel	1	3.92	1.07	4.1944	12.583	37.75
7066	HORIZONTAL LOADING ROD	304 Steel	2	27.84	1.07	29.7888	89.366	268.10
7166	PULLEY ARM	304 Steel	1	12.36	1.07	13.2252	39.675	119.03
7266	PULLEY HOUSING	Sheet Metal	1	4.51	0.32	1.4432	4.329	12.99
7366	GAS SPRING CONNECTOR	LCS	2	0.02	0.24	0.0048	0.014	0.04
7466	UPPER BAR	LCS	1	3.73	0.24	0.8952	2.685	8.06
7566	PIN CONNECTOR	LCS	1	0.13	0.24	0.0312	0.093	0.28
7666	ROPE STOPPER	ABS	1	0.13	1.5	0.195	0.585	1.76
7766	VERTICAL STATIONARY ROD TUBE	304 Steel	1	11.49	1.07	12.2943	36.882	110.65
6001	ELBOW PAD BOARD	LCS	1	1.75	0.24	0.42	1.26	3.78
6002	ELBOW PAD PIN	LCS	2	0.9	0.24	0.216	0.648	1.94
6003	ELBOW PAD FOAM	Polyurethane Foam Rigid	1	0.56	1.58	0.8848	2.654	7.96
					Total	**169.37**	**508.11**	**1524.3**

Table 29: OME of components (cont.)

From the analysis, the cost of manufacturing all the non-OTS components was calculated to be $**508.11.** The selling price of all non-OTS components were calculated to be **$1524.33.**

The cost of OTS components were also calculated with price quote from several bulk manufacturers and is summarised in Table 29:

Part No.	Part Description	Specs	Qty	Price
1060	SCREW FOR HANDLE	SS Socket head	2	0.06
1061	SCREW FOR TABLETOP	Black Oxide Alloy Steel	4	0.08
1062	HINGE FOR PCP	Mortise MNT	2	1.05
1063	SCREW FOR PCP	Alloy Steel Flat Head	8	0.22
1064	SCREW FOR PCP ADJUSTER	Flat Head Phillips Screw	4	0.1
1006	LINEAR BEARING	Thomson AB1420	1	2.1
1016	BALL BEARING	6048	1	2.08
1066	SLEEVE BEARING	High Load Dry Running	1	10
1266	SCREW FOR ADJUSTER	Zinc Pated Steel Ribbed	1	0.277
1366	SPRING PIN	SS Dowell Pin	1	0.14
1566	HITCH PIN FOR PULLEY ARM	Zinc Plated Steel Ribbed	1	0.277
1766	BOLT FOR PULLEY ON ADJUSTER	SS Button Head	1	0.2
1866	LOCKNUT	High Strength Steel	2	0.04
1966	GAS SPRING	Various	2	2.77
2066	PIN FOR GAS SPRING	SS Dowell Pin	1	0.14
2166	LINEAR BEARING	Thomson A81421	1	2.1
2266	RING FOR ROPE	SS	1	.1
2366	PIN FOR UPPER PULLEY	SS Dowell Pin	2	0.28
2466	SCREW FOR LOWER PULLEY	Zinc Plated Steel Ribbed	1	0.277
2566	PIN FOR GAS SPRING	SS Dowell Pin	1	0.14
2666	WIRE ROPE	Nylon Core SS wire rope	1	1.8
			Total	24.231

Table 29: Price of OTS components

So, the total selling price of the product (OTS and Non OTS combined) based on OME was estimated to be **$1548.561**

XVII.2. Cost to Manufacture Method

Unlike the OME estimate, the cost to manufacture method takes into consideration the minor details in manufacturing facility and so is much comprehensive. For the cost analysis we did on our product, we had the following assumptions:

- 5000 number of products to be manufactured
- 50 weeks per year operation
- 18 hours of machine operation per day in 3 shifts
- In case of components which are same in design but appears multiple times in a unit of the product, parts to be manufactured will be multiplied to the number of repeats it has in the design

Cost to manufacture method considers the following variables in its estimates:

1. **Material Cost**

The material cost of a component can be calculated using the following formula,

$$C_M = \frac{mc_m}{1-f}$$

Where,

$$C_M = Material\ cost$$
$$m = Mass\ of\ component$$
$$c_m = Unit\ cost\ of\ the\ component$$
$$f = Fraction\ of\ element\ that\ is\ scrap$$

2. Labor cost

Labor cost determines the price added on to the unit cost of the component due to the labor wages in production. Labor cost can be calculated by the formula,

$$C_L = \frac{c_w}{n'}$$

Where,

$$C_L = Unit\ cost\ of\ labor$$
$$c_w = Labor\ cost\left(\frac{\$}{h}\right)$$
$$n' = Production\ rate$$

3. Tooling cost

Tooling cost determines the fraction of price that contributes to the overall price of the product due to the expense in tools used during its manufacture. Tooling cost can be determined by,

$$C_T = \frac{c_t k}{n}$$

Where,

$$C_T = Unit\ cost\ of\ tooling$$
$$c_t = Tooling\ cost\left(\frac{\$}{set}\right)$$
$$k = sets\ of\ tooling\ required$$
$$n = total\ production\ run\ (units)$$

4. Equipment cost

The unit cost of equipment used in production of the component can be found out by the formula,

$$C_E = \left(\frac{1}{n'}\right)\left(\frac{c_e\ n_e}{L t_{wo}}\right) q$$

Where,

$$C_E = unit\ cost\ of\ capital\ equipment$$
$$c_e = capital\ cost\ (\$)$$
$$n_e = number\ of\ equipment\ used$$
$$t_{wo} = capital\ write\ off\ time (yrs)$$
$$L = Load\ fraction$$
$$q = Load\ sharing\ fraction$$

5. Overhead cost

$$C_{OH} = \frac{c_{oh}}{n'}$$

Where,

$$C_{OH} = unit\ cost\ of\ factory\ overhead$$
$$c_{oh} = factory\ overhead$$

6. Total cost

Total cost of a component can be calculated as,

$$Total\ unit\ cost = C_M + C_L + C_T + C_E + C_{OH}$$

Based on the method, all non-OTS components of the original design were put to cost to manufacture analysis. Details into the calculation is provided in Table 30.

	Material cost				Labor cost			Tooling cost				Equipment cost						Overhead cost		Total cost
Equation	$C_M = \frac{mc_m}{1-f}$				$C_L = \frac{c_w}{n'}$			$C_T = \frac{c_t k}{n}$				$C_E = \left(\frac{1}{n'}\right)\left(\frac{c_e\, n_e}{Lt_{wo}}\right) q$						$C_{OH} = \frac{c_{oh}}{n'}$		
Cost element	c_m	f	m (lb)	C_M	c_w ($/h)	n', (units/h)	C_L	c_t ($/set)	n (units)	k	C_T	c_e ($)	Number of equipment used, n_e	t_{wo} (yrs)	L	q	C_E	c_{OH} ($/h)	C_{OH}	**Total unit cost = C_M+C_L+C_T+C_E+C_{OH}**
6677	0.53	0.1	15.2	**8.951**	80	40	**2.000**	7000	5000	5	**7**	70000	1	5	1	0.5	**0.02778**	400	**10.000**	**27.979**
6661	0.32	0.05	13.4	**4.514**	160	700	**0.229**	100000	10000	1	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**16.459**
6662	0.32	0.05	26.28	**8.852**	160	700	**0.229**	100000	15000	1.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**20.797**
6663	0.32	0.05	28.59	**9.630**	160	700	**0.229**	100000	15000	1.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**21.575**
6664	1.07	0.1	2.38	**2.830**	160	3000	**0.053**	50000	10000	0.5	**2.5**	500000	1	5	1	0.143	**0.00076**	1200	**0.400**	**5.784**
6665	0.32	0.05	19.32	**6.508**	160	700	**0.229**	100000	10000	1	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**18.453**
6667	0.53	0.1	1.45	**0.854**	80	50	**1.600**	7000	5000	5	**7**	70000	1	5	1	0.5	**0.02222**	400	**8.000**	**17.476**
6668	0.32	0.05	11.04	**3.719**	160	700	**0.229**	100000	10000	1	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**15.664**
6669	0.32	0.05	13.16	**4.433**	160	700	**0.229**	100000	5000	0.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**16.378**
6670	0.24	0.05	0.21	**0.053**	20	10000	**0.002**	10000	5000	0.25	**0.5**	4000	1	8	1	0.1	**0.00000**	50	**0.005**	**0.560**
6671	1.07	0.1	0.92	**1.094**	160	3000	**0.053**	50000	5000	0.25	**2.5**	500000	1	5	1	0.143	**0.00076**	1200	**0.400**	**4.048**
6616	0.32	0.05	9.53	**3.210**	160	700	**0.229**	100000	5000	0.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**15.155**
6626	0.24	0.05	2.68	**0.677**	20	10000	**0.002**	10000	20000	1	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**1.184**
6636	1.07	0.1	17.88	**21.257**	20	10000	**0.002**	10000	5000	0.25	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**21.764**
6656	1.07	0.1	3.92	**4.660**	180	80	**2.250**	55000	5000	0.1	**1.1**	55000	1	5	1	0.33	**0.00720**	700	**8.750**	**16.768**
6676	0.24	0.05	0.62	**0.157**	20	60	**0.333**	20000	5000	0.25	**1**	100000	1	5	1	0.2	**0.01058**	90	**1.500**	**3.001**
6686	1.07	0.1	2.95	**3.507**	20	10000	**0.002**	10000	5000	0.25	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**4.014**
6696	0.24	0.05	0.93	**0.235**	20	60	**0.333**	20000	5000	0.25	**1**	100000	1	5	1	0.2	**0.01058**	90	**1.500**	**3.079**
6166	0.32	0.05	9.53	**3.210**	160	700	**0.229**	100000	5000	0.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**15.155**
6266	0.32	0.05	10.3	**3.469**	160	700	**0.229**	100000	25000	2.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**15.414**
6366	0.24	0.05	4.64	**1.172**	160	700	**0.229**	100000	5000	0.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**13.117**
6466	0.24	0.05	0.92	**0.232**	20	10000	**0.002**	10000	5000	0.25	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**0.739**

Table 30: Cost to manufacture analysis (contd. in next page)

	Material cost				Labor cost			Tooling cost				Equipment cost						Overhead cost		Total cost
Equation	$C_M = \frac{mc_m}{1-f}$				$C_L = \frac{c_w}{n'}$			$C_T = \frac{c_t k}{n}$				$C_E = \left(\frac{1}{n'}\right)\left(\frac{c_e\, n_e}{Lt_{wo}}\right) q$						$C_{OH} = \frac{c_{oh}}{n'}$		
Cost element	c_m	f	m (lb)	$\boldsymbol{C_M}$	c_w (\$/h)	n', (units/h)	$\boldsymbol{C_L}$	c_t (\$/set)	n (units)	k	$\boldsymbol{C_T}$	c_e (\$)	Number of equipment used, n_e	t_{wo} (yrs)	L	q	$\boldsymbol{C_E}$	c_{OH} (\$/h)	$\boldsymbol{C_{OH}}$	**Total unit cost = C_M+C_L+C_T+C_E+C_{OH}**
6566	0.3	0.05	1.18	**0.373**	20	60	**0.333**	20000	10000	0.5	**1**	100000	1	5	1	0.2	**0.01058**	90	**1.500**	**3.217**
6766	0.3	0.05	17.57	**5.548**	60	10	**6.000**	7500	5000	1	**1.5**	300000	1	6	1	0.2	**0.15873**	20	**2.000**	**15.207**
1166	0.3	0.05	1.014	**0.320**	60	20	**3.000**	7500	10000	2	**1.5**	300000	1	6	1	0.2	**0.07937**	20	**1.000**	**5.900**
1466	0.3	0.05	1.08	**0.341**	60	20	**3.000**	7500	10000	2	**1.5**	300000	1	6	1	0.2	**0.07937**	20	**1.000**	**5.920**
6866	1.07	0.1	12.26	**14.576**	20	10000	**0.002**	10000	5000	0.25	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**15.083**
6966	1.07	0.1	3.92	**4.660**	180	80	**2.250**	55000	5000	0.1	**1.1**	55000	1	5	1	0.33	**0.00720**	700	**8.750**	**16.768**
7066	1.07	0.1	27.84	**33.099**	20	5	**4.000**	700	10000	100	**7**	180000	1	5	1	0.2	**0.22857**	200	**40.000**	**84.327**
7166	1.07	0.1	12.36	**14.695**	180	30	**6.000**	55000	5000	0.1	**1.1**	55000	1	5	1	1	**0.05820**	700	**23.333**	**45.186**
7266	0.32	0.05	4.51	**1.519**	40	100	**0.400**	25000	5000	0.25	**1.25**	150000	1	5	1	0.2	**0.00952**	180	**1.800**	**4.979**
7366	0.24	0.05	0.02	**0.005**	60	20	**3.000**	7500	10000	2	**1.5**	300000	1	6	1	0.2	**0.07937**	20	**1.000**	**5.584**
7466	0.24	0.05	3.73	**0.942**	160	700	**0.229**	100000	5000	0.5	**10**	500000	1	5	1	0.091	**0.00206**	1200	**1.714**	**12.887**
7566	0.24	0.05	0.13	**0.033**	60	20	**3.000**	7500	5000	1	**1.5**	300000	1	6	1	0.2	**0.07937**	20	**1.000**	**5.612**
7666	1.5	0.05	0.13	**0.205**	20	3000	**0.007**	7000	5000	0.5	**0.7**	150000	1	5	1	1	**0.00159**	800	**0.267**	**1.180**
7766	1.07	0.05	11.49	**12.941**	180	80	**2.250**	55000	5000	0.1	**1.1**	55000	1	5	1	0.33	**0.00720**	700	**8.750**	**25.049**
6001	0.24	0.05	1.75	**0.442**	20	60	**0.333**	20000	5000	0.25	**1**	100000	1	5	1	0.2	**0.01058**	90	**1.500**	**3.286**
6002	0.24	0.05	0.9	**0.227**	20	10000	**0.002**	10000	10000	0.5	**0.5**	4000	1	8	1	0.167	**0.00000**	50	**0.005**	**0.734**
6003	1.58	0.1	0.56	**0.983**	80	100	**0.800**	800	5000	1	**0.16**	10000	1	10	1	1	**0.00159**	100	**1.000**	**2.945**
																				528.426

Table 31: Cost to manufacture analysis (contd.)

The cost of non OTS components was found out from the analysis to be $**528.426.**

XVII.3. Custompartnet

From the custompartnet online cost estimator service, the total unit cost of product was estimated to be **$580.**

XVII.4. Breakeven analysis

To get the selling price of the manufactured components, a break-even analysis needs to be done. Break-even analysis provides the margin in which the selling price of a certain component has to be set, in order to achieve profit within the business goals of a company.

In order to do break-even analysis, it was assumed that the business goal of the company is to achieve profit after production of **650** units of the manufactured component.
The break-even point of a product is given by the equation:

$$Q_B = \frac{f}{P - v}$$

Where,

$$Q_B = Breakeven\ point$$

$$f = fixed\ cost\ (\$)$$

$$P = Sales\ price\left(\frac{\$}{unit}\right)$$

$$V = variable\ cost\left(\frac{\$}{unit}\right)$$

In the current problem, we have to find out the sales price for 650 units of material production. So, from the above equation, the sales price can be derived as:

Sales price $P = \frac{f}{Q_B} + v$

Break even analysis of the manufactured components before redesigning is shown in Table 31.

Part	G&A Expenses	Factory Expenses	Sales & OH	Depreciation	Total Fixed Cost per month, *f* ($)	Labor cost	Material cost	Total Variable cost per unit, *v* ($/Unit)	Break-even target (Units)	Selling price ($/unit)
6677	10000	800	1200	4666.67	**16666.67**	1.60	8.95	**10.55**	**650**	**36.192**
6661	10000	4800	1200	33333.33	**49333.33**	3.20	4.51	**7.71**	**1300**	**45.662**
6662	10000	7200	1200	33333.33	**51733.33**	3.20	8.85	**12.05**	**1950**	**38.582**
6663	10000	7200	1200	33333.33	**51733.33**	3.20	9.63	**12.83**	**1950**	**39.360**
6664	10000	2400	1200	33333.33	**46933.33**	3.20	2.83	**6.03**	**1300**	**42.132**
6665	10000	4800	1200	33333.33	**49333.33**	3.20	6.51	**9.71**	**1300**	**47.657**
6667	10000	800	1200	4666.67	**16666.67**	1.60	0.85	**2.45**	**650**	**28.095**
6668	10000	4800	1200	33333.33	**49333.33**	3.20	3.72	**6.92**	**1300**	**44.867**
6669	10000	2400	1200	33333.33	**46933.33**	3.20	4.43	**7.63**	**650**	**79.838**
6670	10000	100	1200	266.67	**11566.67**	0.40	0.05	**0.45**	**650**	**18.248**
6671	10000	100	1200	33333.33	**44633.33**	3.20	1.09	**4.29**	**650**	**72.960**
6616	10000	2400	1200	33333.33	**46933.33**	3.20	3.21	**6.41**	**650**	**78.615**
6626	10000	200	1200	266.67	**11666.67**	0.40	0.68	**1.08**	**2600**	**5.564**
6636	10000	50	1200	266.67	**11516.67**	0.40	21.26	**21.66**	**650**	**39.375**
6656	10000	2400	1200	3666.67	**17266.67**	3.60	4.66	**8.26**	**650**	**34.825**
6676	10000	90	1200	6666.67	**17956.67**	0.40	0.16	**0.56**	**650**	**28.182**
6686	10000	50	1200	266.67	**11516.67**	0.40	3.51	**3.91**	**650**	**21.625**
6696	10000	90	1200	6666.67	**17956.67**	0.40	0.23	**0.63**	**650**	**28.261**
6166	10000	2400	1200	33333.33	**46933.33**	3.20	3.21	**6.41**	**650**	**78.615**
6266	10000	12000	1200	33333.33	**56533.33**	3.20	3.47	**6.67**	**3250**	**24.064**
6366	10000	2400	1200	33333.33	**46933.33**	3.20	1.17	**4.37**	**650**	**76.577**
6466	10000	50	1200	266.67	**11516.67**	0.40	0.23	**0.63**	**650**	**18.350**
6566	10000	180	1200	6666.67	**18046.67**	0.40	0.37	**0.77**	**1300**	**14.655**
6766	10000	2500	1200	20000.00	**33700.00**	1.20	5.55	**6.75**	**650**	**58.595**
1166	10000	5000	1200	20000.00	**36200.00**	1.20	0.32	**1.52**	**1300**	**29.366**
1466	10000	5000	1200	20000.00	**36200.00**	1.20	0.34	**1.54**	**1300**	**29.387**
6866	10000	50	1200	266.67	**11516.67**	0.40	14.58	**14.98**	**650**	**32.694**
6966	10000	2400	1200	3666.67	**17266.67**	3.60	4.66	**8.26**	**650**	**34.825**
7066	10000	2000	1200	12000.00	**25200.00**	0.40	33.10	**33.50**	**1300**	**52.883**
7166	10000	700	1200	3666.67	**15566.67**	3.60	14.69	**18.29**	**650**	**42.243**
7266	10000	180	1200	10000.00	**21380.00**	0.80	1.52	**2.32**	**650**	**35.211**
7366	10000	5000	1200	20000.00	**36200.00**	1.20	0.01	**1.21**	**1300**	**29.051**
7466	10000	2400	1200	33333.33	**46933.33**	3.20	0.94	**4.14**	**650**	**76.347**
7566	10000	2500	1200	20000.00	**33700.00**	1.20	0.03	**1.23**	**650**	**53.079**
7666	10000	900	1200	10000.00	**22100.00**	0.40	0.21	**0.61**	**650**	**34.605**
7766	10000	2400	1200	3666.67	**17266.67**	3.60	12.94	**16.54**	**650**	**43.105**
6001	10000	90	1200	6666.67	**17956.67**	0.40	0.44	**0.84**	**650**	**28.468**
6002	10000	100	1200	266.67	**11566.67**	0.40	0.23	**0.63**	**1300**	**9.525**
6003	10000	300	1200	666.67	**12166.67**	1.60	0.98	**2.58**	**650**	**21.301**
										1552.990

Table 31: Breakeven Analysis

In the Breakeven estimation done above, parts that have more than one quantity in a single unit were dealt with increasing the breakeven point proportionally. Including the OTS components (Table 29), the total selling cost estimates to amount **$1577.221** From the estimation we found out that the selling cost of the manufactured product can be set to an amount of **$1577.221** per unit in-order to break even at 650 units of the product. The comparison of values obtained from various estimation methods are summarised in Table 32.

	Estimation Technique	Estimated value
Manufacturing Cost	OME	$508.11
	Cost to manufacture	$528.426
	Custom Partnet	$580
Selling Price	OME	$1548.561
	Breakeven Analysis	$1577.221

Table 32: Cost Comparison Table

XVIII. PROFESSIONAL, ETHICAL, AND SAFETY CONSIDERATIONS

Professional considerations involve adhering to the rules of professional arm-wrestling as well as the professional requirements needed to meet standards of commercial gyms, in terms of gym machinery. Addressing the former, the World Armwrestling League (WAL) uses a specific arm-wrestling table for professional tournaments. The WAL arm-wrestling table uses the same specifications as the American Armsport Association (AAA) and World Arm-wrestling Federation (WAF) (Figure 46). To date, 56 armwrestling associations across the United States follow similar specifications to these main organizations (ref. Armsport). The follow specifications are met with our design as follows:

1. Overall dimensions are 26" wide x 38" long with 1" solid, round pegs 6" high from the table top, and set 1" from the edge of the table. Inside dimensions are 36" long from the center of the peg to the center of the opposite peg.
2. Table frames should be made of square or round tubing or pipe, and bolted securely to wood no less than ½" thick in order to maintain stability during competition.
3. Elbow and pin pads are made of rubber or high-density foam, upholstered, and screwed, bolted, or pinned onto the table top.
   a. In our case, we do not have a pin pad, but a marking, 4" above the table, on the pin to show the level at which arm-wrestler's break the "plane" to win a match
4. Elbow pads are 7" square x 2" thick, set in 2" from the competitor's edge of table. The left edge of the elbow pad is 16 ½" from the center of the left peg. Right edge of the elbow pad is 12 ½" from the center of the right peg.

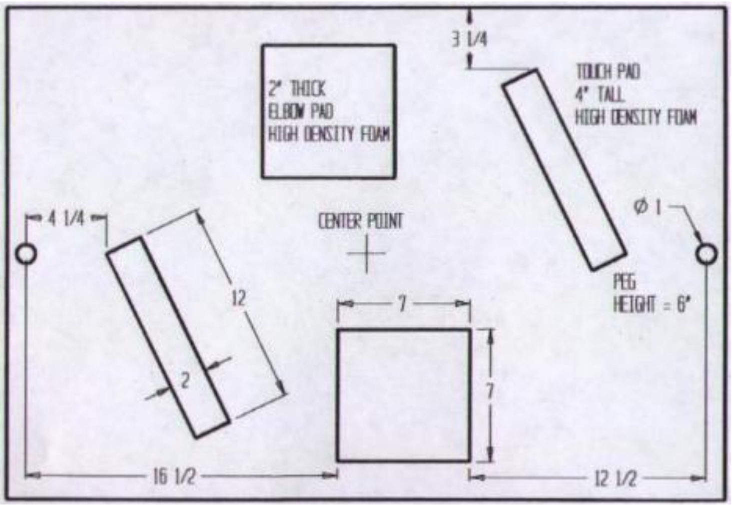


Figure 46: Dimensions of WAL/WAF/AAA Armwrestling table

One professional specification was overlooked, however, in our final design. That is – Table tops are padded with ¼" foam and upholstered, which is a specification that our product does not meet. In future iterations, this can be an addition to the design, to provide not only professional legitimacy to the product, but also addressing safety concerns. For example, if a challenge were to occur and one individual is overwhelmingly stronger than his opponent, they could injure that opponent's hand if it makes contact with the table top wood at a very accelerated speed. Looking at the professional standards of commercial gyms, they are required to abide that each "equipment or machine must have clear floor space of at least 30 by 48 inches and be served by an accessible route" (U.S. Access Board). Our designs and dimensions are optimal for the gym setting as it is compact and can sit in the open floor area of the gym.

Ethically, our manufacturing and assembly analysis takes into consideration the wellbeing of its manufacturers. The cost analyses reflect that our product will be made in a factory located in the United States, as opposed to cheaper options, and rightly so, as Arm-wrestling can be deemed an American sport.

In the same vein, safety considerations revolve around manufacturing and assembly processes. The product involves a lot of sheet-metal work, so the DFA analysis and assembly considerations have been thoroughly examined to ensure the safety of its workers, noting which components need or do not need to be handled by machines, as oppose to humans, as sheet metal can be very sharp and a safety hazard in assembly processes. As for safety requirements that commercial gyms require in gym equipment, an addition of safety warning stickers as well as instructional stickers on operations would be needed, but have not been made or included in the Bill of Materials, as it was considered to be outside the scope of the course, by the team (although it was something we considered). In future work, this could be of value when we can work closely with the commercial gym that we want to have our product in. Other gym-related safety considerations involve inspection of the components of the product:

1. Inspect: Cables for wear, tension and proper connection.
2. Inspect: Nuts and bolts are tightened, pins, spring pins, set screws, gas springs, and pulleys.
3. Initial cleaning of guide rods and lubricate accordingly with Teflon lubricant

As the product still has room for improvement and future iterations, as an initial novel product, still in the process of verifying its concept, these considerations will be progressively considered.

XIX. CONCLUSION

Revisiting our project objective: the team set out to design a product resembling a gym machine that would be compatible to arm-wrestling training, the sport of arm-wrestling itself, and exist in the commercial gym industry. And in doing so, justification of its concept would be upheld by the engineering concepts taught throughout the course, MCEN 5045: Design For Manufacturability, taking a novel product and – essentially saying – this can and should be made.

With that objective in mind, the team concludes that the final design ultimately met its goals within the scope of the course, during the global pandemic COVID-19, which did not affect the scope too much, but rather, the mental state of the team. However, this particular situation resembles a real-life scenario similar to a company in budgeting season, finding meaningful work to justify its employee's salaries amidst unfortunate circumstances. All that being said, the team was able to improve the initial design quite drastically through a series of design changes that were tailored specifically to the important processes emphasized in the course. For example, extensive time was spent on the discussion of manufacturing methods, such as casting, injection molding, and sheet-forming processes. As the structure of our product was primarily comprised of sheet metal, low carbon steel, stainless steel, 304 steel, and the like, sheet-forming processes proved beneficial in our analyses and design considerations.

Take for example our Pulley Housing component, it is design in such a way that it can be bent from one sheet of metal, as it can fit two pulleys in between this “folded sheet”. To add, the team was aware of sharp corners and areas where tear could potentially happen; therefore, the Pulley Housing has several radii in its design to avoid this very problem. Furthermore, for hole locations in the Pulley Adjuster, bar frames, or the Pulley Housing once more, holes are spaced apart to avoid any structural defects. In the team’s careful consideration as well as application of these processes, the final design achieves an appropriate justification to its manufacturability, as well as assembly.

Along with manufacturing processes in mind, design changes within the Weight System Sub-assembly provided the greatest change in the Design for Assembly analysis and metrics from the initial to final assembly. This included a major reduction of parts, use of standardized and on-the-shelf (OTS) parts, as well as a series of design changes that removed several secondary operations. Material, Process, and FEA analysis followed in providing a case for the product’s manufacturability as those results verified that it was structurally sound.

As the team’s objective also indicated its marketability, initial market analysis and patent search reiterated that a product of this kind is still in its early stages, not refined, yet has an expanding potential of returns. The patent search and research on other gym machines was reflected in both the initial and final design of the product, as the team did not want to infringe on any current designs, yet see the merits in certain standardized parts and modify and improve upon, ultimately creating a design that could very well fit within a commercial gym. Research into the sport of arm-wrestling also made the product unique in the way that it provides a training system to strengthen each area of an arm-wrestler’s technique, in supination pronation, radial and ulnar deviation, flexion, and extension. Lastly, an economic analysis verified encouraging results with a very large profit margin in the difference in pricing between its manufacturing cost and its selling cost.

To conclude, the team is satisfied with the end results, but realizes the final design can follow the same procedure through a series of continual design iterations, to improve its overall metrics. This could come in the form of optimizing bending radii, complex notch designs, improvements in locating or eliminating fasteners, and so on. But, with some certainty, the team can say that this product could potentially be something manufactured and sold for a profitable gain, to help promote a growing sport, especially with continued engineering, with the core of it all, being - design for manufacturability.

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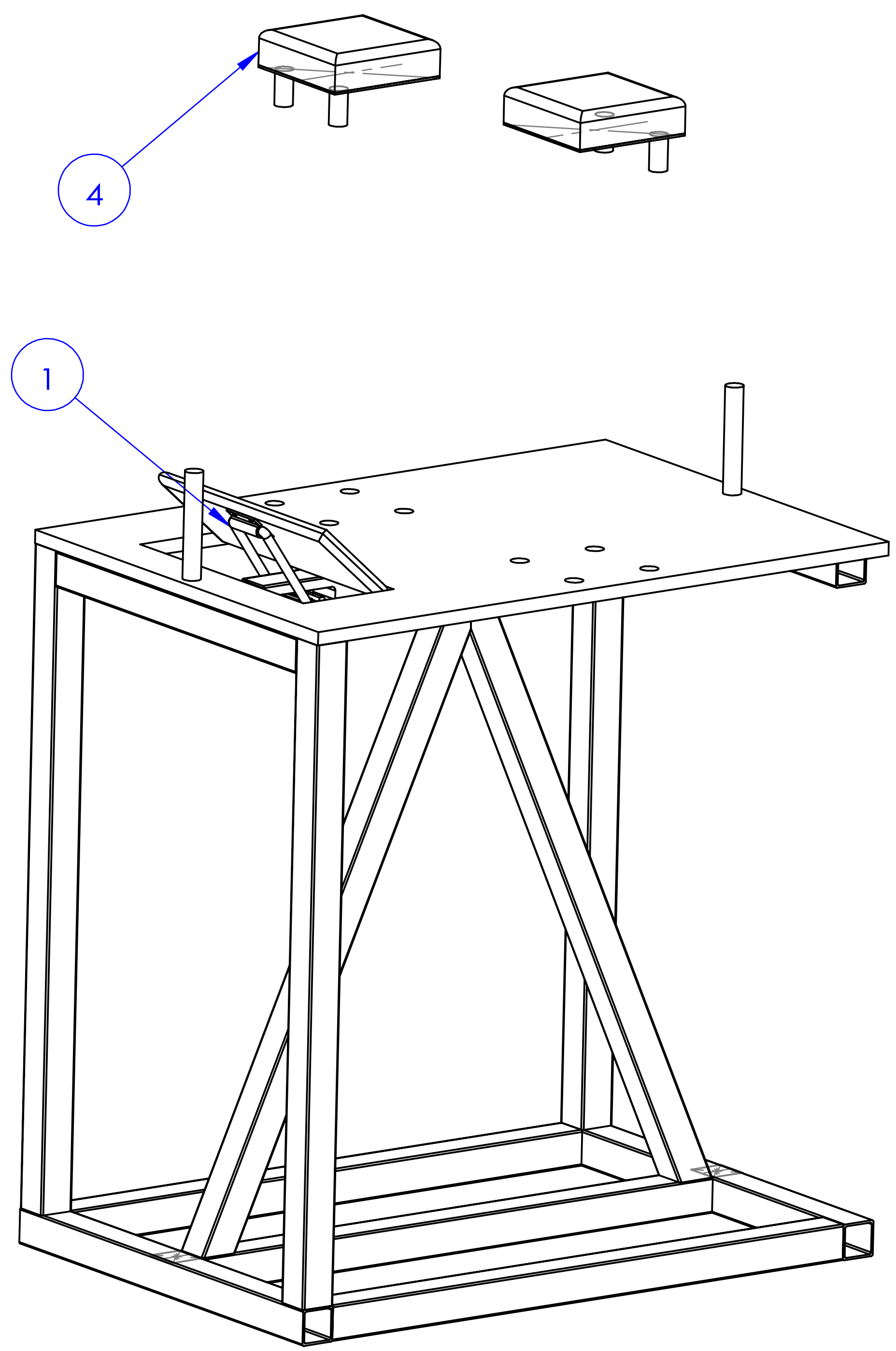
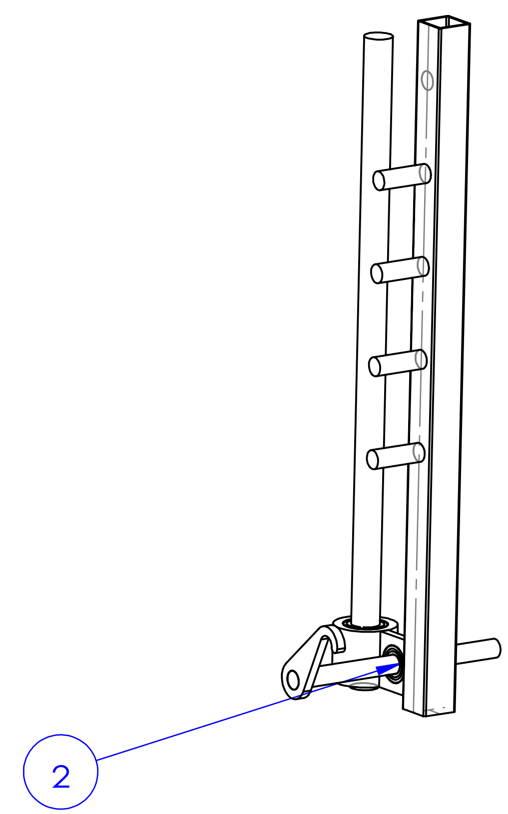
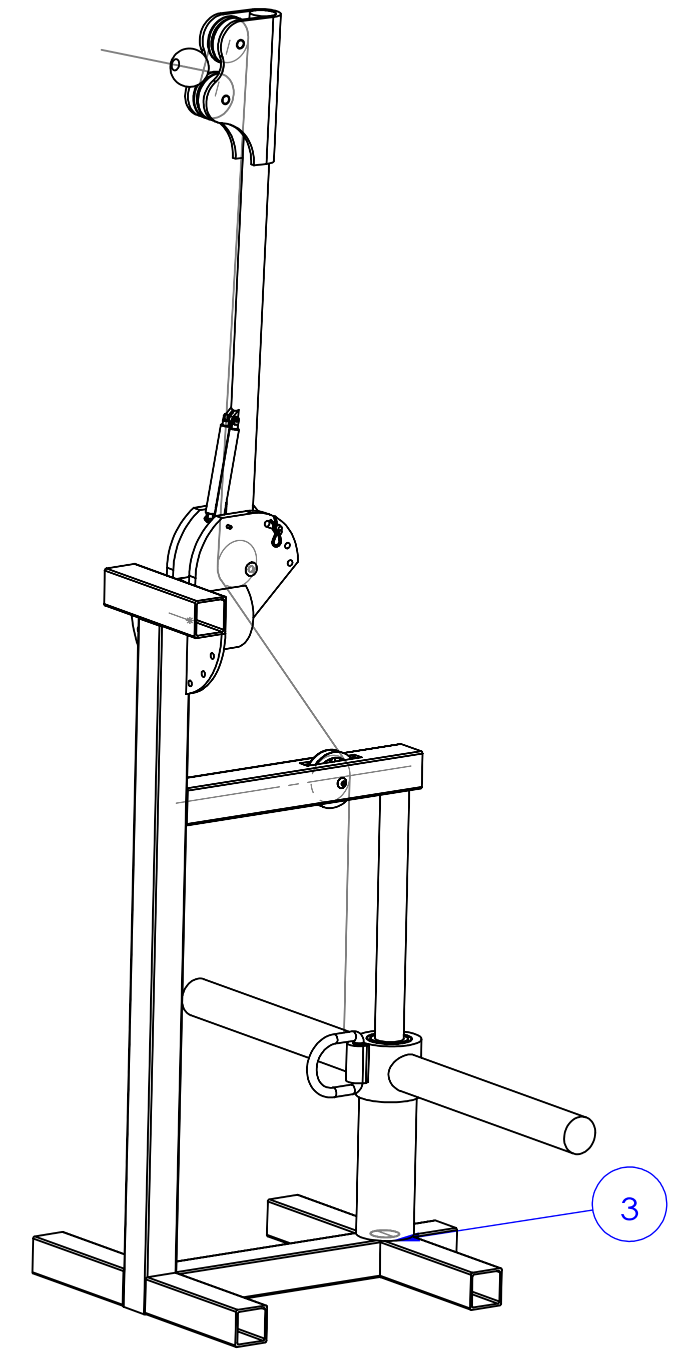
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6660	MAIN BODY SUBASSEMBLY	1
2	6606	SMITH MACHINE SUBASSEMBLY	1
3	6066	WEIGHT SYSTEM SUBASSEMBLY	1
4	6000	ELBOW PAD SUBASSEMBLY	2

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	2020/4/20





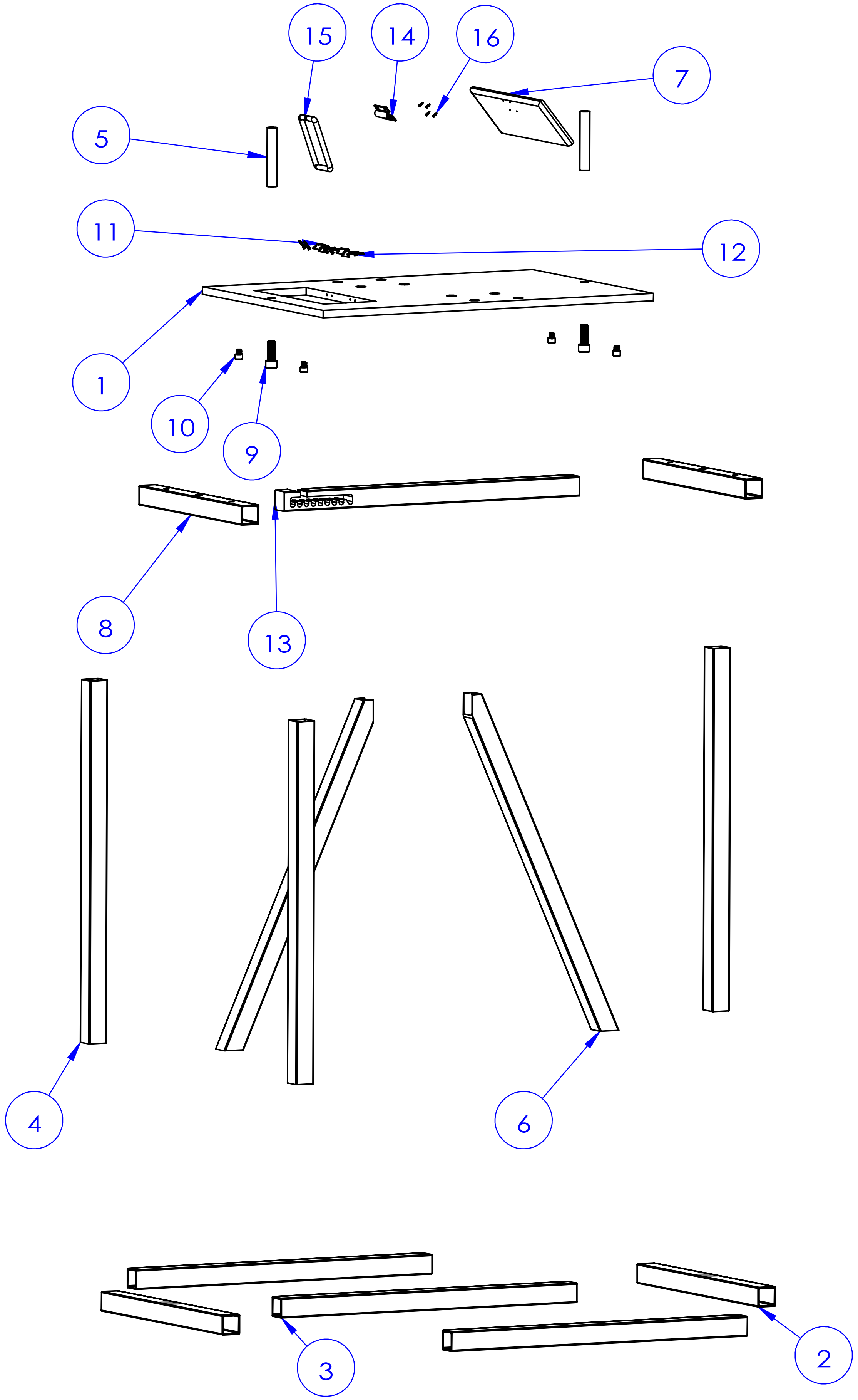


UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

DESCRIPTION
ARMWRESTLING TRAINING MACHINE

PN	REV	SHEET
6666	A	1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	2020/4/20



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6677	TABLETOP	1
2	6661	HORIZONTAL BAR WIDTH	2
3	6662	HORIZONTAL BAR LENGTH	3
4	6663	VERTICAL BARD HEIGHT	3
5	6664	GRIPPING PEG	2
6	6665	DIAGONAL BAR	2
7	6667	PREACHER CURL PAD (PCP)	1
8	6668	UPPER HORIZONTAL BAR WIDTH	2
9	1060	SCREW FOR HANDLE	2
10	1061	SCREW FOR TABLETOP	4
11	1062	HINGE FOR PCP	2
12	1063	SCREW FOR PCP	8
13	6669	UPPER HORIZONTAL BAR	1
14	6670	PCP ADJUSTER CONNECTOR	1
15	6671	PCP ADJUSTER	1
16	1064	SCREW FOR PCP ADJUSTER	4

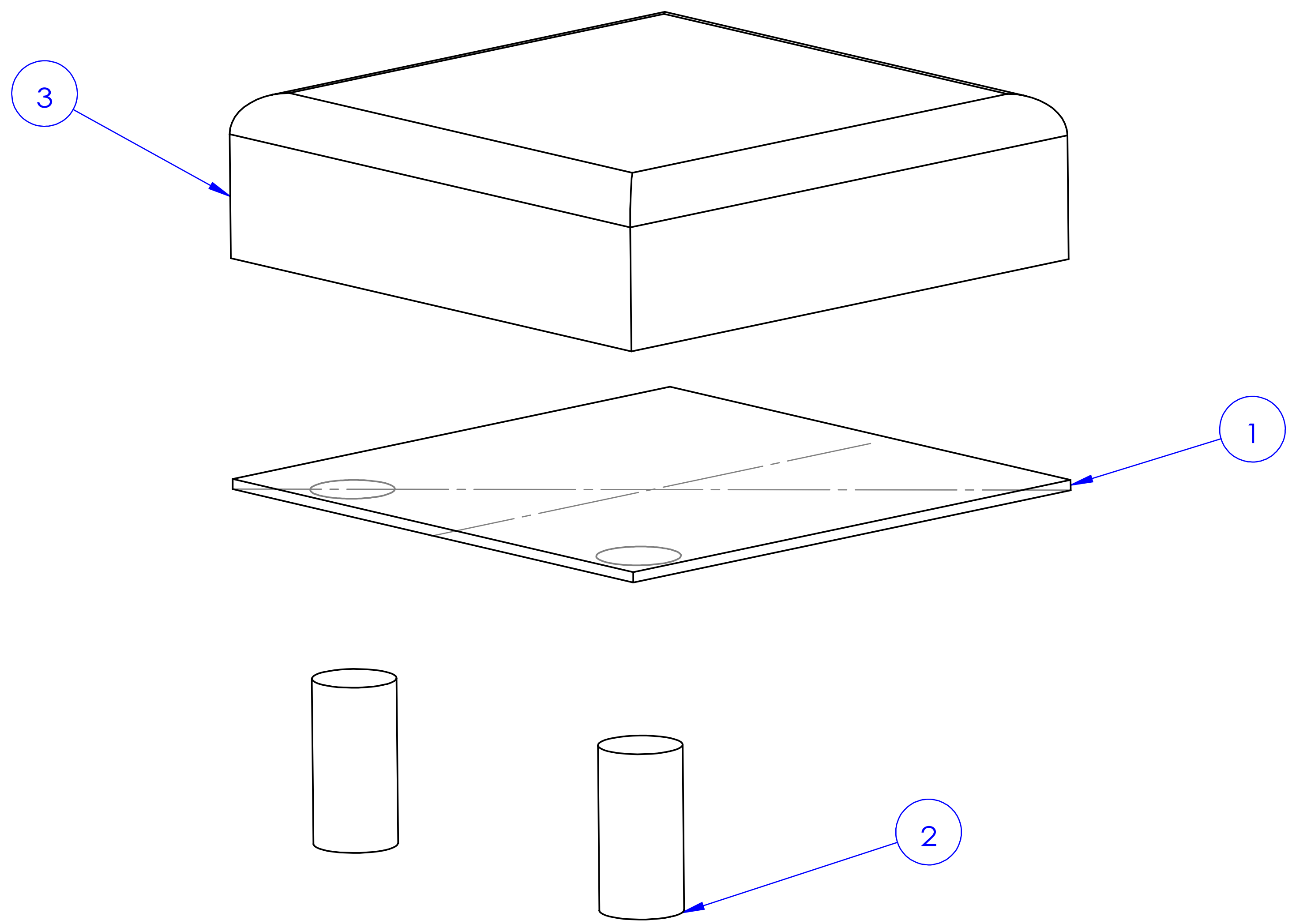
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

DESCRIPTION
MAIN BODY SUBASSEMBLY

PN	REV	SHEET
6660	A	1 of 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6001	ELBOW PAD BOARD	1
2	6002	ELBOW PAD PIN	2
3	6003	ELBOW PAD FOAM	1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	2020/4/20



UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

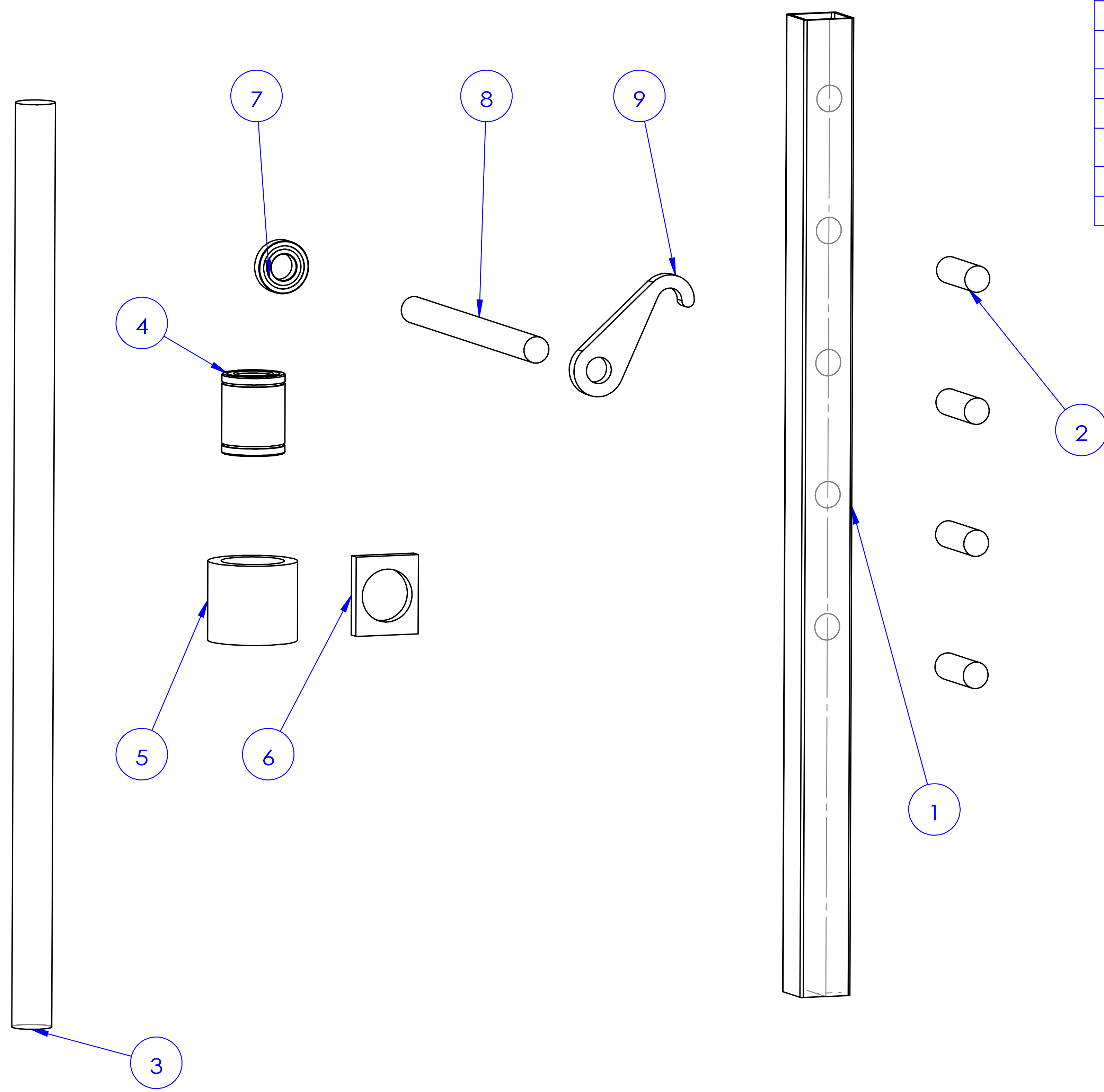
DESCRIPTION
ELBOW PAD SUBASSEMBLY

PN	REV	SHEET
6000	A	1 of 1

PROPRIETARY AND CONFIDENTIAL

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	2020/4/20

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6616	VERITAL BAR	1
2	6626	POSITION ROD	4
3	6636	ROD	1
4	1006	LINEAR BEARING	1
5	6656	SLIDER	1
6	6676	SLIDER BLOCK	1
7	1016	BALL BEARING	1
8	6686	HANDLE	1
9	6696	POSITION HOOK	1



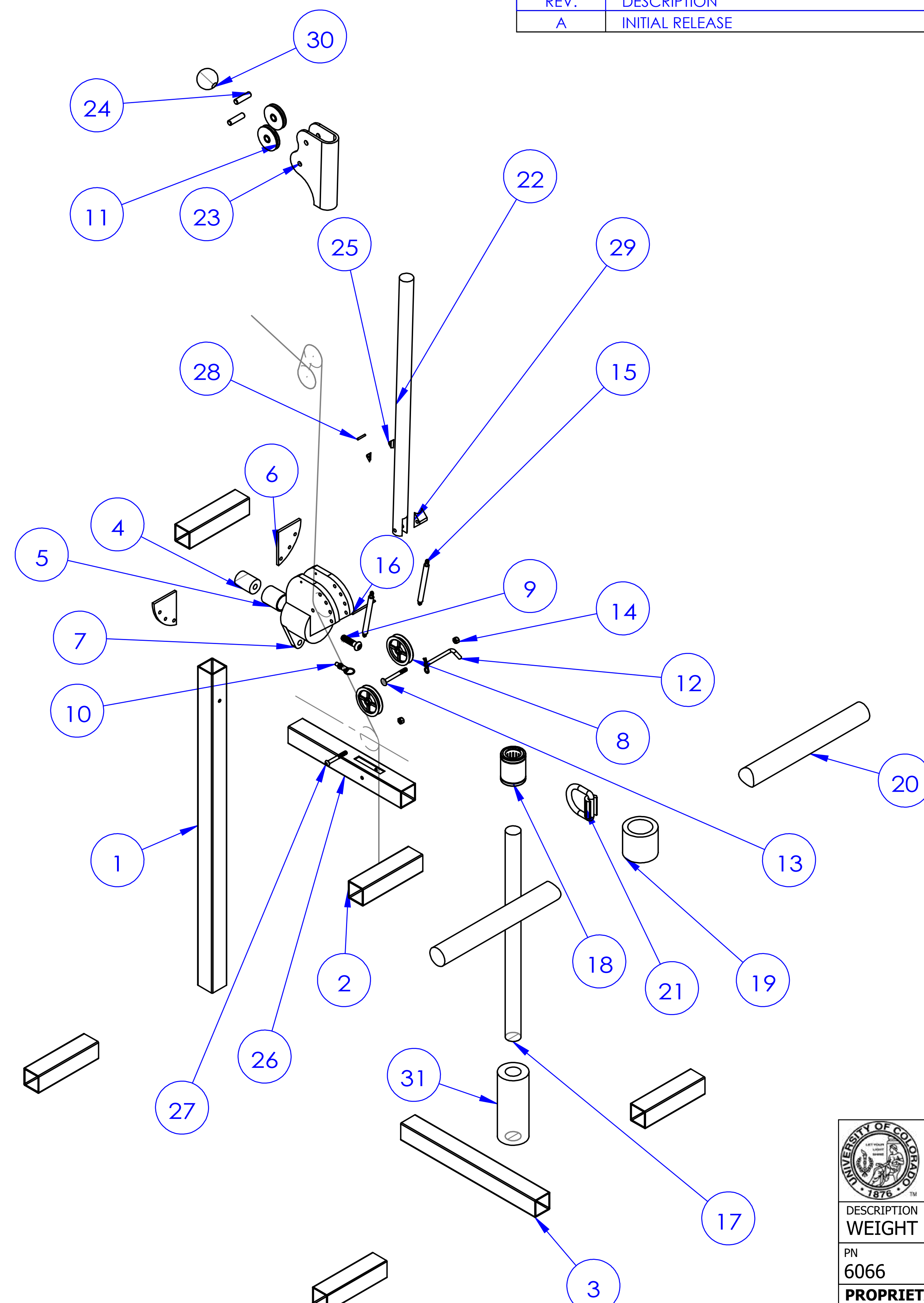
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

DESCRIPTION
SMITH MACHINE SUBASSEMBLY

PN	REV	SHEET
6606	A	1 of 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6166	VERTICAL BAR	1
2	6266	HORIZONTAL BAR	5
3	6366	GROUND BAR	1
4	6466	ADJUSTMENT ROD	1
5	1066	SLEEVE BEARING	1
6	6566	ADJUSTER PLATE	2
7	6766	ADJUSTER	1
8	1166	LOWER PULLEY	2
9	1266	SCREW FOR ADJUSTER	1
10	1366	SPRING PIN	1
11	1466	UPPER PULLEY	2
12	1566	HITCH PIN FOR PULLEY ARM	1
13	1766	BOLT FOR PULLEY ON ADJUSTER	1
14	1866	LOCKNUT	2
15	1966	GAS SPRING	2
16	2066	PIN FOR GAS SPRING	1
17	6866	VERTICAL STATIONARY ROD	1
18	2166	LINEAR BEARING	1
19	6966	VERTICAL SLIDING ROD	1
20	7066	HORIZONTAL LOADING ROD	2
21	2266	RING FOR ROPE	1
22	7166	PULLEY ARM	1
23	7266	PULLEY HOUSING	1
24	2366	PIN FOR UPPER PULLEY	2
25	7366	GAS SPRING CONNECTOR	2
26	7466	UPPER BAR	1
27	2466	SCREW FOR LOWER PULLEY	1
28	2566	PIN FOR GAS SPRING	1
29	7566	PIN CONNECTOR	1
30	7666	ROPE STOPPER	1
31	7766	VERTICAL STATIONARY ROD	1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	2020/4/20



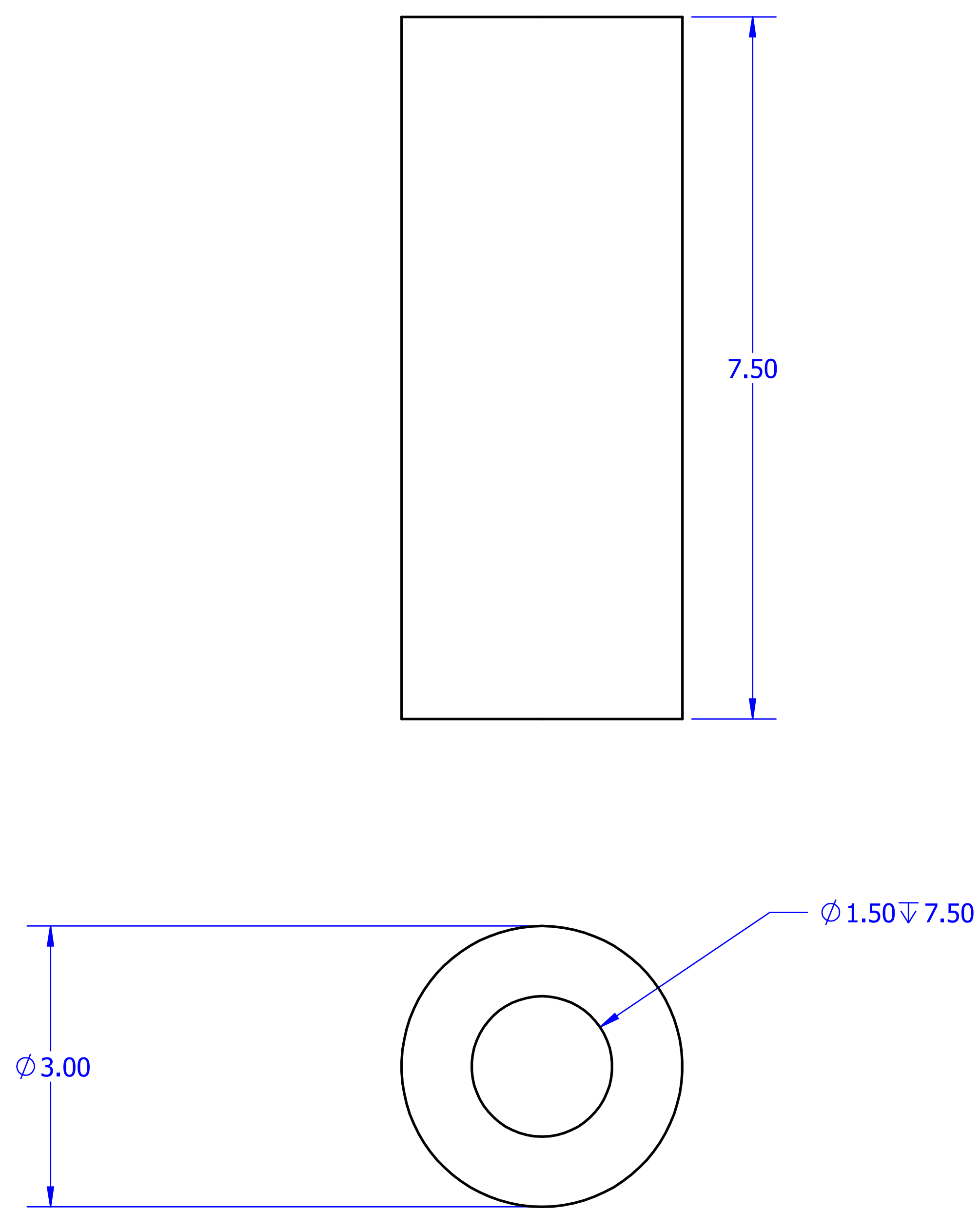
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

DESCRIPTION
WEIGHT SYSTEM SUBASSEMBLY

PN	REV	SHEET
6066	A	1 of 1

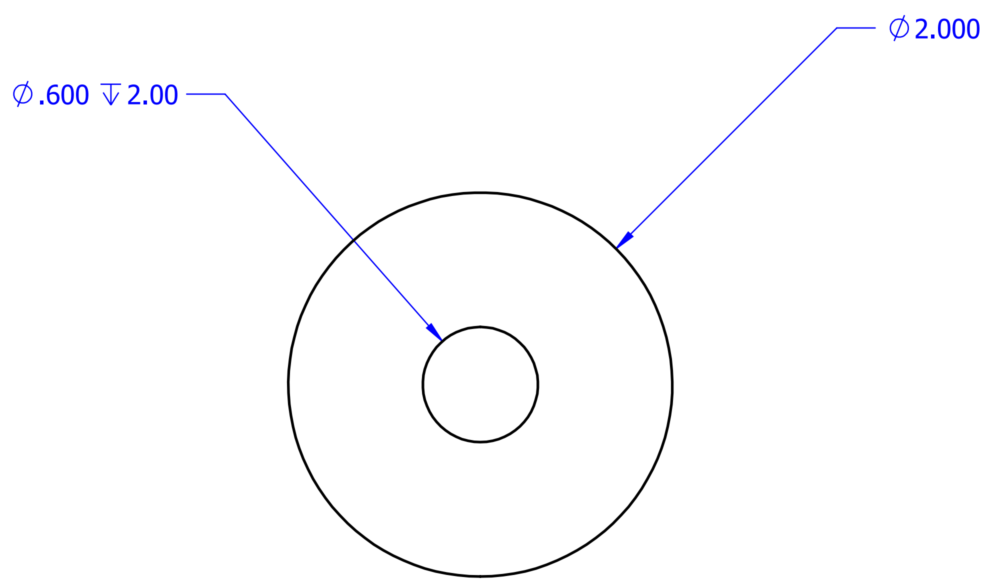
PROPRIETARY AND CONFIDENTIAL

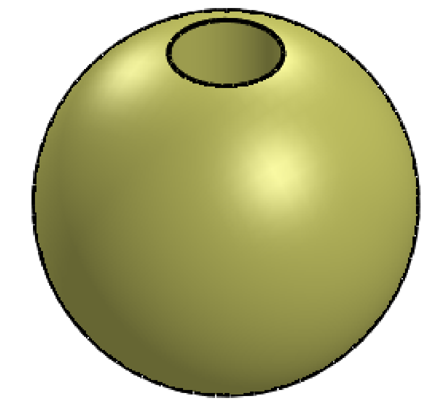
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/20/2020



TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 304		DESCRIPTION VERTICAL STATIONARY ROD
FINISH CHROMIUM PLATING		PN 7766 — REV A — SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020





TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427			
UNITS: INCHES					
MATERIAL ABS		DESCRIPTION ROPE STOPPER			
FINISH NONE		PN 7666	REV A		SHEET 1 of 1

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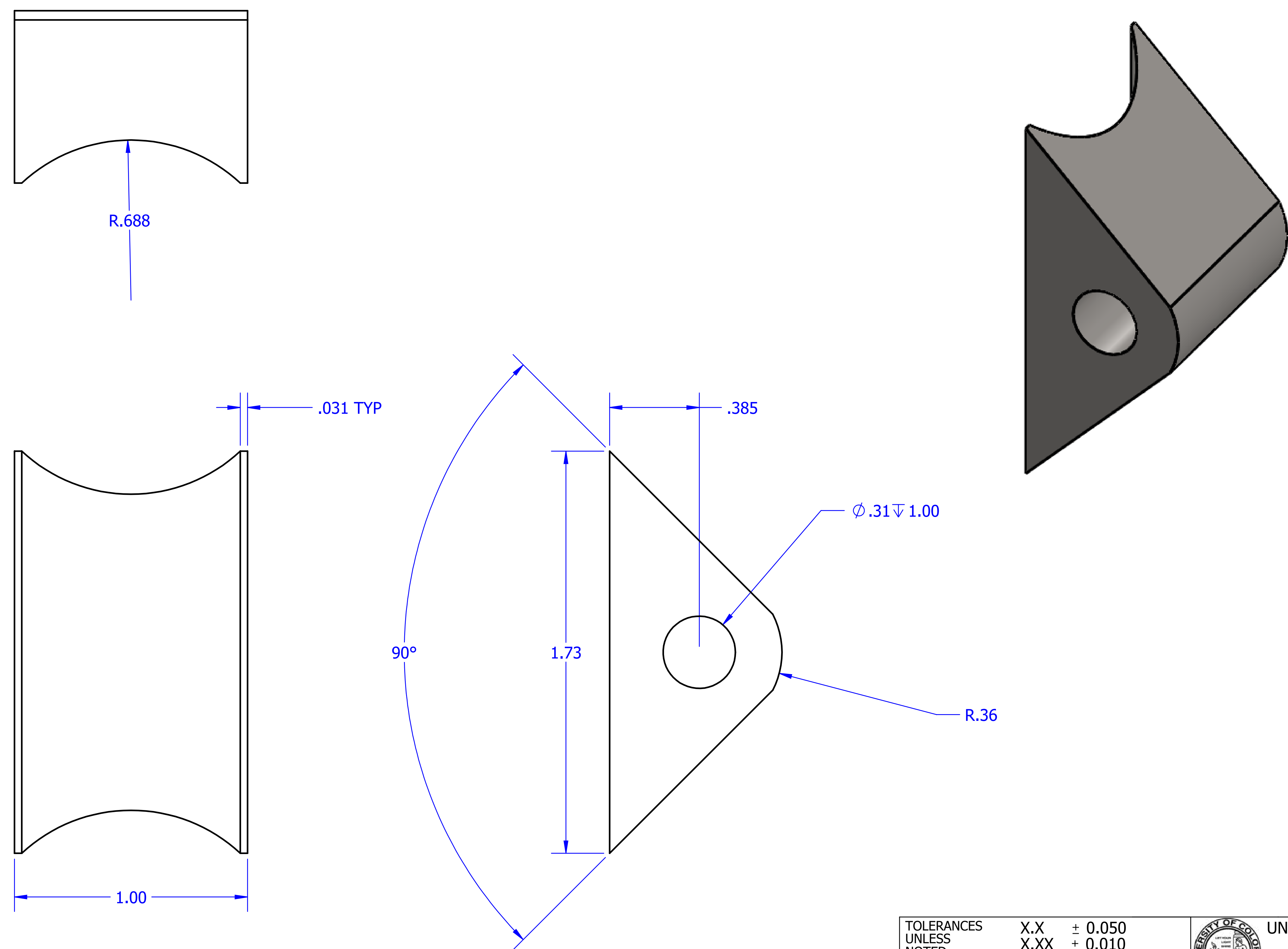
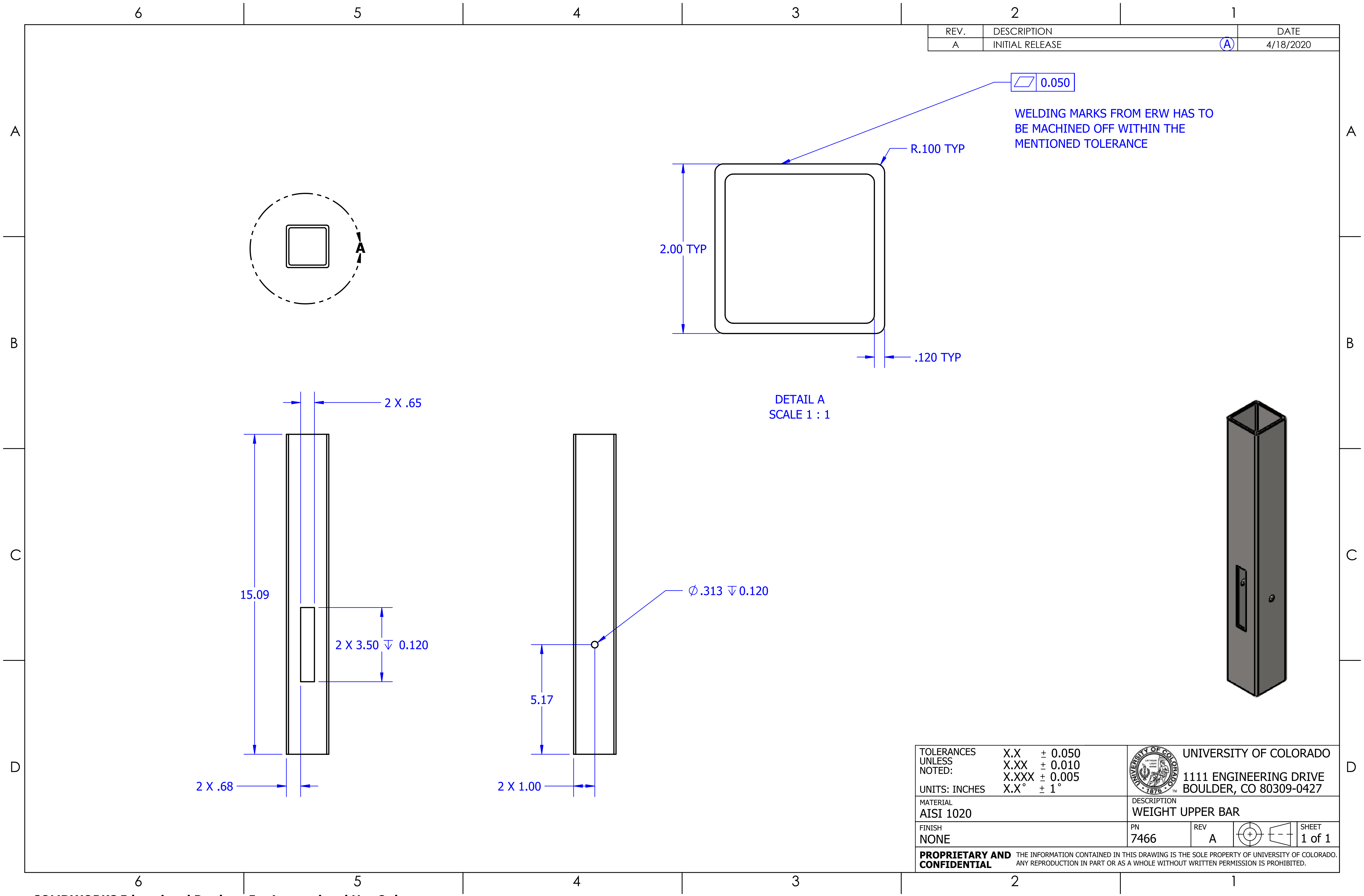
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427		
UNITS: INCHES				
MATERIAL AISI 1020		DESCRIPTION WEIGHT PIN CONNECTOR		
FINISH NONE		PN 7566	REV A	SHEET 1 of 1


REV.
DESCRIPTION
DATE
A
INITIAL RELEASE
A
4/18/2020
0.050
WELDING MARKS FROM ERW HAS TO
BE MACHINED OFF WITHIN THE
MENTIONED TOLERANCE
R.100 TYP
2.00 TYP
.120 TYP
A
DETAIL A
SCALE 1 : 1
2 X .65
15.09
2 X 3.50 ↧ 0.120
2 X .68
∅.313 ↧ 0.120
5.17
2 X 1.00
TOLERANCES UNLESS NOTED:
X.X ± 0.050
X.XX ± 0.010
X.XXX ± 0.005
X.X° ± 1°
UNITS: INCHES
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
MATERIAL
AISI 1020
DESCRIPTION
WEIGHT UPPER BAR
FINISH
NONE
PN
7466
REV
A
SHEET
1 of 1
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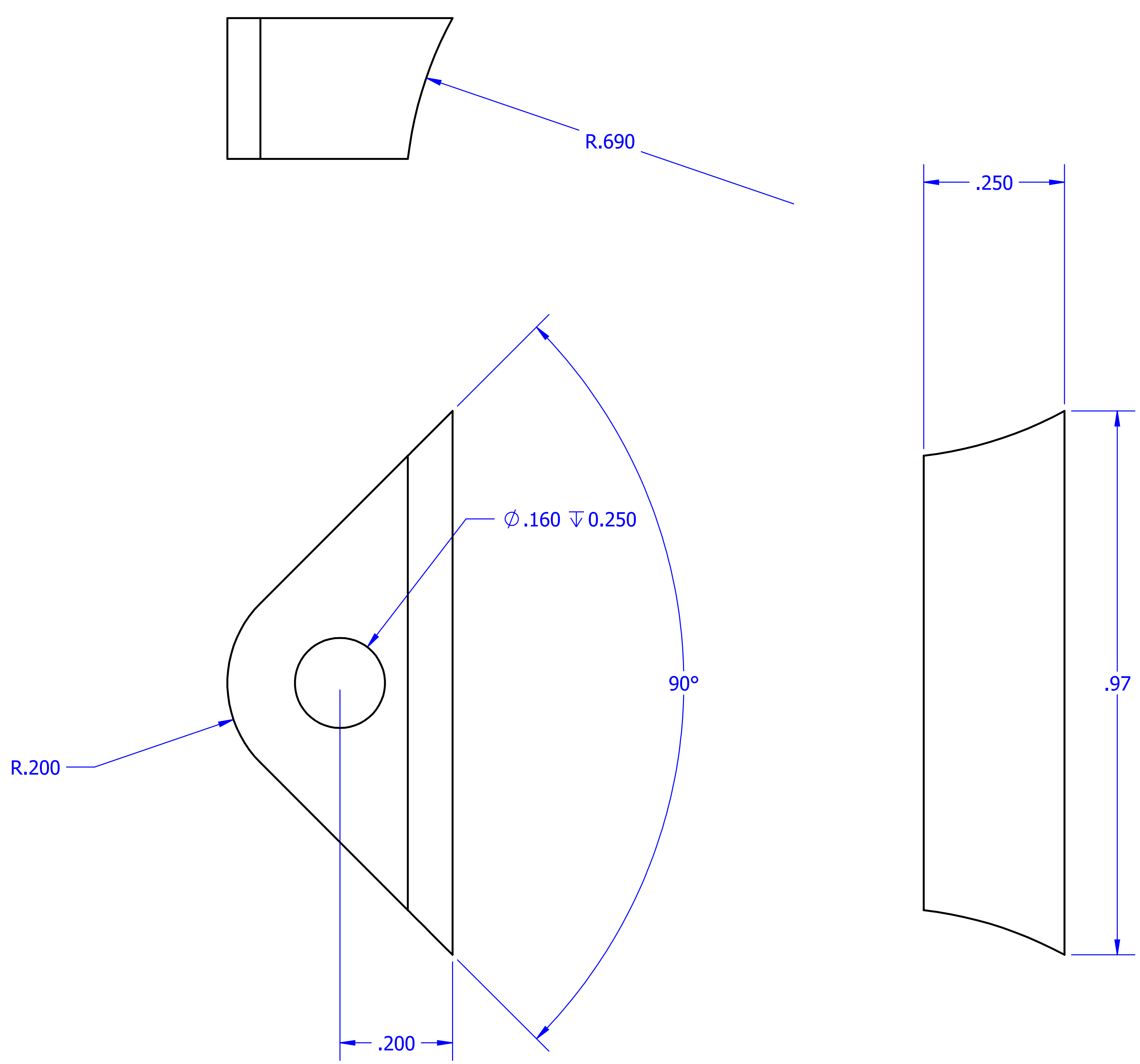
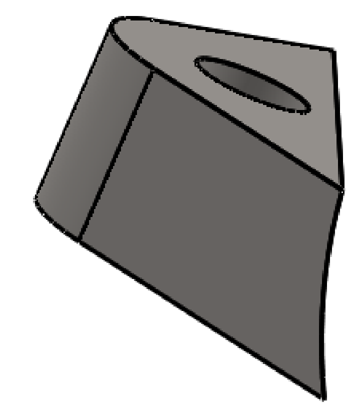
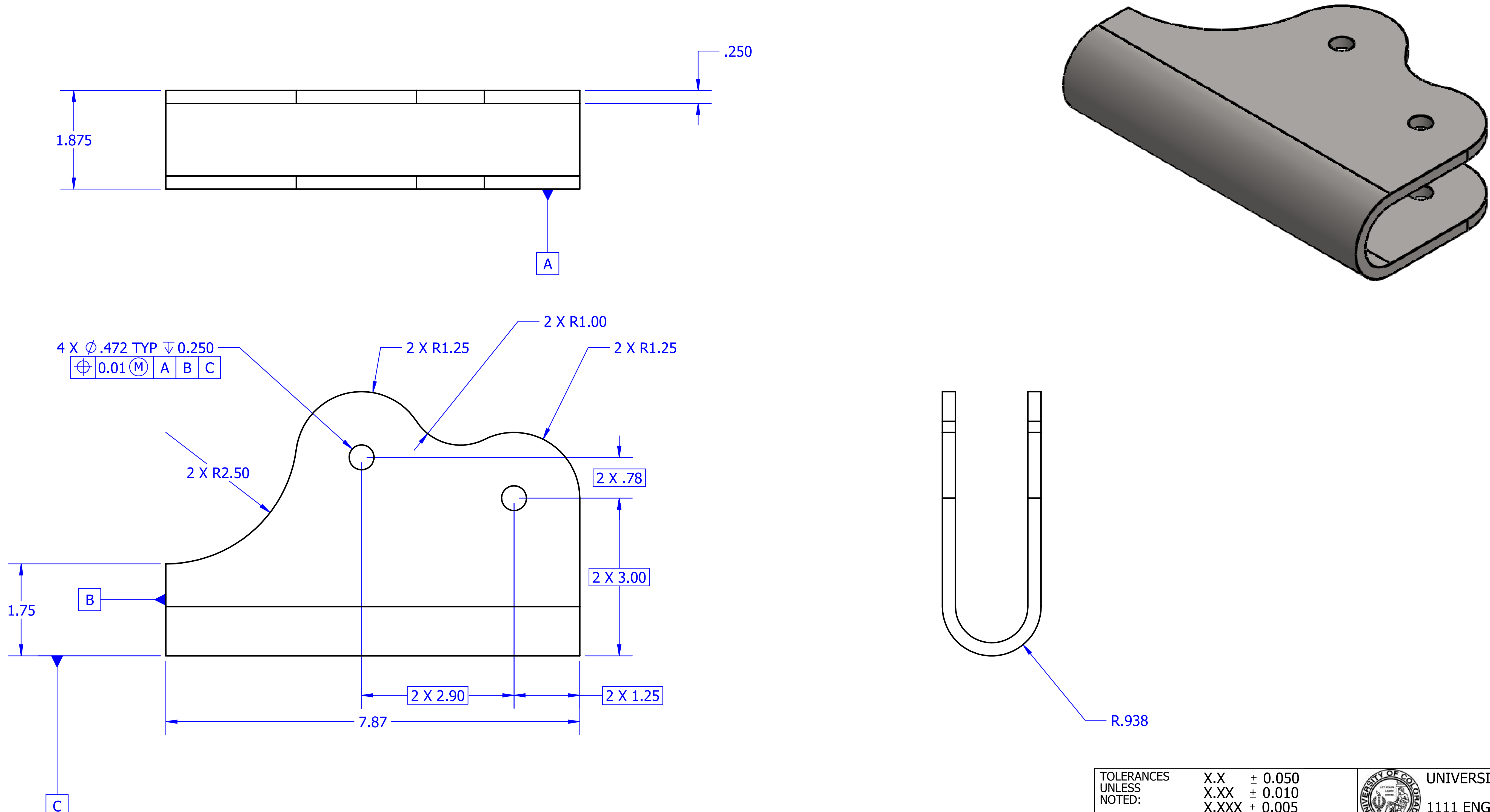
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020





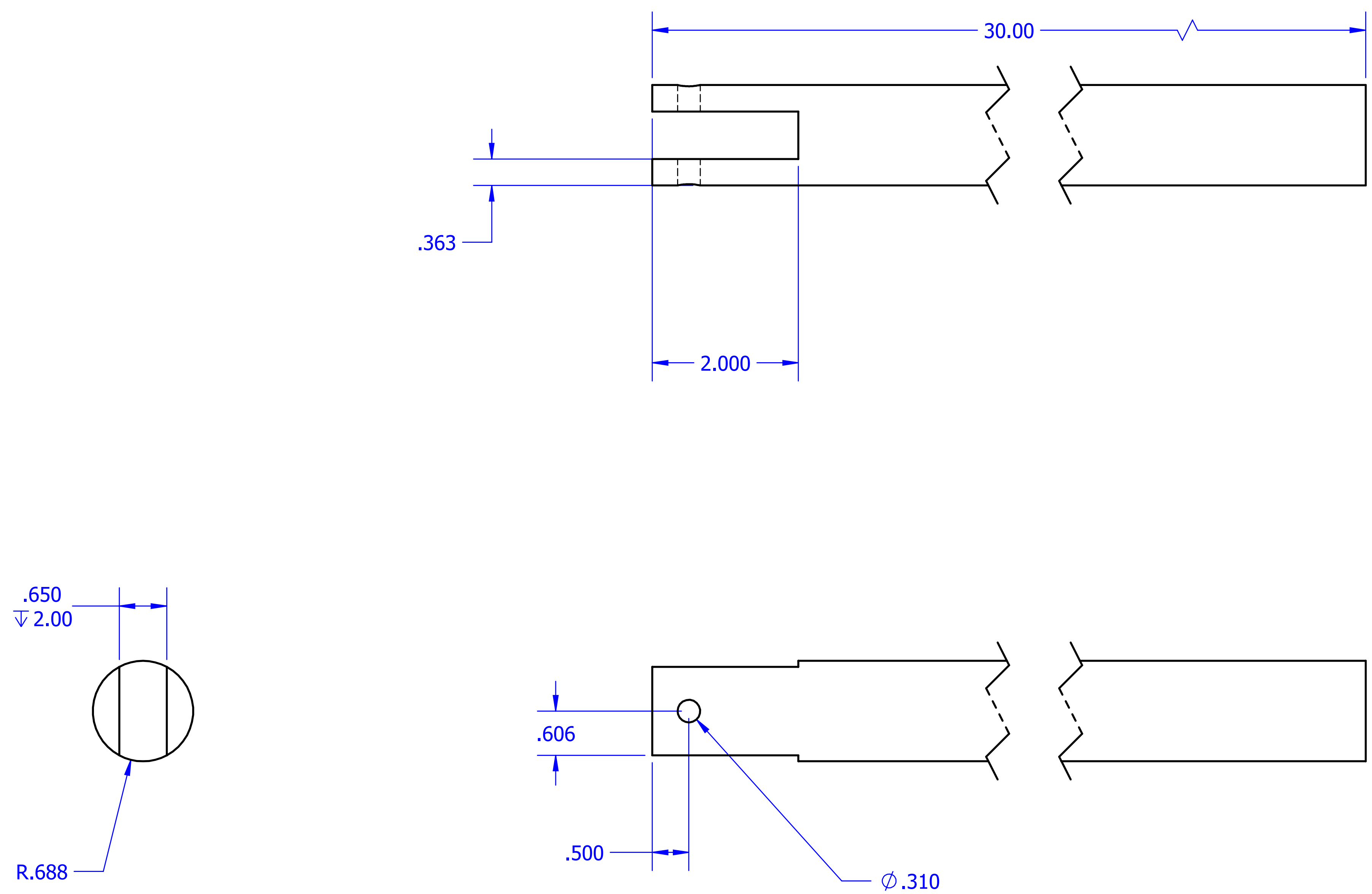
TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 1020		DESCRIPTION GAS SPRING CONNECTOR	
FINISH NONE		PN 7366	REV A · SHEET 1 of 1

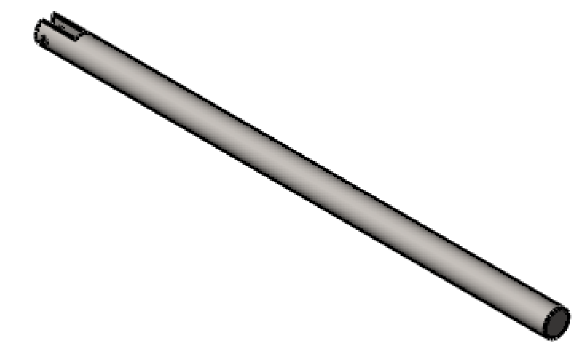
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL AISI 1020		DESCRIPTION PULLEY HOUSING	
FINISH NONE		PN 7266 · REV A	SHEET 1 of 1

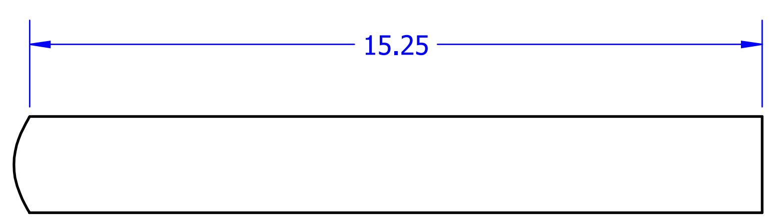
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/19/2020

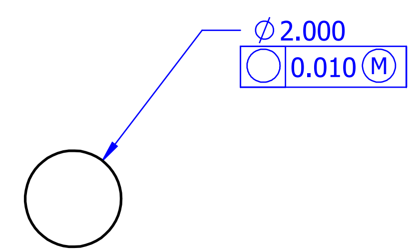


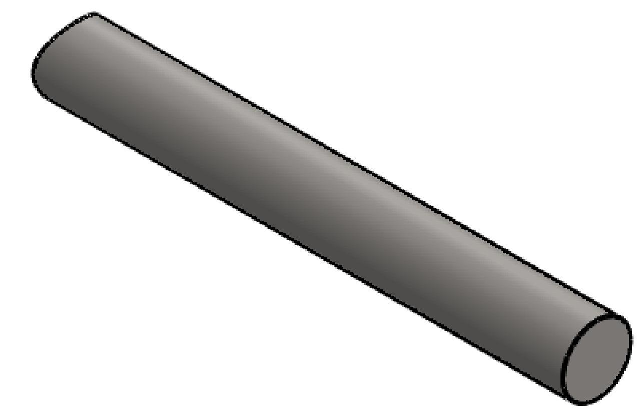


TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES	X.X° ± 1°		
MATERIAL AISI 304		DESCRIPTION PULLEY ARM	
FINISH NONE		PN 7166	REV A · SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020







TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 304		DESCRIPTION WEIGHT HORIZONTAL LOADING ROD	
FINISH NONE		PN 7066	REV A	SHEET 1 of 1

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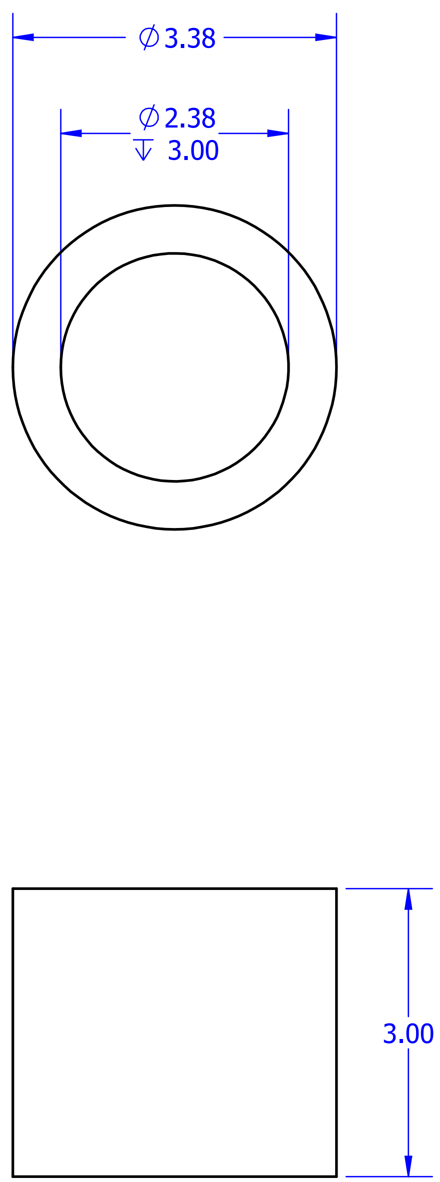
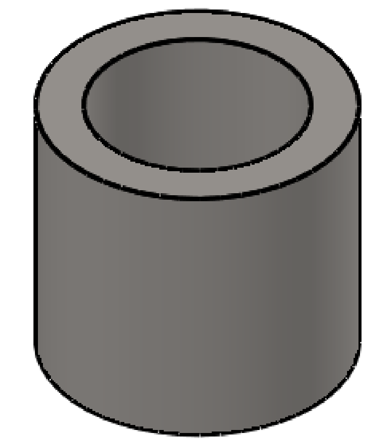
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020





TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 304		DESCRIPTION WEIGHT VERTICAL SLIDING ROD	
FINISH CHROMIUM PLATING		PN 6966	REV A — SHEET 1 of 1

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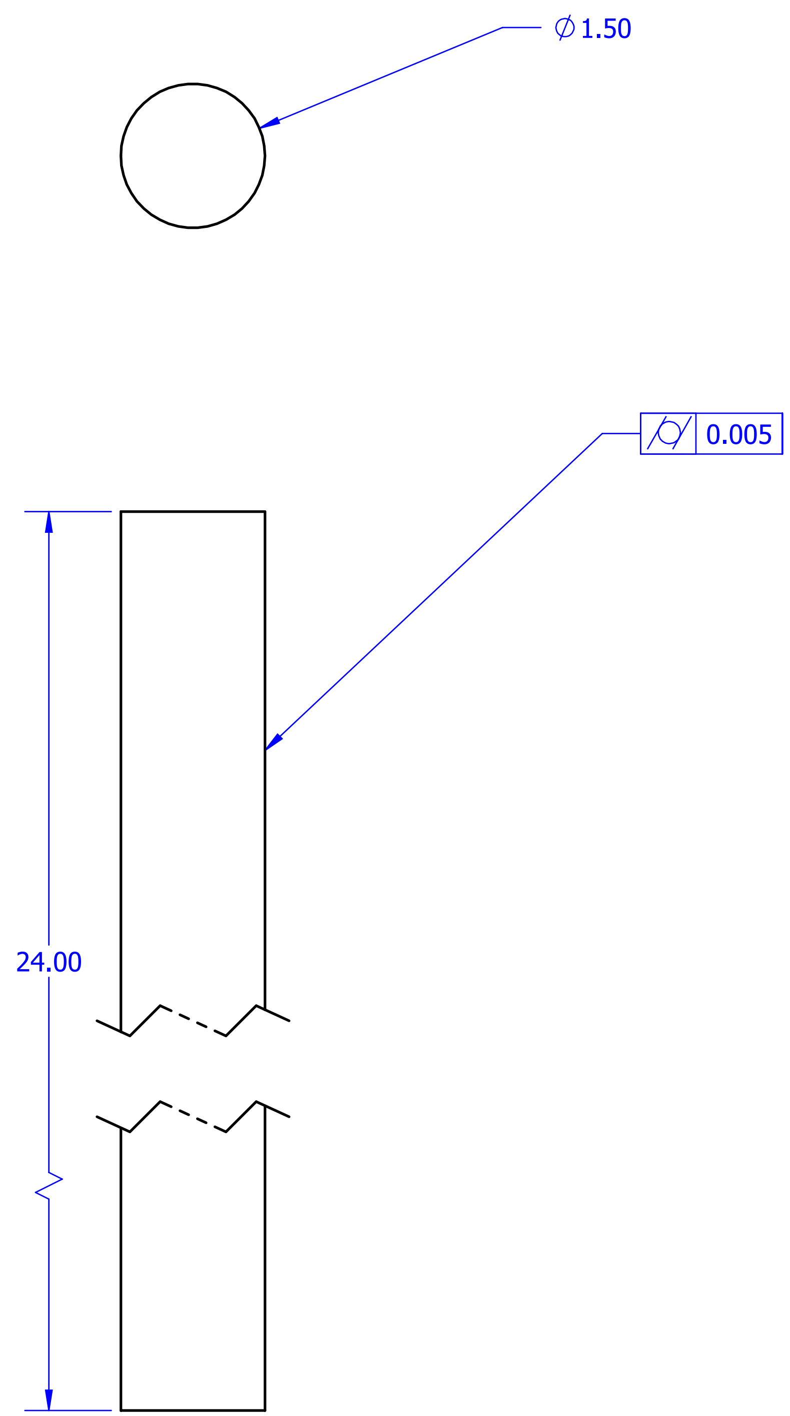
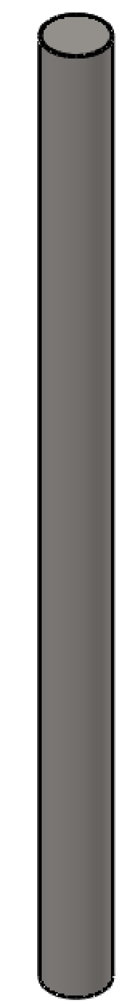
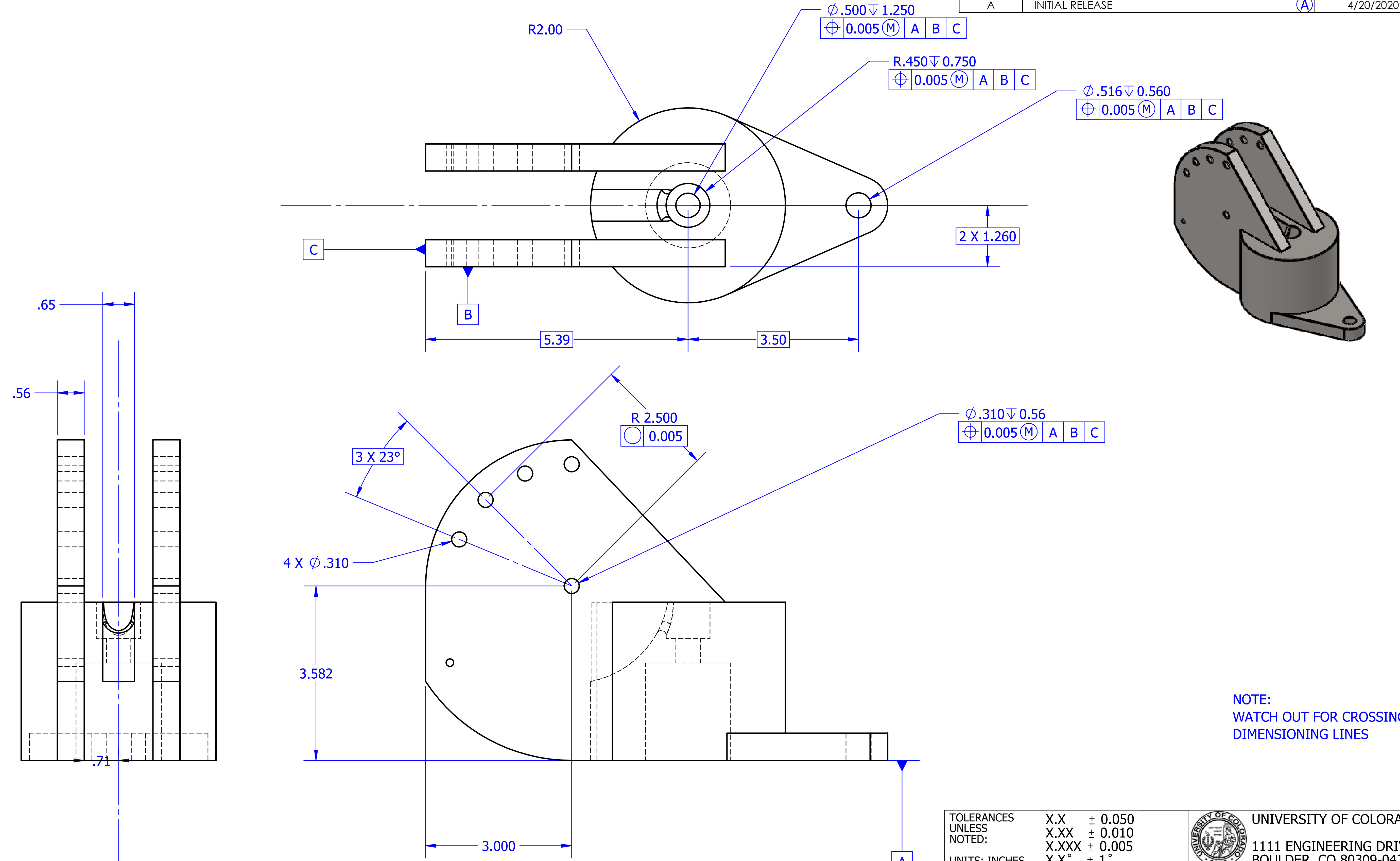
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020





TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427			
MATERIAL AISI 304		DESCRIPTION WEIGHT VERTICAL STATIONARY ROD			
FINISH CHROMIUM PLATING		PN 6866	REV A		SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/20/2020



NOTE:
WATCH OUT FOR CROSSING
DIMENSIONING LINES

TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL Cast Carbon Steel		DESCRIPTION WEIGHT ADJUSTER
FINISH NONE		PN 6766 · REV A · SHEET 1 of 2

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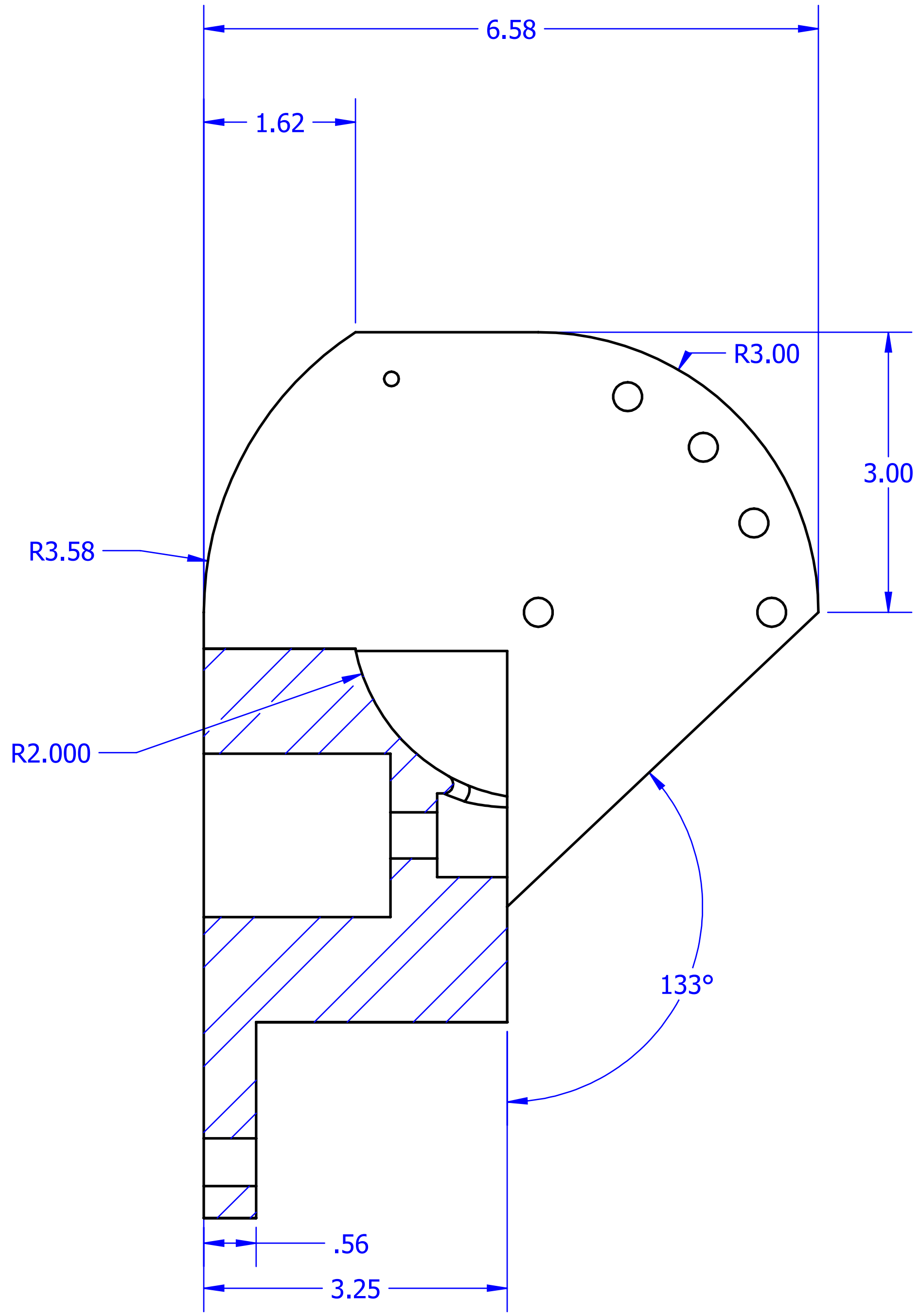
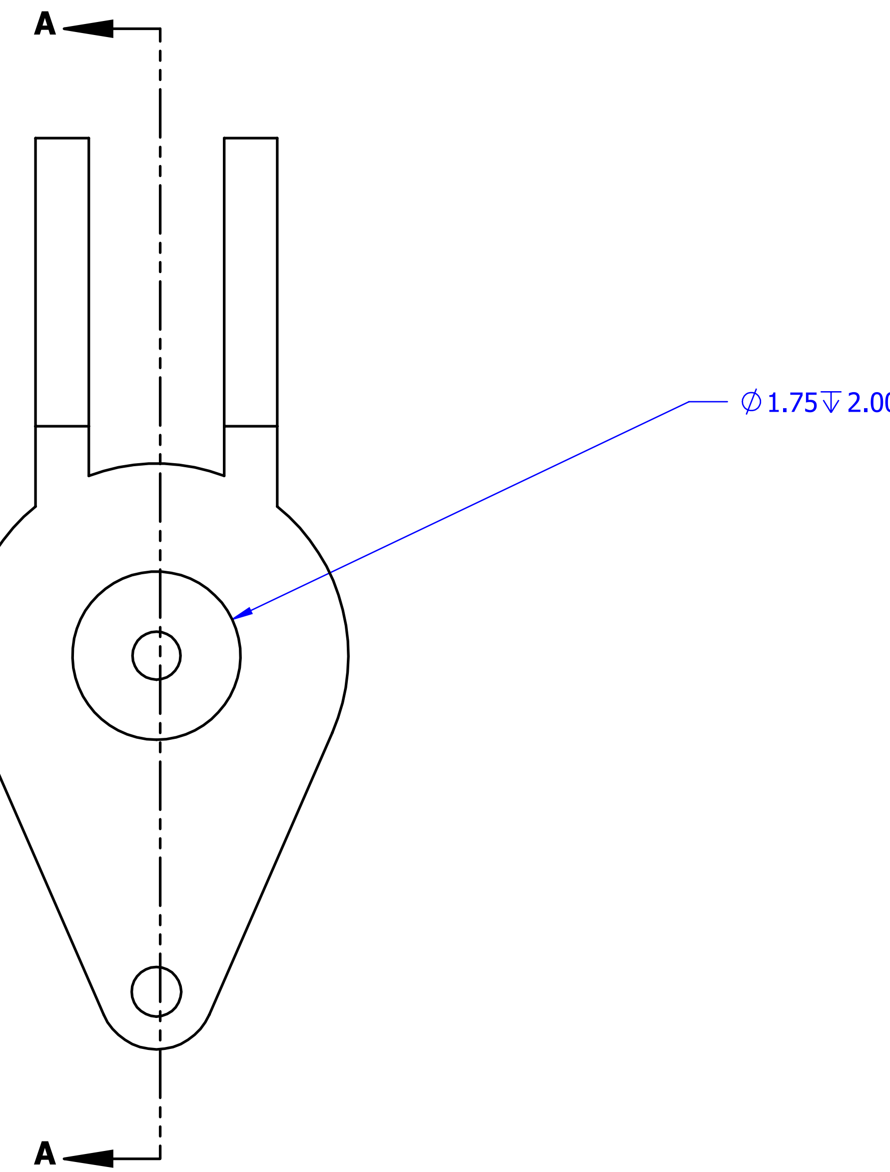
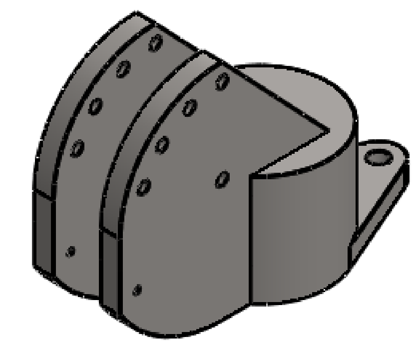
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/20/2020



SECTION A-A
SCALE 1 : 2

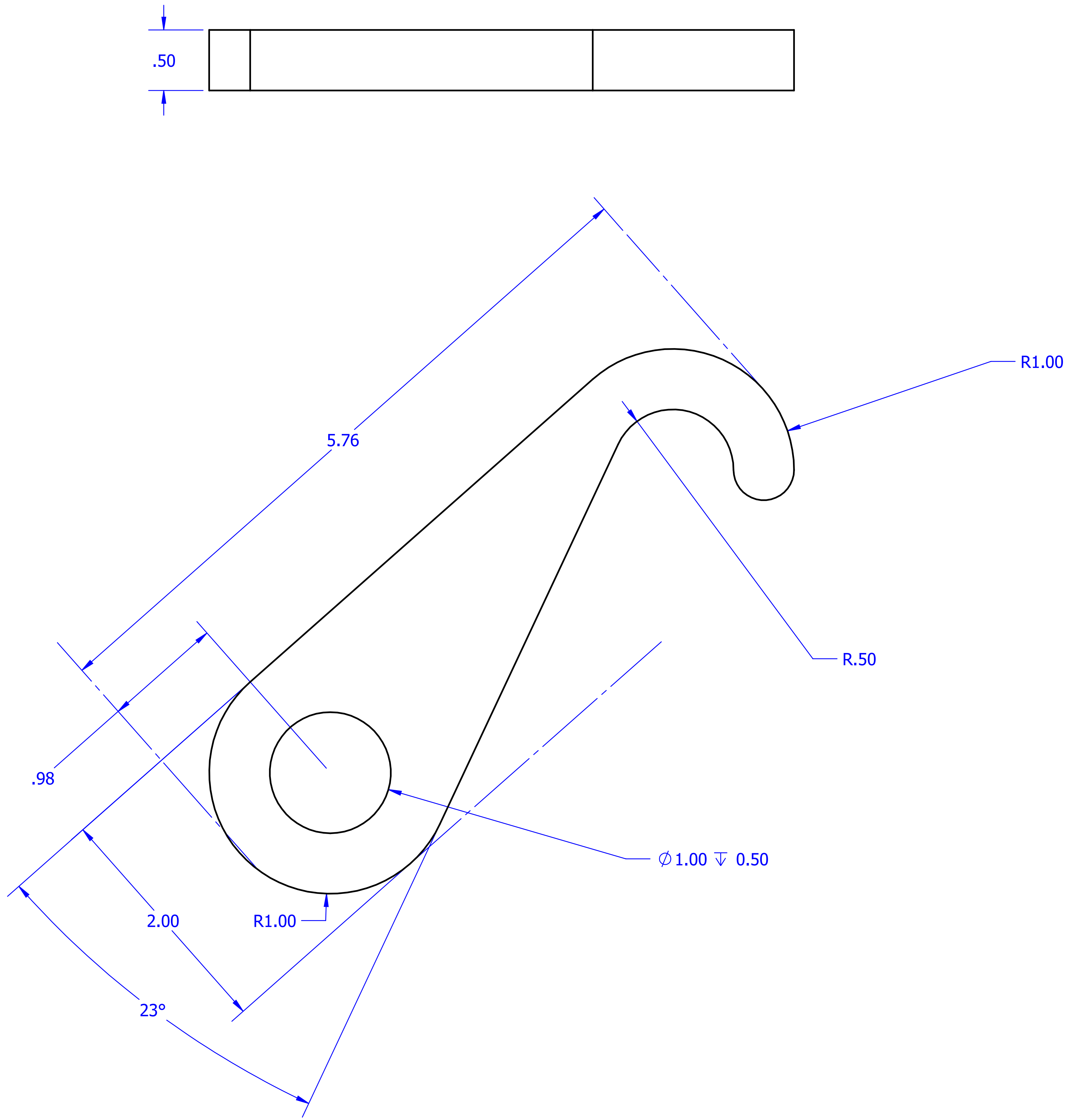


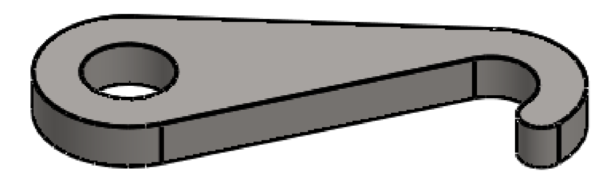


NOTE:
WATCH OUT FOR CROSSING
DIMENSIONING LINES

TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL Cast Carbon Steel	DESCRIPTION WEIGHT ADJUSTER	
FINISH NONE	PN 6766 · REV A	SHEET 2 of 2

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



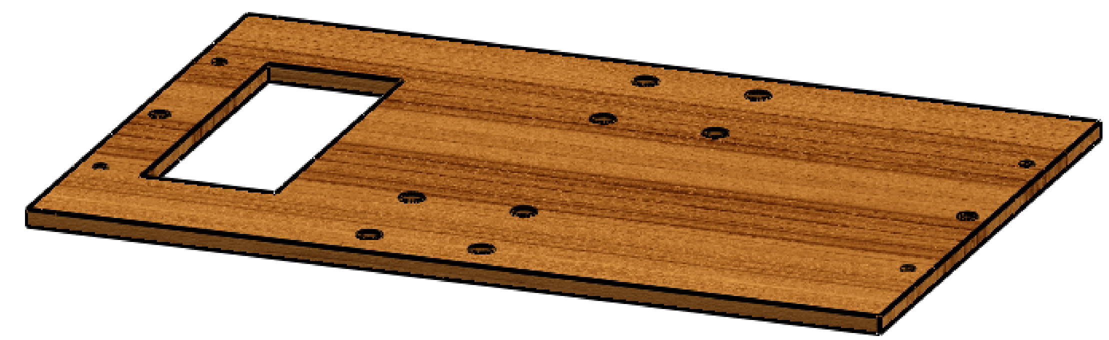


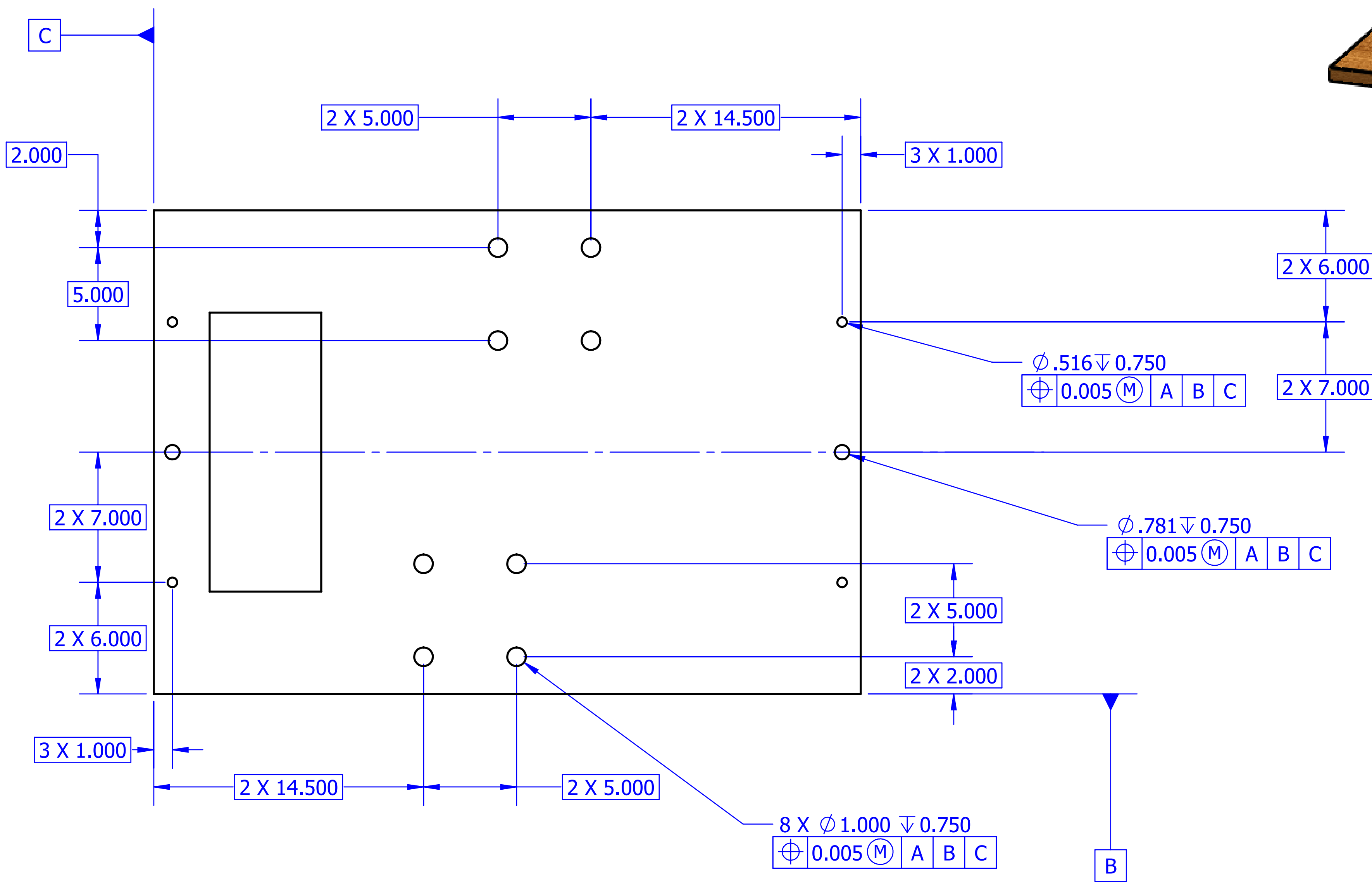
TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427				
UNITS: INCHES						
MATERIAL AISI 1020		DESCRIPTION SMITH MACHINE POSITION HOOK				
FINISH NONE		PN 6696	REV A			SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020

TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
UNITS: INCHES		
MATERIAL AISI 304		DESCRIPTION SMITH MACHINE HANDLE
FINISH CHROMIUM PLATING		PN 6686 · REV A · SHEET 1 of 1

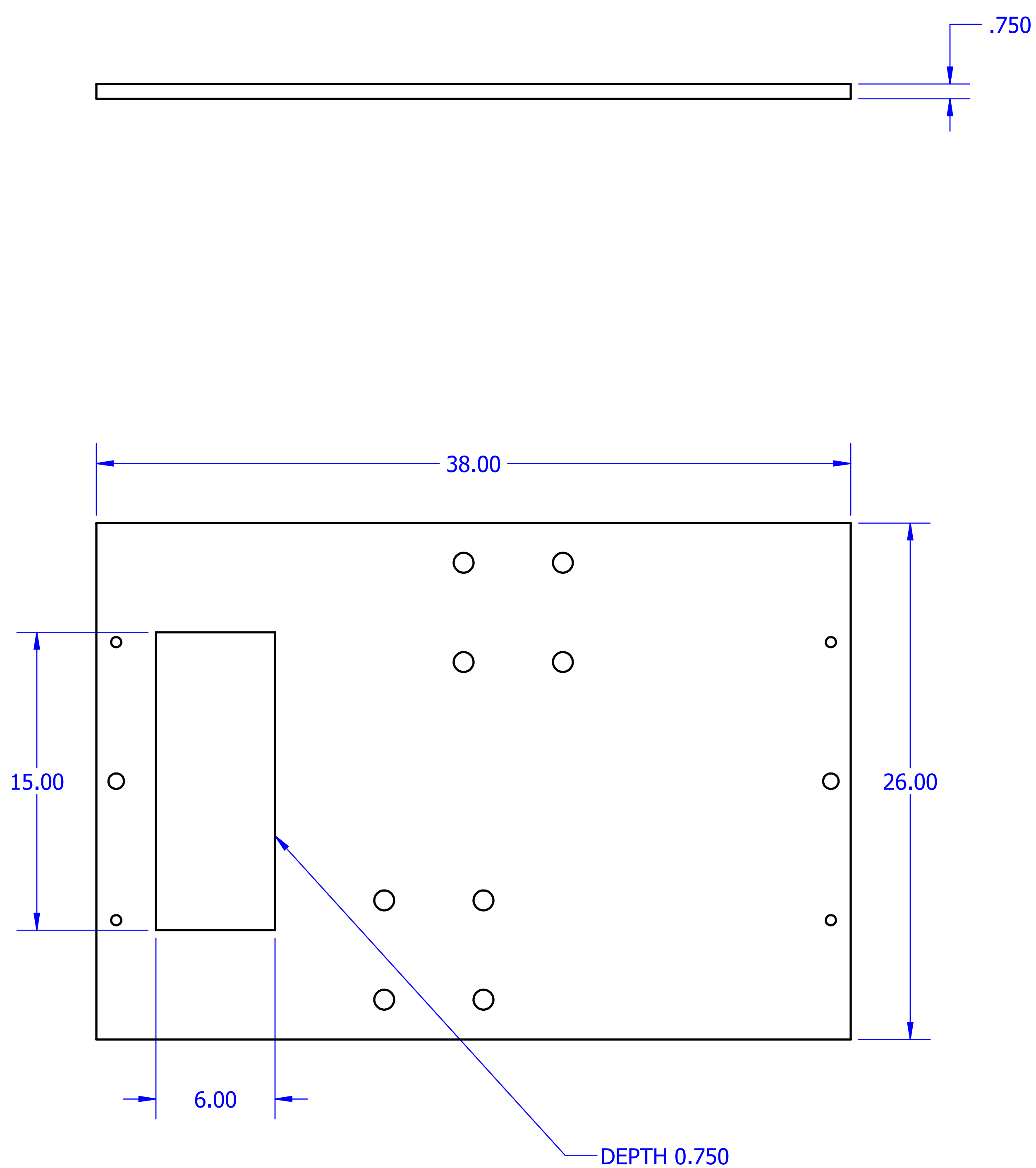
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020





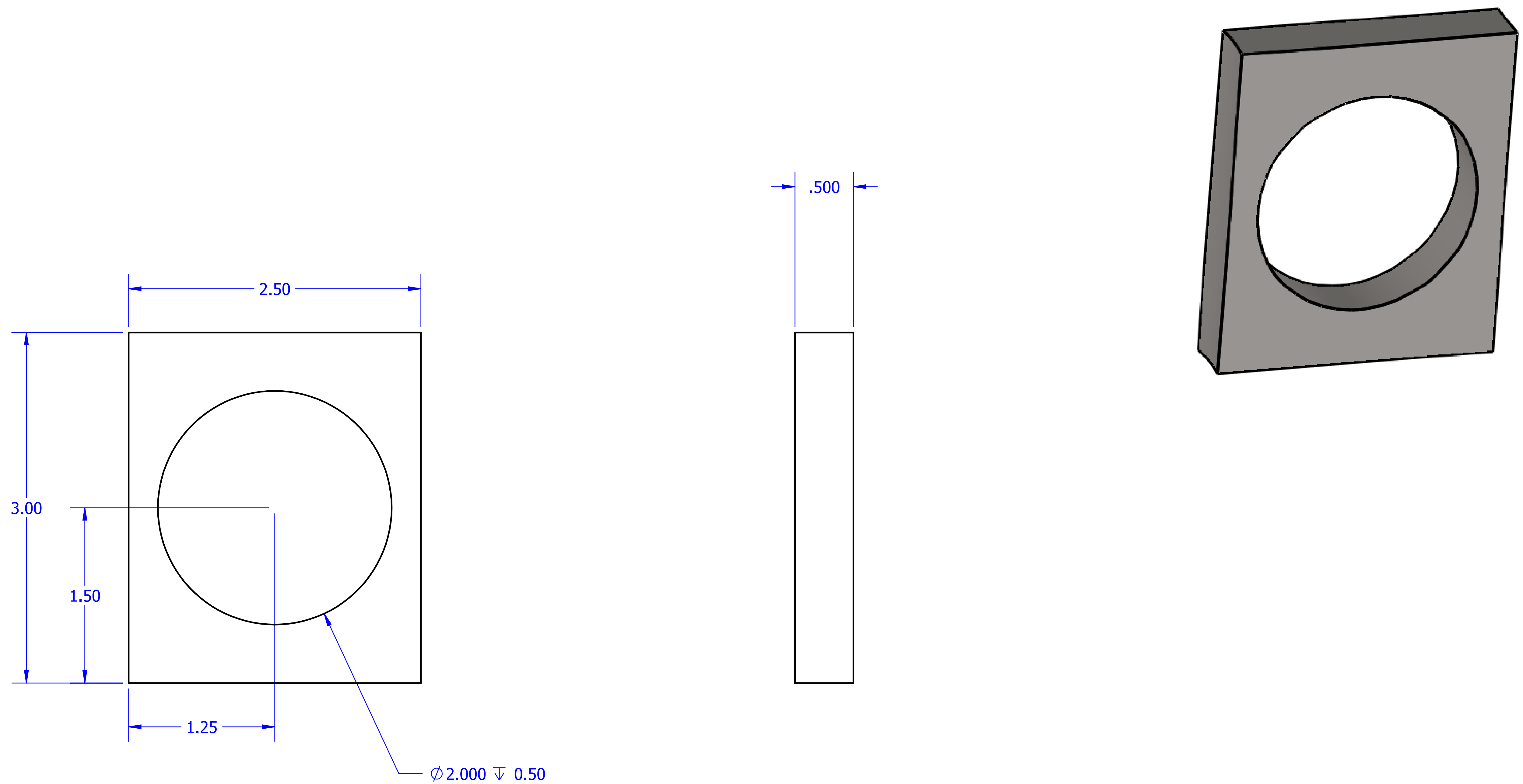
TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427		
UNITS: INCHES				
MATERIAL Teak		DESCRIPTION TABLE TOP		
FINISH POLYURETHANE		PN 6677	REV A	SHEET 1 of 2

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL Teak		DESCRIPTION TABLE TOP	
FINISH POLYURETHANE	PN 6677	REV A	SHEET 2 of 2

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



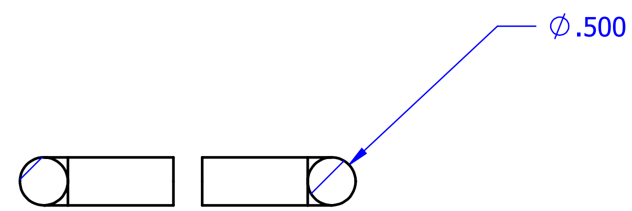
TOLERANCES UNLESS NOTED:	X.X	± 0.050
	X.XX	± 0.010
	X.XXX	± 0.005
UNITS: INCHES	X.X°	± 1°

UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

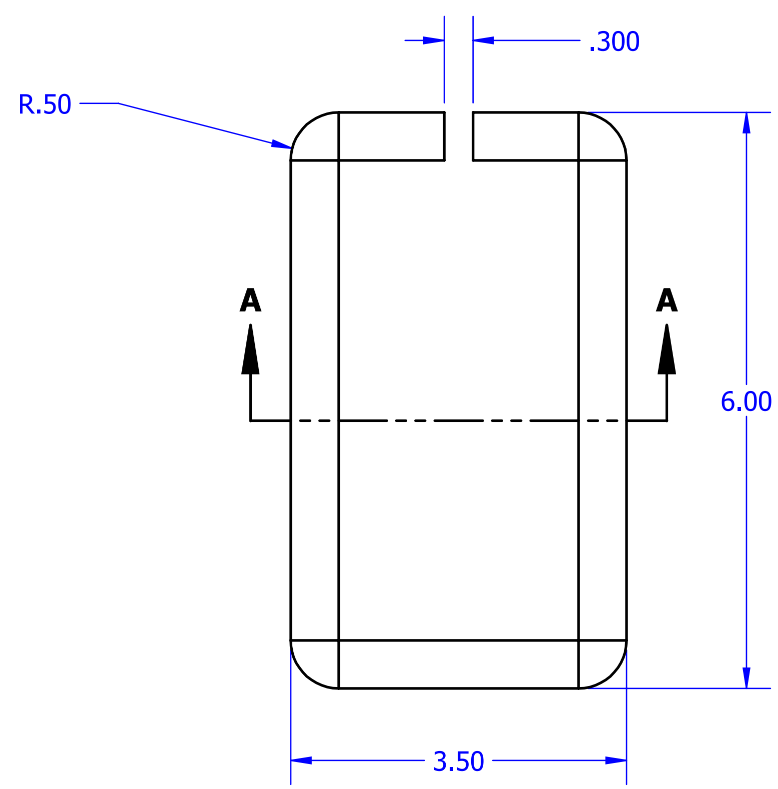
MATERIAL	DESCRIPTION
AISI 1020	SMITH MACHINE SLIDER BLOCK

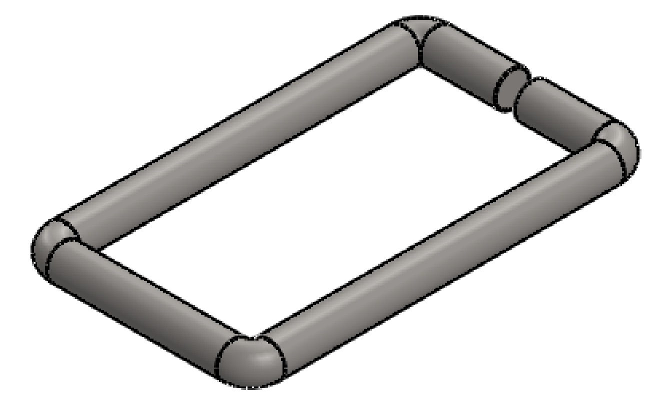
FINISH	PN	REV	SHEET
NONE	6676	A	1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



SECTION A-A





TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 304		DESCRIPTION PCP ADJUSTER	
FINISH NONE		PN 6671	REV A — SHEET 1 of 1

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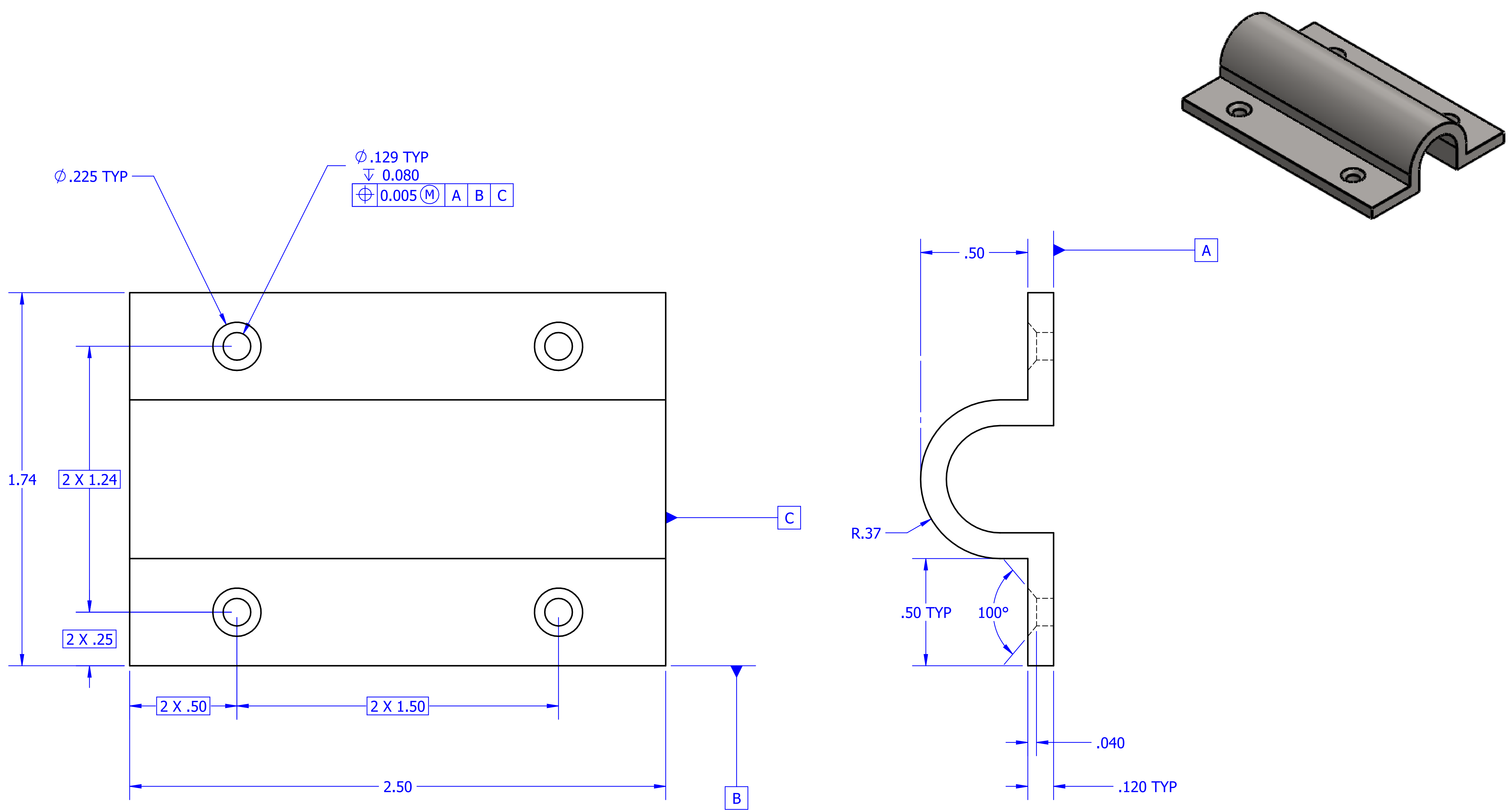
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION PCP ADJUSTER CONNECTOR
FINISH NONE	PN 6670 REV A	SHEET 1 of 1

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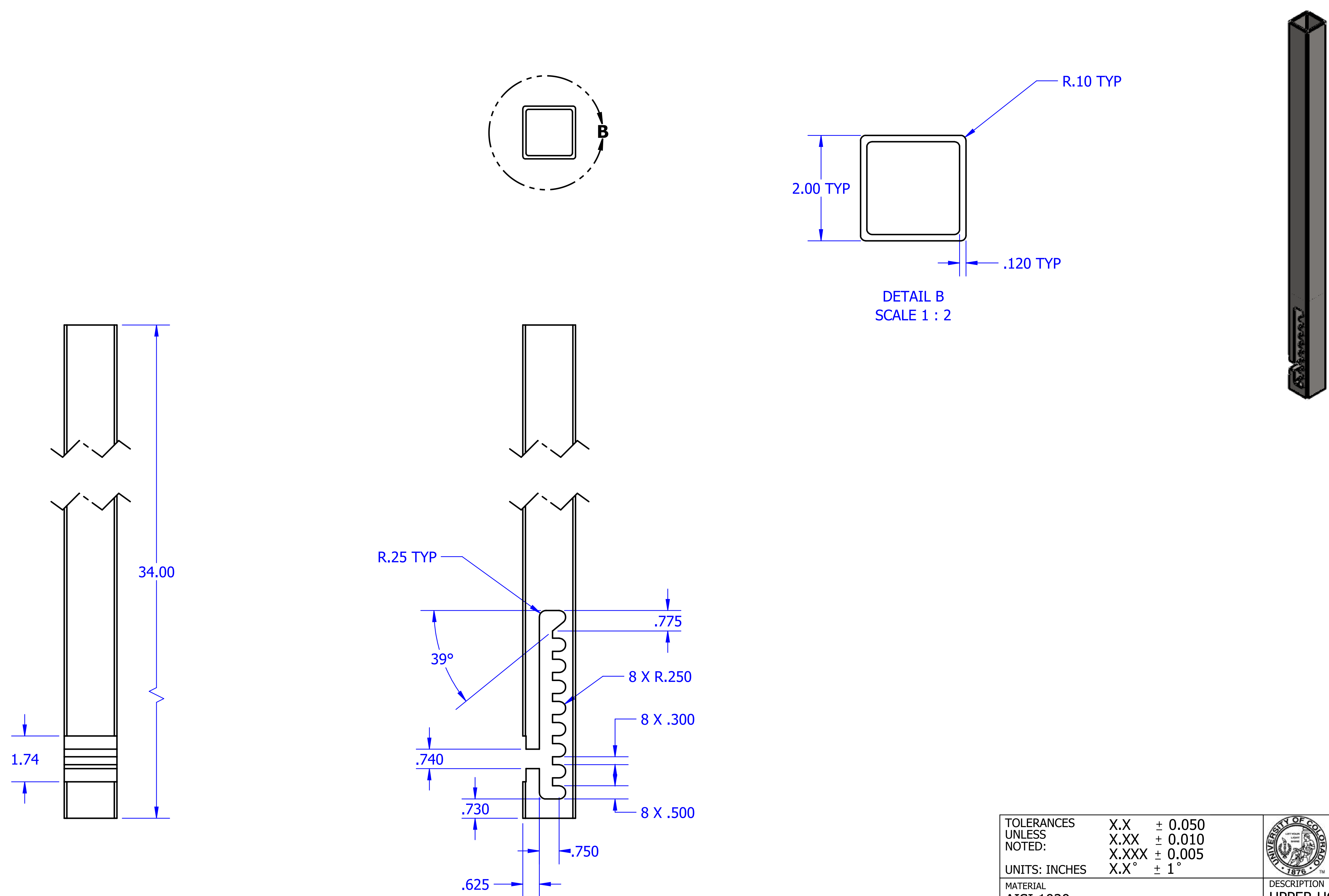
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/20/2020



TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 1020		DESCRIPTION UPPER HORIZONTAL BAR	
FINISH NONE		PN 6669	REV A
			SHEET 1 of 1

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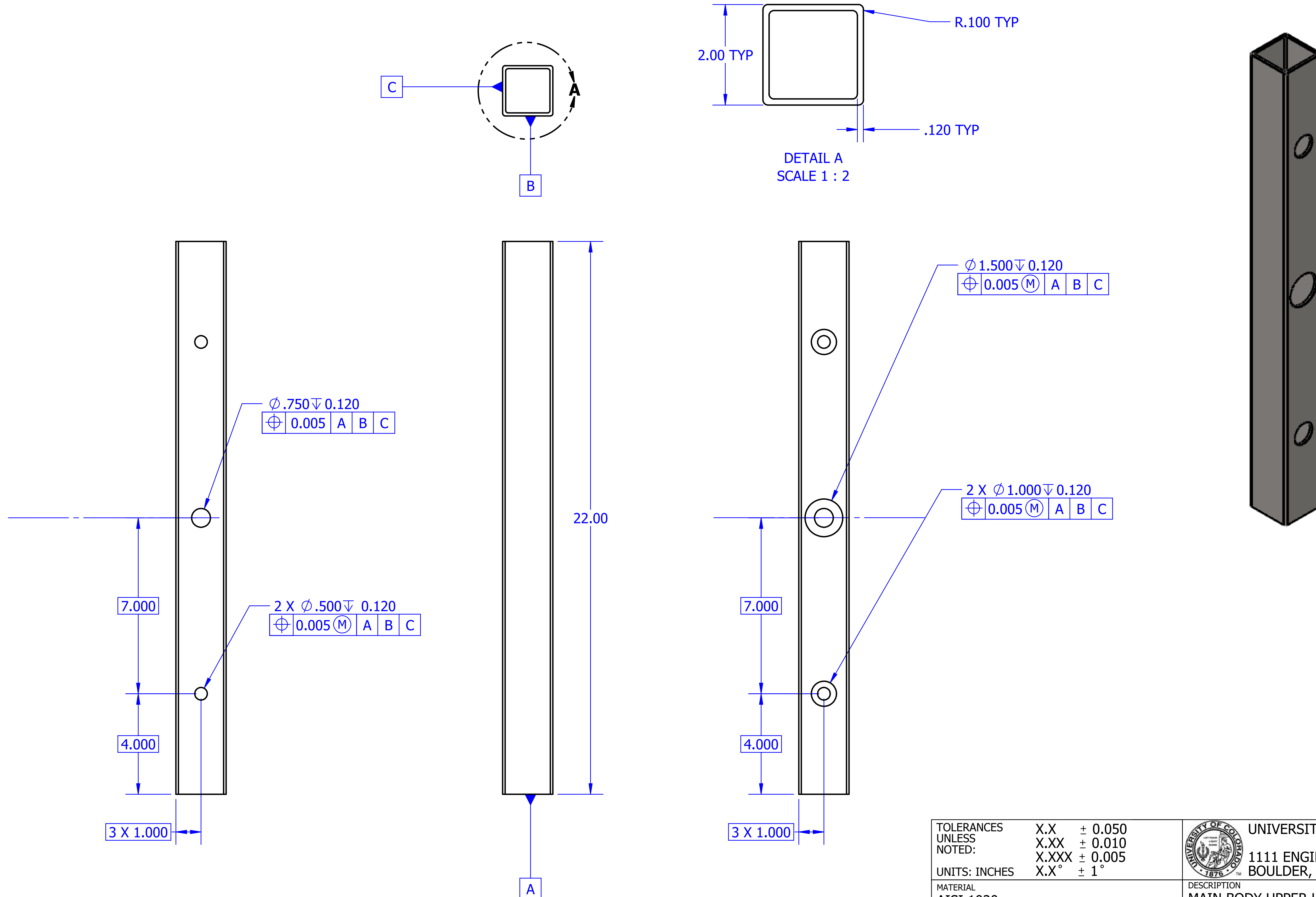
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/19/2020



TOLERANCES UNLESS NOTED: X.X ± 0.050; X.XX ± 0.010; X.XXX ± 0.005; X.X° ± 1° — UNITS: INCHES	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL AISI 1020	DESCRIPTION MAIN BODY UPPER HORIZONTAL BAR WIDTH	
FINISH NONE	PN 6668	REV A — SHEET 1 of 1
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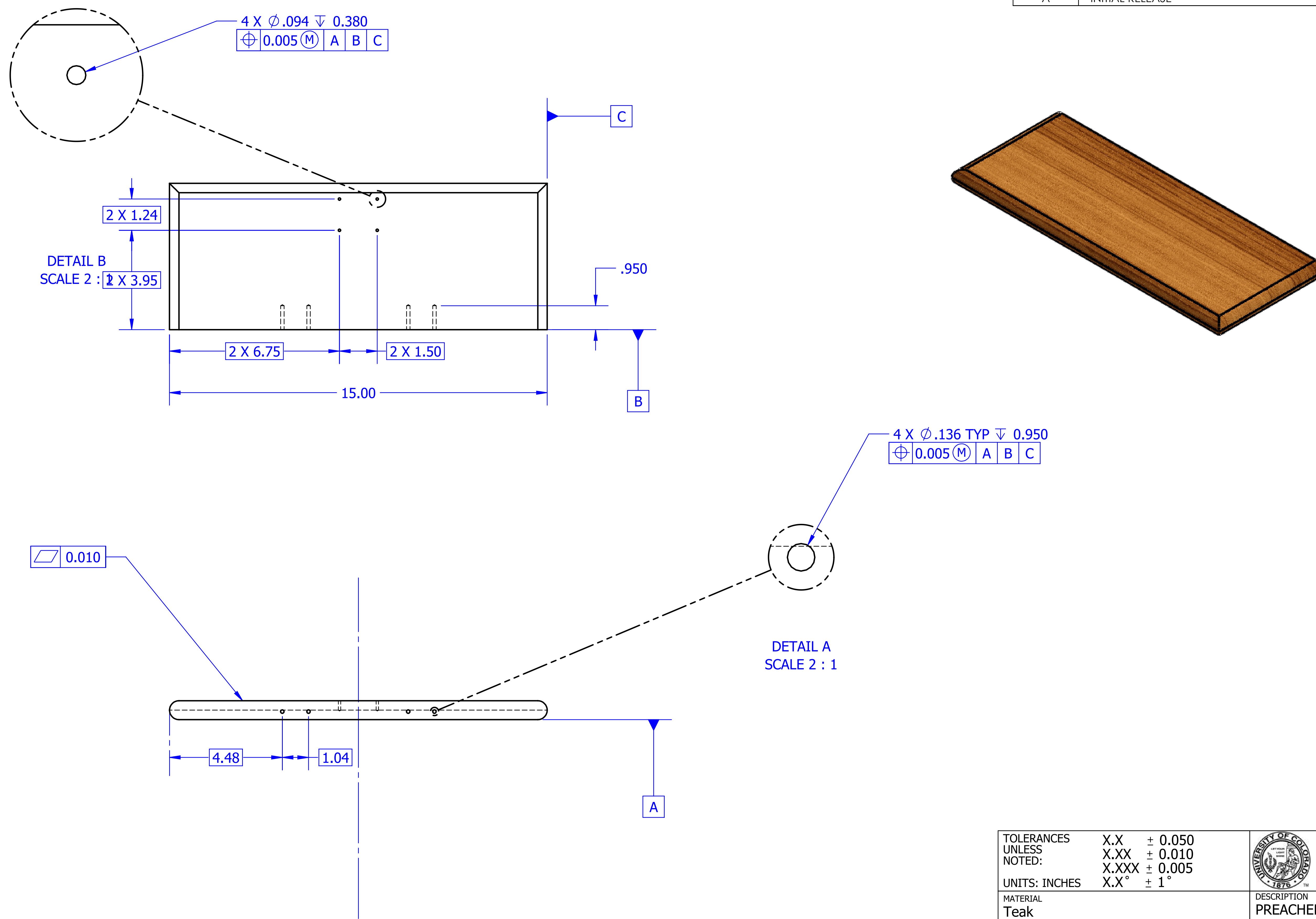
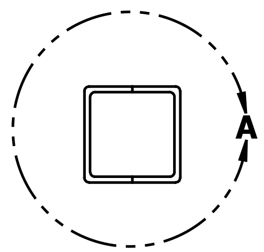
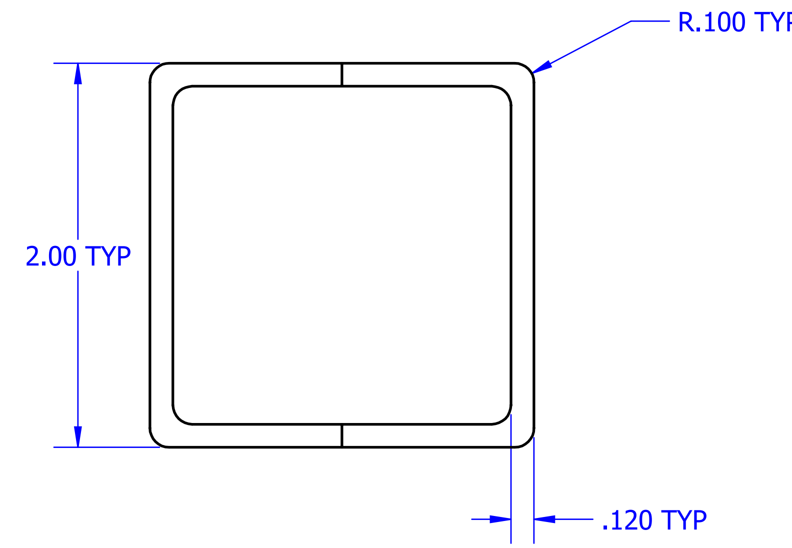
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



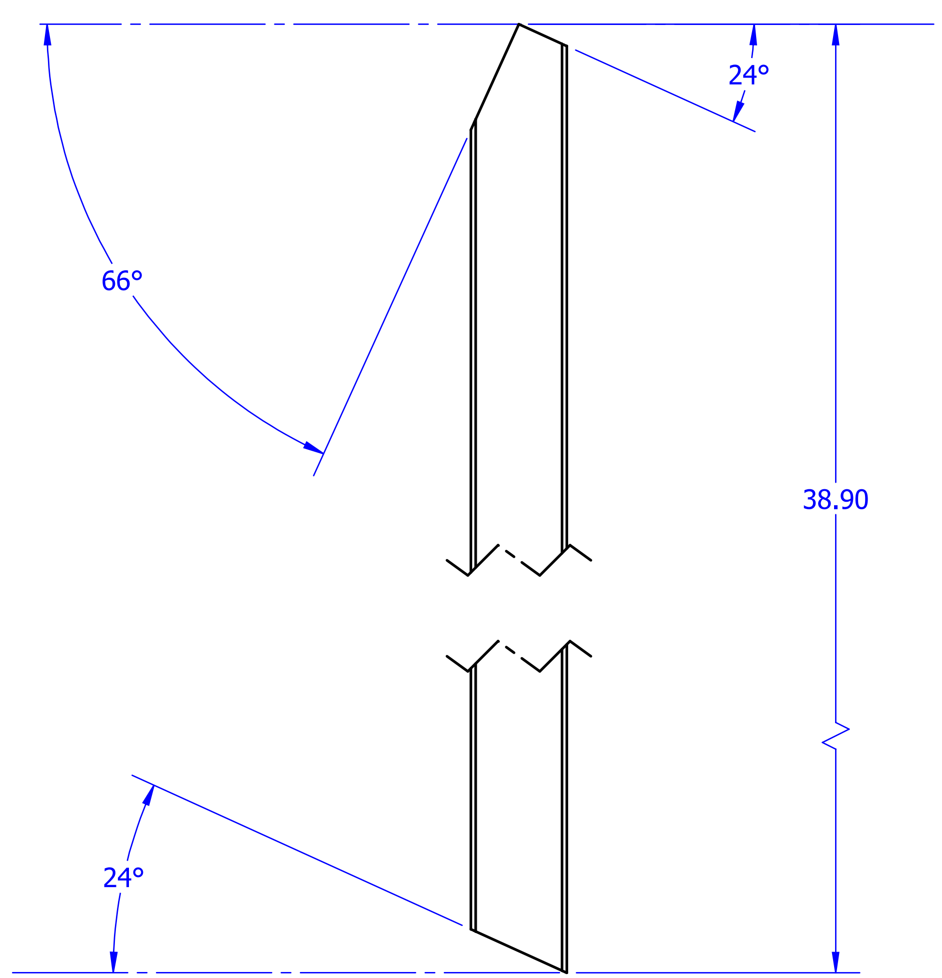
TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
UNITS: INCHES		
MATERIAL Teak		DESCRIPTION PREACHER CURL PAD
FINISH POLYURETHANE		PN 6667 · REV A · SHEET 1 of 1

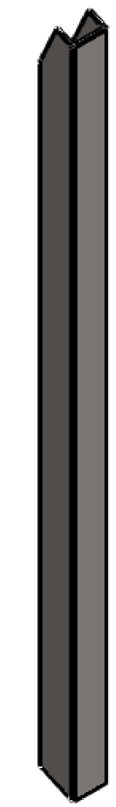
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020





DETAIL A
SCALE 1 : 1





TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020	DESCRIPTION MAIN BODY DIAGONAL BAR
FINISH NONE	PN 6665 REV A SHEET 1 of 1

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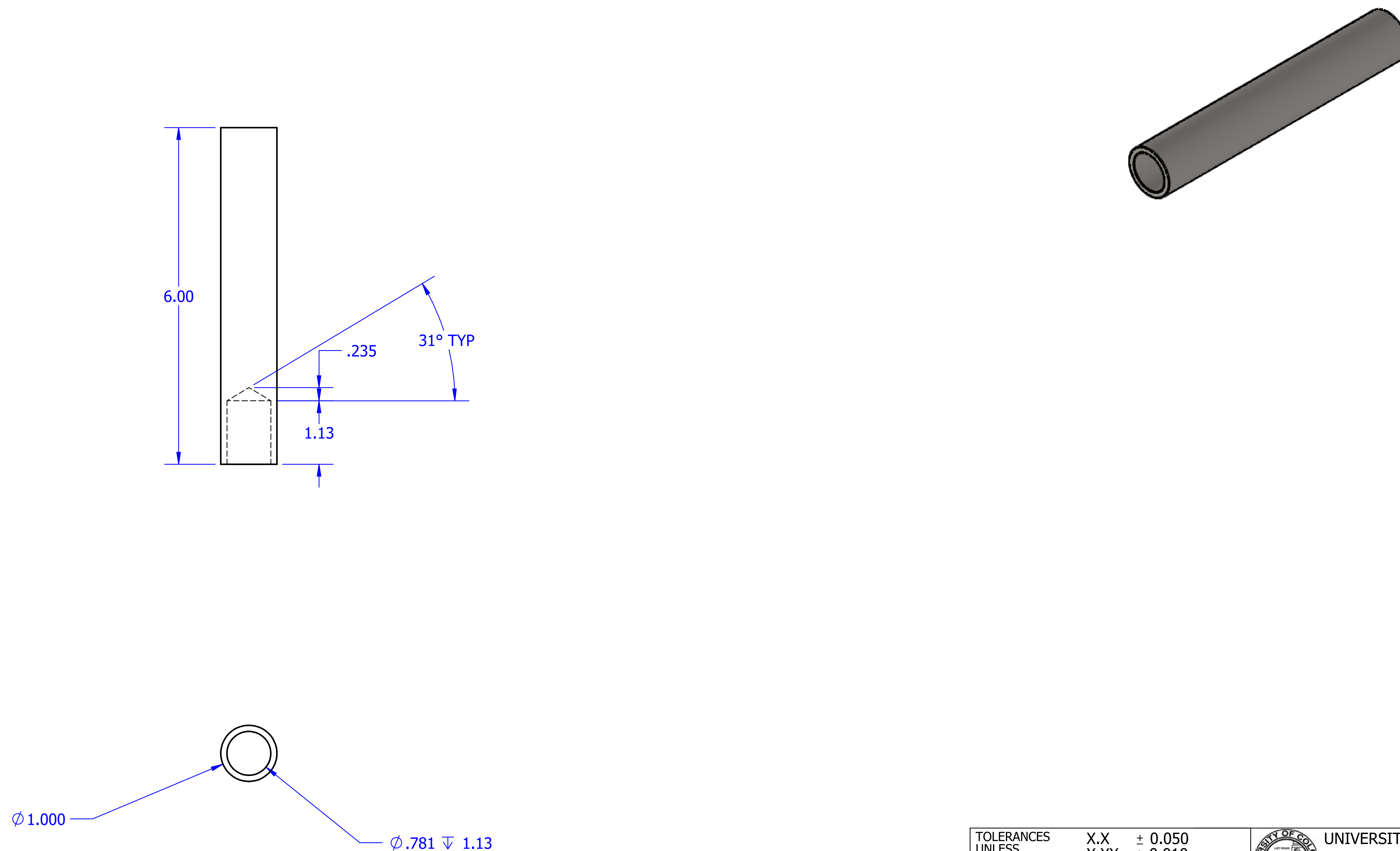
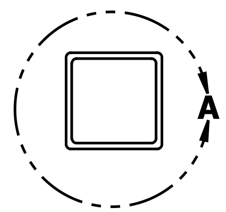
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020

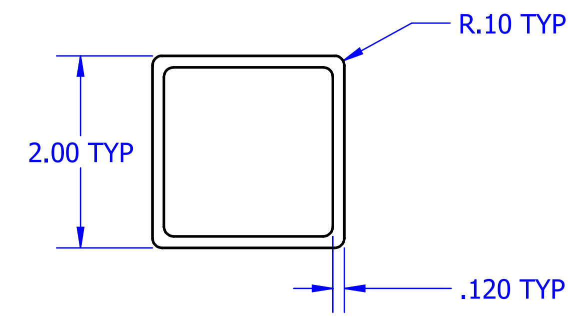


TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 304		DESCRIPTION GRIPPING PEG	
FINISH NONE		PN 6664	REV A · SHEET 1 of 1

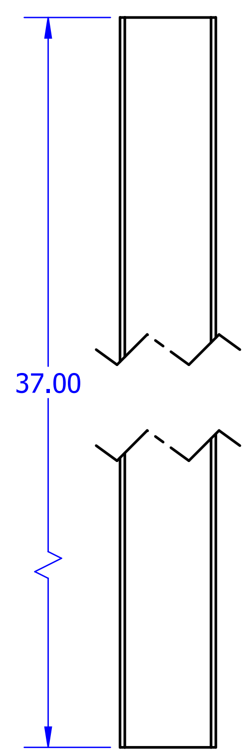
PROPRIETARY AND CONFIDENTIAL

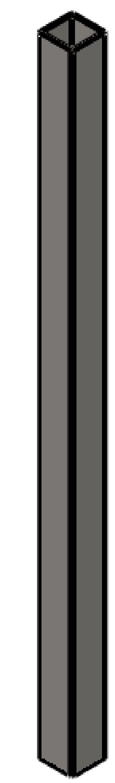
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/19/2020





DETAIL A
SCALE 1 : 2





TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1°; UNITS: INCHES		UNIVERSITY OF COLORADO, 1111 ENGINEERING DRIVE, BOULDER, CO 80309-0427
MATERIAL: AISI 1020		DESCRIPTION: MAIN BODY VERTICAL BAR HEIGHT
FINISH: NONE	PN: 6663	REV: A; SHEET: 1 of 1

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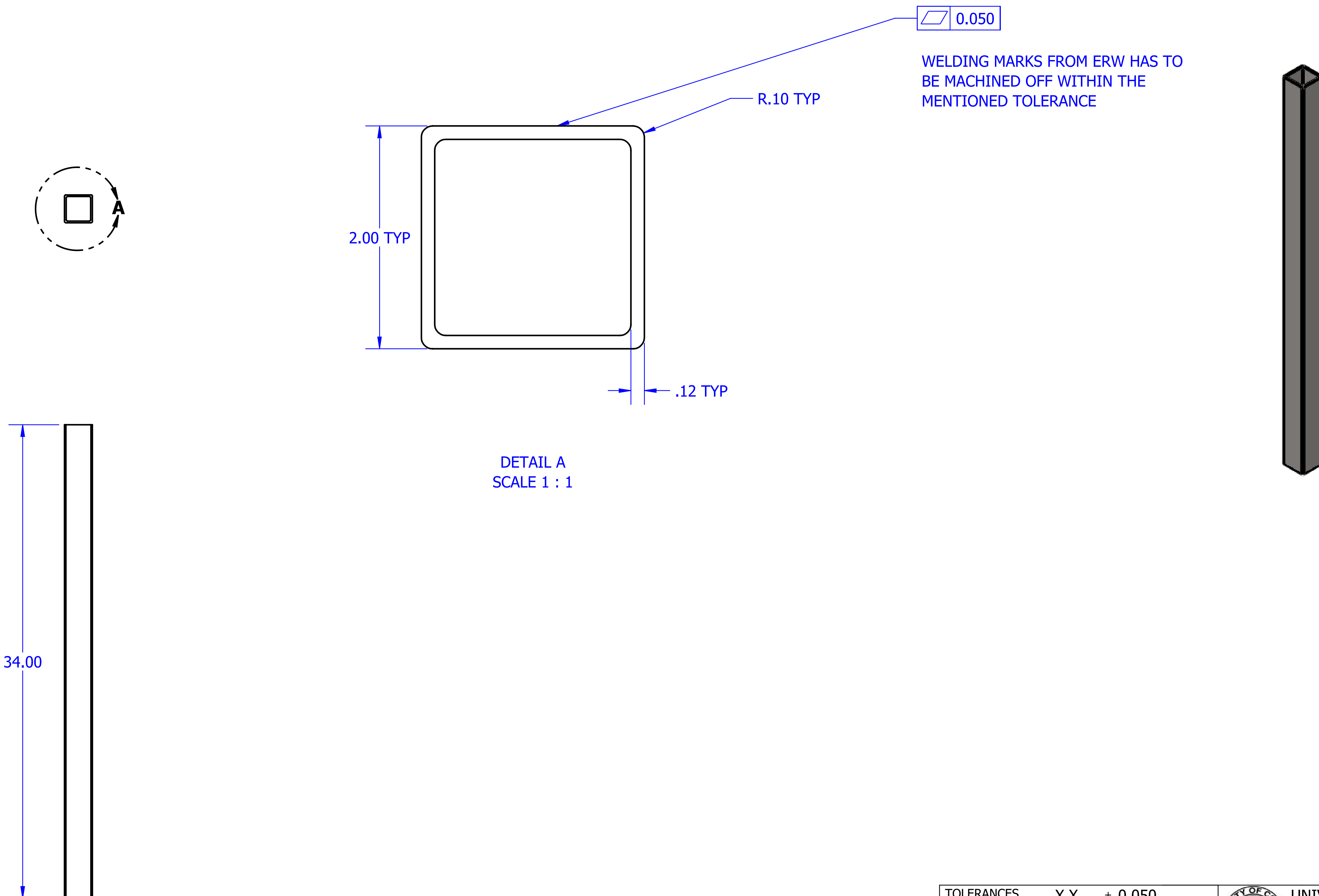
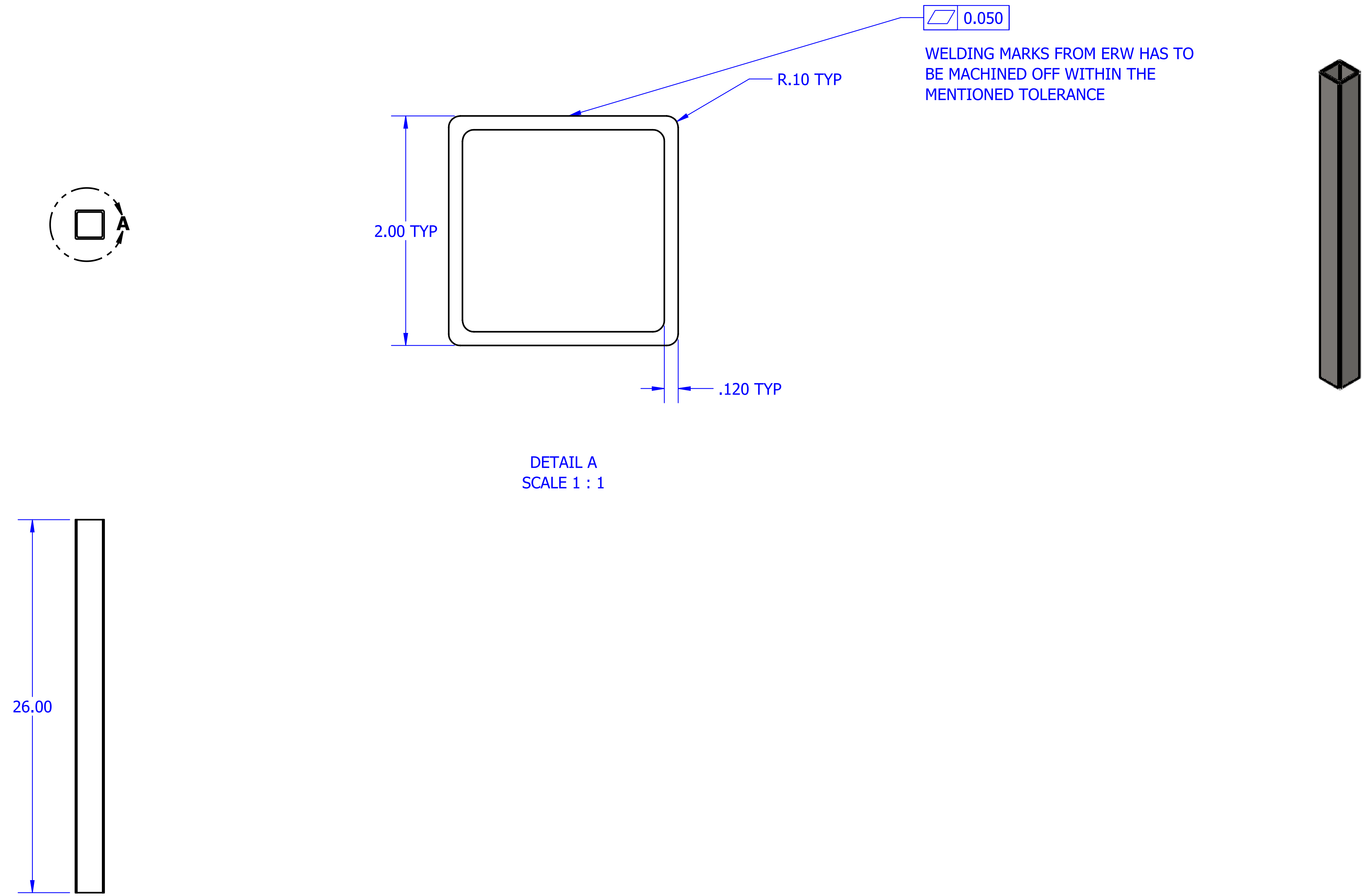
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL AISI 1020		DESCRIPTION TABLE LENGTH HORIZONDAL BAR	
FINISH NONE		PN 6662 / REV A	SHEET 1 of 1



REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020

TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1°; UNITS: INCHES		UNIVERSITY OF COLORADO, 1111 ENGINEERING DRIVE, BOULDER, CO 80309-0427	
MATERIAL: AISI 1020		DESCRIPTION: TABLE WIDTH HORIZONTAL BAR	
FINISH: NONE	PN: 6661	REV: A	SHEET: 1 of 1

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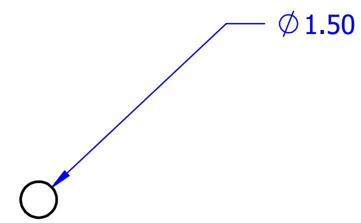
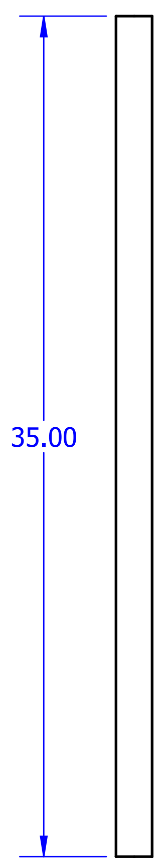
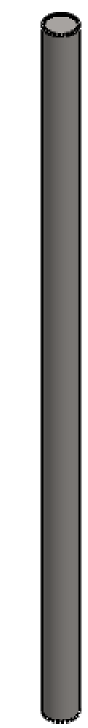
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020

TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 304		DESCRIPTION SMITH MACHINE SLIDER
FINISH CHROMIUM PLATING		PN 6656 · REV A · SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020

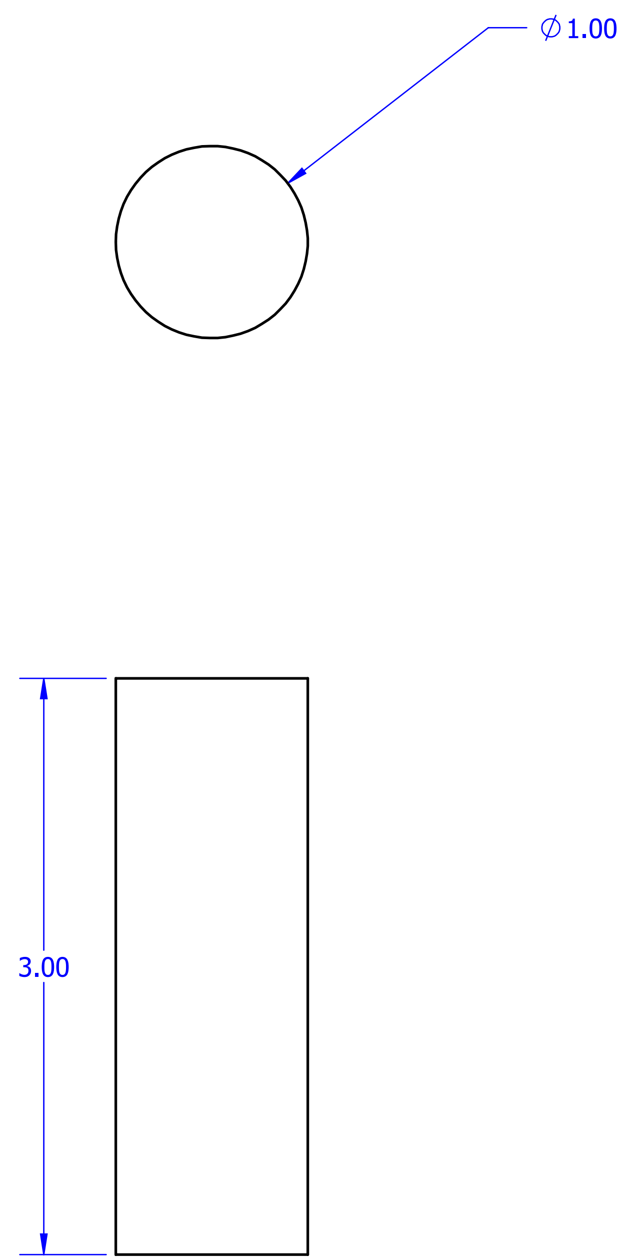






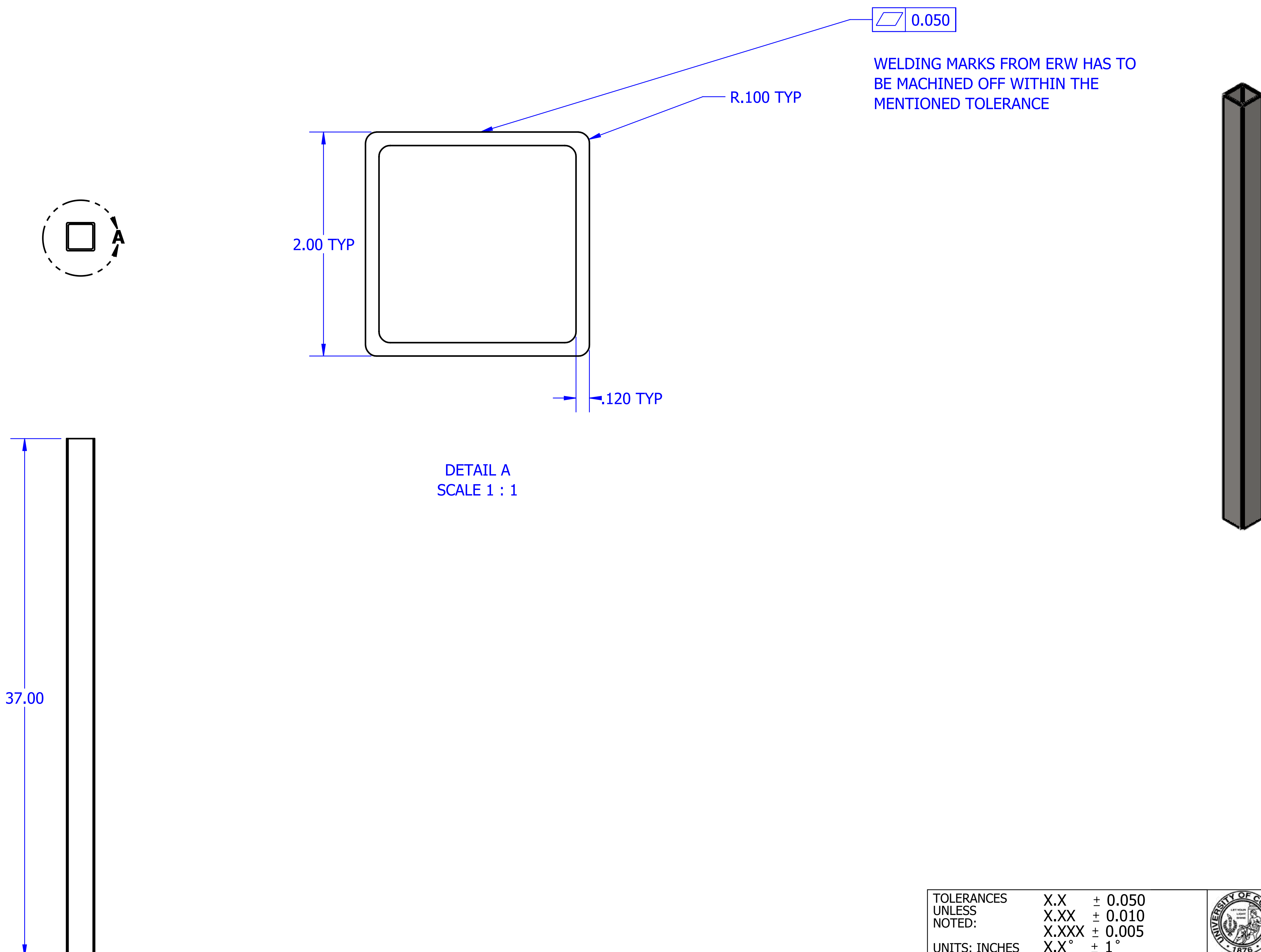
TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL AISI 304		DESCRIPTION SMITH MACHINE ROD	
FINISH CHROMIUM PLATING		PN 6636	REV A
		SHEET 1 of 1	

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



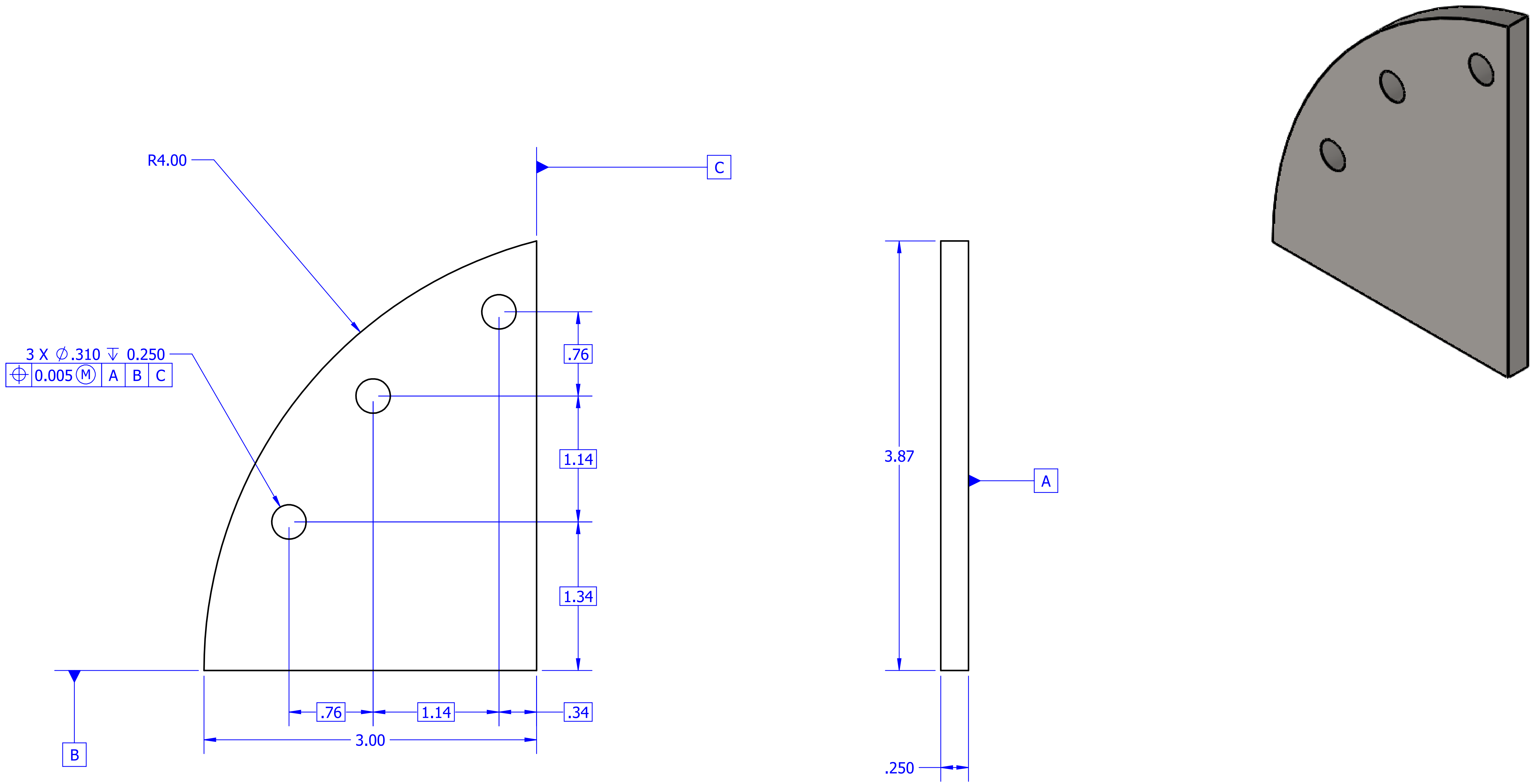
TOLERANCES UNLESS NOTED: X.X ± 0.050; X.XX ± 0.010; X.XXX ± 0.005; X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION SMITH MACHINE POSITION ROD
FINISH NONE		PN 6626 · REV A · SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION SMITH MACHINE VERTICAL BAR
FINISH NONE		PN 6616 · REV A · SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
UNITS: INCHES			
MATERIAL Cast Carbon Steel		DESCRIPTION WEIGHT ADJUSTER PLATE	
FINISH NONE		PN 6566	REV A
		SHEET 1 of 1	

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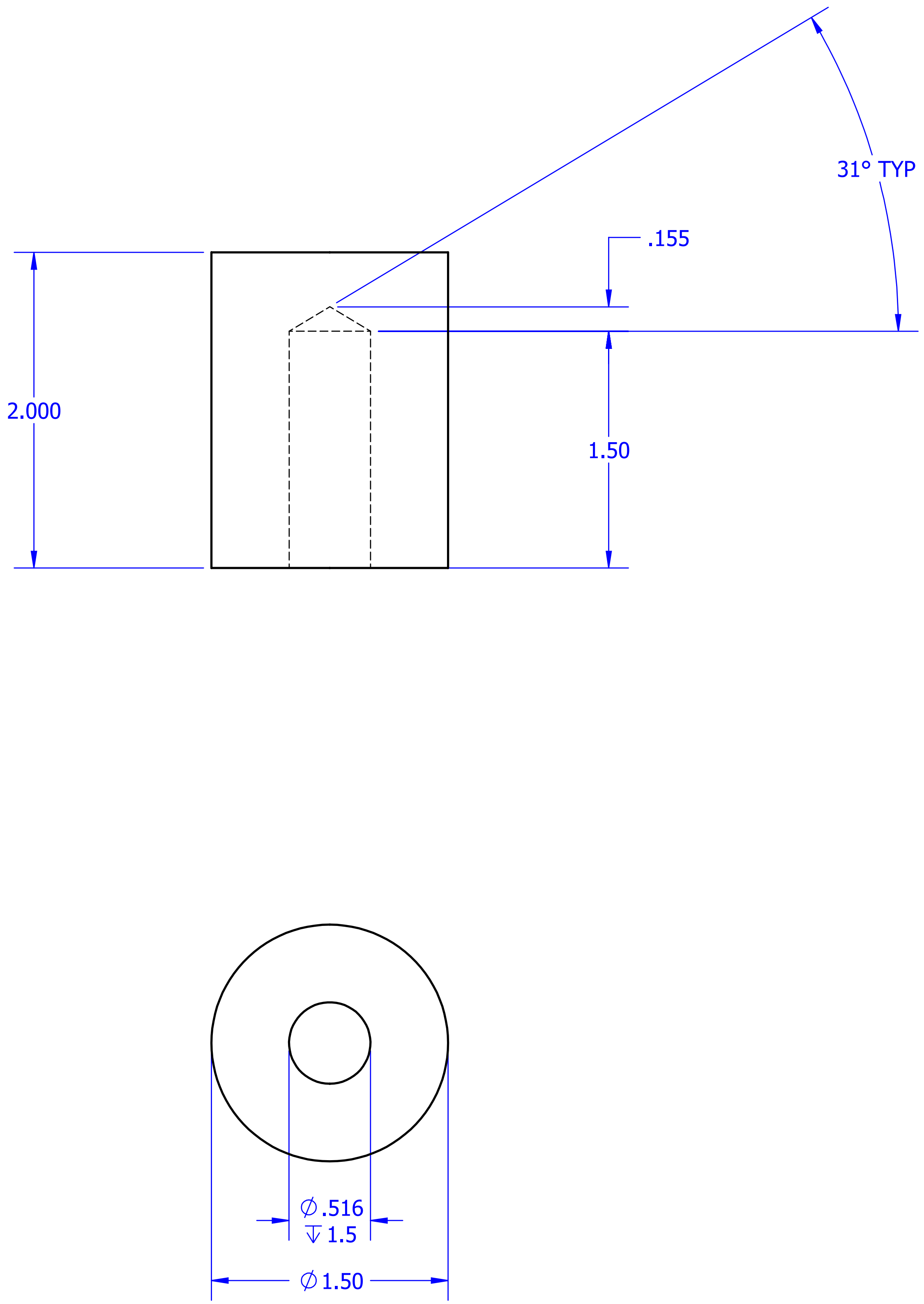
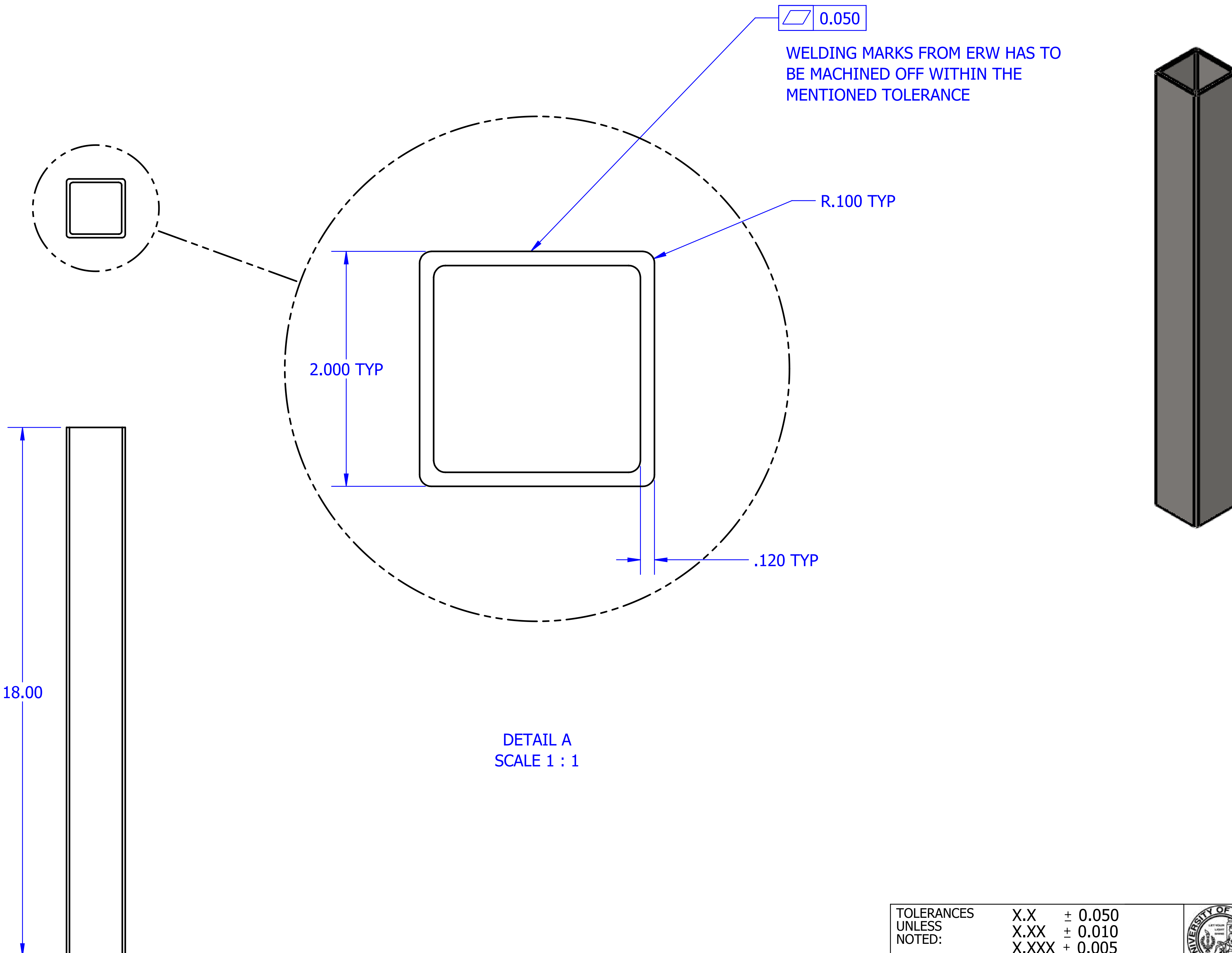
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1°; UNITS: INCHES	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL AISI 1020	DESCRIPTION WEIGHT ADJUSTMENT ROD	
FINISH NONE	PN 6466 · REV A	SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/18/2020



TOLERANCES UNLESS NOTED:	X.X	± 0.050
	X.XX	± 0.010
	X.XXX	± 0.005
UNITS: INCHES	X.X°	± 1°

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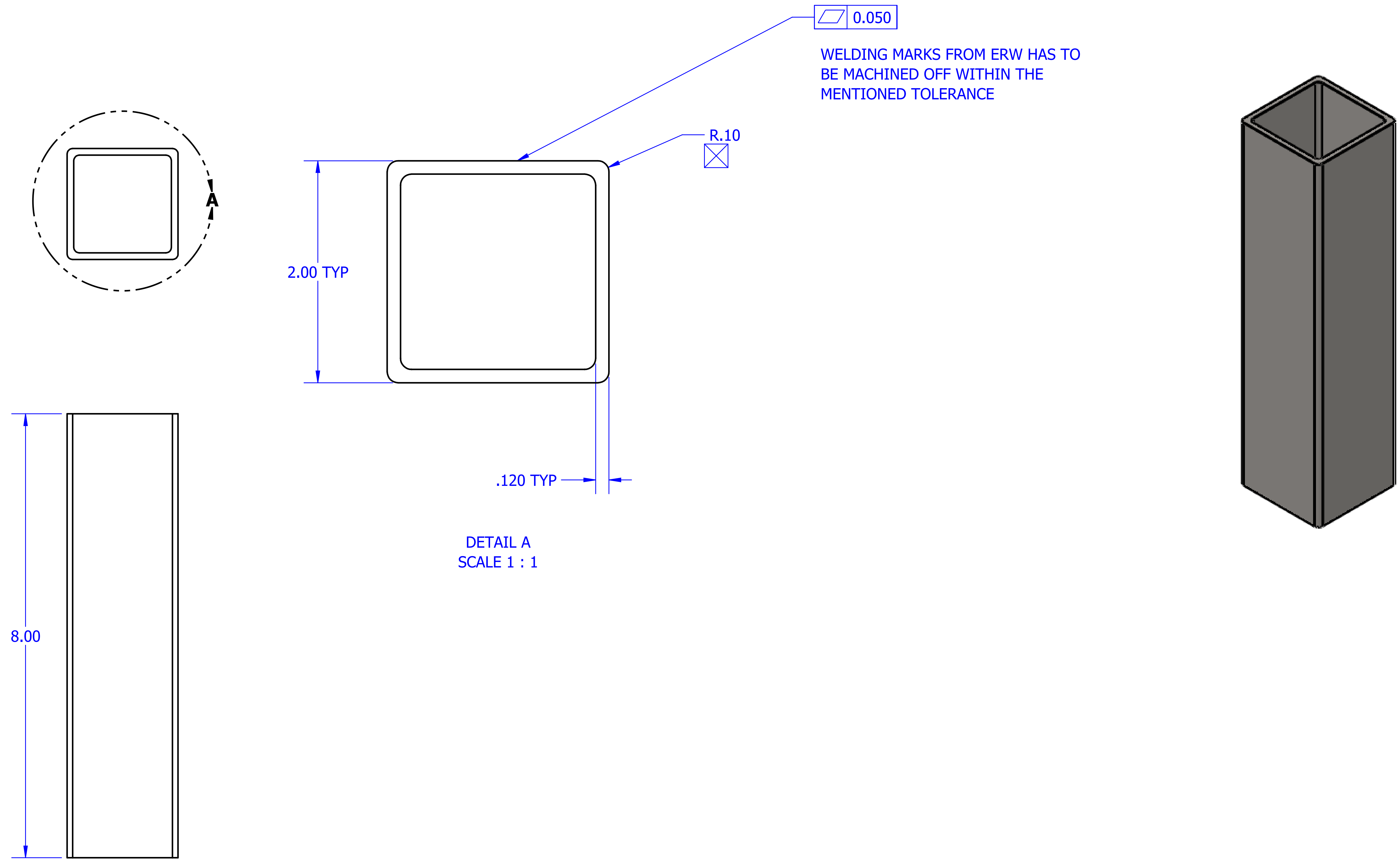
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

MATERIAL: AISI 1020
DESCRIPTION: WEIGHT GROUND BAR
FINISH: NONE
PN: 6366
REV: A
SHEET: 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1°; UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION WEIGHT HORIZONTAL BAR
FINISH NONE		PN 6266 · REV A · SHEET 1 of 1

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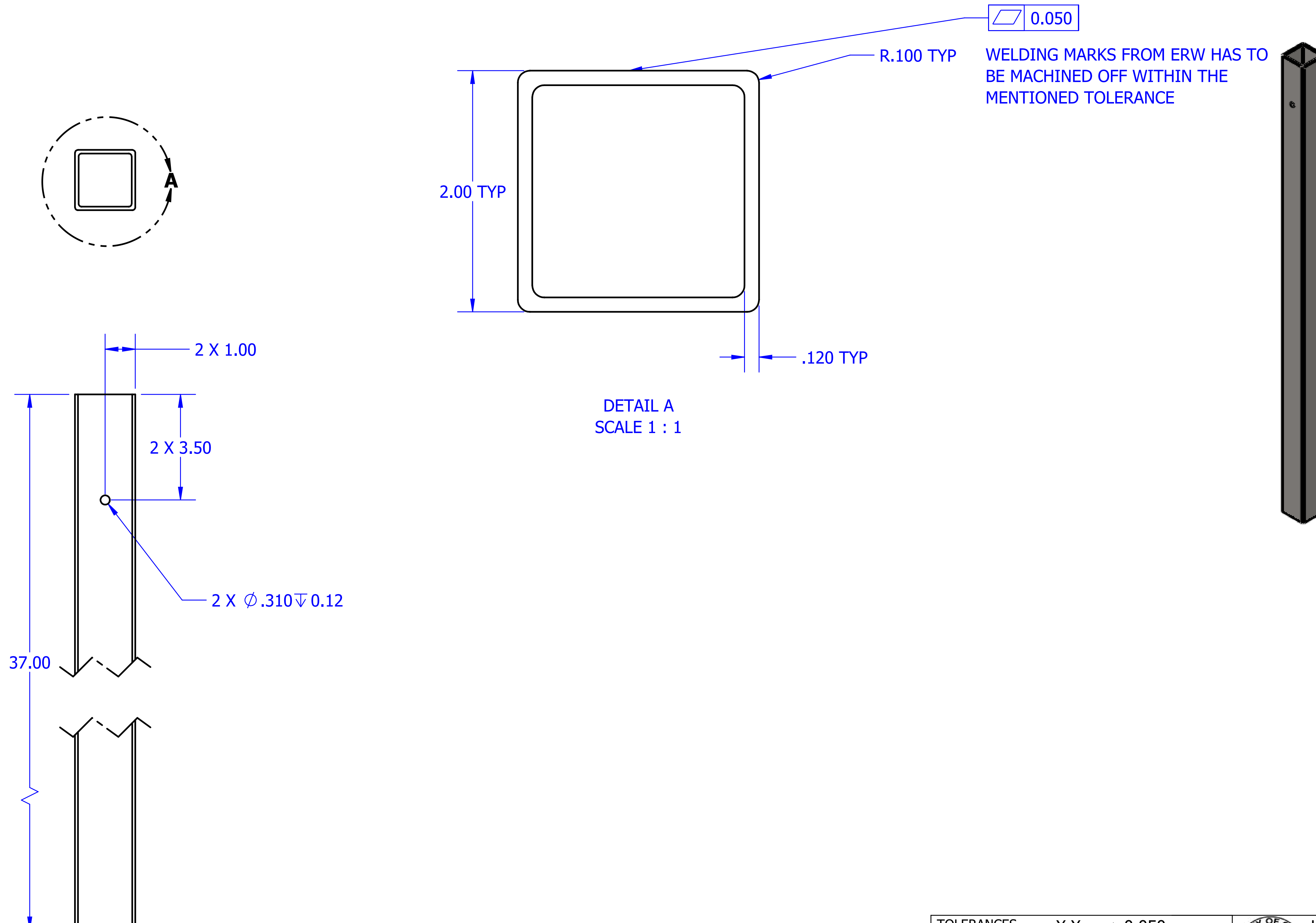


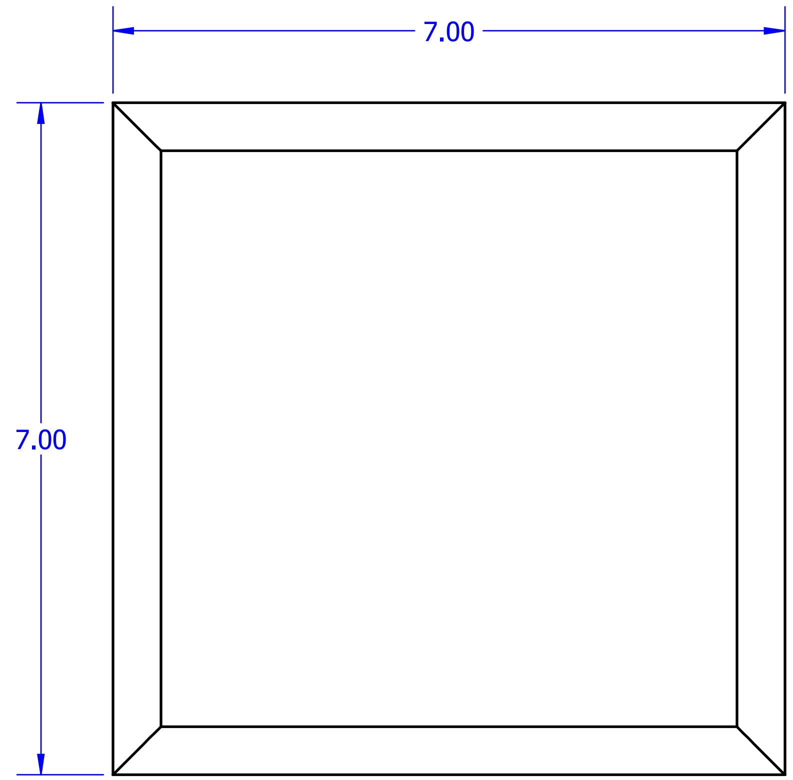
DETAIL A
SCALE 1 : 1

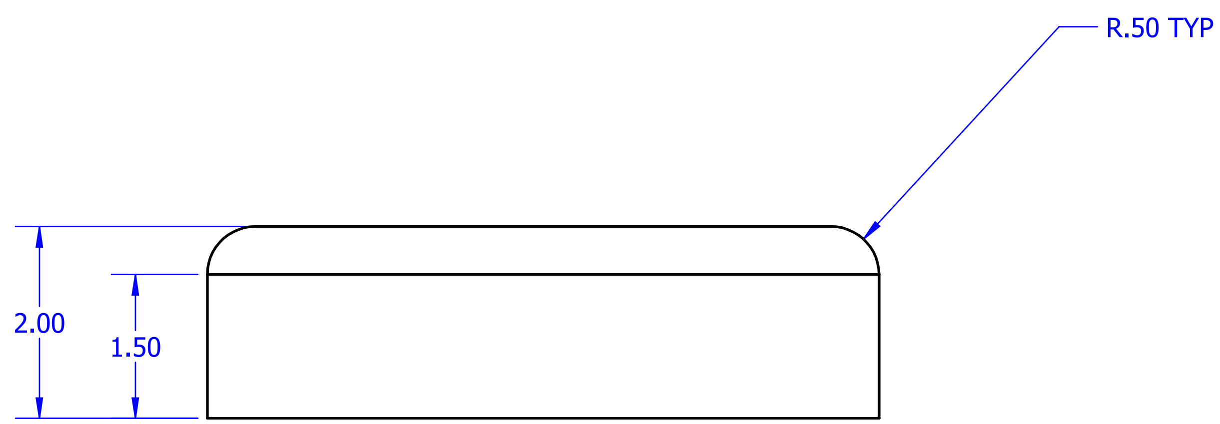
WELDING MARKS FROM ERW HAS TO BE MACHINED OFF WITHIN THE MENTIONED TOLERANCE

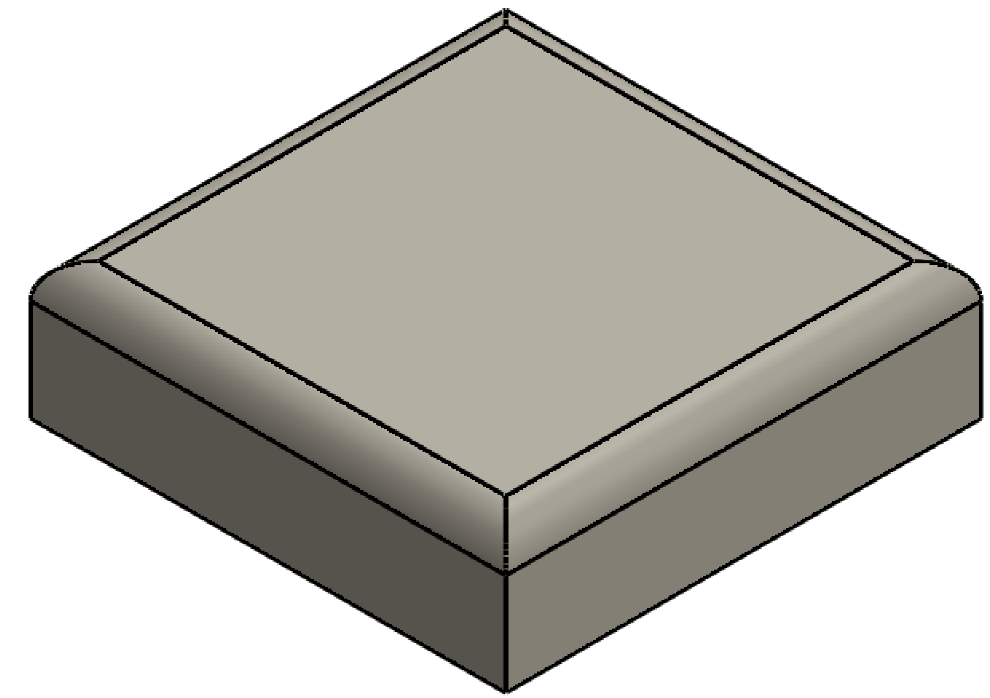
REV.	DESCRIPTION	DATE
A	INITIAL DESIGN	4/18/2020

TOLERANCES UNLESS NOTED: X.X ± 0.050; X.XX ± 0.010; X.XXX ± 0.005; X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION WEIGHT VERTICAL BAR
FINISH NONE	PN 6166	REV A; SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/20/2020

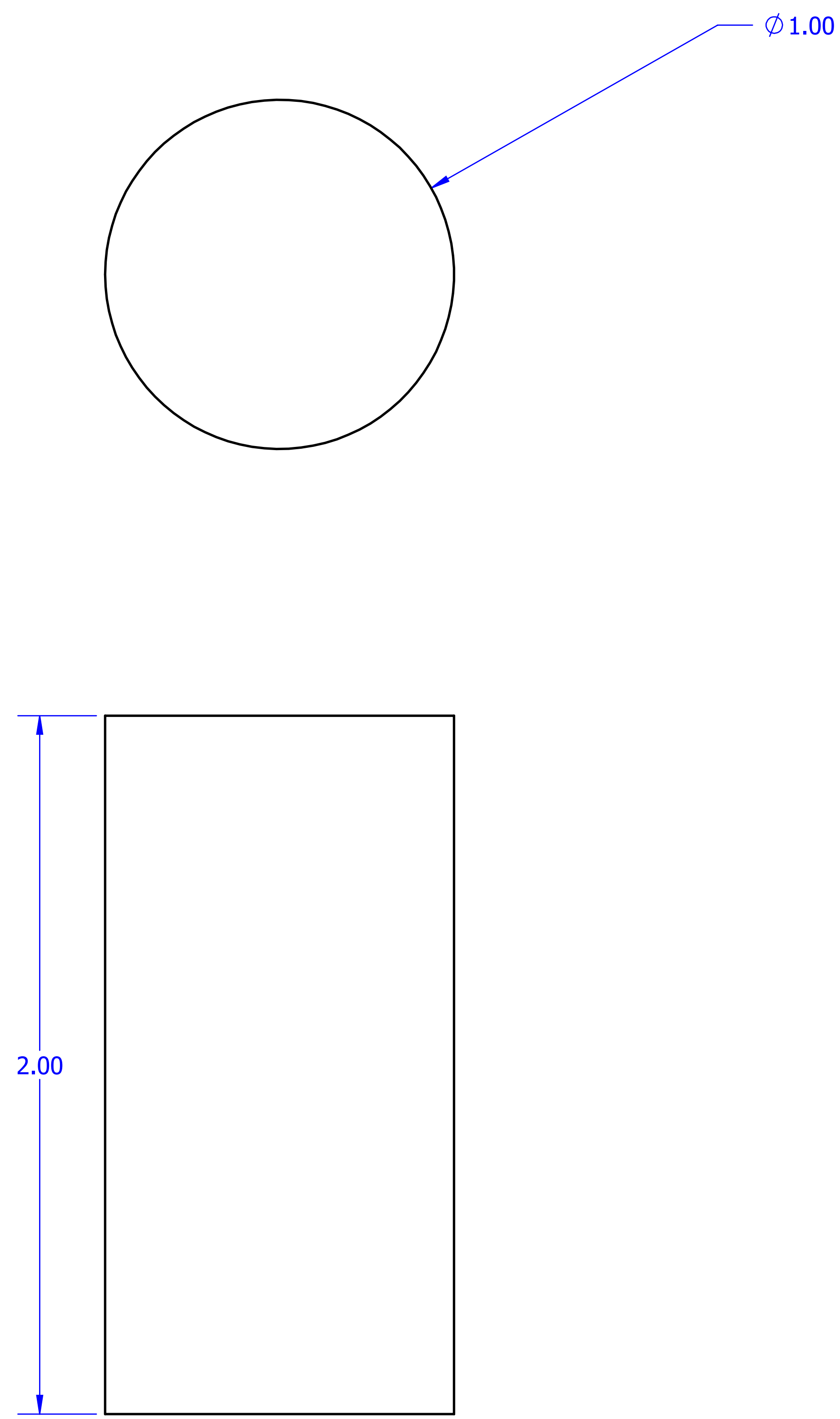


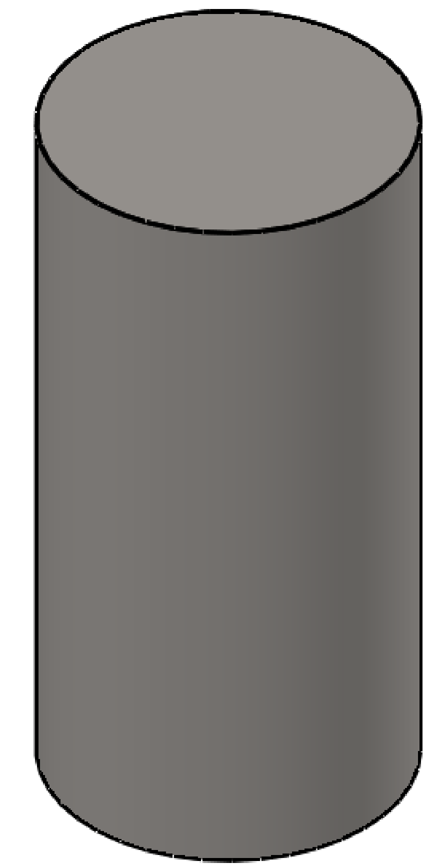




TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL Polyurethane Foam Rigid		DESCRIPTION ELBOW PAD FOAM	
FINISH NONE	PN 6003	REV A	SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE Ⓐ	4/18/2020





TOLERANCES UNLESS NOTED: X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL AISI 1020		DESCRIPTION ELBOW PAD PIN	
FINISH NONE		PN 6002	REV A	SHEET 1 of 1

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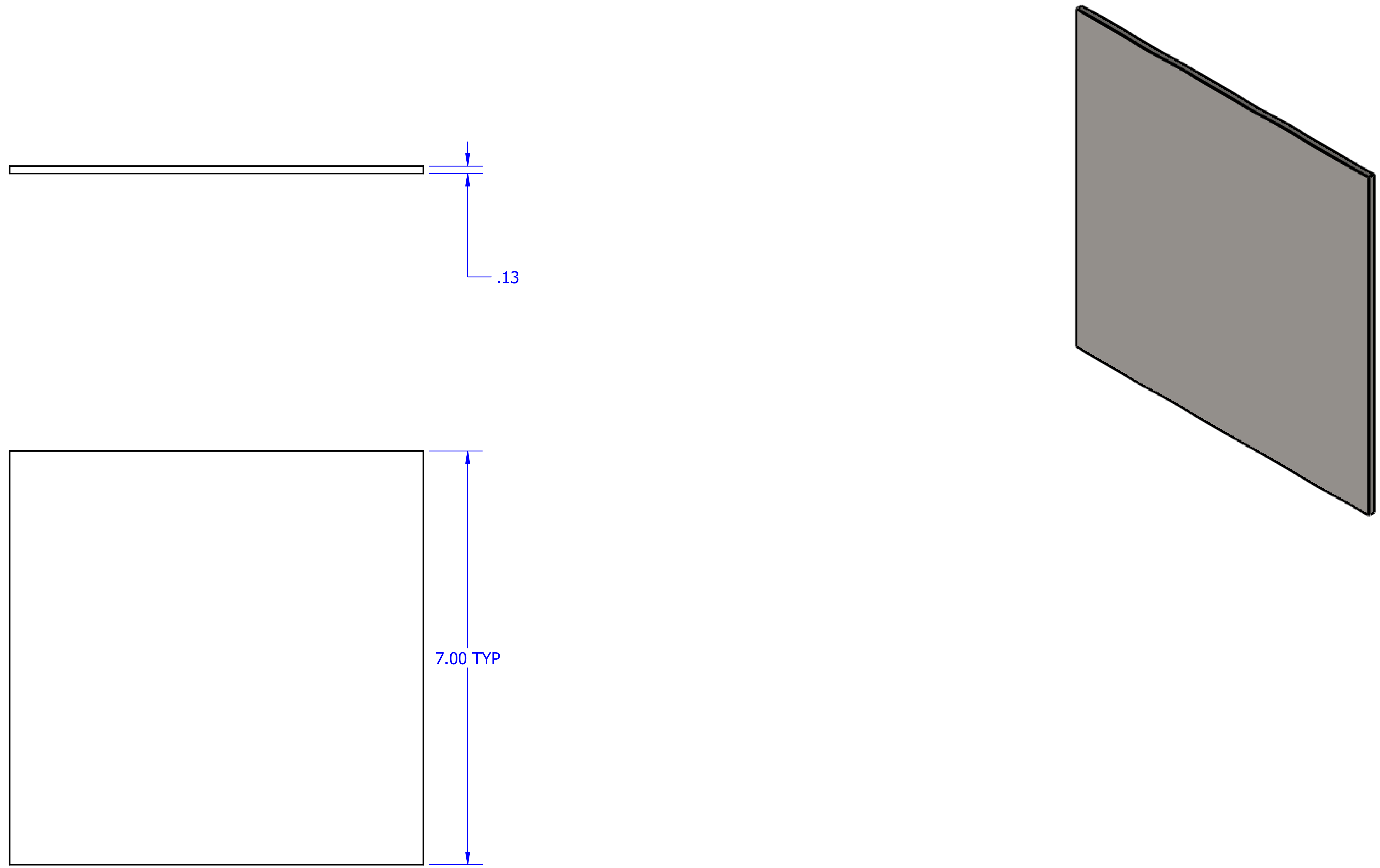
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE (A)	4/18/2020



TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° ± 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL AISI 1020		DESCRIPTION ELBOW PAD BOARD
FINISH NONE		PN 6001 | REV A | SHEET 1 of 1