Designing a Mechanism for a Thermoforming Machine

Project Lead: Annie Cardinal
Gabriel Baraban, David Beck, Daniel Brooker, Adam Geilker, Silken Jones, Ryan McDonnell, Matthew Walsh, Elana Woldenberg, Joshua Zimmer

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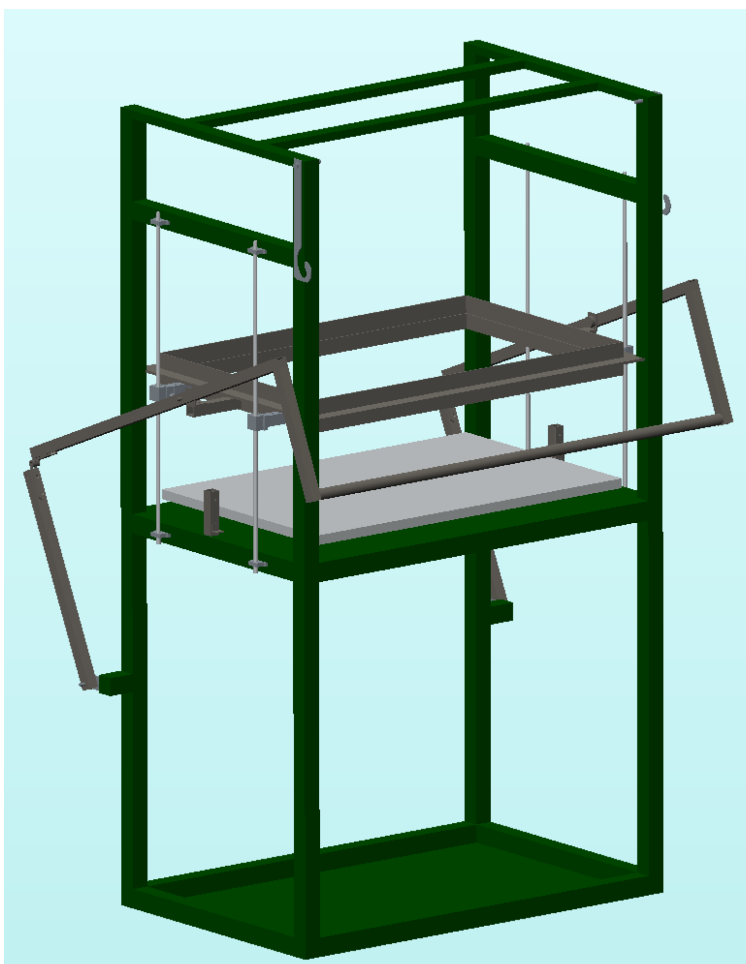

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2 EXECUTIVE SUMMARY

As a class, we designed and built a thermoforming machine with a key focus on three very important attributes: ease of use, durability, and maintainability. The class formed six teams that divided up the design and manufacturing processes into manageable chunks: the vacuum system, the vacuum plate, the heater, the plastic holder, the mechanism, and the machine frame.

Our team tackled the mechanism and therefore took on primary responsibility for the machine's mechanical ease of use due to the mechanism's important role in lifting the plastic holder. Thus, our design had to both smoothly transport the plastic holder between the heating element and vacuum plate as well as facilitate maintenance. These considerations led us to design a mechanism with the properties expected from a professional quality machine. First, the mechanism is designed such that a person of any height can easily reach and operate the lever. Second, to allow for inexpensive repairs and modifications, the entire mechanism is removable and disassemble-able to allow for easy modular swaps. Third, because the plastic holder is bolted directly to the mechanism, it too can be easily removed and replaced in case it malfunctions.

The main design specifications for the mechanism were to move the plastic between the heating element and the vacuum plate, hold it securely at these heights, and make the motion smooth and easy to operate. The machine also needed to be able to fit through a regular-sized door. The mechanism also has precise integration with other pieces, mainly the plastic holder and frame, and thus clear and frequent communication with other groups was essential to successfully create the mechanism.

Our design consisted of two hinged lever arms and four linear bearings on guide shafts to convert the lever arm motion to vertical motion. The arms provide mechanical advantage that help the user lift the plastic holder and maintain control over its descent. Magnetic stoppers hold the plastic holder during heating and allow for hands-free use.

3 INTRODUCTION

3.1 DESIGN CONSTRAINTS AND SPECIFICATIONS

The purpose of the mechanism in a thermoforming machine is to move the plastic sheet between the heating element and the vacuum plate. The mechanism must interface with the plastic holder and frame, and must accommodate the vacuum plate's dimensions and the temperature constraints imposed by proximity to the heating element.

The primary design criteria were user-friendliness and reliability. The mechanism and all of its parts needed to be able to lift the required load repeatedly, regardless of the height or strength of the user. In addition, there was a financial criterion. The project budget was $5,000 for the entire system, of which about $600 was designated for the mechanism.

The mechanism has four major components: the bearing system, the connections to the plastic holder, lever arms and handle, and the stopper system.

The bearing system consists of four linear bearings mounted to each corner of the plastic holder, and guide rails attached to the frame that run between the vacuum plate and heating element. This bearing system must support only vertical motion and allow smooth travel between the vacuum plate and heater. The bearings need to be able to slide or roll freely on the guide rails while still supporting the weight of the plastic holder assembly, which is approximately 50 pounds.

The connection to the plastic holder must be both robust and removable to facilitate maintenance, and must enforce the alignment with the bearings and shafts. Furthermore, all bearing components must be heat resistant because they will be in very close proximity to the heating element, with a predicted temperature of 400 degrees Fahrenheit for metal near the heating element.

The lever arms and the handle allow the user to easily lift the mechanism up and down while retaining control. As the handle moves, the attached lever arms move accordingly to raise and lower the plastic holder. This motion creates dynamic loading that must be accounted for in the design of the levers. Ideally, the lever arm also provides some degree of mechanical advantage to assist in the lifting of the plastic holder.

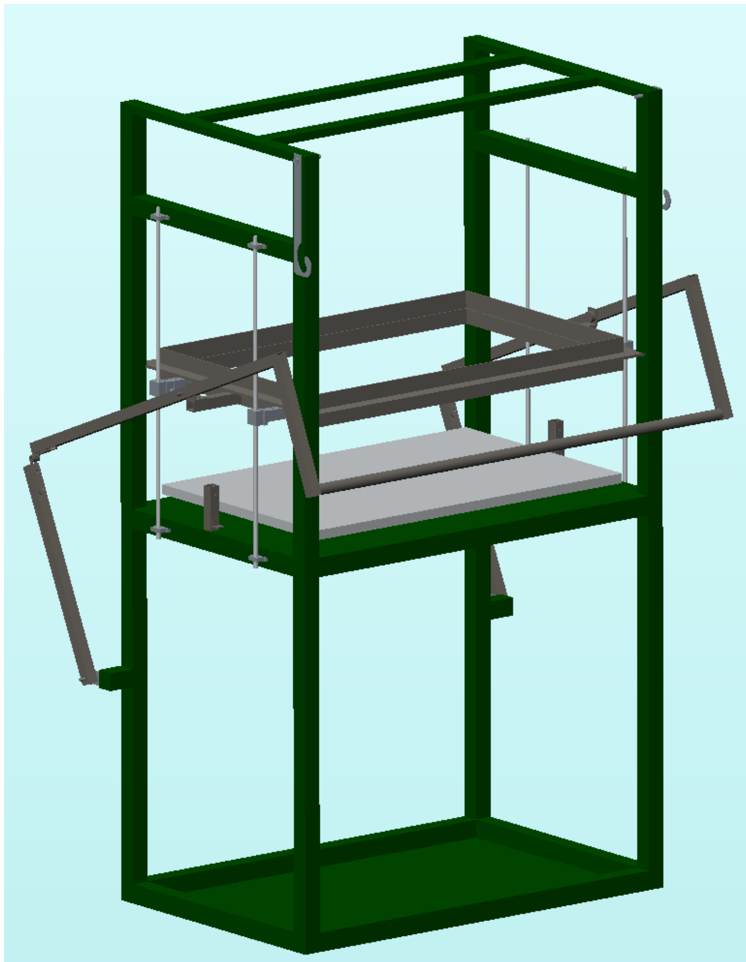
The stoppers hold the plastic holder at the top range of its motion to allow for heating, and at the bottom of the range of motion to keep it level with the vacuum plate during forming. The upper stoppers must be usable without the user touching them, as they will be very hot after the plastic has been heated. The stoppers serve two purposes: to keep the mechanism from exceeding its proper range of motion, and to hold the plastic holder at certain desired positions. The top stopper holds the plastic holder 7.5 inches away from the heater to allow thorough heating of the plastic sheets. The bottom stopper holds the mechanism in three main positions: the lower position creates a seal against the vacuum plate during forming, the second position is half an inch higher to accommodate the inserts, and the third is raised about five inches above the vacuum plate to allow removal of the plastic holder and modifications to the inserts. Both the top stopper and the bottom stoppers must support the full weight of the plastic holder.

Finally, the entire machine needed to be able to fit through a standard door, so all components were designed to be removable and modular.

3.2 Background Research and Influence on Design

The general design concept came from Chappell Customs, a company that builds custom parts for motorcycles, and a YouTube video that depicted their homemade thermoforming machine. This involved a simple set of two lever arms that, combined with vertical guide rails, created vertical motion with mechanical advantage. From this design, we knew that the mechanism we wanted to build could be made with limited resources, was simple to design and build, and would perform effectively. Other design options included a four-bar linkage, but after discussion with the plastic holder team, we realized that the slight arc motion would not work with their design, which required fully linear motion.

Initially, we chose to use homemade bearings made from L-beams and Teflon tape that slid up square tube railings, imitating Chappell Customs' design exactly, but we then decided to make something more reliable and precise, albeit more expensive. We thought bearings that could slide up and down 80/20 were suitable because they would maximize precision with low cost, modular design, and ease of assembly, but their temperature tolerances were insufficient. After researching linear bearings and various guide rail options on McMaster, we decided to use high-temperature pillow block bearings capable of withstanding 400 degrees Fahrenheit, just over the 392 degrees Fahrenheit maximum temperature predicted by the heating element group, and simple shafts for these bearings to ride on.



CAD design of the final mechanism assembly on a simplified version of the thermoforming machine

4 Detailed Design and Analysis

4.1 Basic Design Approach

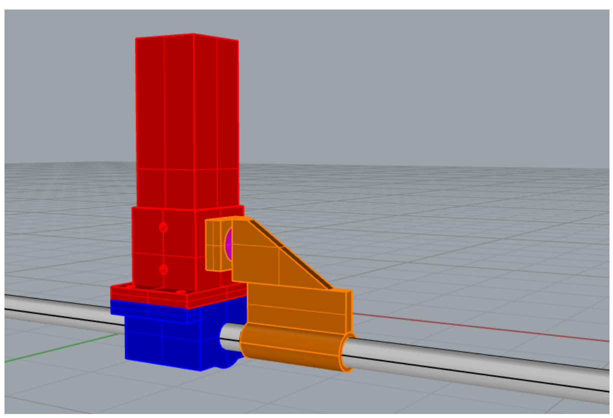
The design of the mechanism was divided into four pieces: The upper and lower stoppers, mechanism arms, bearings and motion, and connection to the plastic holder. In this section, the design process for each piece will be described in detail.

4.1.1 Stoppers

The motion of the plastic holder needed to be constrained at the top and bottom of its range of motion, so the upper and bottom stoppers were designed to serve this purpose.

Upper Stopper

The upper stopper needs to hold the plastic holder at the top of its range of motion to allow the plastic to heat. Initially, the heating element group requested that the upper stoppers have continuously variable positions, so that the distance from the heater to the heating position of the plastic sheet could be matched to the thickness of the sheet. As a result, the initial design of the stopper was attached to the rails and moved up and down on them using a collar and a set screw or hand brake. The exact holding mechanism was undecided at this point, but a flexural stopper, a magnetic connection, and hand operated clamps were considered.



A concept design for the continuously variable magnetic stopper (orange) the linear bearing (blue) and the plastic holder attachment (red).

When the heating element group decided against the continuously variable position constraint, the design parameters became much simpler. With permanent discrete positions, it was possible to use bolts to attach the stoppers to the frame, a stronger and more durable solution than a set screw or hand brake. The stoppers comprise a piece of rectangular tube steel welded to an L bracket that holds the magnet case.

Design Process of the Upper Stopper

Our first preliminary solution was a simple handbrake. Because the breaks would be attached directly to the bearings, it would be possible for the hand brakes to be in close enough contact with the heating element where the temperature tolerance of approximately 400 degrees Fahrenheit would become an issue. Additionally, they would need to be engaged directly by the user when in close proximity to the heating element, which we wanted to avoid. This would also be difficult to do because all four bearings would need to be engaged before the mechanism would be held in place, unless we added a separate mechanism for engaging and disengaging all four brakes at once. With so many issues with the hand brakes, we began redesigning the stopper.

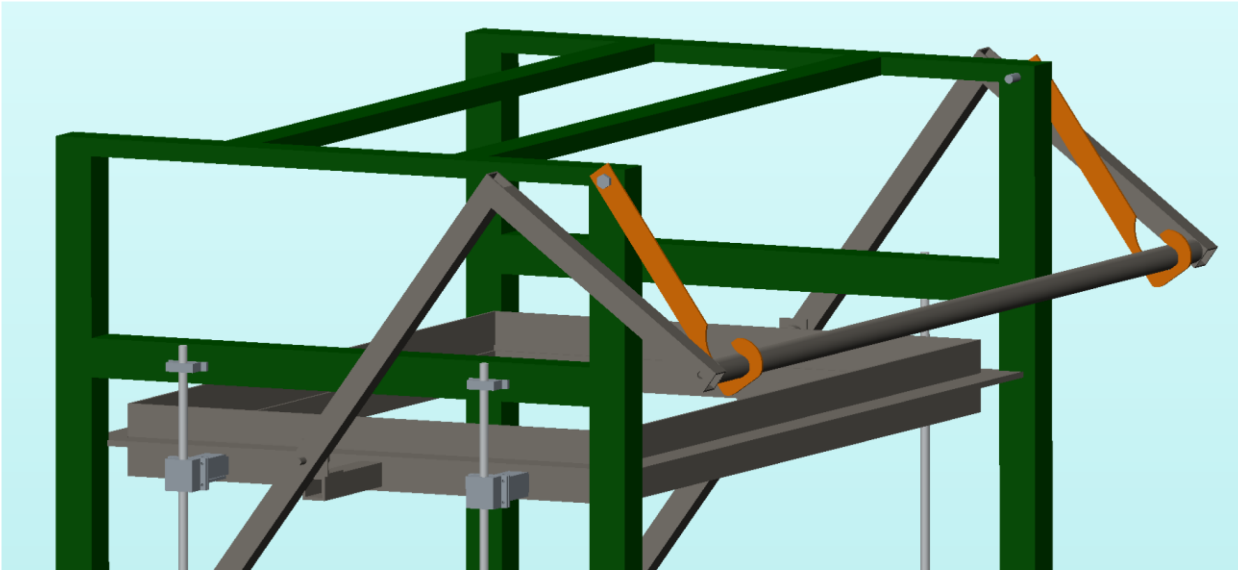
The next idea was to use a clipping or catching mechanism, similar to those used to hold cabinets shut. Such mechanisms could be engaged by simply moving the mechanism into place with the main handle. They are also commonly made out of materials that have higher temperature tolerances than the hand brakes we examined. However, after some research, we could not find any such mechanism designed to hold the required amount of weight. Because holding a cabinet closed does not require a large amount of force, one that meets our specifications is not likely to exist. Additionally, easily removable catches are difficult to design when the load exceeds a small number of pounds, since increasing the strength decreases the ease with which the mechanism can be disengaged.

We then contemplated a magnetic mechanism. The majority of the assembly was to be made out of steel, so a magnetic stopper was possible. Magnets can be made to hold loads up to several hundred pounds - far in excess of what was required - and they create a method of attachment that can be removed fairly easily. Magnetic force drops off rapidly with distance, so the mechanism would be strongly held in place when close to the magnet, but moving the mechanism a small distance away from the magnet would break this bond. We were also able to find temperature resistant magnets.

We bought four small ring magnets rated for 30 lbs in direct tension. Thus the theoretical combined strength of the four magnets was 120 lbs— more than double the amount we estimated they would need to hold. However, to verify their strength, we estimated how much they could actually lift by weighting them to failure with large steel scraps. Two magnets would easily lift approximately 25 lbs, and the main limiting factor was difficulty in finding suitable handles. Thus, the magnets were shown to have sufficient strength for the stopper based upon the given criteria.

The original mounting design for the magnets consisted of a L-bracket affixed to a square tube steel shaft with magnets positioned on the L-bracket such that when the steel plastic holder was raised to an appropriate height, the magnets would stick to its surface and hold it in place. The magnets would be inset in steel cases, and these cases would be secured to the L-bracket with screws. However, the diameter of the magnets was too large to fit on this surface. We thus had to alter the dimensions of these parts to make the magnets fit. The center connections to the plastic holder could not be enlarged, but the surface on the L-bracket could be, so it was enlarged to fit the magnets. The magnets were positioned such that they would have the maximum possible area of contact with the plastic holder.

A backup plan was required, however, in the event that the magnets failed. Once the entire mechanism was assembled in the shop, it appeared that the magnets could work, but were not perfectly secure, which became an issue due to the weight of the plastic holder and the danger it would present if it fell. The backup solution consisted of two hooks that swing out to hold up the handle at the required height, and can be released by simply lifting the handle gently. It’s a simple and effective solution that has the required strength to hold up the plastic holder. In the final version, we actually removed the upper stoppers entirely and only used the hooks.



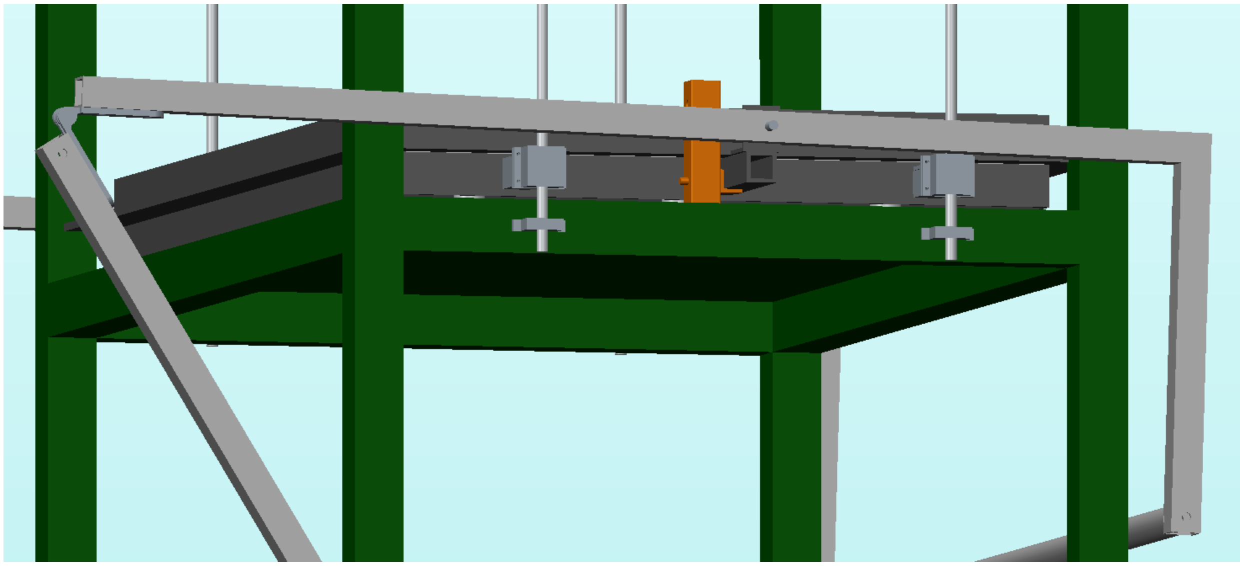
Mechanism in its top position, held in place by two hooks (highlighted in orange)

Bottom Stopper

The bottom stopper needed to incorporate three different heights. One height for when the plastic holder needed to be level with the vacuum plate, one for when the plastic holder had inserts, and one about five inches above the surface of the vacuum plate so that the plastic holder could be modified and inserts added.

The bottom stopper initially had magnets as well, but we soon realized that the weight of the plastic holder would keep it in the lowest position easily. After many complicated solutions with attaching various shaft collars to the bearing shafts, we realized that a height-adjustable L-bracket secured with a bolt would be the simplest solution. The bolt slides through holes at pre-specified heights in a piece of tube steel that is mounted to the shelf that holds up the vacuum plate and is secured with a wing nut on the other side. The plastic holder then hits the L-bracket and is stopped at that height.

The first of the three positions is restricted by a permanently welded L-bracket. The second position is restricted by the plastic holder itself, as the inserts are strong enough to keep the plastic holder at the desired height by simply resting on the vacuum plate. The third position is restricted by the removable L-bracket.



Mechanism in its bottom position, held up by the bottom stopper

4.1.2 Mechanism Arms, Motion, and Bearings

The initial mechanism design came from Chappell Customs and their homemade Vacuum Form machine. This included two lever arms hinged together that provided mechanical advantage and linear bearings that allowed for vertical motion. There was a possibility of using a four-bar linkage, but we decided upon the dual linkage lever arm based on its better leverage and user friendly interface. The four-bar linkage would not have the same mechanical advantage, and the user's arms would tire faster as they would need to control the descent of the plastic holder without mechanical advantage. This would make it more prone to falling, and in addition, there was a small arc in the motion that would reduce the amount of clearance with the vacuum plate. Upon consultation with the plastic holder group and when considering their concerns with the clearance, the slight arc in the motion was a large enough problem that the four-bar linkage was no longer feasible.

The 90 degree bend in the longer lever arm was a modification discussed early on in the design process, but not implemented until discussion with the vacuum system group made it clear that our lever arm might block the control panel. In its lower position, the modified arm would end up below the control panel and would allow for better user control of the arms. This modification has the added benefit of allowing a shorter person to comfortably reach and control the lever arm in the upper position when the plastic is being heated.

We initially chose to make L-bracket linear bearings as shown in the Chappell Customs video because of their low price, simplicity, and high alignment tolerances, but finding good lubrication proved to be difficult. There were concerns with Teflon tape at high temperatures due to the possibility that it might emit toxic fumes. At the recommendation of Professor Craig Arnold, Molybdenum Disulfide became a possibility due to its high heat tolerance and usability, but we ended up deciding that prefabricated bearings would be more reliable, and because their low tolerances to misalignment meant they would create a very smooth motion when set up properly. However, the linear bearings were much more expensive than the L-bracket bearings, which was why we did not consider them initially. It meant that we would not have to make our own bearings, but it also removed our ability to modify the setup once we had ordered the bearings.

We then moved to an 80/20 setup due to its ease of installation and strength, but the bearings compatible with 80/20 could only withstand 180F, and components that got closest to the heater had chances of getting to 200C, or 392F. Frelon coated bearings, which rode on specially-shaped rails, could withstand 300F, which was closer to the necessary temperature. It was possible to use a heat shield to keep the bearings from reaching the high temperature.

However, we realized that we had been relying on our mechanism design to hold up the heating element. Discussion with the frame group revealed that our design did not need to support the weight of the heating element and that they could hold up the heater with their own frame. We modified our guide rails to be simple lightweight shafts instead of specially shaped rails attached to sturdy tube steel, because we no longer needed to support the heater. This meant that our design was much more modular, less expensive, and more easily repairable. We then decided upon pillow block linear sleeve bearings because of their simplicity, reasonable price, and ability to tolerate up to 400F. This also meant that we would not need a heat shield, which simplified the design of the thermoforming machine as a whole.

The shorter mechanism arm was attached to the longer one by way of store-bought hinges. They were then attached to the frame and plastic holder using custom-made cup and bearing L-brackets and shoulder screws as a pin.

4.1.3 Connection to the Plastic Holder

The initial design for connecting the plastic holder to the linear bearings was a simple, permanently welded connection. This was the same connection we saw in the Chappell Customs machine. We thought this would be sturdy and easy to make. However, after discussing with the plastic holder team, we realized we needed more flexibility in our connection, because they wanted the ability to entirely remove the plastic holder from the machine.

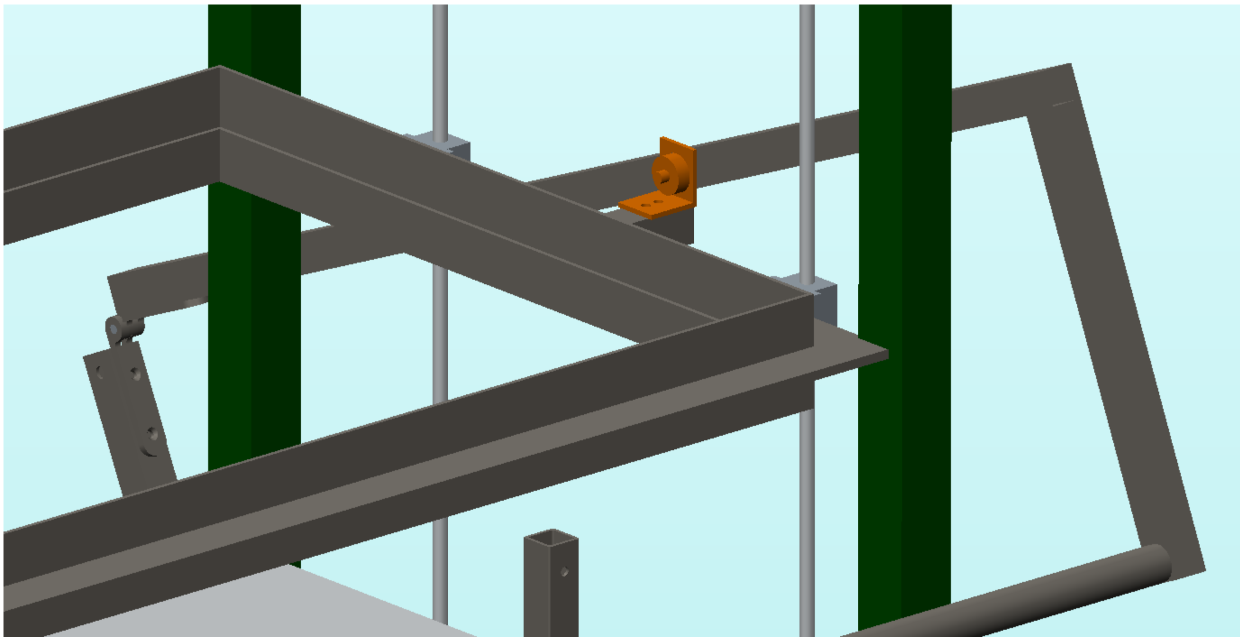
We decided to make the connection modular, so that the plastic holder could be removed at will. Taking the plastic holder out of the machine makes it easier to access the both the vacuum plate and the plastic holder if any parts need to fixed or replaced.

This modular design is achieved with the use of nesting beams. Four pieces of square steel tube are welded to the outside of the bottom of the plastic holder, and a hole is drilled vertically through each one. A c-channel, milled to perfectly nest on the outside of the square tube, is welded to a small plate, with screw holes that line up with those on the linear bearing. These two components, the square tube and the c-channel with a mounting plate for the linear bearing, fit together, and have concentric holes so that they can be bolted together during normal use of the machine.

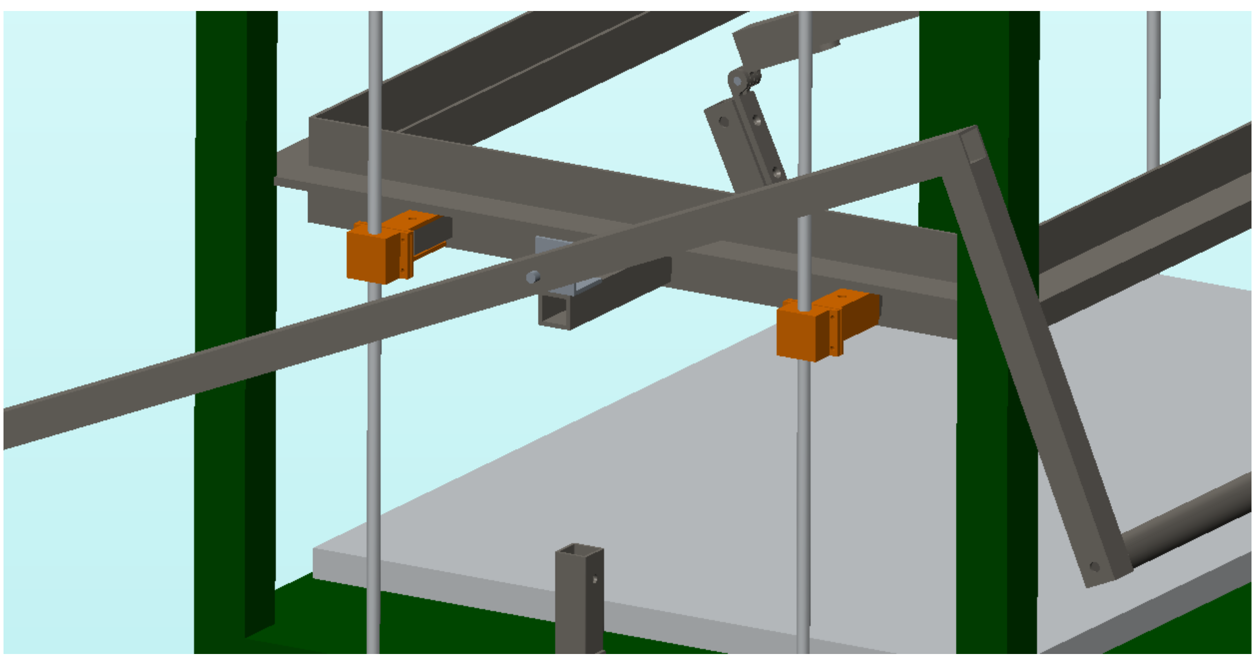
When it is necessary to remove the plastic holder, the bolts can be removed. Once unbolted, the c-channel components pivot out of the way using the linear bearings and the shafts as a pin, and the plastic holder can be entirely removed from the machine. This makes maintenance of the thermoforming machine, especially the plastic holder and vacuum plate, much easier.

The plastic holder is attached to the lever arms using two more pieces of tube steel, one welded to the center of each side of the bottom of the plastic holder. An L-bracket with a cup and bearing was attached to each of these pieces of tube steel, and a shoulder screw slid through the bearing and acted as a pivot point between the longer mechanism arm and the plastic holder. Lifting the mechanism thus converted the arm's motion to vertical motion through the use of this pivot and the linear bearing shafts. The shorter mechanism arm was hinged to the longer mechanism arm and had a similar pivot point connecting it to the frame.

We decided to use steel as our main material due to the plastic holder's choice to use steel and our desire to be able to weld to the plastic holder. Also, steel had the strength we desired in terms of shaft strength and resistance to bending.



L-bracket and bearing connecting the mechanism arms to the plastic holder



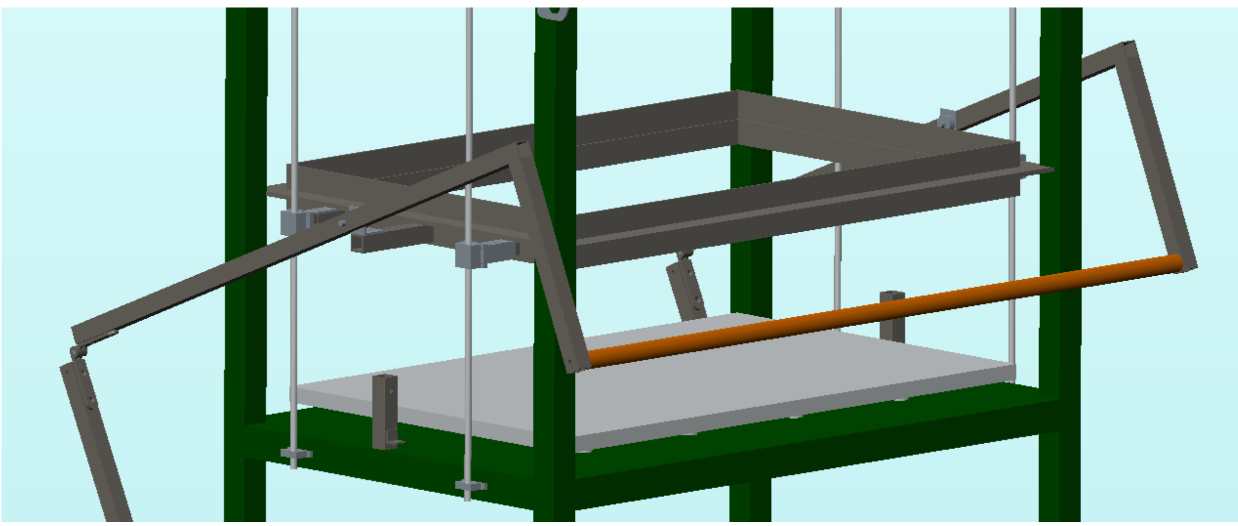
Linear bearings and c-channel pieces connecting the plastic holder to the mechanism rails

4.1.4 Handle Design

The handle for the mechanism is a round steel tube. Initially, this tube was going to be directly welded to the mechanism arms. However, we realized that by welding the handle straight to the mechanism arms, we would never be able to remove the handle. This can be problematic if the handle or mechanism arm break or if the mechanism arm needs to be removed for another reason. Therefore, we redesigned the handle to make it modular.

Instead of welding the handle and mechanism arms together, we decided to use a small disk spacer and a screw to attach the two pieces, making the handle detachable. One spacer is welded onto each end of the round steel tube. Each spacer has a ¼"-20 threaded hole through its center so that a screw can go through it to secure the handle to the lever arms. A matching ¼" hole exists on opposite sides of the mechanism arm, allowing the screw to go through the arm and screw into the handle. The fact that the arms are removable also allowed us to meet the design criteria that the system could fit through doors.

We also purchased grip tape to wrap onto the handle and aid the user in gripping the handle more safely. The grip tape has a tolerance of 250F and thus will not be affected by being in close proximity to the heating element.



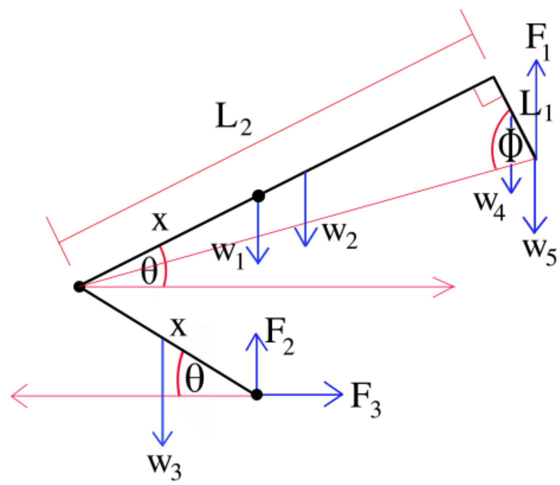
Mechanism handle, attached to the arms with screws (grip tape not shown)

4.2 FREE BODY DIAGRAM AND ANALYSIS OF FORCES

For force analysis, the mechanism is considered to be held static by a force applied on the handle by the user, with all forces and torques balanced. While this analysis allows a static treatment of the mechanism, it does not consider dynamic loading, but is a good approximation for the mechanism moving slowly at constant speed.

Force and moment balance equations can be obtained for the system, with moments taken about the hinge connecting the two arms. However, because only three equations can be made for this structure without approximating it as a system of trusses, some assumptions must be made to make it statically determinate. The handle moves approximately vertically over its operational range of motion, so the force applied on the handle is assumed to be vertical. The bearings are assumed to move without friction on the shafts, so the attachment point to the plastic holder may exert no vertical forces except for the weight of the plastic holder. Using these assumptions, the following diagrams and equations describe the forces present in the mechanism.

4.2.1 Free Body Diagram of Mechanism



$$\sqrt{(L_1^2 + L_2^2)}F_1\sin(\theta + \varphi) - xw\cos(\theta) = 0$$

$$F_1 + F_2 - w = 0$$

$$F_2\cos(\theta) - F_3\sin(\theta) = 0$$

$$\varphi = \mathrm{atan}(L_2/L_1)$$

Where the variables represent the following quantities:

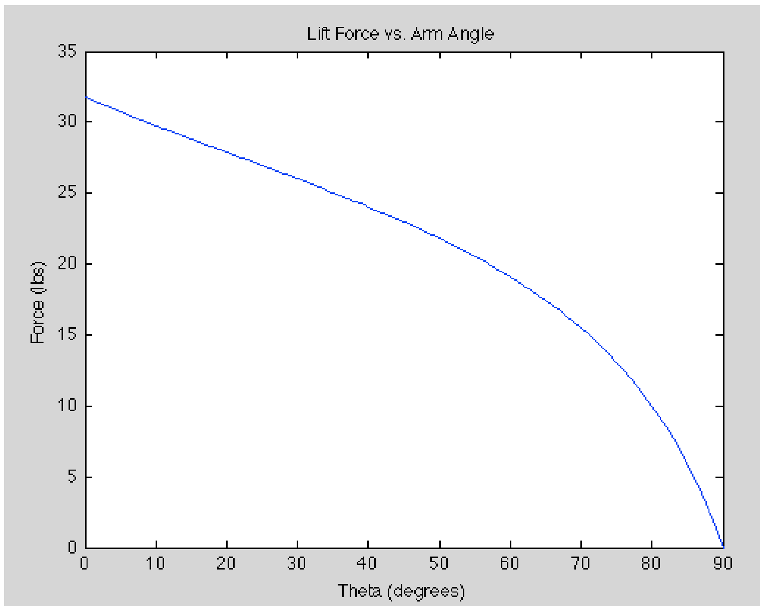
- F_1 = force applied by user
- F_2 = vertical force applied by bottom hinge
- F_3 = horizontal force applied by bottom hinge
- L_1 = distance from handle to main lever arm
- L_2 = length of main lever arm
- x = length from pivot to plastic holder attachment point
- w = weights of plastic holder and lever arm components
- θ= angle between main lever arm and the horizontal

Measurements from our original mechanism design:

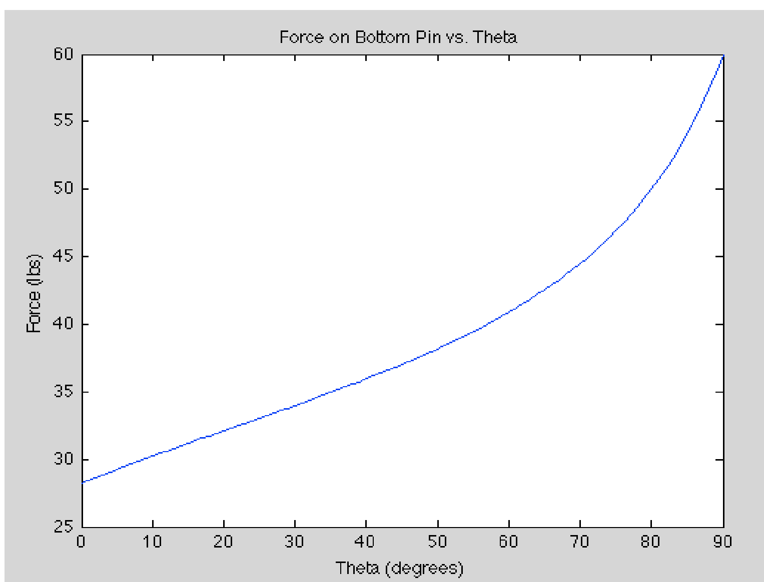
- w = 60 lbs
- x = 18 in
- L1 = 13 in
- L2 = 34 in

Some mechanical advantage is gained by the ratio of x to L_2, that is, how far along the upper arm the plastic holder is attached, as seen by equation 3, where the applied force by the user balances out the torque produced by the weight about the hinge. In our mechanism, this ratio is 0.53, so that the user will be able to lift the 60lbs plastic holder by applying approximately 30 lbs of force (neglecting self-weight). The other 30 lbs is supported by the mechanism's bottom hinge.

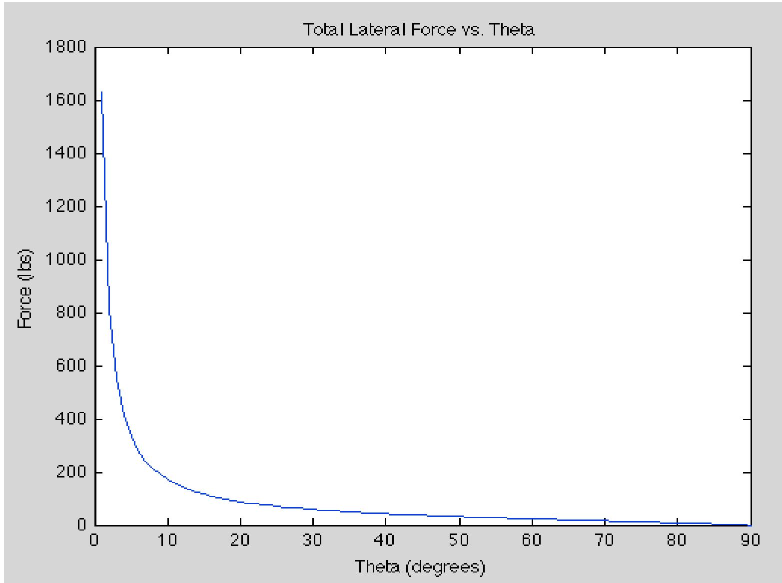
The following three plots show how the lift force, force on the bottom pin, and the total lateral forces change as a function of the angle between the two lever arms, theta.



The smaller the angle, the higher the lift force necessary. This makes sense, as there is less mechanical advantage with a smaller angle.



The force on the bottom pin is largest when theta is 90 degrees



The lateral force is huge when theta is very small, which is why the singularity is such a large issue.

The lateral force on the mechanism decreases asymptotically with increasing theta, while the vertical lift force required decreases more gradually with increasing theta. However, the large lateral force for small values of theta poses a risk of racking and increases friction, making the plastic holder more difficult to lift from its fully lowered position.

It should be noted that the location of the bottom hinge has been modified since our initial force calculations were completed. This location change reduced the singularity and horizontal force issues we previously had and greatly decreases the racking.

4.3 Prediction of Failure Loads and Modes of Failure

The parts of our design that are subjected to the most significant loading are the hinge shoulder screws, stoppers and connections to the plastic holder. These components are accordingly over-designed, to ensure that they will not fail under any circumstances. The addition of a counterweight mechanism would ease the loading on the connections to the plastic holder, but would introduce an additional load on the hinges and stoppers.

The shoulder screws that attach the long lever arm to the rotational bearings on either side of the plastic holder are subject to the greatest design load, and thus are the most likely points of failure. These pins will be subject to a shear force when the mechanism is loaded, and may break or bend from the resulting bending moment if this force gets too large. The screw connecting the mechanism to the frame will be subject to a large force as the angle between the arms and the horizontal becomes large, while the screw connecting the mechanism to the plastic holder will be subject to the greatest forces while the mechanism is in motion. The maximum shear stress these shoulder screws can support is about 43511 psi.

Both stoppers may also fail under certain conditions, as they must support the entire weight of the mechanism and plastic holder when engaged. The screws connecting the L-brackets of the stoppers to the tube steel supports will be subject to a shear stress due to at least the weight the stoppers are supporting, and more if the mechanism hits them when in motion. These screws have a maximum stress of 25237 psi in shear. When supporting the entire weight of the mechanism, the stresses in the screws on the stopper will be 1222 psi.

The arm hinge is another potential point of failure. This hinge effectively transmits forces between the two arms and thus is supporting a load at all times when the plastic holder is raised, and also prevents translational motion of the arms relative to each other. However, because it is held in place by two screws on each arm and itself is much thicker than the screws, its failure is also unlikely.

The most likely components to fail are the shoulder screws connecting the mechanism to the plastic holder and base, as they will be closest to their failure stresses under normal operating conditions. If the mechanism is constantly and repeatedly subject to conditions where these pins are under high stress, they may fail due to fatigue and/or creep. However, the final mechanism design mitigates this issue by making sure that the angle of the lower mechanism bar remains large, thus diminishing the lateral forces involved while the vertical shear remains the same.

Either stopper may fail if it is subject to a large enough shock (ie, dropping the assembly from the top onto the bottom stopper). Such a situation should be avoided by careful use of the machine, and is prevented by the action of a spring mechanism designed to keep the plastic holder level at the bottom of its motion.

4.3.1 Existing Flaws and Modes of Failure

The component of our machine most likely to fail is the guide rails and their holders. When the plastic holder slips out of alignment, it tries to pull the bearings out of alignment. But since these linear bearings have to ride their rails, they end up transferring this force to the rails themselves. When the force gets high enough, the rails will simply slide out of their holders. Luckily, it’s very simple to fix - simply slide the rail back into its holder, and re-tighten the hex screws to ensure the rail doesn’t slip in the future.

Additionally, the connection between the plastic holder and the lever arms is made by welding a single piece of tube steel on to the plastic holder. Due to the weight of the plastic holder and the loads on the lever arm during operation of the mechanism, the shaft is subject to significant horizontal forces. This force causes the tube to bend and pull on the weld. We have made the weld as strong as possible, but due to the concentration of forces at this location, this is another potential site of failure. The plastic holder is also prone to racking out of plane when being lifted and lowered, and our mechanism is not strong enough to guide its motion evenly on all four shafts. The user may need to guide the plastic holder down by maneuvering the handle to allow for an even rise and descent. However, recent modifications have reduced this issue greatly.

We discovered the plastic holder is actually unevenly weighted, which is a contingency we did not account for in our original design. This imbalance causes the plastic holder to rack and tilt backwards, magnifying the backwards pull of the lever arm near singularity. It is possible to operate the mechanism in spite of this flaw; we added springs to keep the plastic holder level, and to improve operation further, the user should pull backwards and up on the handle when operating it towards the bottom of its range of motion.

The main difficulty in designing the connection with the plastic holder was that our manufacturing schedule was dependent on the completion of the plastic holder. This created a delay and pushed our manufacturing schedule back. The bearing alignment was dependent on the precise connection to the plastic holder, and as the task of designing the connection was assigned to our group, we could not attach to the plastic holder until it was completed. In addition, the plastic holder's design was changed without our knowledge and conflicted with the areas we had requested them to leave clear for us to weld. If we had pre-drilled holes in the frame for the bearing supports, they would have been incorrectly placed, as the alignment of our C-channel pieces would have conflicted with the clamp holding blocks on the plastic holder. This emphasizes the importance of two-way communication in a project with multiple interacting parts.

Errors in the manufacturing of other components show worse in the mechanism than they do in their own parts, as the error is compounded by the number of connections. Our mechanism was designed to be very precise due to the nature of our linear bearings, but the plastic holder was not perfectly parallel with itself. In addition, the plastic holder was easily warped and bent under its own weight and therefore didn't put up much resistance to racking, which meant that our welded connections weren't aligned as well as we hoped, and our shafts had to withstand additional torques and horizontal forces due to the plastic holder's irregularity.

4.3.2 Corrections Currently Implemented

In order to compensate for the flaws present in the operation of the mechanism, we implemented a few corrections in the days after our initial assembly. First, we corrected the tilt of the plastic holder when it was at rest around the vacuum plate. This was done by adding springs to support the plastic holder from underneath. We riveted plates to the middle shelf of the frame, with countersunk holes cut in the bottom to accommodate an upward-protruding screw. A short, fairly sturdy spring was placed around the screw, and when the plastic holder came to rest of the springs, they kept it level and counteracted the imbalance due to its much heavier back weight. This helps to correct some of the backwards-acting force when operating the mechanism at small angles, as well as providing some extra upwards force from the compression of the springs.

Additionally, we had issues getting the magnets to securely hold the plastic holder near the heater. This was due to several factors - the plastic holder wasn't entirely square and level, which made it more difficult for the magnets to make a good solid contact with it, and the magnets were not as versatile as we initially thought. The magnets are given strength ratings for pure tension and cannot resist significant leverage. In this capacity, it would be essential for the magnets to connect to the plastic holder along a very flat and level surface. They are capable of holding the whole weight of the plastic holder at the top of its range of motion, but if disturbed, this connection could easily break and the plastic holder could fall. Failure of the magnets is a significant safety concern, so we needed a failsafe to keep the plastic holder from falling even if the mechanism was bumped. We attached a steel hook to each side of the frame, and these hooks catch the mechanism handle when it is at the top of its range of motion. To release the hooks, the user just gently lifts the handle, and they fall back to their resting position by the force of their own weight.

Additionally, due to the high forces present when operating the mechanism, we also decided to strengthen the welds that connect the steel connection tubes to the plastic holder. These welds are subject to the greatest concentration of forces, and thus we made these welds as strong as possible.

This should prevent the welds from breaking in the future, although it is rather imprecise to predict when or if a weld will fail due to their irregular nature.

After constructing our mechanism, we soon realized that the horizontal forces posed an issue in the mechanism's operation. We knew that moving the lower pivot point would greatly reduce the issue, but could not think of an easy way to do this. However, we later realized that we could move the lower pivot point to be on the back lower frame supports rather than the center of the horizontal cross support. This modification removed the singularity and greatly reduced the horizontal forces. Four inches needed to be added to the longer lever arms to increase the range of motion of the plastic holder, but this minor correction made the mechanism easily usable by one person.

4.3.3 Future Corrections and Improvements

If we were to improve the mechanism further, we would design and build a counterweight system. The plastic holder is rather heavy at around forty pounds, and even with the lever arm system requires some effort from the user to move. By creating a counterweight system, similar in concept to those used in elevators, we could make the mechanism nearly effortless to operate.

The racking of the plastic holder also caused some problems for our mechanism. Had we realized the magnitude of this problem, we would have used larger shafts for our linear bearings. The bearings currently in use are sized for a ⅜" shaft, which can bend when the mechanism is operated. This is especially evident in the lower range of motion, where the mechanism is near singularity; luckily this behavior is elastic, as there is no permanent bending deformation in the shafts. Using thicker shafts would minimize the effect racking has on our mechanism's motion.

Additionally, we could implement another guide rail to prevent the backwards force near singularity. When the angle between the lever arms is sufficiently small, lifting the handle actually makes the mechanism want to move backwards. A vertical rail aligned with the center of the longer lever arm and securely attached to the frame would prevent this. A roller could be attached the center of the longer lever arm, and this roller would fit inside the vertical guide rail. This would force the mechanism to move vertically instead of horizontally when lifting the handle, no matter what angle it was at.

Our bearings only had about 1.5" of contact with the shaft. This relatively thin length allowed the lever arm to noticeably angle the bearings during operation, thus causing the shafts they ride on to bend. If these bearings were thicker, their contact with the shafts would be greater, and thus it would be more difficult to twist them from their vertical position as there would be more resistance and guidance from the shafts.

The stoppers could be improved further as well. Currently, a total of four magnets hold the plastic holder near the heating element. These magnets are not quite sufficient to safely hold up the plastic heater. We added the hooks for precisely this reason, because if the mechanism was bumped, the magnets would lose connection with the plastic holder and cause it to fall. If we added more magnets to the upper stopper, it would make the connection between plastic holder and stopper stronger, and thus we might not need the hooks as an alternate stopper system.

A future modification could be to reinforce the plastic holder to prevent racking and warping and to have two lift points on either side of the plastic holder instead of one point at the center. This would reduce the uneven weighting issue and would allow for more even lifting of the plastic holder.

5 CONCLUSIONS

The three main design specifications for the mechanism were to move the plastic between the heating element and the vacuum plate, hold it securely at these heights, and make the motion smooth and easy to operate. The mechanism has precise integration with other systems, mainly the plastic holder and frame, making it necessary to carefully coordinate these connections. Our design's strength comes from its simplicity, modularity, and ease of use.

Our mechanism is very simple. The lever arms produce motion, and the bearing shafts restrict the motion vertically. One smooth motion of the arm moves the plastic holder vertically two feet, and the lever arm allows the user to have control over the speed of this action.

Our mechanism is modular. Each piece is attached using screws or bolts, which allows for easy assembly and maintenance. The connection to the plastic holder is not permanent, allowing for the plastic holder to be removed for maintenance.

Our mechanism is easy to use. The bend in the handle allows someone of any height to use the machine easily, making it safer to use, as no one has to strain to reach the handle. Magnets at the top of the mechanism retain the plastic holder without the user needing to hold onto the handle, allowing the user to arrange molding parts on the vacuum plate and let go of the handle while the plastic is being heated.

When our initial assembly was completed, the mechanism did not work as we had envisioned. It often stuck, the plastic holder racked, and it took a considerable amount of force to lift and control the plastic holder. This was not the picture of ease we had hoped for. However, after many modifications and tweaks, the mechanism now acts almost as well as we had designed for. It is operable by one person without necessitating excess strength or extra pairs of hands to guide the plastic holder. As the magnets may not hold up the plastic holder, we have successfully implemented our backup plan of hooks to ensure usability of the machine. It is not as smooth of a motion as desired, but it is usable as a machine and serves the functions given in the design specifications. With the short assembly time available to us due to the fact that the mechanism is dependent on components of other groups that had to be completed first, the mechanism has been debugged and fixed to a usable level.

In a second iteration, the modifications listed in the previous section could be made to aid usability, but there are a few elements of our mechanism of which we are particularly proud. The pivot points in the bearings are aligned nearly perfectly, the C-channel pieces have the precision necessary to align with the pieces we welded to the plastic holder and let the linear bearings ride easily on their rails, and we were able to debug and modify our design with limited time after its initial assembly to successfully work as a thermoforming mechanism.

We do predict that there may be some difficulty in usability due to issues mentioned previously, but we believe that the mechanism will serve the functions it was required to perform in order to complete the thermoforming machine.

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7 ACKNOWLEDGEMENTS

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Gabriel Baraban: Sole contributor to final parts drawings for report; Preliminary Creo; Bearing selection and research; Preliminary stopper design; Manufactured upper and lower stoppers, L-bracket stopper pieces, magnets; Major manufacturing contributions during last week of classes and reading week

David Beck: Primary Creo modeler; Finalized Creo design and made nearly all modifications to Creo during the entire design process (spent as much time doing Creo as others did manufacturing); Added pictures of Creo design to report; Initiated and executed last-minute design changes (modifying pivot point location, moving hooks, re-aligning bearings)

Daniel Brooker: Designed connection to plastic holder; Magnet analysis and stopper design; Specified nut and bolt parts numbers; Advice and contributions to all designs; Force analysis and free body diagrams for lever arms; Major manufacturing and debugging during reading week; Co-designed hook and initiated spring modification; Major contributions to report content and editing

Annie Cardinal: Project lead; Coordination with other groups throughout project; Group scheduling, task delegation, and timeline; Preliminary Creo design; Ordered materials and determined specifics of connections; Planned connections with frame and plastic holder groups; Oversaw nearly all manufacturing tasks and contributed to major manufacturing for last week of classes, reading period, and through last-minute changes; Delegating manufacturing tasks in shop; Report organization, content, editing, and final formatting; Wrote acknowledgements; Wrote mechanism section of operations manual

Adam Geilker: Co-manufacturing lead and delegator in shop; Primary welder and machinist of group; Contributed general intuition and advice to every part of the design process; Designed preliminary stopper in Creo; Turned general ideas into realities (determined how connections would actually work and what parts we would need); Major machining during last week of classes and reading week (too much to count!); Free body diagrams for report; Report editing, major contributions to content; Co-designed and manufactured final hook

Silken Jones: Preliminary Creo design; Presented preliminary design review to class; Researched and chose linear bearings; Compiled and tabulated materials list and assisted in ordering parts; Major manufacturing, assembly, and testing throughout final week of classes and reading week; Primary report editing and contributions

Ryan McDonnell: Magnet analysis and initial stopper brainstorming; Manufactured spring holders, backup guide system, bearing cups, handle ends, sliding shaft supports; Assisted in initial assembly

Matt Walsh: Lubrication design and bearing research; Stopper design; C-channel dimensioning and initial drawing; Force analysis and FBD; Major manufacturing contributions, and assisted in both assembly and testing; Major report content contribution

Elana Woldenberg: Preliminary Creo design; Determined arm lengths and cut them; Designed handle connection; Edited both design review PowerPoint presentations; Manufactured handle ends, sliding shaft supports, assisted in assembly and testing; Report bibliography and handle design section

Josh Zimmer: Compiled and tabulated materials list; Edited design review PowerPoints; Assisted with general manufacturing and tapped handle ends; Wrote executive summary and edited report

We pledge our honor that we have not violated the Honor Code on this project

8 Final Design Drawings and Renderings

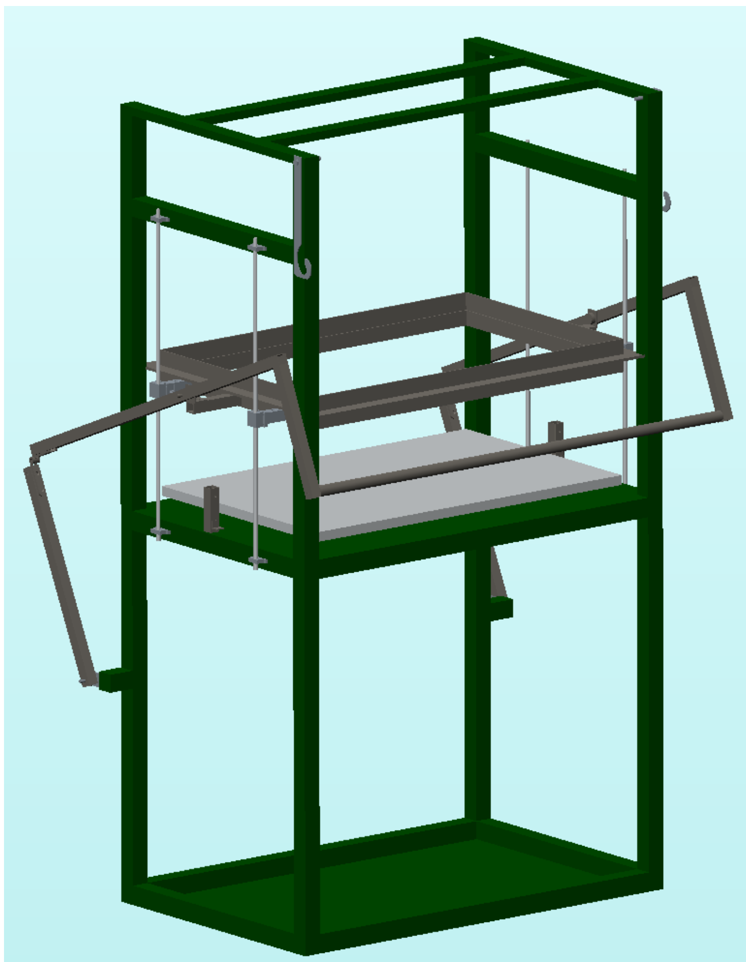
The following pages include our 3-D renderings and CAD drawings of individual components.

8.1 List of Drawings

1. Full Assembly
2. Preliminary Drawing
3. C-Channel
4. C-Channel Outer Tube
5. Plate between bearing and C-Channel
6. Inner Bearing Tube
7. L-bracket Bearing Pivot
8. Short Arm
9. Long Arm
10. Handle Tube
11. Hook
12. Bottom Stopper L-bracket
13. Bottom Stopper Post

Full Assembly

Complete Thermoforming assembly shown, with mechanism parts defined in grey.

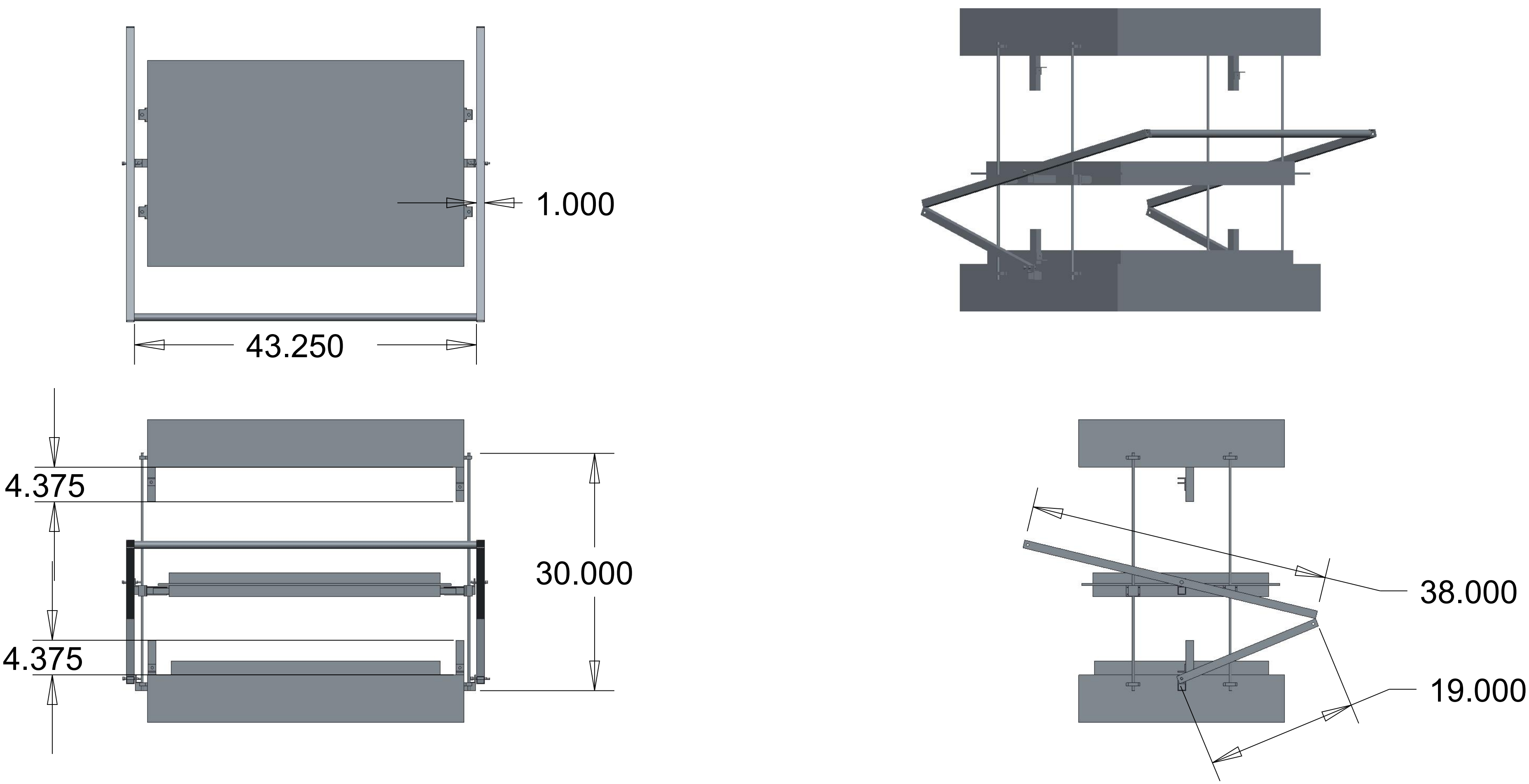


Preliminary Mechanism Drawing
Showing Arm and Rail dimensions

The Arms connect to each other by a hinge and to the plastic holder and frame by pins. The holder connection uses a C-channel for easy removal (see next page)

All Units in Inches

Scale 0.05

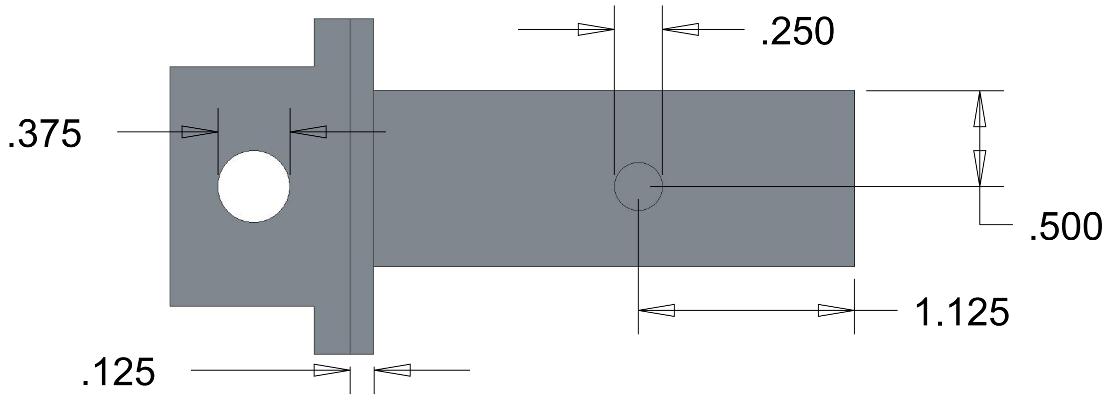


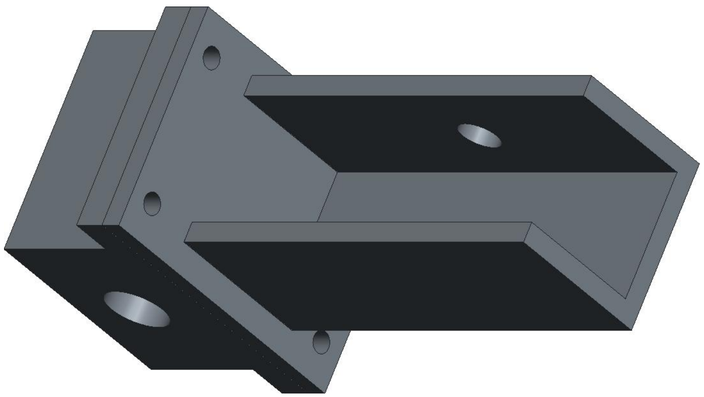
C-Channel Connecter

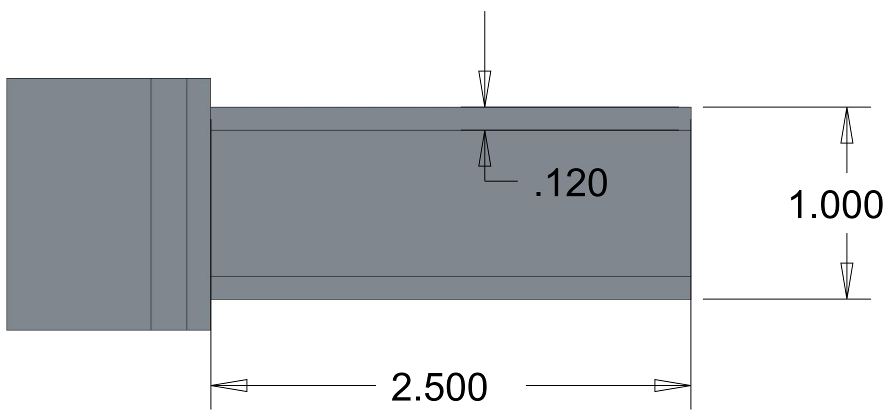
A 1/4 inch bolt holds the plastic holder spar in the channel.

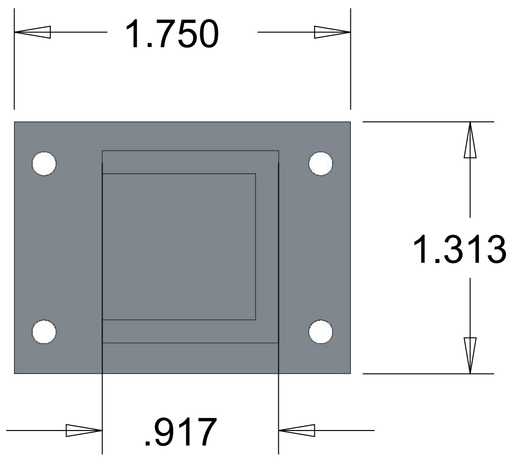
All Units Inches

All scales 1

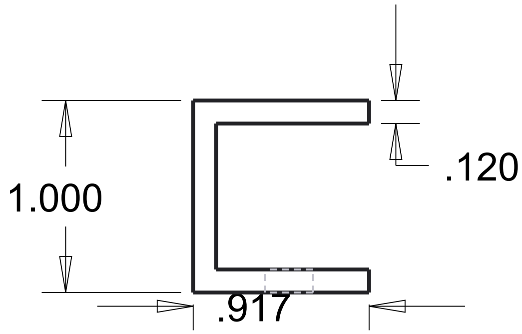


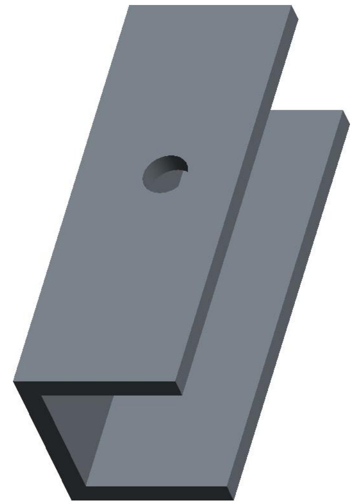


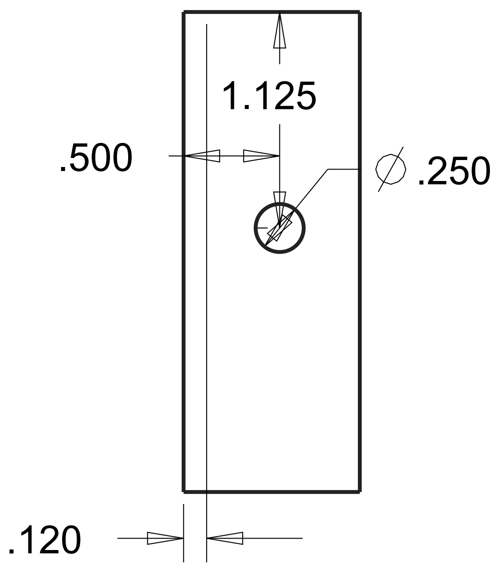


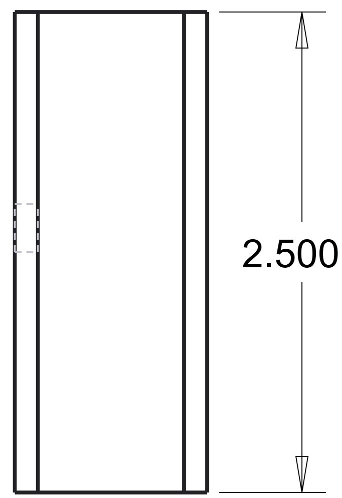


C-Channel
All Units Inches
All scales 1
Material: Steel
4 Req'd

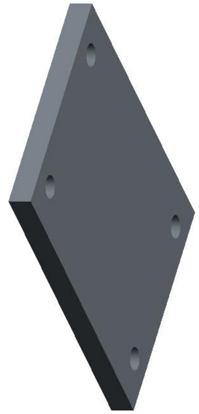


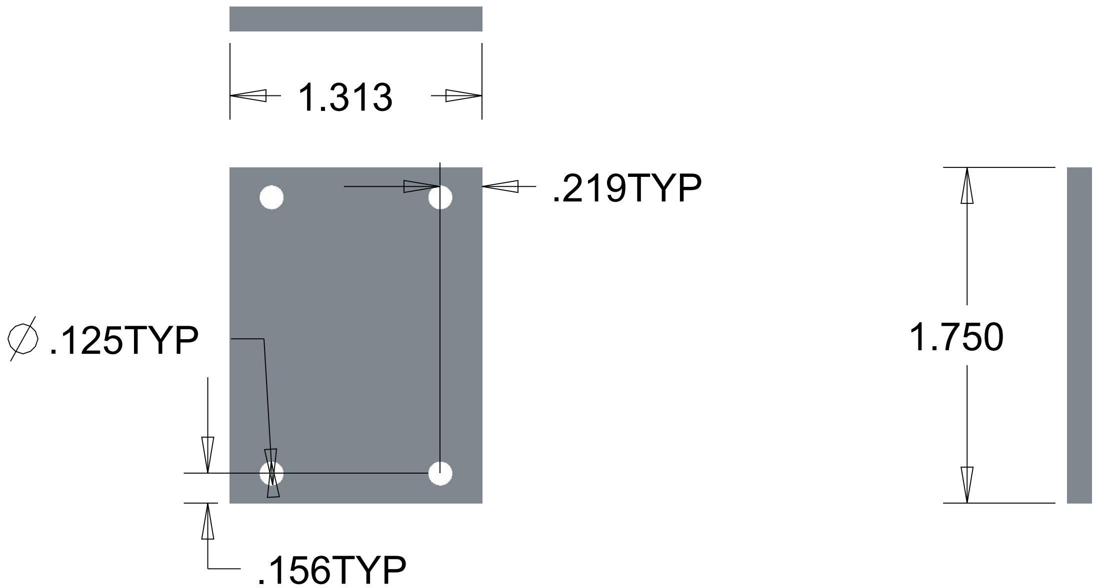






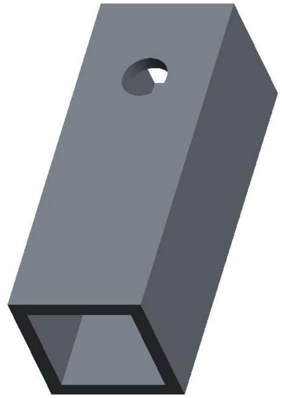
Pin Block
Scale: 1
All Units Inches
Material: Steel
4 Req'd
Designed to screw onto the bearings and weld to the C-Channel

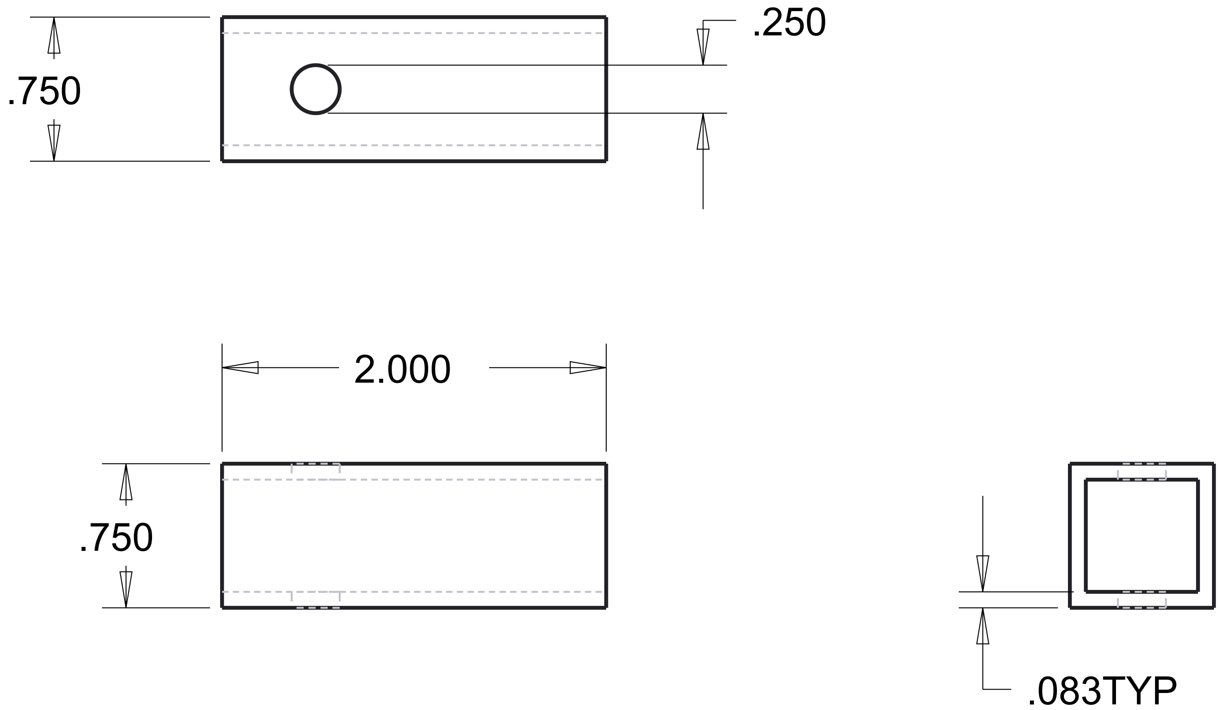




Inner Bearing Tube
All units in inches
Scale: 1:1
Material: Square Tube Steel
Req'd: 2

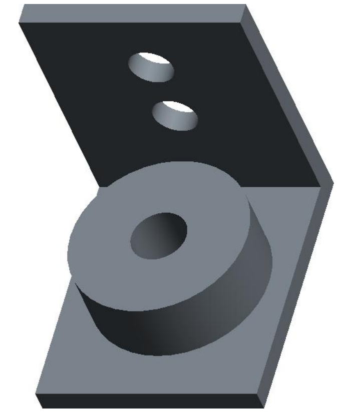
Welds to the Plastic Holder and rests inside
the C-Channel, where it is secured by a bolt

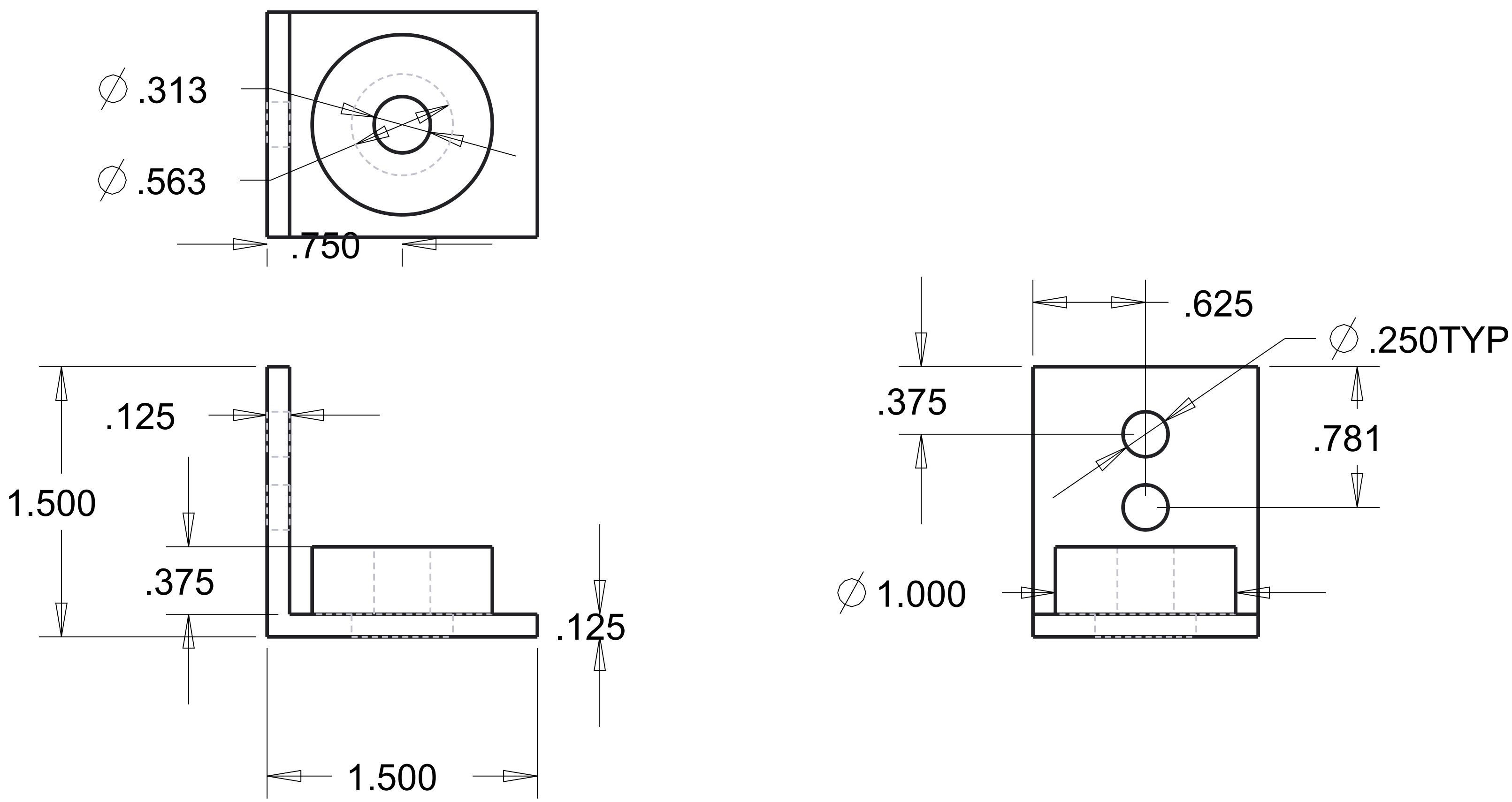




PIvot Mount
All Units Inches
Scale 1:1
Material: Steel L-Brace and Steel Enclosed Bearing
Req'd: 4

Connects the Frame to the Short Arm and the
Plastic Holder to the Long Arm





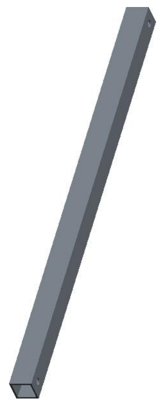
Short Lever Arm

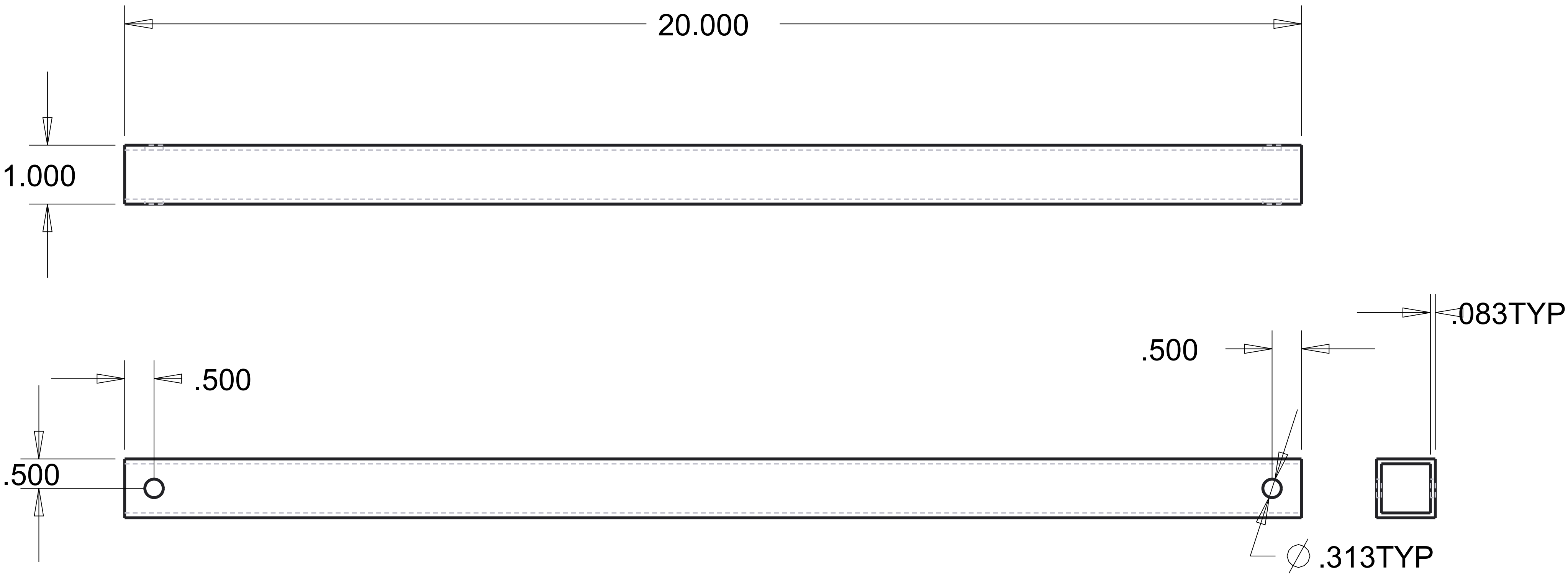
All units are in inches

Material: Square tube steel

Scale 0.400, except where noted

2 Req'd





Long lever arm

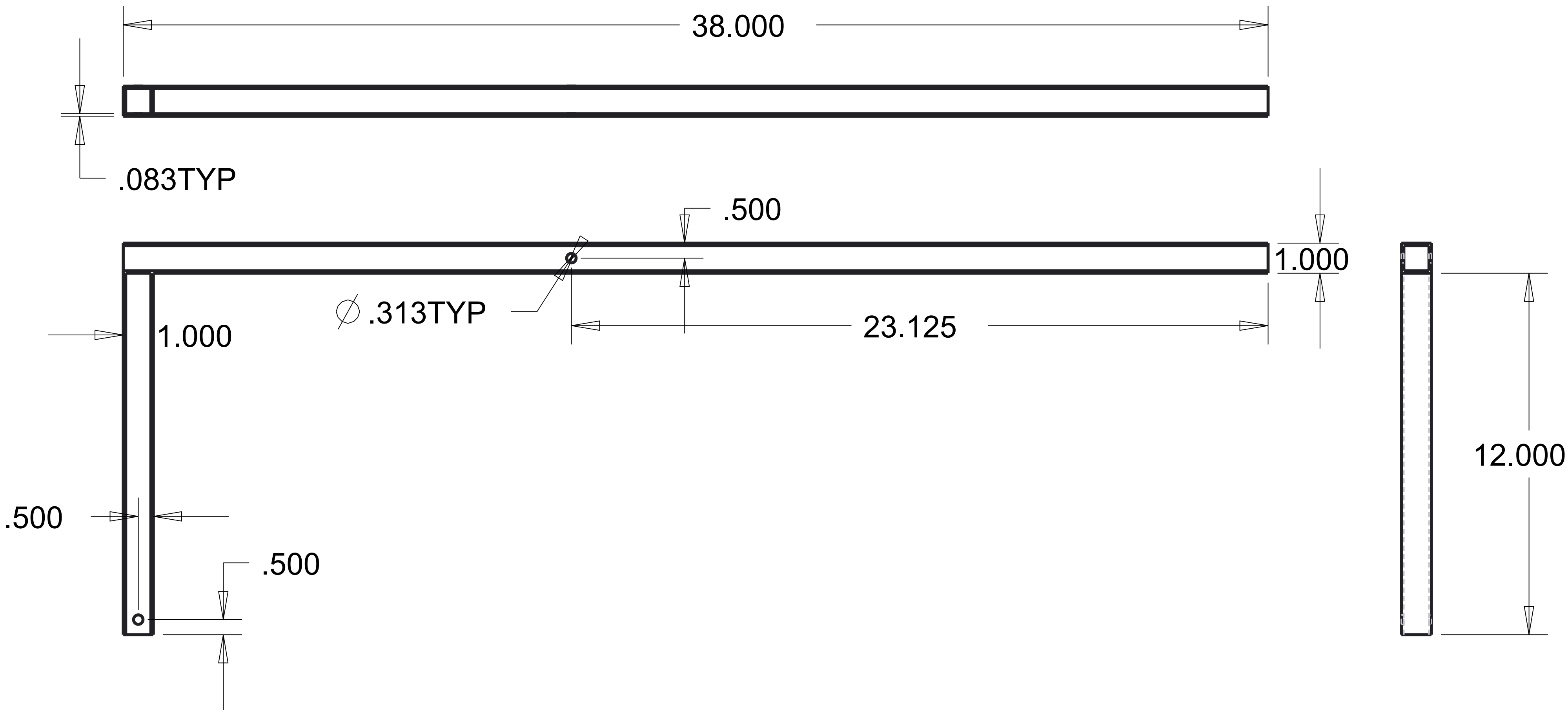
Scale .2 except where noted

All units inches

Material: Square Tube Steel

2 Req'd

SCALE 0.050



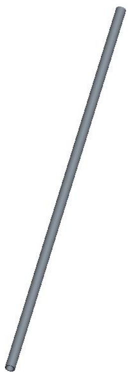
Handle Tube

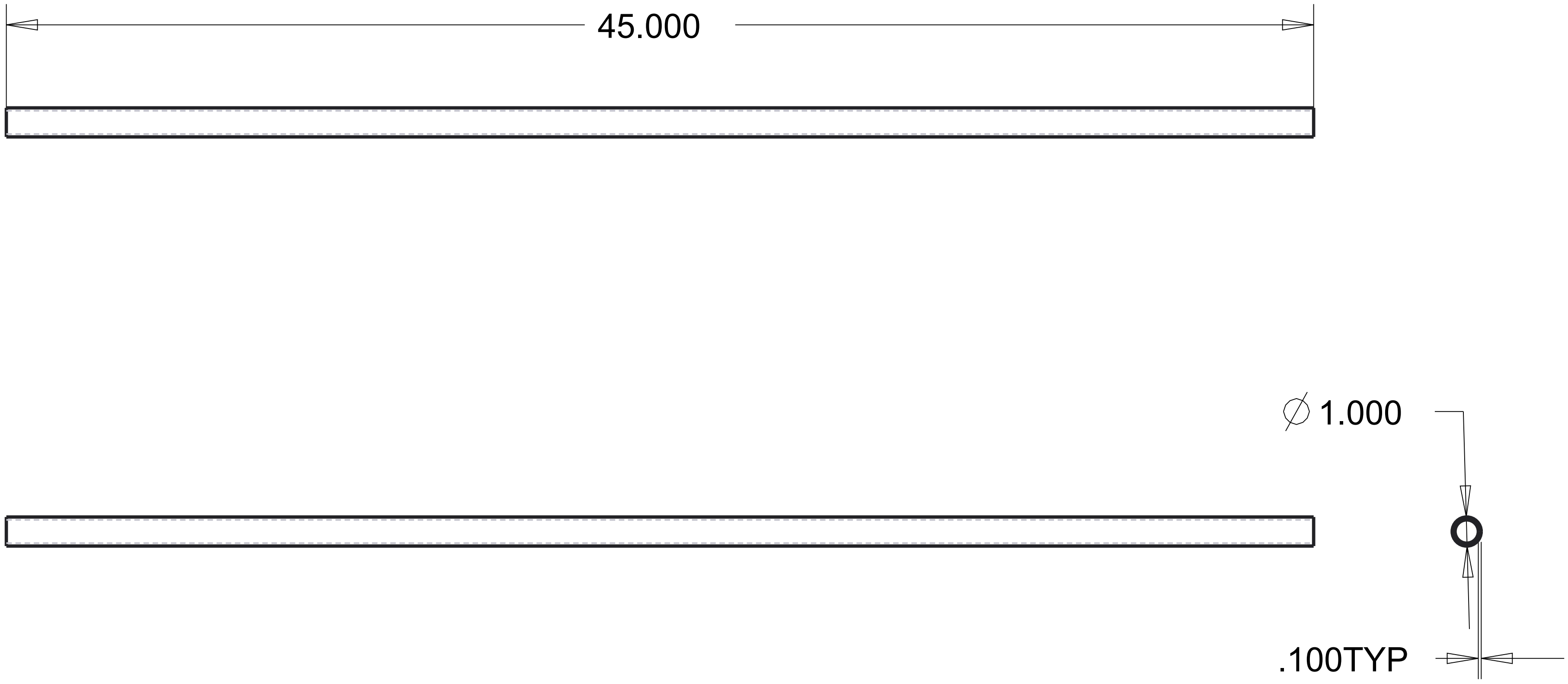
All units in inches

Material: Cylindrical steel tube

Scale 0.175 unless otherwise noted

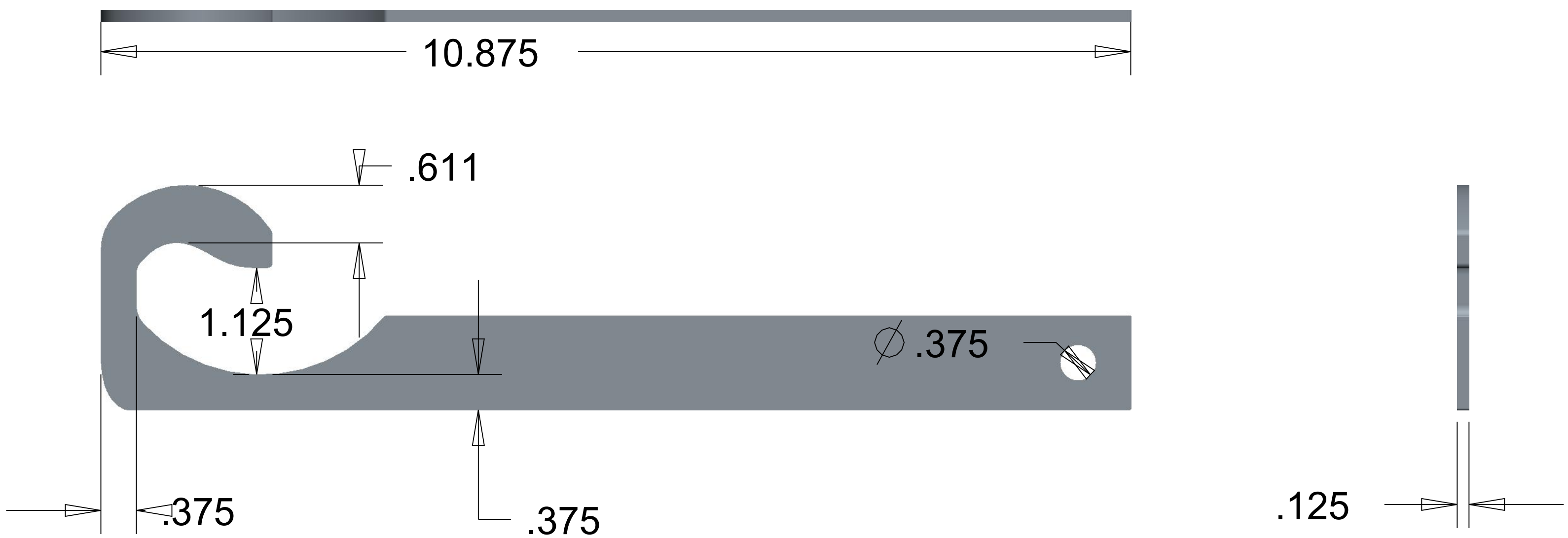
1 Req'd





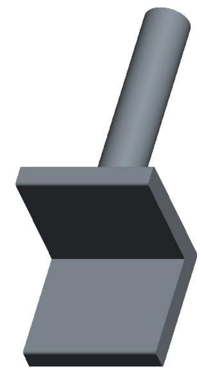
Safety Hook
All Units Inches
Scale: .5 unless noted
Material: Steel
2 Req'd
Attaches to the Frame and catches the Handle
at the top of its motion.

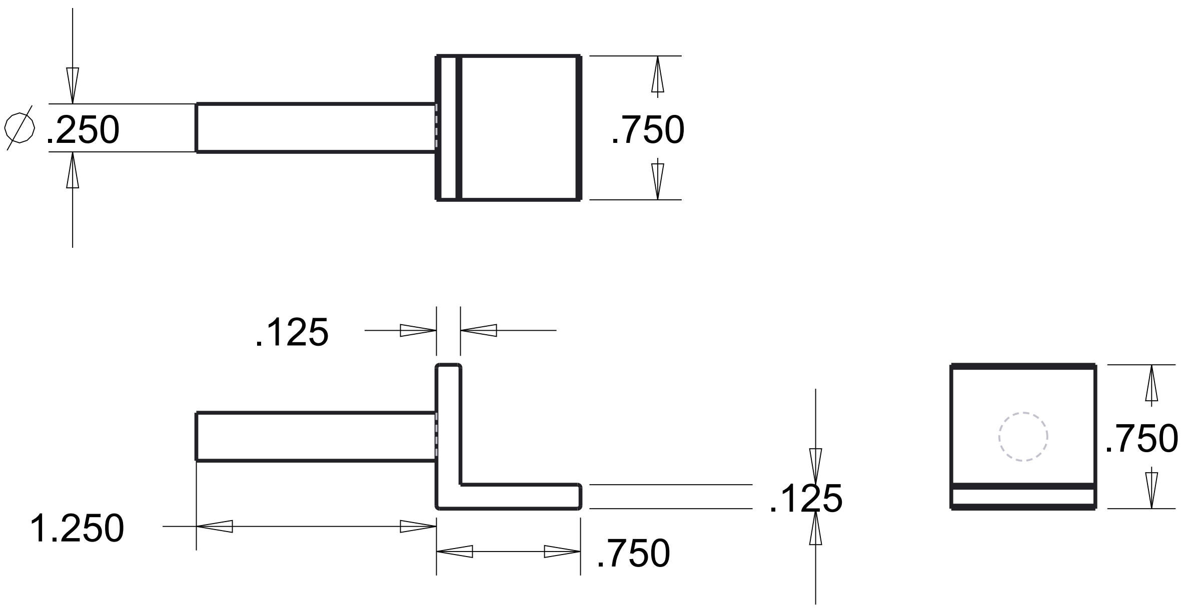
SCALE 0.250



Bottom Stopper
Material: Steel
Scale: 1
All Units Inches
2 Req'd

Constructed by welding a 1/4 x 20 screw into a hole in a piece of angled steel. During use, it is run through the Bottom Stopper Post and secured with a wing-nut





Bottom Stopper Post
Scale 1 except where noted
All Units Inches
Material: Steel
2 Req'd
Attached to Frame as a place for the Plastic Holder to rest when the inserts are taken out or put in