Extrusion Blow Molding

Kayak Rack Project

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Introduction

The product that will be created is a storage component for kayaks and kayak equipment. It is designed to be a standalone component and will be molded as a single part. The piece is designed in a similar manner to a set of stairs with a cutout in the middle and will be able to fit two kayaks on several tiers as seen below in figure two. This design will allow for different kayak sizes to be used as there is no wall limiting a large kayak from fitting. The area where the kayak is placed will be angled inward to prevent it from falling off the rack. As a result of the blow molding process, the inside of the part will be hollow. This large, enclosed space will be accessed by a door on the side wall that is able to open and allow the area to be used to store lifejackets, paddles, or other accessories. The part will be best suited leaned up against a wall, either outside or inside a garage. As is, the product will be able to serve its purpose, but has no real personality and would likely not be very desirable to display. To counteract this, on the top and outside walls of the part, an art aspect with a nautical or outdoor theme will be molded into the part to make it more visually appealing and enable it to serve also as a decorative piece.

Having an efficient system for storing any large item such as a kayak can be a difficult task. As a result, many kayaks do not have a place where they can be properly stored and often end up sitting in a garage, in the yard, or on the shore. While there are kayak storage racks that can be purchased, there is not really an industry standard design, and in fact, many of the currently used kayak storage systems are homemade. The most used seems to be two metal or wooden posts with a rung or hook system for holding the kayaks, like the rack shown in figure one. Overall, this is a fairly simple design, likely one of the reasons why it is used. Additionally, this rack would come in a compact box, providing shipping, and transporting benefits. While the blow molded design would certainly not ship as easily, this is a product that once it has a place where it is going to be used, it is likely not going to move often if at all. Additionally, having one large component requires no additional assembly for the consumer and limits the overall supply chain management the manufacturer would need to do to outsource other possible materials needed.

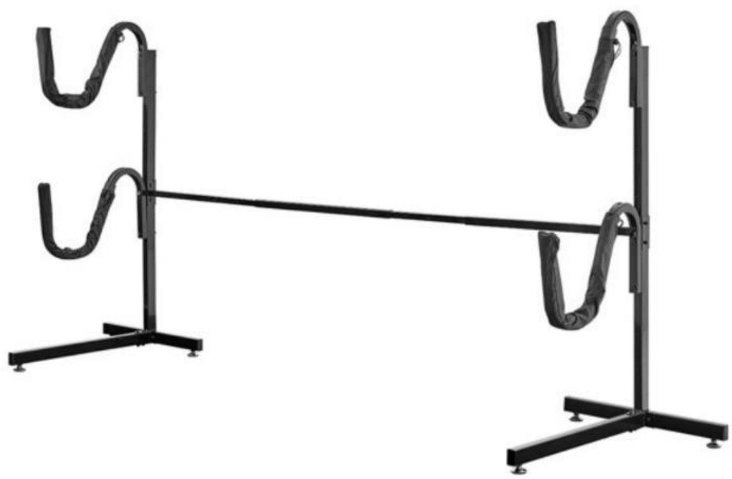


Figure 1: Traditional Kayak Rack Design

https://www.walmart.com/ip/XtremepowerUS-Freestanding-Kayak-Rack-Heavy-Duty-Dual-Storage-Height-Adjustable-Carrier-Stand-Kayaks-SUP-Paddle-Boards-Canoes-Max-Load-175-Lbs/741417424 n

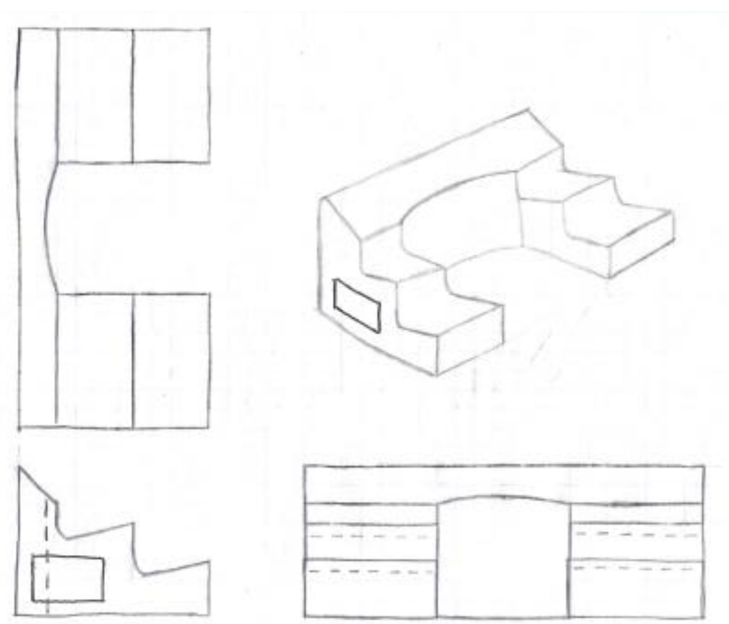


Figure 2: Blow Molded Kayak Rack Design

Application to Process

The extrusion blow molding process (EBM) is widely used within the plastics industry due to its ability to produce hollow parts of just about any shape or size. This gives the product designer the ability to develop a broader range of possibilities when trying to develop an initial concept for a part. Plastic can naturally produce complex shapes and organic features due to the material properties and vast variety of processing methods available. Thus, converting a regular kayak rack to a large hollow plastic part now allows the addition of design features that would not be possible if it were made from wood or metal piping. The cycle time of the process may be slower due to the intermittent EBM process, but the advantages of being able to design and produce a part of this size and shape that is hollow outweighs this factor.

When looking at the initial concept sketches of the kayak storage unit above, EBM is easily the best plastic process to mold the part. The complex shape, size, and design of the part would be impossible to make in any other process other than rotational molding. Rotational molding still falls short though because of the long cycle times required for the process. Other processes such as injection molding, thermoforming, and compression molding are also not feasible due to the size and design goal of the part.

The injection molding process is limited in terms of the size and complexity of parts it can produce. Designing parts for this process can become a difficult task, as there are many rules and guidelines that must be followed such as maintaining a nominal wall, rib/boss design, and many other factors. Not following these rules would most likely result in problems on the shop floor such as warpage in the parts or maybe not being able to mold the part at all. In terms of the kayak rack, injection molding would never be able to make the part as one piece because of the hollow design. Even if it was somehow designed to be injection molded by following the design guidelines, the model would be complex and would result in a very large and expensive piece of tooling. At this point, it would be difficult to find a machine that fits the mold and has the shot capacity required to fill the part. The pressure requirements for EBM are also way lower than injection molding. This means that the tooling cost can be significantly lower because cheaper materials can be used, as the mold does not have to withstand the high pressures and fast cyclic pattern of an injection molding process (1). The ability to develop cheaper tooling now opens the possibilities to produce lower production volume parts that were not feasible before due to the high tooling cost (1). Being able to have a relatively cheaper mold made for a part the size of the proposed kayak rack idea makes producing it more feasible.

The thermoforming process is also not a valid option as it also would not be able to produce a hollow part. The only way this would be possible is if you defined the parting line and created two mold halves for the part. Then using plastic sheets, thermoform both sides of the part and weld each half together to create the hollow part (1). This could work, but it would not be the best option due to the post processing requirements that would need to take place. EBM would take away the need to weld each side together because it can mold the part as one hollow object. Compression molding is out of the picture as well due to hollowness and size of the part. Two halves of the part might be able to be made and welded together like it would in thermoforming but doing so would not make sense since the EBM process is available. This would also require two molds to be made for each half shell of the part.

Overall, the EBM process is a unique and viable way to produce hollow plastic parts. The process opens the possibility to fulfil design goals and create part geometries that were not thought possible before. Creating the kayak rack as one hollow object takes away the need for assembly and allows it to have a more visually appealing design than one made from other materials. EBM is the best process for a part like this because of its ability to create hollow objects, tooling costs can be cheaper than injection molding tooling, and there is little to no post processing work required.

Part Specifications

When examining the loads and other factors the kayak storage unit will encounter during its end use, the primary mechanical load the rack will see is the weight of the kayaks themselves. To get an idea of the loads the rack must withstand, a survey was conducted to obtain the average weights and dimensions from many of the bestselling kayak brands across numerous different websites. The loading from the weight of the kayak will be the primary concern, but it must also be designed to accommodate the length, width, and height dimensions of the kayaks as well. After reviewing multiple brands, the average recreational kayak length was found to be 9-10 feet long, 29 inches wide, and 12.5 inches in height. The average weight was around 42 pounds and the 95th percentile being 63 pounds. The force itself will be distributed across the entire surface of each rack portion rather than a direct load acting on one section of the part. ANSYS will be used to analyze the reaction the part has to the force acting on the racks. A static structural analysis will be conducted, assuming the kayaks are stationary, and the rack is at full capacity. Since the average weight of multiple different recreational kayaks will be used, a safety factor of 1.5 – 2 will be added to accommodate the possibility of the rack being used for kayaks heavier than those of which were surveyed (2). If the part yields and deforms because of the kayak weight, this will be considered a failure and the wall thickness and/or design of the part will have to be reconsidered. While analyzing the results from ANSYS, the flexural yield stress of the material will be compared to the von Mises stress shown from the simulation (3). If the von Mises stress is higher than the yield limit of the material, this will be considered a failure (4). The goal is to design the part right up to the materials yield limit so the applied load can be maximized. This will result in having the lightest possible part which in return will save on transportation and material costs. The primary mechanical requirement for the kayak rack is going to be its ability to withstand the weight of the kayaks. As previously mentioned, the 95th percentile weight for kayaks is about 63 pounds and with a safety factor of around two, the material selected must be strong enough to withstand a distributed load of around 120 pounds. Other considerations regarding the chosen material will be UV, chemical/weatherability, and creep resistance capabilities assuming the part is under a mechanical load less than the materials yield limit. These factors will ensure the part is held to a certain quality and will further ensure failure will not occur.

Material Selection

To determine which material would best meet the expectations of all the factors that are important for the kayak racks use, a material selection matrix was created as shown in Table 1 below. Each material property was weighted 1-15 depending on its importance to the application. They were then ranked 1-4 to show either how poor or strong each material is for the property. A rank of one means the material is poor for those properties, two is moderate, three is good, and four is very good. In many applications, the kayak is going to be placed in an outdoor setting, so temperature it will see is something to be consideration. The materials glass transition temperature will be an important factor as the rack may be subject to both very hot temperatures in the summer and cold temperatures in the winter. The heat would cause the polymer chains to have more free volume between each other and could lead to more creep in the part overtime if it has a constant load applied to it. Cold temperatures during storage in the winter could also make the material become more brittle and potentially crack. Both extremes on the temperature scale could be a potential concern for failure in the part.

Due to being such a large object, the rack will often be stored outside by a wall or beside a body of water and because of this, UV resistance is important. This factor was weighted at a 10 because the part will have to withstand the harsh UV rays if it is outside all the time. Both HDPE and PP are expected to do worse with UV light compared to PVC because the rays will refract off the crystals back in the structure and harm the polymer chains. Unlike these two materials, PVC has an amorphous structure where the UV rays can pass through the material more easily and not harm the chains as much.

Chemical resistance and weatherability of the part will also be important due to the nature in which the part will be used. If the kayak rack is used near the ocean, salt water will have to be considered for the effects on the material. This factor was only given a weight of 3 though because it will not see many chemicals in its use. It is still a factor due to the chance it may be used near an ocean where there is salt water. Each material reviewed all have good chemical resistance due to HDPE and PP having crystallinity and PVC having the large chlorine atom in its structure. Also, in an area where winter is a prevalent season and the kayaks may be stored on the rack for a few months, creep resistance will be looked at to ensure that it can hold a certain weight for a specified amount of time without deflecting to the point of failure. Since not everyone lives where it gets cold in the winter and the kayaks may not be always on the racks, creep resistance was given a lower weight of six. Both HDPE and PP have a rank of one due to their low glass transition temperatures which can affect the creep of the parts. One of the most important factors for material selection will be the material cost itself which has a weight of 15. This is mainly due to the large size of the part, which will take a lot of material to produce the item. Using a more expensive material, despite potentially providing mechanical advantages, may make the product too expensive and not feasible to sell to consumers at a reasonable price. This would defeat the purpose of trying to create and sell the product.

Due in large part to the mechanical load requirements for the part, a blow molding grade of polyvinylchloride (PVC) was considered. PVC generally has tensile strength of around 8,000psi and a tensile modulus of around 400,000psi. The Tg of PVC is about 185 degrees Fahrenheit, meaning it would do well in high temperature uses. PVC is perhaps best known for its chemical resistance, which is something the kayak rack may need if it is near salt water. Other positives for using PVC would include its good resistance to weathering, processability, and creep resistance. Perhaps the biggest downside to choosing PVC would be the cost, especially for such a large part like this. The price of the finished product would be much greater than the cost of the alternative material options.

Polypropylene (PP) was another material option reviewed to use for the kayak rack. One of Polypropylenes largest benefits would include the low cost as well as its strong resistance to chemicals. PP has a tensile strength around 4,500psi and a tensile modulus of 175,000psi. The Tg for PP is 15 degrees Fahrenheit and is quite susceptible to creep as result. Also, in outdoor applications polypropylene is vulnerable to weathering from both extreme cold and UV from the sun. Overall, Polypropylene would have worse mechanical traits compared to PVC, but would provide a significant price advantage.

The other candidate for the part was polyethylene. Choosing HDPE over LDPE would provide more rigidity to the part. HDPE has very similar characteristics as PP, with a major plus for using the material being the lower cost of production and the strong chemical resistance. Downsides of the material would include the mechanical properties, low Tg, creep resistance, and susceptibility to weathering. However, HDPE is a better choice despite being quite similar characteristically to polypropylene for several reasons. HDPE is the most used blow molding material and is about 5 cents per pound cheaper than PP (5). While this may not seem like a huge cost difference, in a part this large, any increase in price for the material will have a significant impact on the final product cost.

After considering all these factors, HDPE will be the chosen material for this application, beating the second choice PVC by six and the third-choice polypropylene by fifteen in the material selection matrix. The two main factors that aided in this decision were the price and the processability. HDPE is a widely used material in blow molding that will make the processing of the part easier and more well documented. Also due to the popularity, there is a wide range of blow molding grades available to choose from. Perhaps the most important factor was the cost, however. To be able to compete with other kayak rack options, or even homemade alternatives, the part needs to be inexpensive to produce. Polyethylene provides the most budget friendly option and still holds up to the specifications in which it needs. Due to the large size of the part and thus potentially high shipping costs, choosing one of the more expensive options would put this part at a price range that would severely limit the potential market of buyers. While choosing HDPE will mean getting worse creep resistance, chemical resistance, and mechanical properties compared to the second choice PVC, the reduced cost and good processability for the material is what made it the preferred choice. These factors are all important, but they were weighted lower due to what the actual end use of the product will be.

After choosing HDPE, the Lyondellbasell blow molding material selection guide for HDPE was used to determine what grade of material will be used (6). The most fitting material for the application was Lupolen 5021 DX. This grade has good environmental stress cracking resistance and good overall chemical resistance. The grade is most used in applications including toys, packaging, engineering parts, and consumer goods. These traits combined with the additional advantages HDPE provides makes it well suited for the kayak rack.

Material Selection Matrix							
		HDPE		PP		PVC	
Specifications	Weight (1-15)	Rank (1-4)	Total	Rank (1-4)	Total	Rank (1-4)	Total
Mechanical Properties	6	2	12	2	12	3	18
Chemical Resistance	3	4	12	4	12	4	12
UV Resistance	10	2	20	2	20	2	20
Weatherability	10	1	10	1	10	4	40
Processability	15	4	60	4	60	2	30
Creep	6	1	6	1	6	4	24
Price	15	4	60	3	45	2	30
Final Score			180		165		174

Table 1: Material Selection Matrix

Manufacturing Details

There are three main types of extrusion blow molding processes that all have different uses depending on the needs of the part being created. These include the continuous, intermittent, and 3D processes. A continuous process is best suited for smaller parts, including bottles, that can quickly be formed, cooled, trimmed, and ejected. Parts being created in a continuous process most likely do not require a parison as big as those needed for large parts, so the time to build up the material is not a limiting factor in the production process. The molds for this type of process could also have multiple cavities, creating more than one part per cycle. The parisons for the next parts are extruded at the same time as the parts are being blown to shape. This allows for a complete, continuous cycle, hence the name.

The intermittent process is more suited towards large objects, such as water tanks and playhouse slides. Unlike the continuous process, as the part is being formed, the screw is building the amount of material needed for the next parison. Once the material is built up, a ram pushes the material through the head and the die to create the parison. The mold clamps shut, and a blow pin blows air through the hollow parison to create the part. The location of the parison relative to the part geometry is important to ensure that there is good surface contact between the polymer and the mold walls once the air is blown. This is also important to make sure there won't be any thin regions in the part. The thickest area of the part will be where the parison first touches the mold walls. After that, the parison will have to stretch to reach the other surfaces of the part, causing the walls to become thinner as it is stretched out. The blowing time also is important, as it acts as a cooling mechanism as well. The size of the part limits how fast each cycle can happen because it takes more time than in a continuous process to build the material for the parison, cool the part, and eject the part. The molds for the parts are also most likely single cavity tooling, also due to the size of the parts. The cycle is slower than a continuous process, but the parts being created from an intermittent process are commonly not as high of demand parts as ones being created in the continuous process. An example would be comparing large playhouse parts to commercial soda or water bottles. The consumption of bottles is way higher than playground equipment, so even though the intermittent process is slower, it makes up for the fact that the parts being created with it are not as largely consumed or needed.

For the kayak rack, the best type of process will be the intermittent process. This was mainly determined by the size of the part and the time it would take to build up the amount of material needed for the parison. The continuous process would not be applicable for this part because the time to create the parison would not be able to keep up with the time it would take to form the part. Unlike the continuous process, the time to eject and move the parts from the mold is longer as well. This extra time needed for removing the part will give more time for the material to build for the next part. A disadvantage of using this process and creating large parts is the fact that there is such a large parison being formed. The parison will be very heavy, and as more material is extruded from the die, gravity will work to pull that material down. This will create parison sag and could result in localized thin regions in the part. To combat this, a parison control could be added to change the amount of material being extruded. Even with a parison control, there could still be thin regions in the part based off the geometry of the object. A sharp corner or any part that sticks out further than the main body of the object could be difficult to maintain a relatively uniform wall thickness due to the parison having to stretch out. The kayak rack could have this problem while trying to form the lands where the kayaks will lay on the opposite side of where the blow pin will be. A pre-blow could be utilized to blow the parison up so that when the mold closes, the parison lays onto the mold and doesn't have to stretch as far.

The type of head that will be used is an accumulator head. This type of head is commonly used for intermittent extrusion blow molding processes because of its ability to "accumulate" material then push it out of the die using the built-in ram. This type of head is best suited for large, heavy parts and it is specifically designed to help avoid parison sag (7). This is extremely important for the kayak rack, as it is a large object that would be susceptible to parison sag which would cause thin regions in the part. Figure 3 below is an example of an accumulator head.

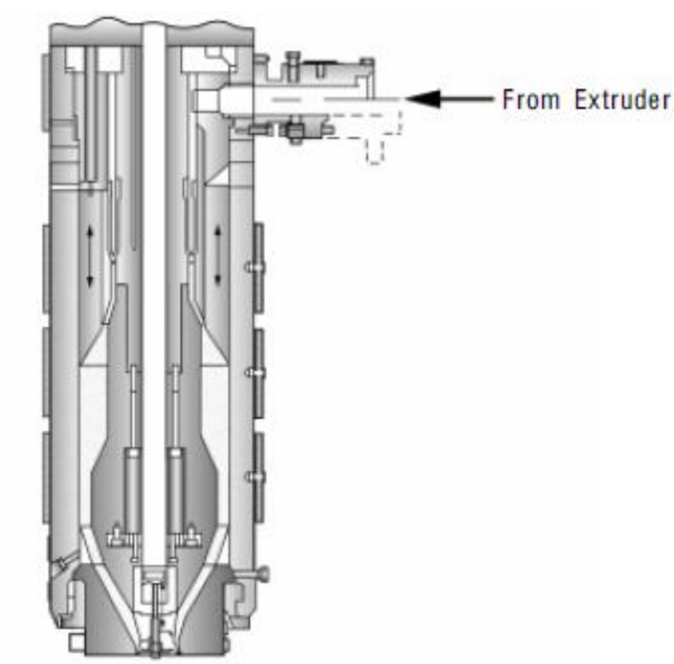


Figure 3: Accumulator Head

Machine Selection

The main factors when choosing a machine for the extrusion blow molding process is the platen size, the max daylight, allowable shot weight/size, and the clamp tonnage. Based on the needs of the kayak rack, Yankang's YK 5000L Blow Molding Machine was chosen. Table 2 below provides some of the important machine specifications needed to be able to mold the kayak rack.

YK 5000L Blow Molding Machine		
Specifications	Value	Units
Platen Size	7.87x8.53	ft
Max. Mold Size (LxW)	7.71x9.12	ft
Max. Mold Thickness	5.09-7.22	ft
Max. Parison Weight	331	lbs
Clamp Force	395	Ton

Table 2: Machine Specifications (8)

The main base dimensions of the kayak rack are 6.8ft x 8ft. To estimate the mold size, 8 inches was added to get final dimensions of 7.5ft x 8.6 ft, proving that this machine will work for the given mold size. Another factor is if the machine has a large enough clamp force to hold the mold shut when the part is being formed. The pressures required for the blow molding process are low compared to those in injection molding. The pressure required for this part is low enough and the clamp force on the machine will ensure the mold will not blow open. The weight of the parison will also be good for our part, as the max weight on the machine is 331 pounds.

Preliminary Calculations

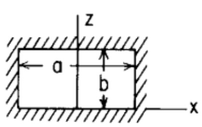
Preliminary hand calculations were solved to determine a minimum wall thickness that will not yield under the materials maximum flexural yield strength of 4,000psi. A flexural yield strength value for the Lyondellbasell grade chosen was not given in the material specifications sheet, so a different but comparable grade of blow molding HDPE was referenced to get the 4,000-psi value. For this calculation, the formula from Roarks formula for stress and strain guide were used, shown in Figure 4 along with the excel sheet with the calculations. Two different equations for stress, one at the center and one at the edge were used and the maximum between the two would be the value used to compare to the yields stress.

The a and b values are the area where the force is acting, which was determined from the CAD model for the part. Dividing A/B gave a value of 1.458 which then was used to find beta 1, beta 2 and alpha from the table also shown in figure 4. To determine the most accurate values to use, values for all three were calculated by interpolating using the table values for 1.4, and 1.6 and the calculated A/B value of 1.458. Q is the pressure acting on the surface. To determine this, the 95th percentile weight of 62.7 pounds was multiplied by the safety factor of 1.5 to get a new weight of 94 pounds. Due the force being a distributed load, this force was divided by the surface area to convert it to a pressure acting upon the surface. Since there are two surfaces that the force will be distributed upon, this value was divided by two to get the final pressure value.

Originally, the thickness was set to .0787inches(2mm). With this initial wall thickness, a maximum flexural stress value of about 2,316 psi was calculated on the edge of the part and 1,119 psi at the center was calculated. The wall thickness was then changed to get the value as close as possible to the yield stress for the material of 4,000psi without going over. Several new thickness changes were made but ultimately a thickness of .06 inches (1.52mm) resulted in a maximum stress of 3,985psi, only 15psi less than the flexural yield value.

The maximum deflection was also calculated from the roarks equation showed in figure five. For this a modulus of 180,000psi, also from the comparable blow molding HDPE was used. The maximum deflection was determined to be 11.2 inches. This value is without the use of any tack offs. This large deflection will be confirmed in ANSYS, and the use of tack offs will be considered.

8. Rectangular plate, all edges fixed



8a. Uniform over entire plate

(At center of long edge) $\sigma_{max} = \frac{-\beta_1 q b^2}{t^2}$

(At center) $\sigma = \frac{\beta_2 q b^2}{t^2}$ and $y_{max} = \frac{\alpha q b^4}{E t^3}$

a/b	1.0	1.2	1.4	1.6	1.8	2.0	∞
β_1	0.3078	0.3834	0.4356	0.4680	0.4872	0.4974	0.5000
β_2	0.1386	0.1794	0.2094	0.2286	0.2406	0.2472	0.2500
α	0.0138	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284

	Distributed on two faces								
	a	35	in						
	b	24	in						
	a/b	1.458333		Edge		Center		Deflection	
Interpolated Values	Q(As Pressure)	0.055982	psi	-3985.892743	psi	1925.786	psi	11.14269	in
	Beta 1	0.444996							
	Beta 2	0.215							
	Alpha	0.023325							
	Thickness	0.06	in	For Material	4000psi				
	E	180000	psi						

Figure 4: Excel Deflection and Stress Calculations

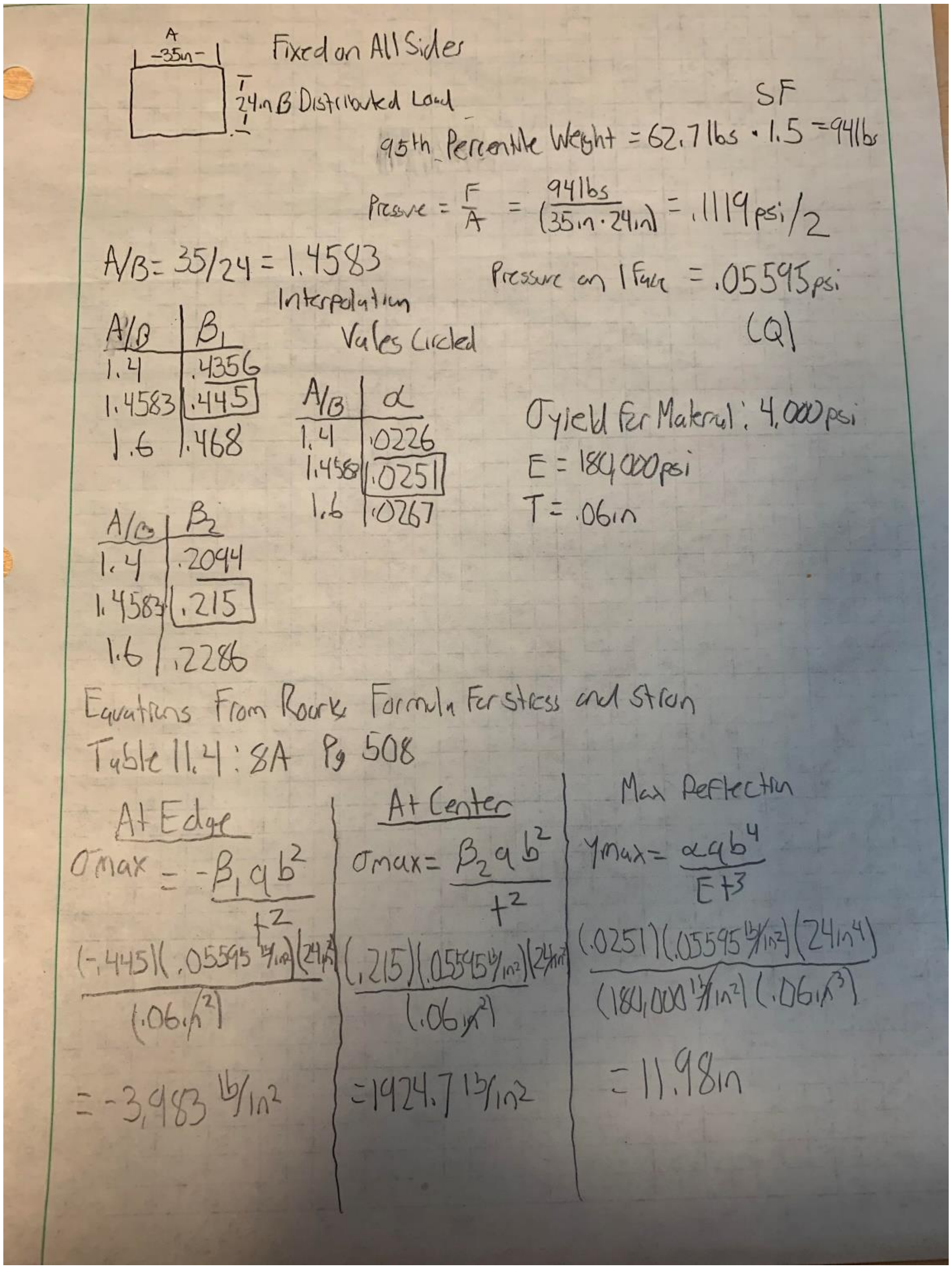


Figure 5: Hand Calculations

Design Details 1

The part specifications, material selection, and the preliminary hand calculations that were done all contribute to the design of the final part. It is important to have this information as a consideration while designing to have a successful molded part. Other important considerations in the design for blow molded parts is the blow ratio, draft and how it effects where the parting line is, ribs or tack-offs, and the use of radii. All this information will be discussed in this section.

Initial Design Concept – Hand Sketch

The hand sketch, as seen in Figure 6, was a simple drawing that helped to depict what the initial idea could look like. The sketch shows a few main features that were wanted in the product which are shown by arrows 1,2, and 3. Arrow 1 shows the main feature, which is where the kayaks will sit. The idea was to have two sloped lands where two kayaks could lay across the gap to the other side of the rack. At this time, the exact size slope of the angle was undecided, but it was made sure to have the idea shown on the initial sketch. Since the part is completely hollow, another idea was to have to kayak rack also act as a storage unit, which is shown by arrow 2. This hole would have to be cut out post-process and would serve as a door to access the hollow cavity of the inside of the part. This space could be used to store kayak paddles, life vests, and other outdoor or kayak related items. The final arrow shows the cut out in the middle. The idea behind this was to reduce the amount of material that would be used since this is such a large part. Having this cut here could also help access a kayak on the second tier if a kayak wasn't already sitting on the first tier. As seen in later iterations, this large cut was taken out of the final design.

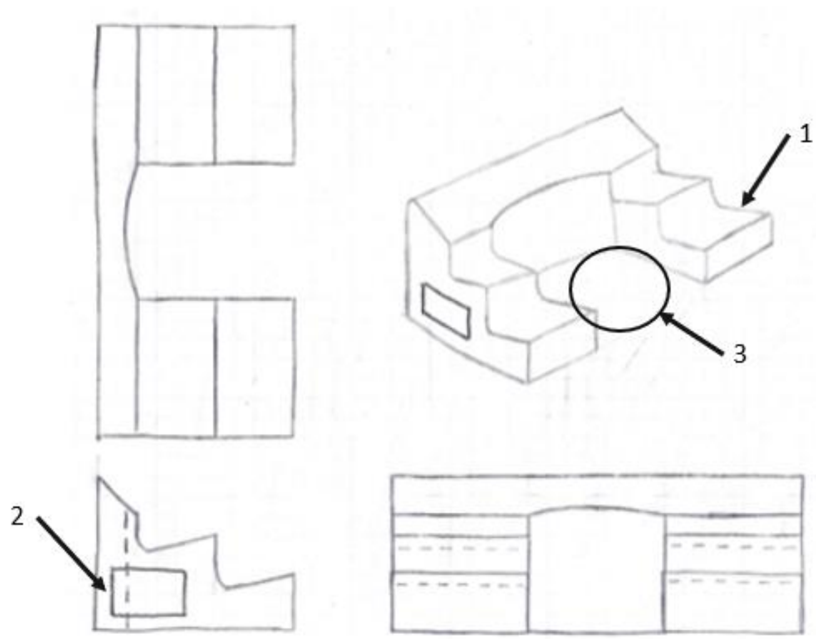


Figure 6: Initial Hand Sketch

Creo Design 1

This first Creo design is the first of two designs that were modeled for the part. Figure 7 below shows the first steps taken in the initial development of the CAD model. The overall shape and design was kept from the hand sketch except the large cut in the middle was reduced to more of a slope shape. This was done to take advantage of the blow molding process and use more of the hollow space that would be produced by the shape of the part. This was also done because it would have been very hard to fully blow out the part and keep a nominal wall thickness with the previous design. The overall design was more pleasing to look at and a large, sloped surface also gave the opportunity to engrave a company or custom logo into the part.

The dimensions of the overall shape of the part were determined based off the of the survey of kayaks that previously mentioned in the part specification section. The overall dimensions are 82” x 96” x 45.34”, or 6.8’ x 8’ x 3.78’. The dimension of each land where the kayaks will sit was determined by the width of an average kayak, which is about 30”. The land width was rounded to 35” to allow for wider kayaks and the addition of rounds in the corners. With the need to hold two kayaks and a land width of 35” led to a total width of the 6.8’. The length of 8’ was determined by the average length of a kayak, which is about 10’. For this design, an allowance of one foot was given for the kayak to hang off the ends each side, resulting in the 8’ length.

Now that the overall dimensions were decided, the next step was to add the slope to the middle of the part. The intent behind this was to take advantage of the hollow space and make the processing of the part easier. The slope connects the top land to about midway up the wall that connects to the bottom land.

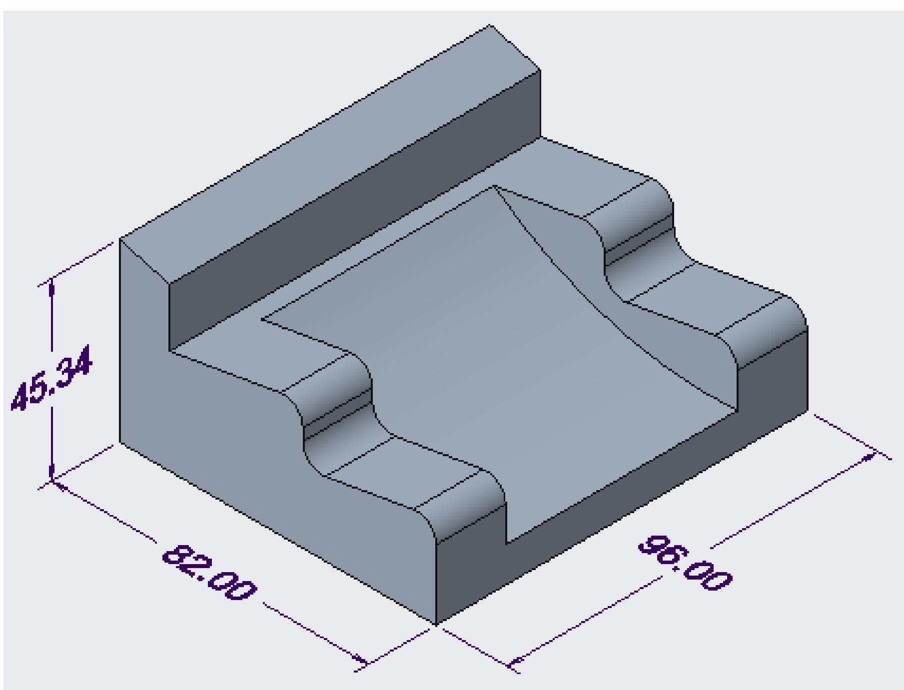


Figure 7: Creo Design 1 without Rounds

Once the overall shape and design of the part was modeled, it was then time to add rounds to the part. Rounds are important in any type of plastic part, especially EBM parts to help prevent the formation of stress concentrations and to have good flow during processing [1]. The addition of correctly sized radii also helps to reduce the amount of material thinning that occurs because it does not have to stretch as far into deep corners. Arrow 1 points to the rounds that were added to the model to reduce the number of sharp corners. Blow ratio was not considered when the model was made, as this initial Creo design was just taking the hand sketch idea and turning it into a CAD model.

Arrow 2 points to the addition of the cut-out hole that would allow access to the inside of the part for storage. Again, this would be added in after the part has been molded. The opening was designed to allow enough room to get paddles, life jackets, and other large items inside of the part. An additional door and hinge system would be added to the opening, so the hole isn't open to the outside all the time. There is currently no model or design for the door.

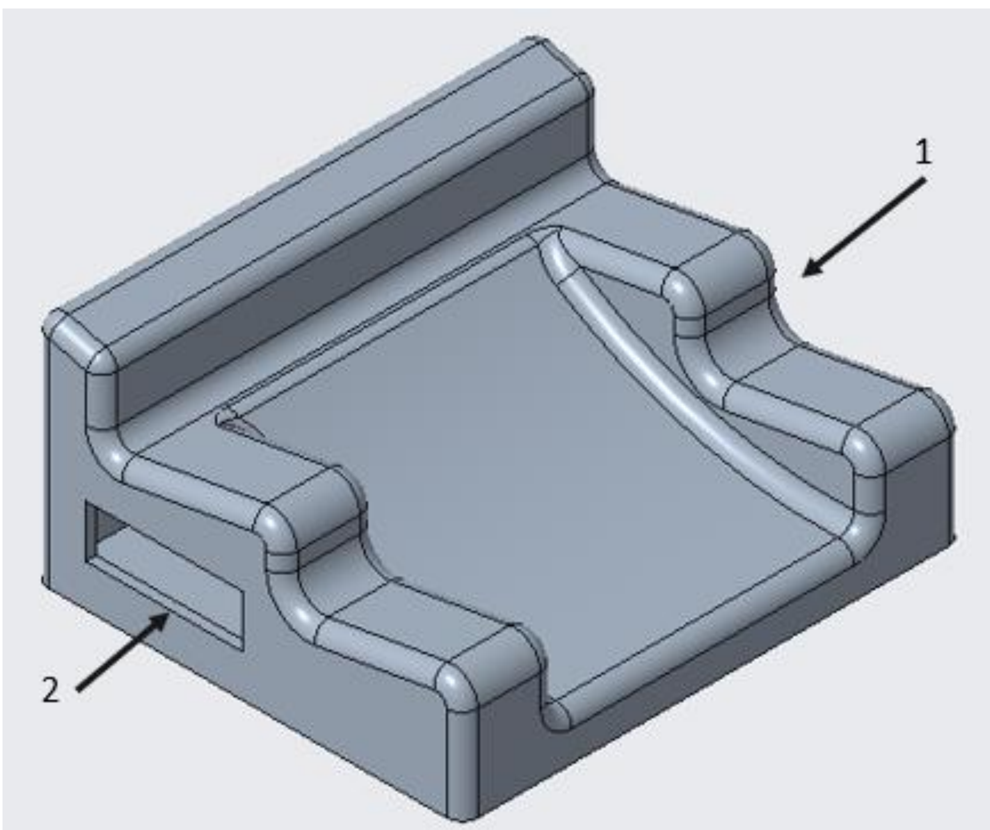


Figure 8: Creo Design 1 with Rounds

Creo Design 2

The second Creo design is a more finalized design to what would be molded on the production floor. This design takes the ideas from the previous ideas and refines them more. The base of this design is smaller than the previous design, and this was done to be more convenient and considerate of the space the kayak rack will take up. The overall base dimension of this design is 4.5' wide X 6' long, compared to the previous of 6.8' wide X 8' long. Assuming an average 10' long kayak, this design allows at least 2' on each side of the kayak to hand off the edge of the part. This could help to make sure the kayak stays on the rack with how it will sit on the part based on the curved shape of the kayak. The large cut and dip in the middle was also removed to allow for better formation and consistent wall thickness throughout the part.

Arrow 1 points to one of the first rounds that was added to the model. With how this new design is shaped, a large round needed to be added in this section due to the deep draw created from the upper rack. It is important to model large rounds into areas of the part that has sections were the parison would have to stretch significantly to fill the part. Tough to reach areas of the part could create very thin walls and this risks the possibility of blowing out one of the walls on the part. Arrow 2 points to the addition of the other rounds there were added throughout the part. These rounds, as explained previously, were added to reduce any sharp corners that were in the model. Having rounds near high stress areas in the part will help to ensure that the part will not fail under load. Arrow 3 points towards the addition of the cutout door, and this will serve the same purpose as described before.

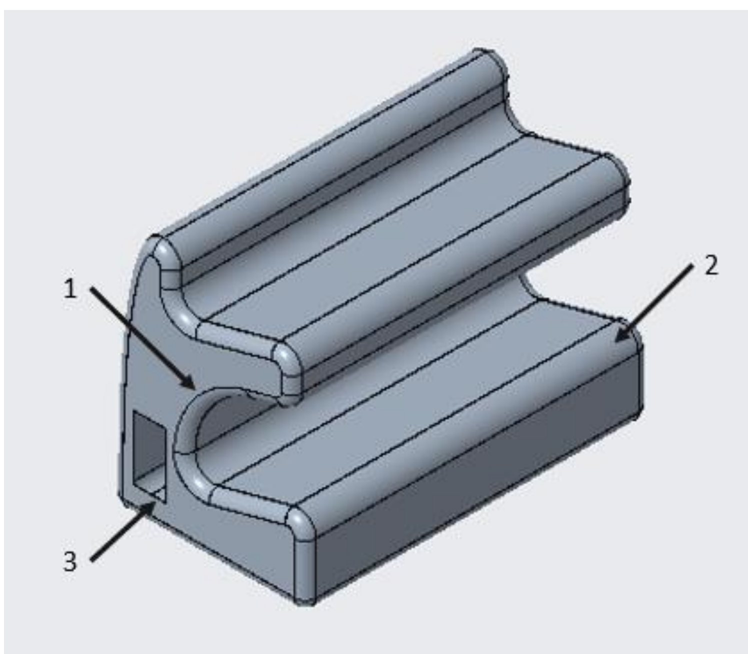


Figure 9: Creo Design 2

Figure 10 below shows what the pull direction of the mold will be. The pull direction will help to determine the parting line of the part and will then help to create the design of the mold. To form the lower section where one kayak will sit, the mold must open in the direction of the arrows. If the mold were to try and open completely horizontally, then there would be an undercut, and the mold would not be able to open. Figure 11 shows what a potential mold split could look like for this part. With how it is split, both sides of the mold would be able to open without interfering with any undercuts on the part. Knowing where the parting line will be will also allow for correct and adequate draft to be added to the part. Draft is a slight angle on a parts surface that allows for an easier release out of the mold. With such a deep cavity in blow molding, it is important to have proper draft on the part so that the part can be pulled out of the mold. A common amount of draft is about 2° per wall, but it could be recommended to go higher to obtain a more uniform wall thickness as this allows for a greater blow ratio [1]. With the large size of the part and the undercut, a draft of 5° will be used to ensure proper ejection from the mold. The distance from the large cut to the furthest point is about 36”. This will be used to help calculate the blow ratio, which is important because this can help to determine the size of the parison needed for the part. A part can also have multiple blow ratios depending on the size and number of deep draws there are. A final blow ratio for this part will be calculated and used within the ANSYS Polyflow simulation software.

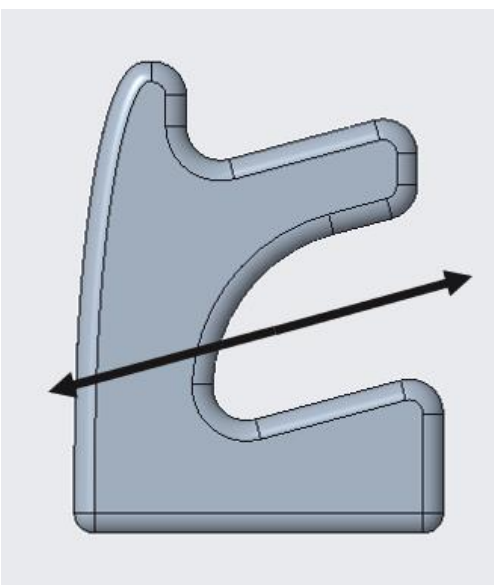


Figure 10: Pull Direction

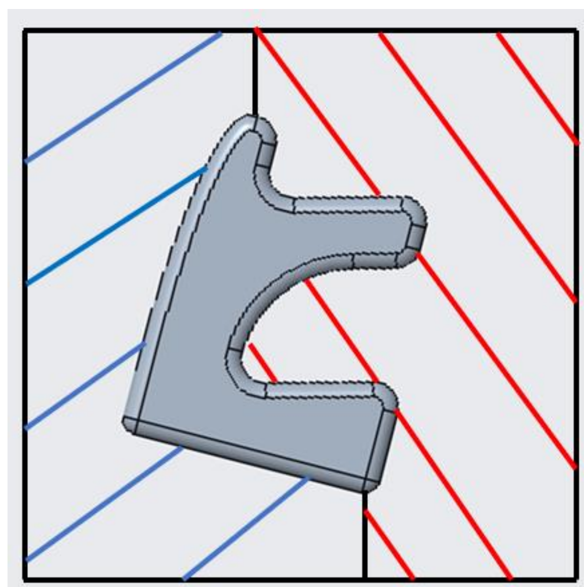


Figure 11: Potential Mold Split

Mold and Tooling Details

Design Change

Upon creating the model in Creo, issues began to arise with creating a model that was moldable due to the large size and geometry of the part. Several large undercuts that would hold the rack and no ideal locations to create the parting line eventually led to the conclusion the current model would not work. At this point we simplified our model into a much smaller and more moldable piece. This new model is shaped like the capital letter H and can be stacked on top of other models to hold as many kayaks as desired. For the rest of the project this new model will be used in mold design and ANSYS simulation. The material and specs for the part will remain the same as the previous iterations.

Blow Mold Design

The overall mold design has two mold halves, splitting the part directly down the center. It consists of cooling lines, vents, pinch-off inserts, and a hole for the blow pin. The overall size is 88”x74”, with 10” of material offset from the overall shape of the part to add structural integrity to the mold. The material for the mold will be machined out of is aluminum. Blow molds typically encounter lower pressures than injection molds, so softer materials such as aluminum can be used. Aluminum is also cheaper than injection mold tooling materials such as steel, which can save a lot of money with such a large tool. The pinch-off inserts will be made from Beryllium-Copper. Since these areas will experience a higher pressure and more cyclic wear, aluminum will not be able to be used. The Beryllium-Copper pieces shown in red in Figure 12 will be separately made on a CNC mill and fastened to the rest of the mold. Since the part is being molded out of HDPE, a shrinkage value was added to the mold to compensate for the natural shrinkage of the material. Making the mold slightly larger than the actual part will ensure the part will be the correct dimensions after the material naturally shrinks.

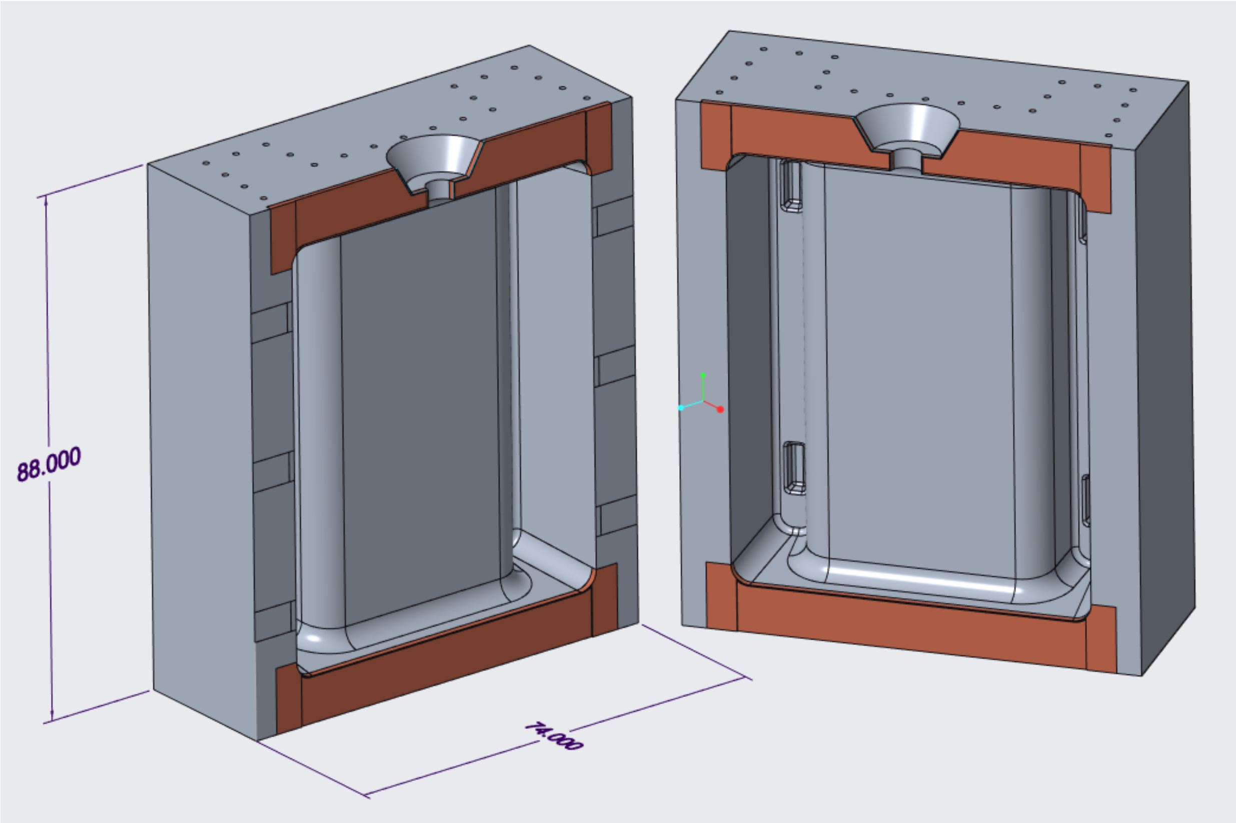


Figure 12: Mold Design

Draft Analysis

As mentioned in the previous section, a 5° draft angle was used on the part to ensure the part can properly be removed from the mold. A recommended draft angle is usually 1-2°, but since the part is large, extra draft was added to assist with ejection. Figure 13 below shows the draft analysis that was completed on the part. The color scale on the left represents the draft that was applied to the part. As shown in the figure, the draft of 5° remains constant throughout the entire part. The geometry of the kayak rack made it so the part could be parted right along the center line. The draft was then able to be applied to each side, resulting in a clean mold split.

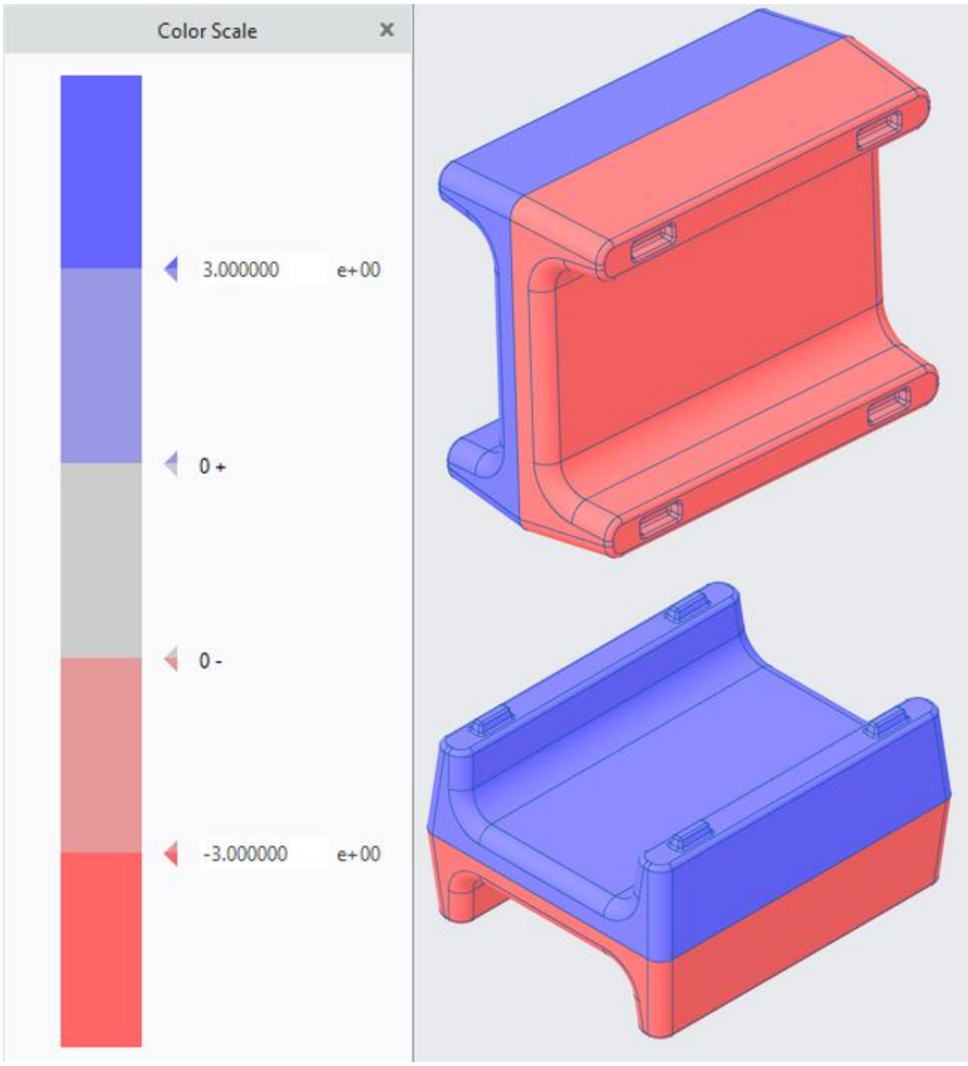


Figure 13: Draft Analysis

Pinch Offs

The purpose of having a pinch-off in extrusion blow molding is to pinch the parison together to create a seam on the part. This will help to completely seal the part and allow for the air to blow the material to the inside walls of the mold cavity. Figure 14 below shows the dimensions of the pinch-off area, which were designed per the Advanced Elastomers Systems design guide. The pinch-off land width was chosen to be 0.03" and the pinch angle is 45° (7). The flash pocket depth of 0.18" was decided from taking 1.5x the wall thickness. The final wall thickness will be decided after the ANSYS analysis is complete, so for now an estimated wall thickness of 0.118" (3mm) was used for this calculation. Beryllium-copper will be used for the pinch-off inserts because this is such a high wear area. Aluminum is a softer metal, so it would wear and need to be replaced often if it was used for the pinch-offs.

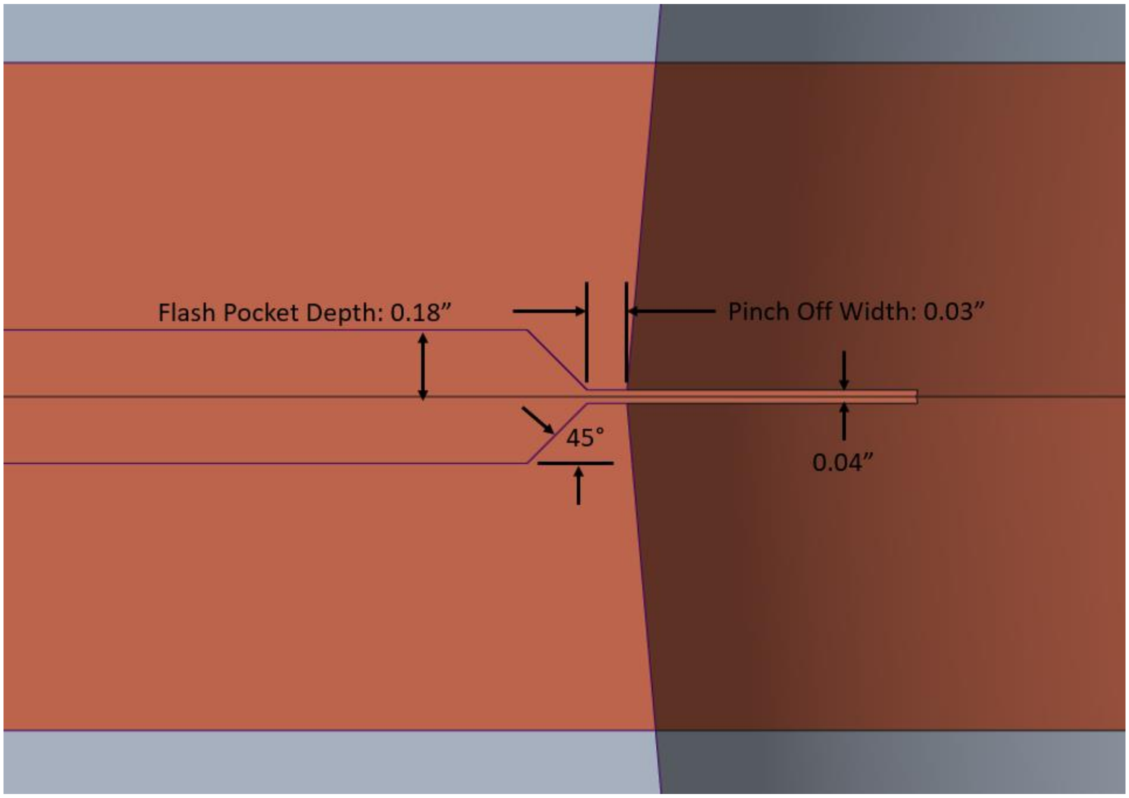


Figure 14: Pinch-Off Dimensions

Venting

Six evenly spaced vents were added to one side of the mold and distributed along the parting line for the kayak rack. These vents will allow any trapped air in the mold to escape while the parison is being blown to the mold walls. The location of the vents can be seen in the mold shown in Figure 12. The vent land depth was designed to be 0.003”, as typical vent land depths are 0.002-0.003” (7). This is deep enough to allow trapped gases to escape while keeping the material inside the mold. Vent land lengths are usually only 0.24”, but since the mold is so large, a length of 1.0” was used for easier machining and to reduce the chance of mushrooming over the vents. The vent dump depth was designed to be 0.016”, since the recommendation is 0.0098-0.016” (7). The high value was chosen since the mold is large. More air will be enclosed in the mold once it is closed, so the vents needed to be as deep as possible while still keeping the material inside the mold.

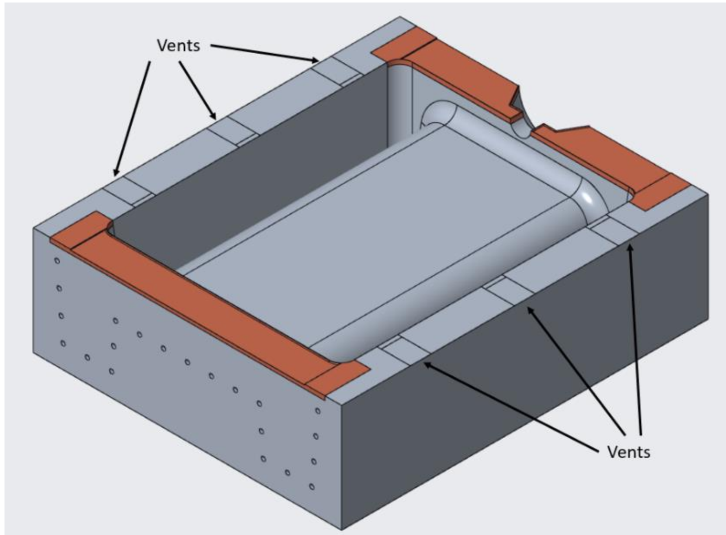


Figure 15: Venting Locations

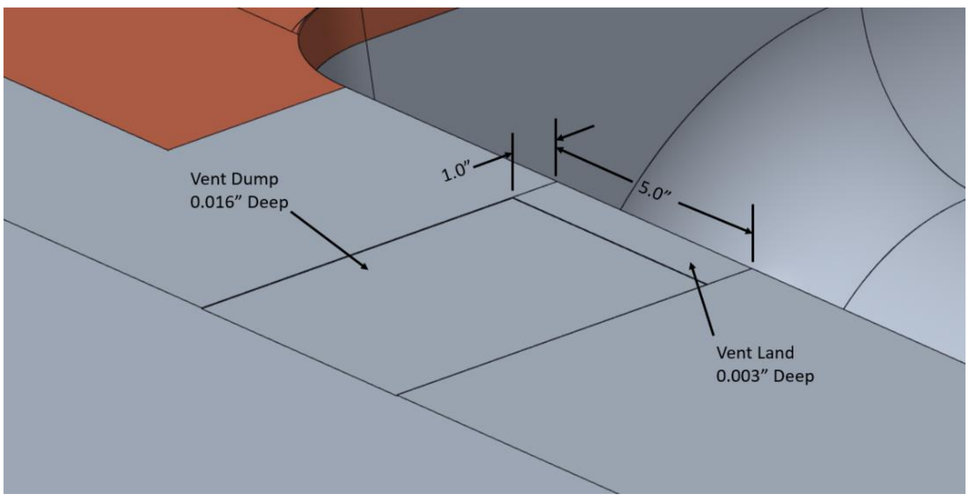


Figure 16: Vent Dimensions

Blow Pin

The use of a blow pin is the primary way in which air can travel into the mold to blow out the part. The hole shown in Figure 17 was designed into the inserts to allow room for the blow pin to get into the part once the mold is closed. A blow pin must be used over a blow needle or hypodermic needle because of the amount of air that is needed to inflate the part. Although a needle offers the ability to hide the blow hole in the part, this would not be feasible for the kayak rack. A rubber plug or cap will be added post process to the model to fill this hole so water does not fill the part.

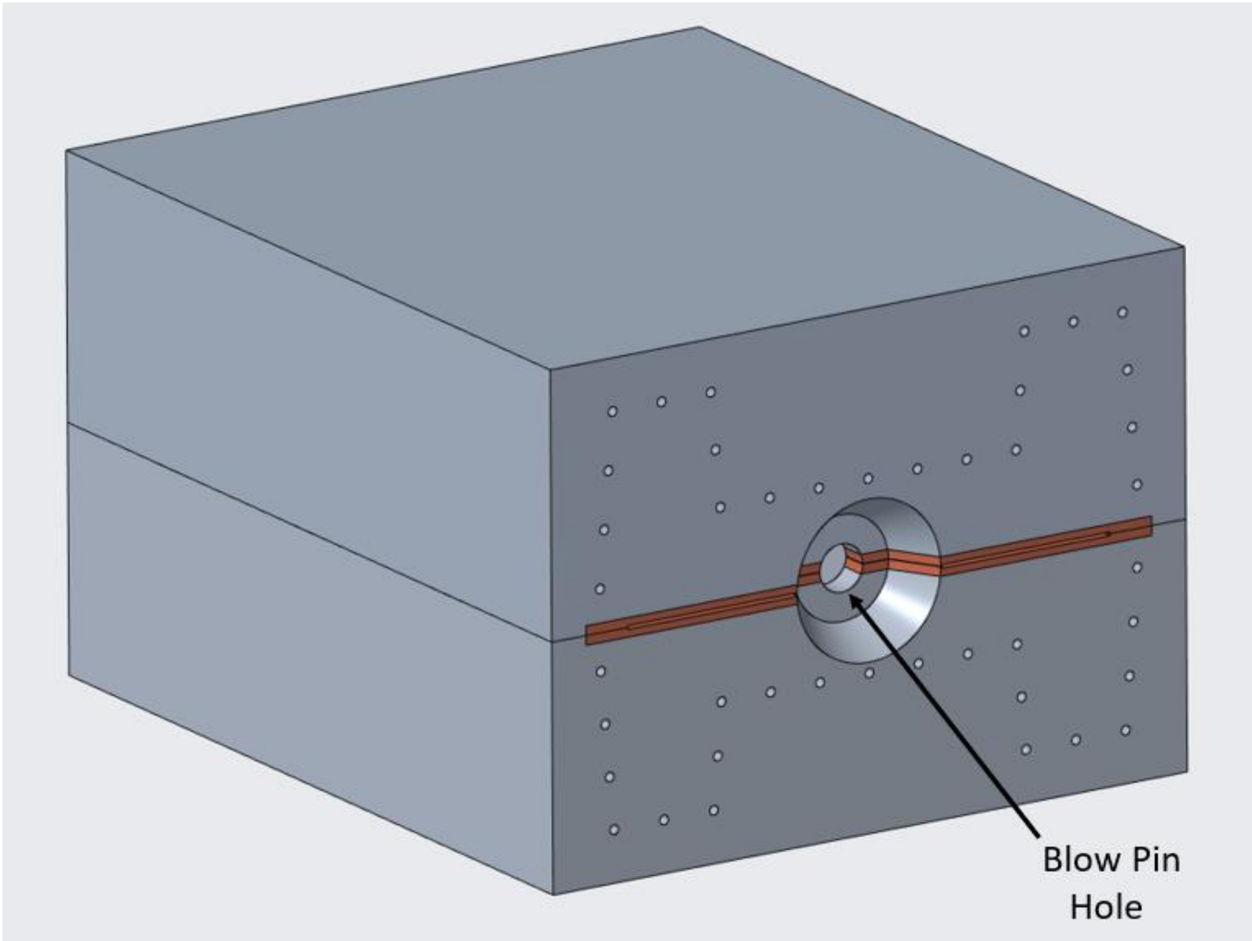


Figure 17: Blow Pin Hole Location

Cooling Channels

Proper cooling is another crucial aspect in effectively extrusion blow molding a part. It is important that parts are cooled evenly and efficiently to decrease the possibility of defects that could arise from uneven cooling. Cooling also ensues consistency in parts made in the blow molding process. With a product this large it is important to ensure there are enough cooling lines to ensure even cooling throughout the entire part. Uneven cooling can create problems with shrinkage and warpage throughout the part, which could affect the dimensional stability and cause problems when trying to stack them together. This uneven warpage could also affect how each part reacts to the loading. The cooling lines are 1.0” in diameter and are evenly spaced around the perimeter of the cavity. Since the mold is so large, the waterlines had to stay relatively small in order for the water to hit a Reynolds number of 10,000. This Reynolds number ensures turbulent flow and will allow for effective heat transfer out of the mold. These waterlines are important because the heat is only able to be removed from one surface of the mold. The bulk of the cooling will come from the air blowing out the part, then the remaining heat will be removed by conduction through the mold walls, then convection via the water lines.

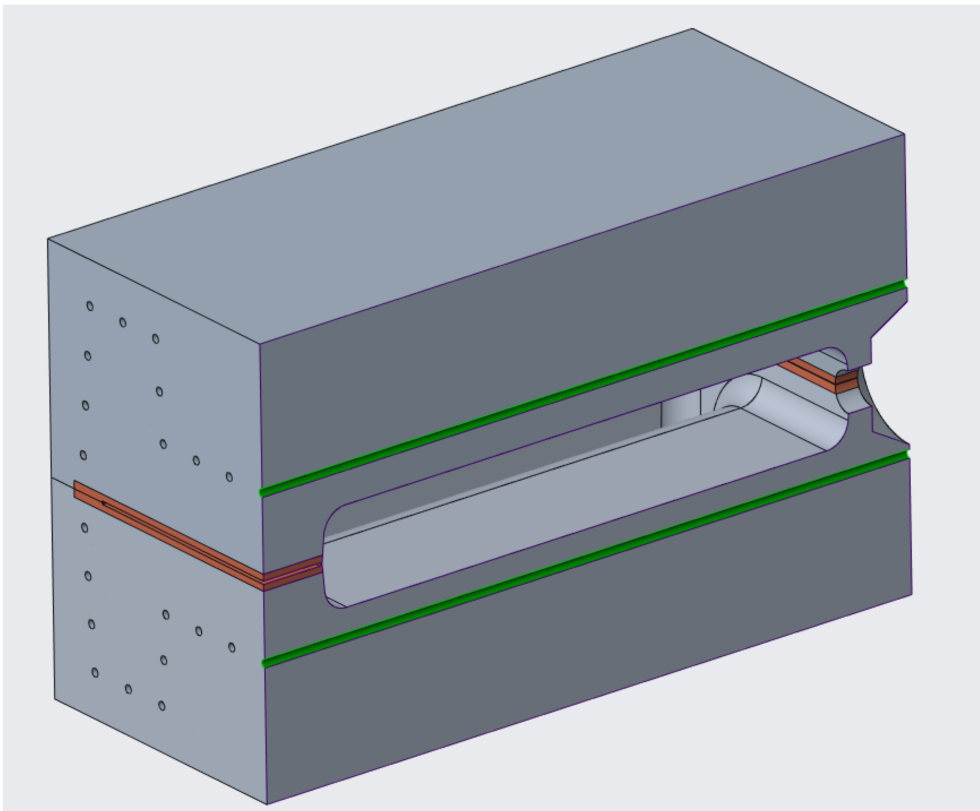


Figure 18: Waterline Layout

Die and Mandrel

For the creation of this part, the use of a die and mandrel will be needed. For extrusion blow molding applications, die heads can be either converging or diverging. Converging die heads are only recommended when an opening less than five inches is used making it non applicable for this part. Instead, a diverging die head will be used. A diverging die head by design will allow the parison to be wider making it better suited for the large kayak rack part. The use of a different die head could also lead to larger parison sag in the part. This would be a potential cause for more issues in this part with differing wall thicknesses, as well as material waste. Both the die and mandrel will likely be manufactured from steel rather than something softer such as aluminum. Doing so allows better resistance to the wear caused from the extrusion, increasing the life span of the die and mandrel. Another major advantage of the diverging die is its ability to reduce curtaining or material folding onto itself during the process.

The size of the die should also accommodate for die swell. In extrusion blow molding, die swell occurs when the material exits the die. When the material is extruded, the polymer chains line up and orient in the direction of flow, but upon exiting, the chains begin to re-entangle, causing an increase in diameter known as die swell. The die swell percentage is expected to be around 10% in the part. To accommodate for this the final diameter of the part will be decreased by 10%, with the effects of die swell allowing the part to reach the final proper dimensions. For the kayak rack the width is 72 inches so the diameter of the die is going to be 64.8 inches to accommodate for the die swell and still reach the expected final dimension. A sketch of the die with dimensions is shown in figure nineteen. The shrinkage of the part should also be considered. For the chosen material HDPE, a considerably high shrinkage of around 2% to 4% is expected. To counteract this the part the mold is created 4% larger than the expected final dimensions.

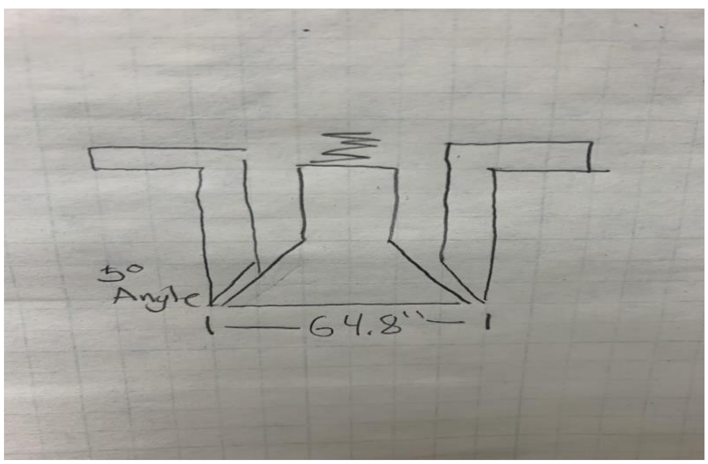


Figure 19: Die Drawing

Parison Programming

Parison programming allows the thickness of the parison to be changed when the material is being extruded through the die. It can be beneficial in reducing scrap and ensuring constant wall thickness throughout the part. It is crucial that the wall thickness remain as consistent as possible in the part to ensure it can withstand the load from the kayak. Parison programming can be beneficial for parts with more complex geometry as it can be programmed to add more material to specific areas to ensure consistency in wall thickness. In the kayak rack part, the parison will first touch off on the middle section of the part. Once the parison touches off on the mold, the parison will have to stretch to blow out the deep draw sections of the part. To accommodate for this, extra material will be added to the two far sides where the parison will drop down into these lower parts. This adjustment will result in a more uniform wall thickness in the part.

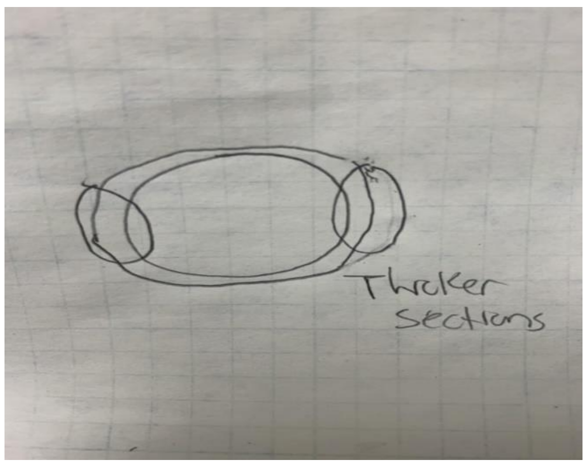


Figure 20: Parison Wall Thickness Adjustment

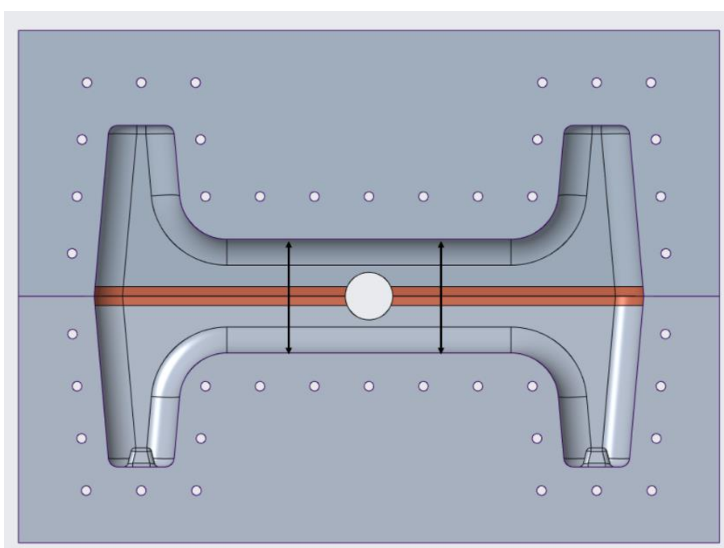


Figure 21: Parison Touch Off

Design Details 2

ANSYS Analysis

To conduct a structural analysis in ANSYS on the kayak rack, the model was exported from Creo Parametric into ANSYS as a Parasolid. Once in ANSYS, the geometry could be simplified due to the symmetry of the model. The geometry was simplified using ¼ symmetry to make the analysis simpler and run faster due to the decreased number of nodes and elements. A preloaded HDPE material from the material database in ANSYS was used for the simulation due to it having similar material properties as the chosen LyondellBassell blow molding HDPE material. Several static structural analyses were run with different loads and wall thicknesses to determine what the wall thickness of the part should be. In all three iterations that were run, the model was meshed as shown in Figure 22. To constrain the model, a frictionless support was added to the bottom surface and two symmetry regions were added on each face where the model was cut for both the X-Y and Y-Z planes. As described in the part specifications section, the average weight of a conventional kayak was found to be about 60lb. Since the model is taking advantage of symmetry, a downward force of 15lbs was used in this simulation to represent the overall 60lbs of a kayak sitting on the model. The main plots analyzed for these simulations were the total deformation and maximum equivalent stress plots. This was to ensure the max deflection of the part wasn't too high and to see if the applied force would yield the material or not.

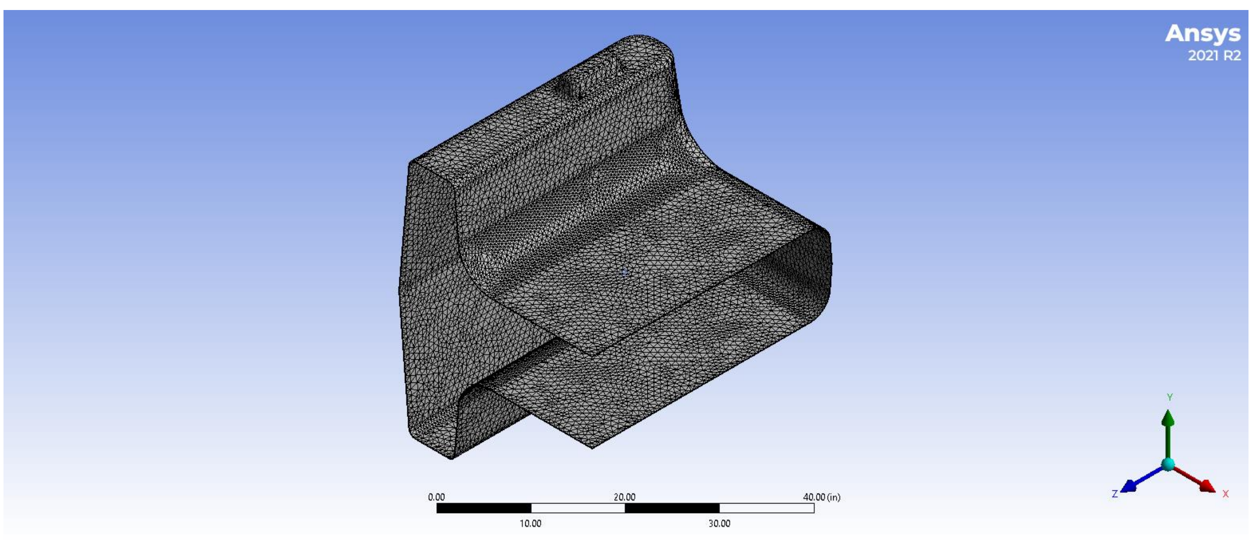


Figure 22: Mesh for ANSYS Analysis

Iteration 1 – 0.12in (3mm) wall thickness w/ force across top face

In the first static structural simulation, a force was applied across the entire top face where the kayak would lay with the whole model having a wall thickness of 0.12” (3mm). This is like the setup for the initial hand calculation that was done in the preliminary calculations section of this report. A downward force of 15lbs was applied across this surface. This number was determined from 95th percentile of average kayak weight found to be 63 pounds, divided by 4 as this simulation is only looking at ¼ of the entire model. The first plot looked at was the total deformation plot shown in Figure 23. Right away it can be seen that there too much deformation in the part. According to the simulation, the highest deflection would be about 6.2”. The maximum deflection would ideally be under 2”, so another iteration had to be run.

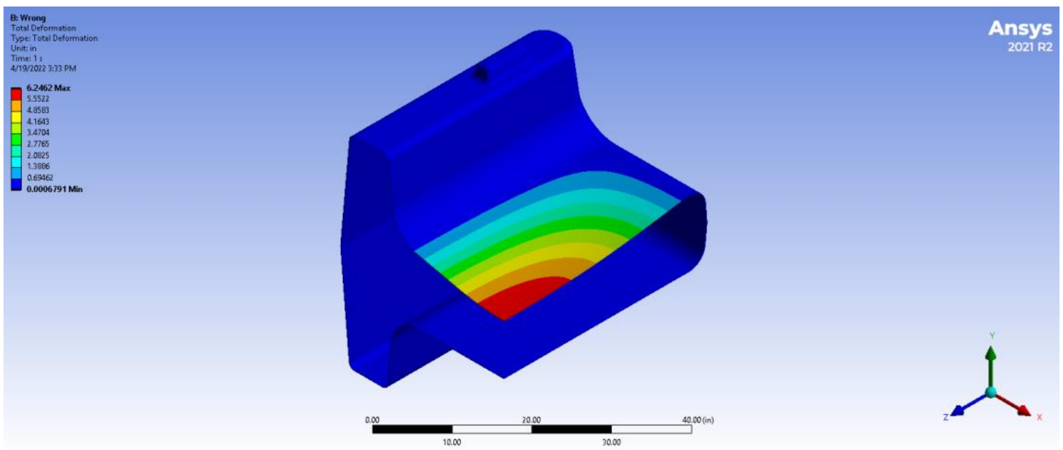


Figure 23: 1st Iteration Total Deformation Plot

The other plot looked at was the maximum equivalent stress, or von Mises stress plot. This plot is useful to evaluate if the model is exceeding the yield strength of the material. Based off the tensile yield strength of the HDPE being around 3625psi, this model does not actually yield the material. Although this is good, the deformation of the model is just too much for the part to be applicable.

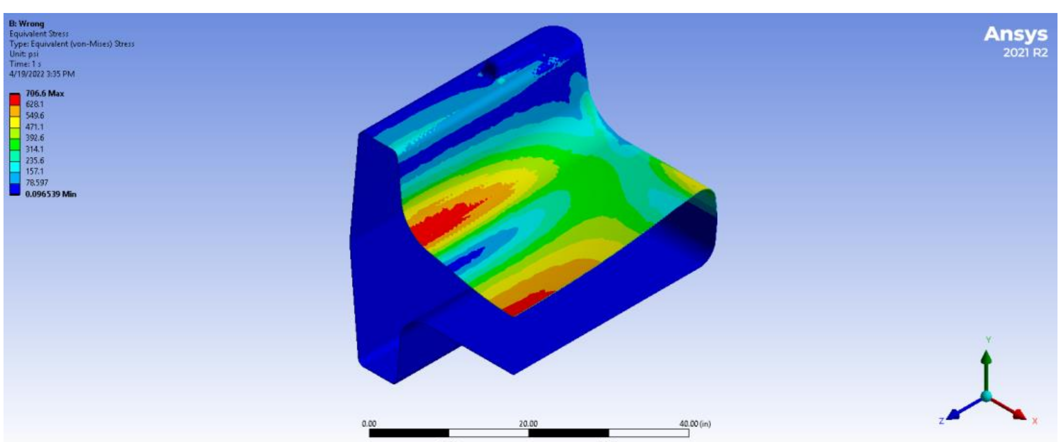


Figure 24: 1st Iteration Equivalent Stress Plot

Iteration 2 – 0.12in (3mm) wall thickness w/ force on radius

For the second analysis on the part, all the parameters and the wall thickness remained the same except for where the force was acting on the part. This time the force was acting on the radius located on the edge of the part. Making this change would result in less total deformation as the edge is better supported than the center of the part would be. This model was designed so that about 2ft of kayak hangs off each end of the part. Due to the curvature of a kayak, when it is placed on the kayak rack, only the two ends of the part where the two radii are will encounter the force. Applying this force on the radii better represents where the force would act on the part instead of applying the force across the top face like in iteration 1. The center of the part will likely not encounter a direct force like the previous analysis was showing. With these changes, the total deformation decreased to 0.147” and the maximum equivalent stress was 116 psi as shown in Figures 25 and 26 respectively. This drastically changed the deformation of the part and put it within the decided allowable limit for deflection.

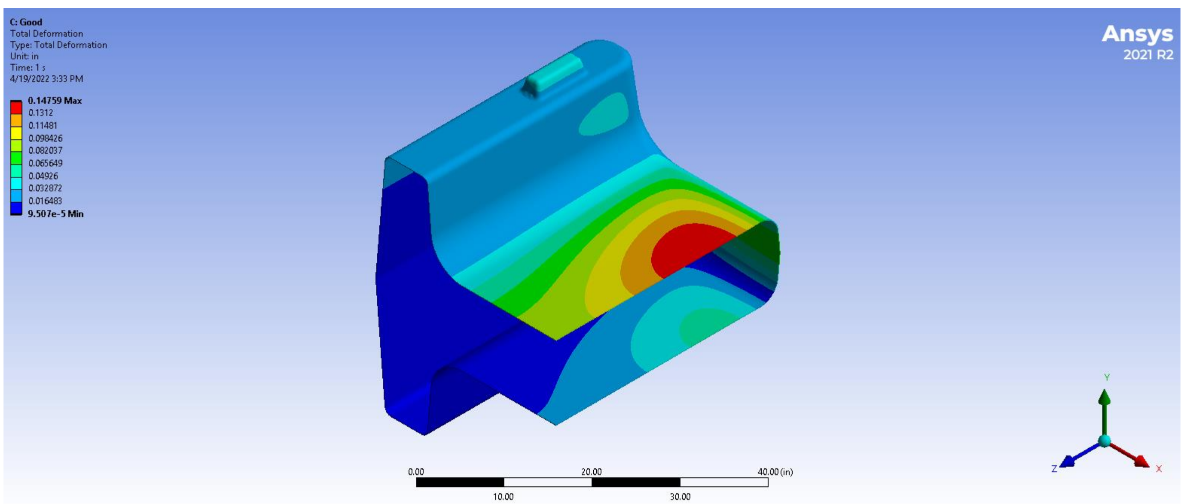


Figure 25: Iteration 2 Total Deformation Plot

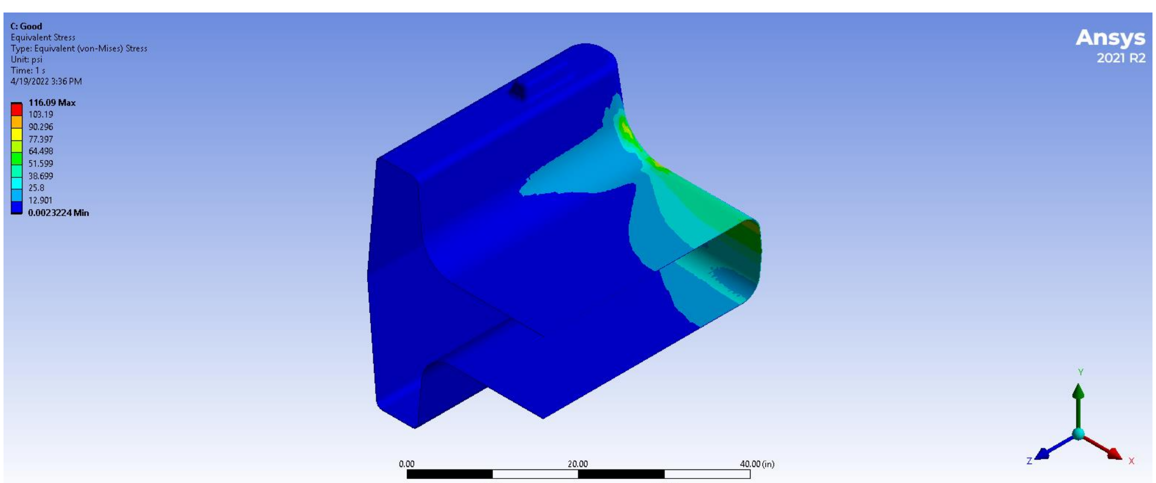


Figure 26: Iteration 2 Equivalent Stress Plot

Iteration 3 – 0.06in (1.5mm) wall thickness w/force on radius

Although the second iterations results showed improvement upon the initial results, the von mises stress was well below the yield stress for the material. For the third iteration, the wall thickness was decreased to 0.06 inches (1.5mm). This is also the wall thickness value the original hand calculation used to reach just under the yield stress value. All the other parameters from the last analysis were kept the same. The maximum value for total deformation increased to 0.619 inches, but this is still a reasonable amount of deformation for the part and is below the allowed 1-2 inches. The von mises stress increased to about 367 psi, still well below the yield stress. Although it is best to design a part right up to the material yield limit so you use the least material as possible and maximize the amount of stress the part can handle, this part will utilize this wall thickness of 0.06 inches. To yield this part, the wall thickness would have to be very thin, which would require a thin parison. This is also assuming the wall thickness is constant throughout the whole part, which in blow molding is very uncommon. A thin parison would most likely rip when the part is being blown out or cause the walls to be paper thin in the deep draw areas of the part. For this reason, the wall thickness that will be used is 0.06 inches. The results of iteration 3 can be seen in Figures 27 and 28.

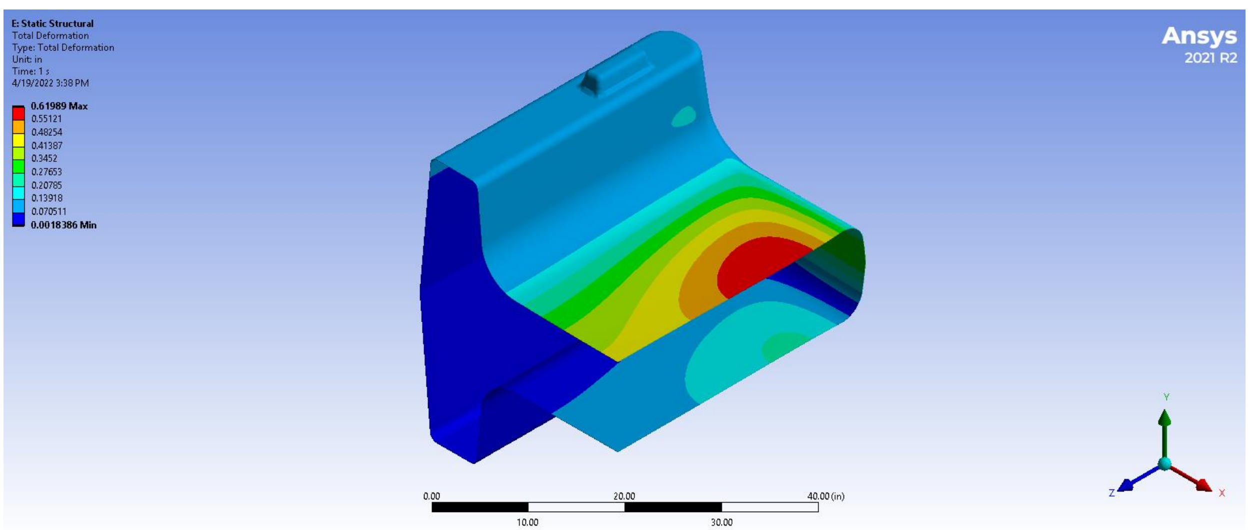


Figure 27: Iteration 3 Total Deformation Plot

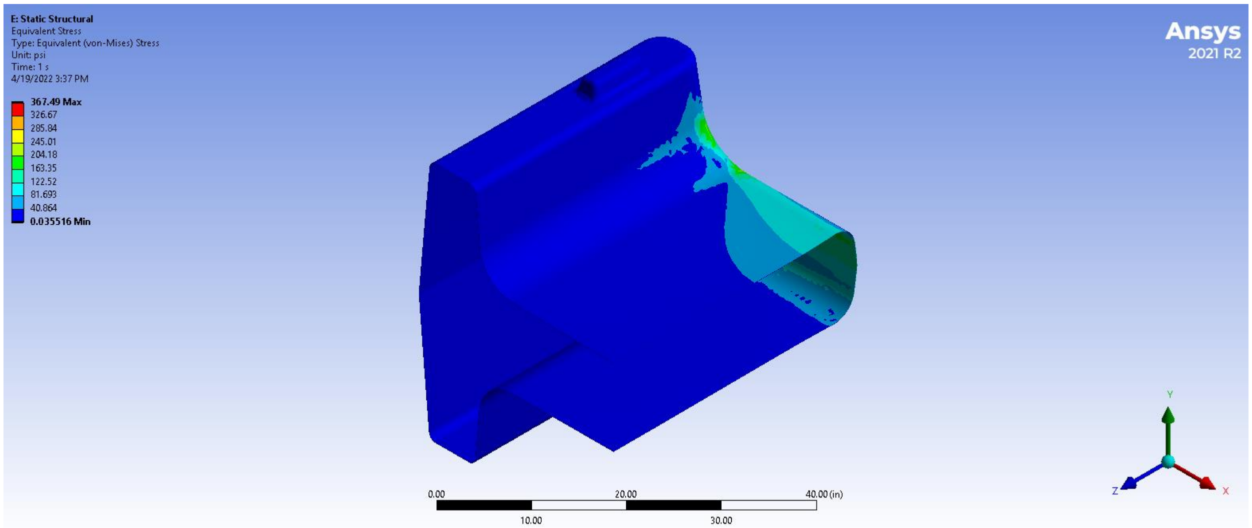


Figure 28: Iteration 3 Equivalent Stress Plot

Polyflow Discussion

Besides the structural analysis tools, ANSYS also has a blow molding simulation called Polyflow. This tool can be very useful when trying to determine the optimum wall thickness for a part because the blow ratio and thickness plots can be evaluated. These plots can help the user see potential problem areas in the part where the wall may become too thin due to the parison having to stretch and become thinner. Although a Polyflow analysis was not run for this part, a discussion can still be had on what the results would have looked like.

While the maximum equivalent stress for the part was still below the yield in the third iteration of the structural analysis, these parameters are the ones that will be used for the final part. The wall thickness could be decreased to get the equivalent stress closer to the yield point, but this could also cause additional problems in the part. The chosen wall thickness of 0.06 inches is already quite thin for a large plastic part and continuing to decrease this wall thickness could cause issues in the part. As mentioned previously, sections in the deep draw areas of the part could get to the point where they become too thin and could blow out. Decreasing the wall thickness even more increases the variation of the wall thickness across the part and increases the chance for other defects or failures in the final blow molded part.

One feature Polyflow has is the ability to plot the blow ratio at different time steps throughout the simulation. The blow ratio is basically just the depth-to-width ratio for the parison in the mold (10). Having a low blow ratio value will help to ensure that the part can form properly and have a relatively uniform wall thickness. It also helps to locate where thin areas in the part will occur. Figure 29 shows the progression of a parison laying down on a mold and how the wall thickness will become thin in the deep draw areas of the part.

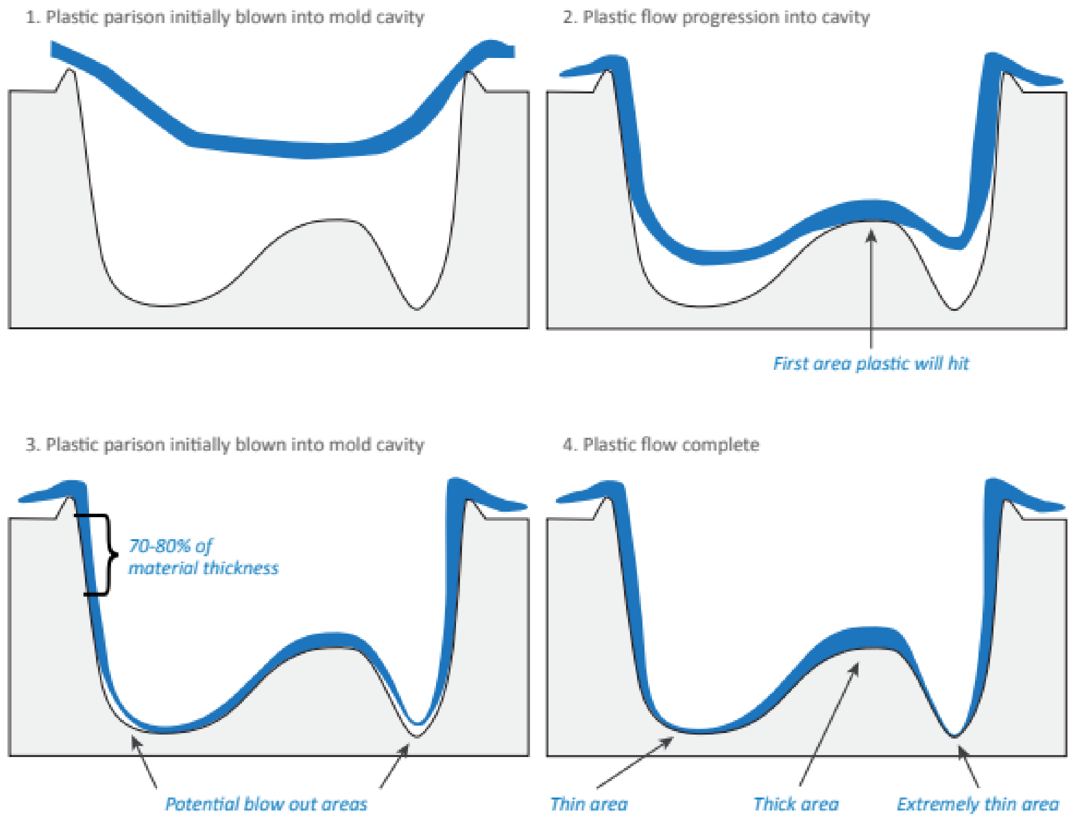


Figure 29: Blow Ratio Progression (10)

What is being shown in Figure 29 can be described for the kayak rack part. The deep draw areas of the part will be thinner with the potential to blow out if the parison must stretch too far or if the thickness of the parison is already too small. The first area for the parison to hit on the kayak rack is the main flat surface along the length, then the parison must stretch the rest of the way to fill out the rest of the part. Figure 30 is an example blow ratio plot that is commonly evaluated in Polyflow. This plot is showing the blow ratio for a bottle at a blow time of three seconds. In the plot, the area with the largest blow ratio is the corner of the bottle where it would be the hardest to stretch the material into.

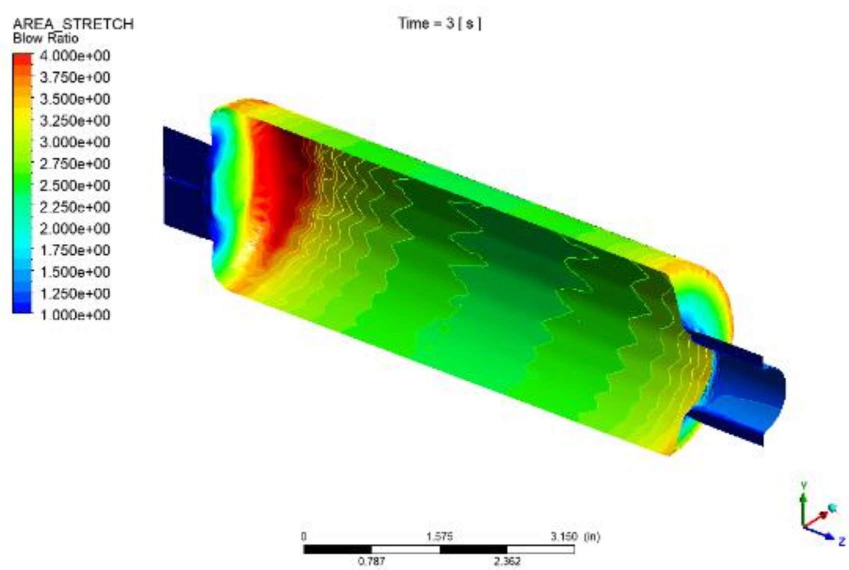


Figure 30: Sample Blow Ratio Plot

Polyflow can also produce a thickness plot for the part, which is useful to see the thickness variation throughout the part. This plot is another useful tool to help determine the problem areas in a blow molded part. If a Polyflow analysis was run for the kayak rack, the thickness plot would show the highest thickness in the main flat land of the part and the thinnest areas in the leg areas. Figure 31 shows a sample thickness plot produced from Polyflow. Like the blow ratio plot, this one also shows what the thickness of a blow molded bottle would be at a blow time of 3 seconds. This plot correlates with the blow ratio plot, as the area with the highest blow ratio is the same area that shows the thinnest wall in the thickness plot. Based on this, it can be assumed that areas with high blow ratios will also be areas with the thinnest wall section within the part. For the kayak rack, the thinness areas would again be in the leg sections of the part.

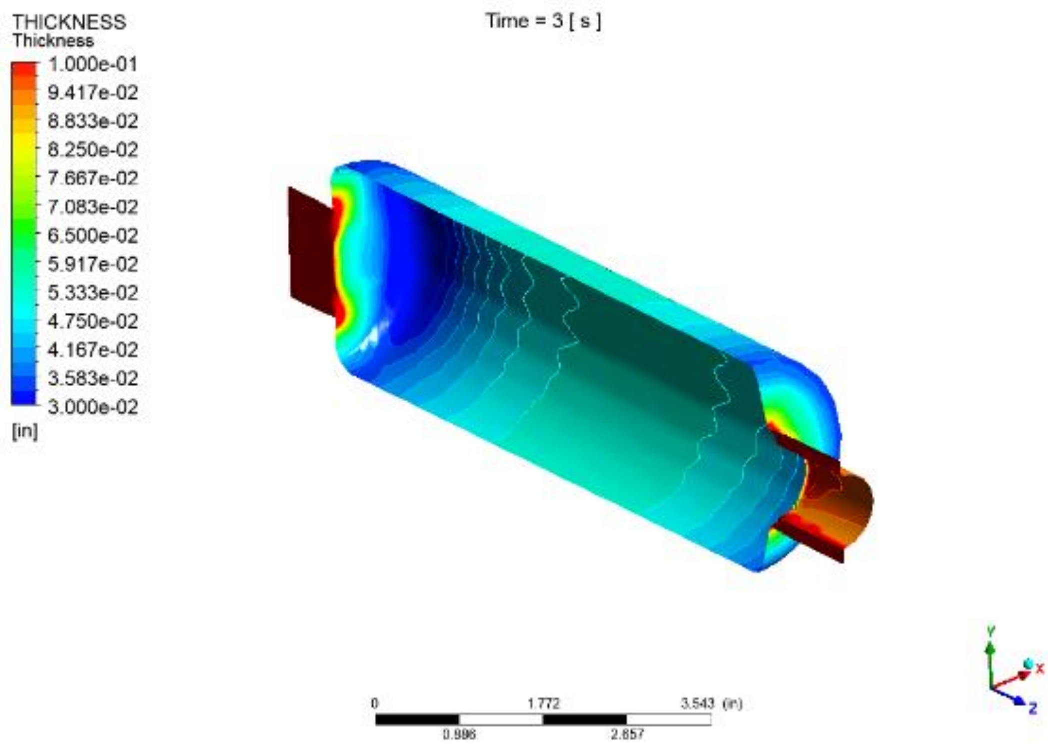
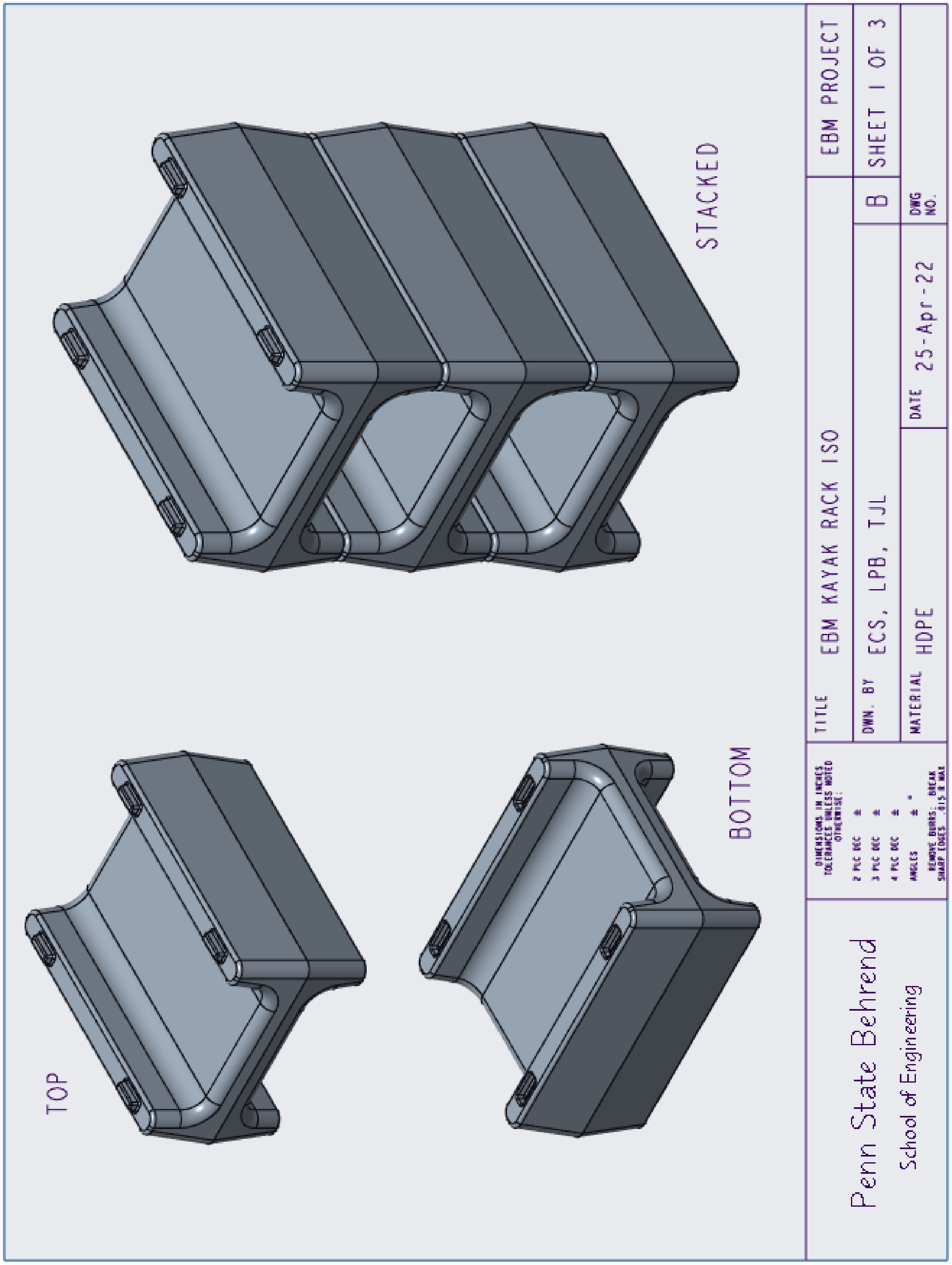


Figure 31: Sample Thickness Plot

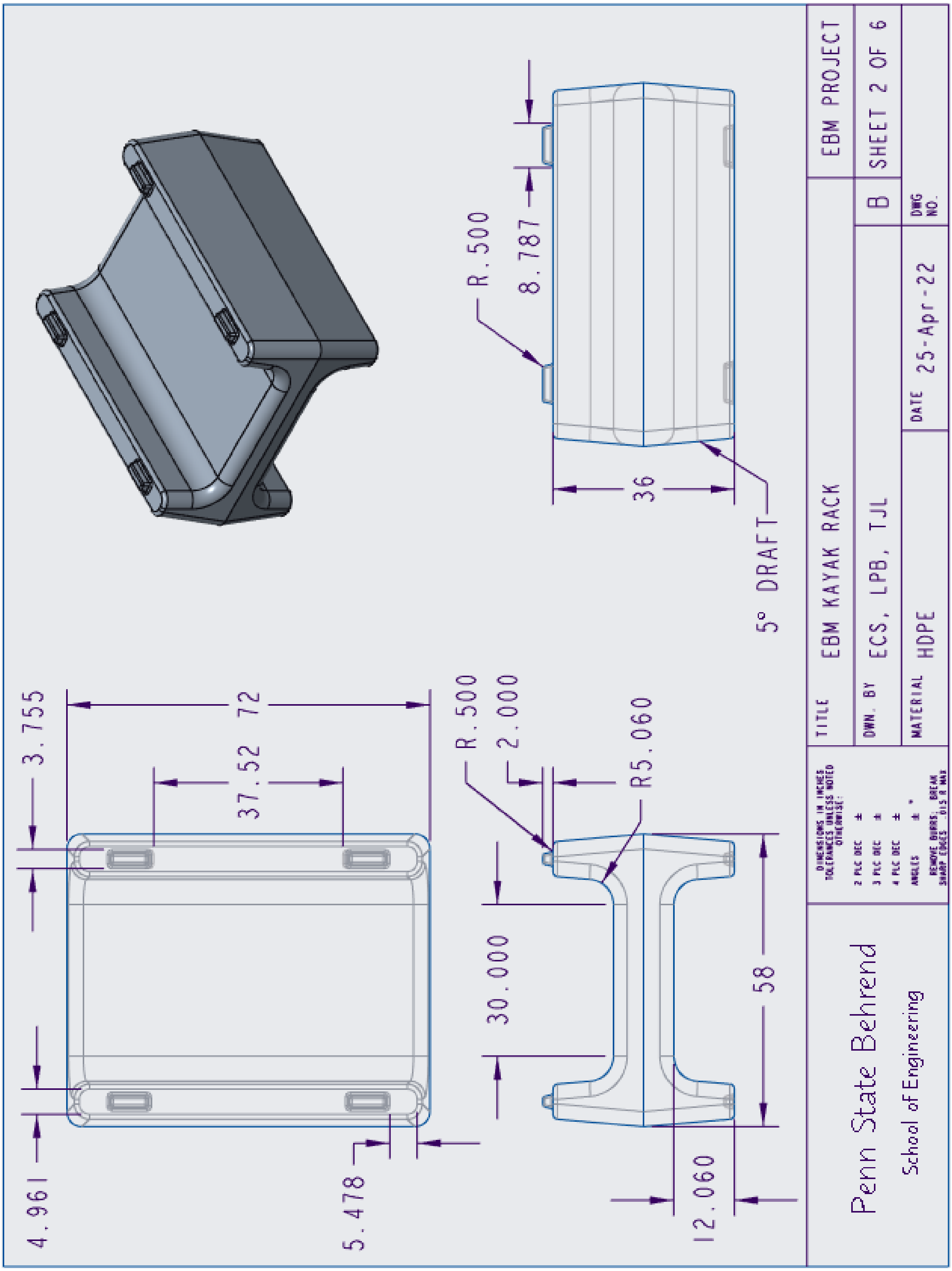
Table of Contents – Design Drawings

Kayak Rack

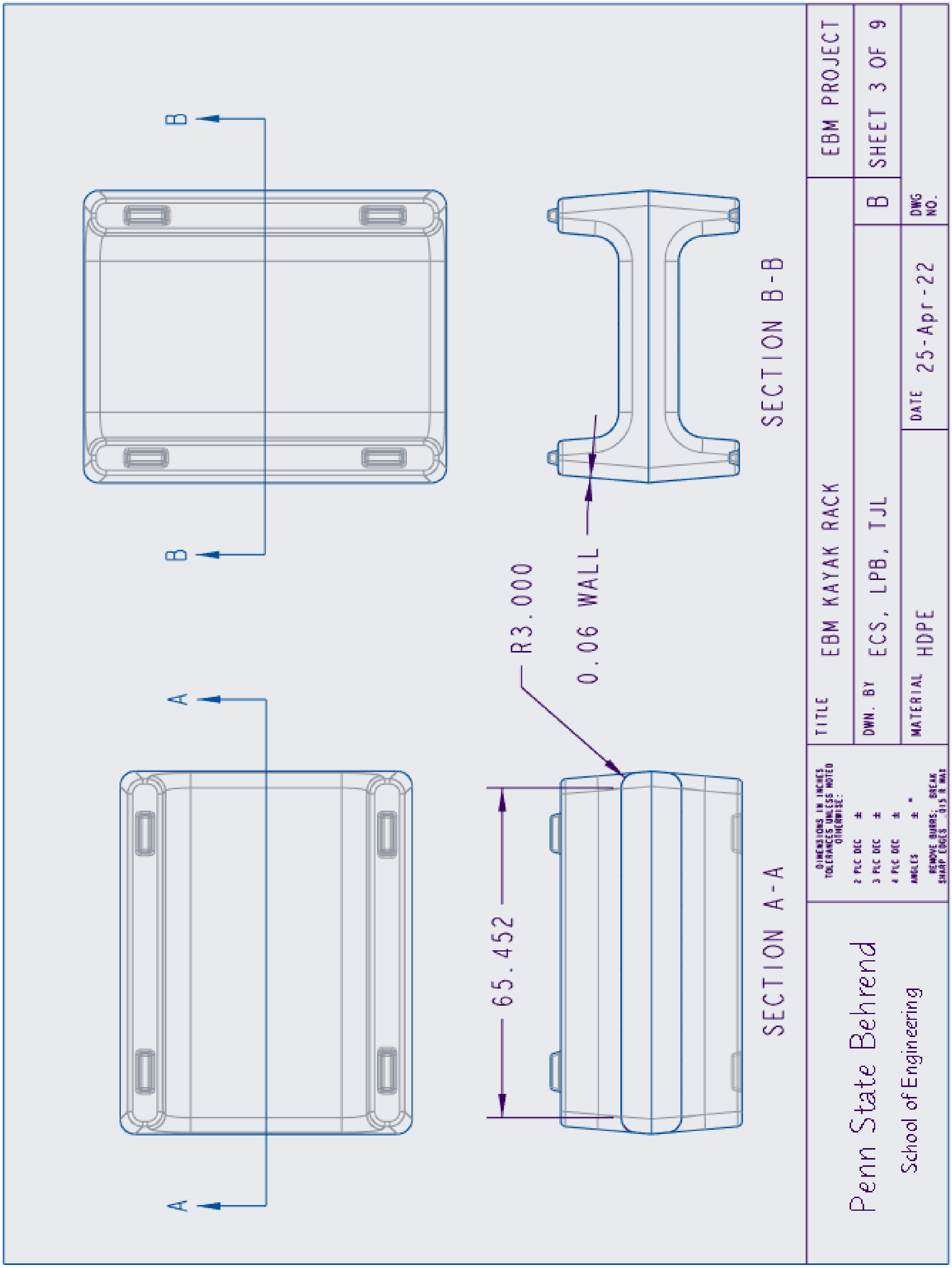
Isometric Views



Design Dimensions

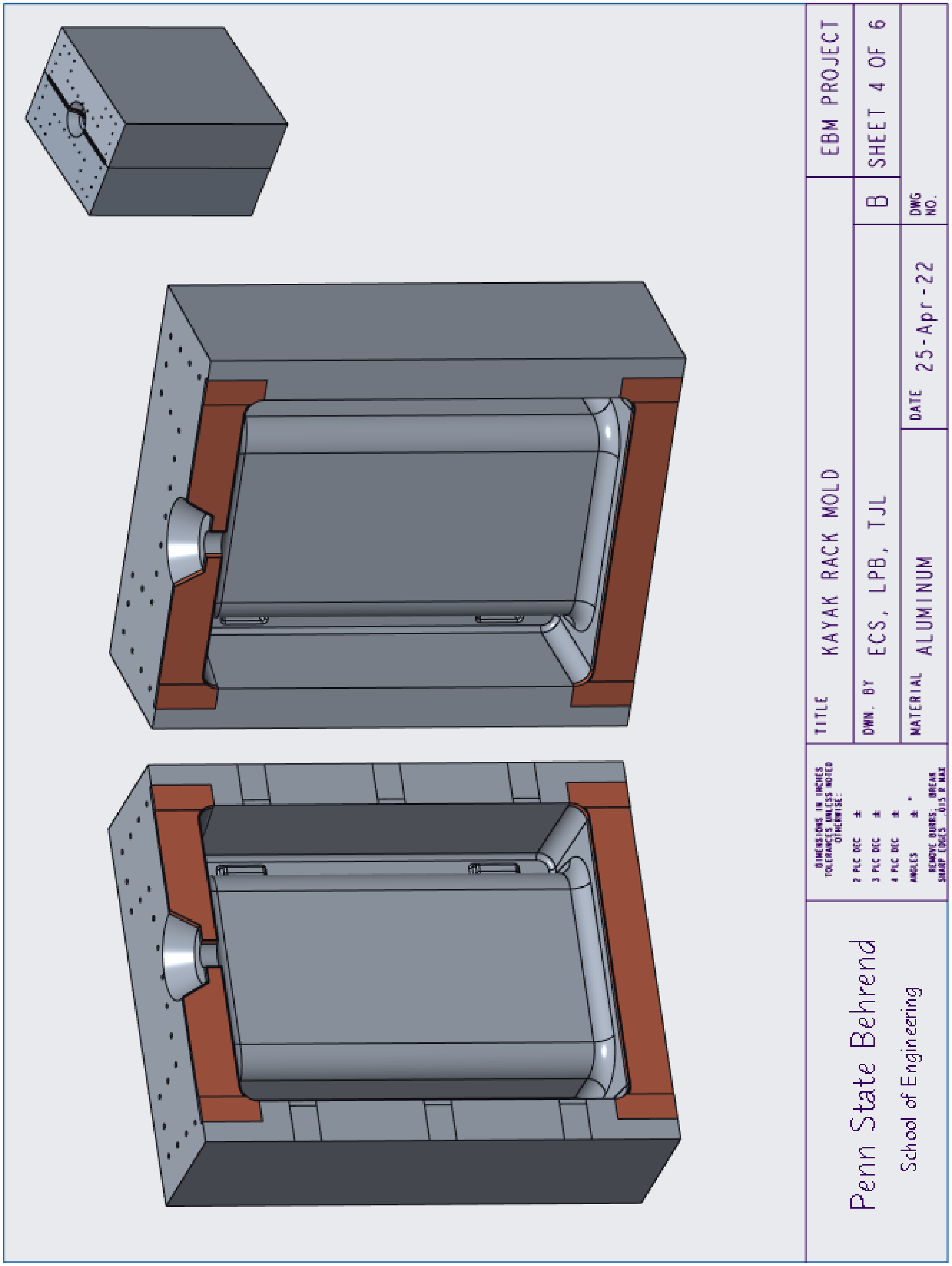


Section Views

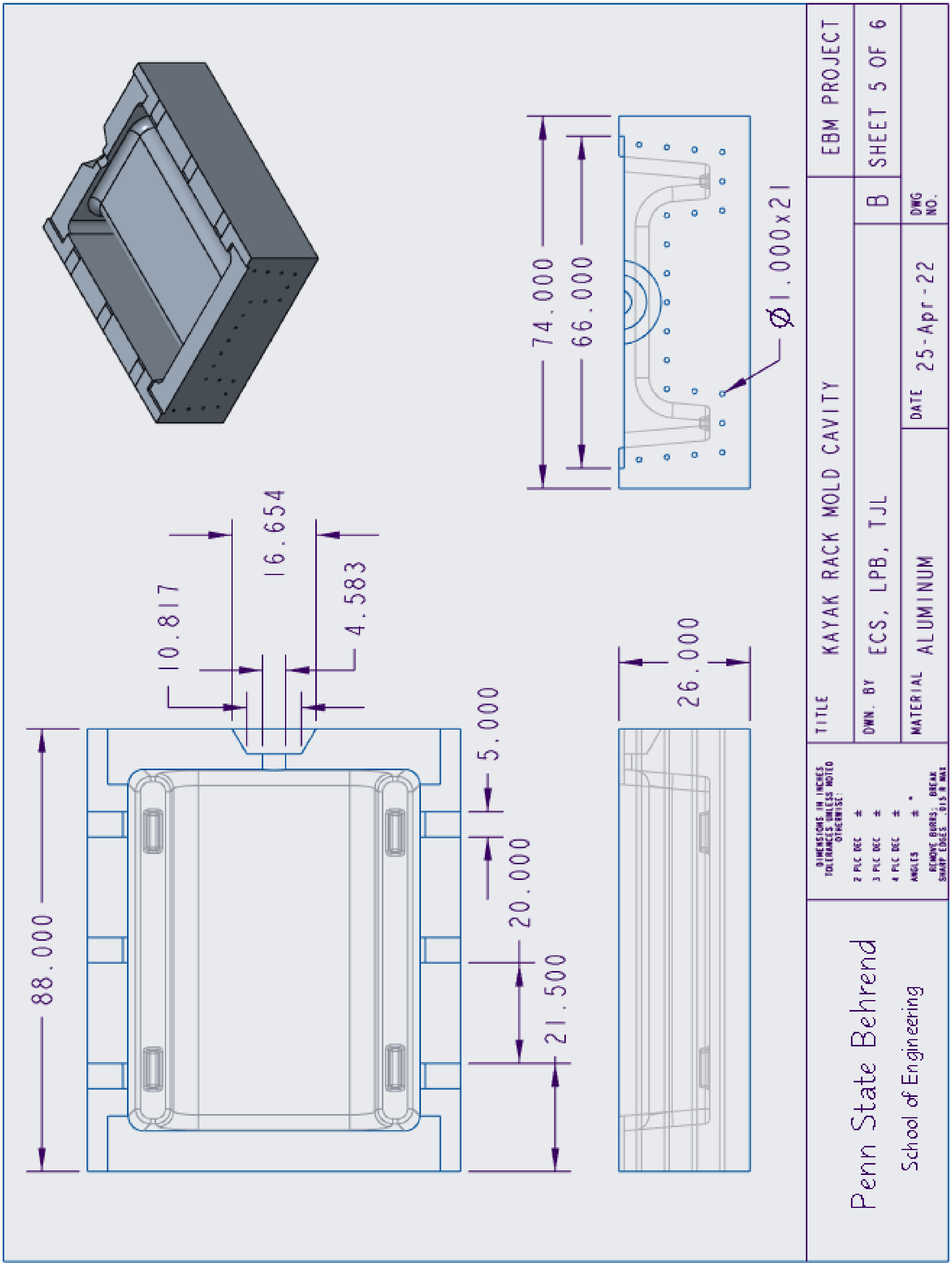


Kayak Rack Mold

Isometric Views



Mold Cavity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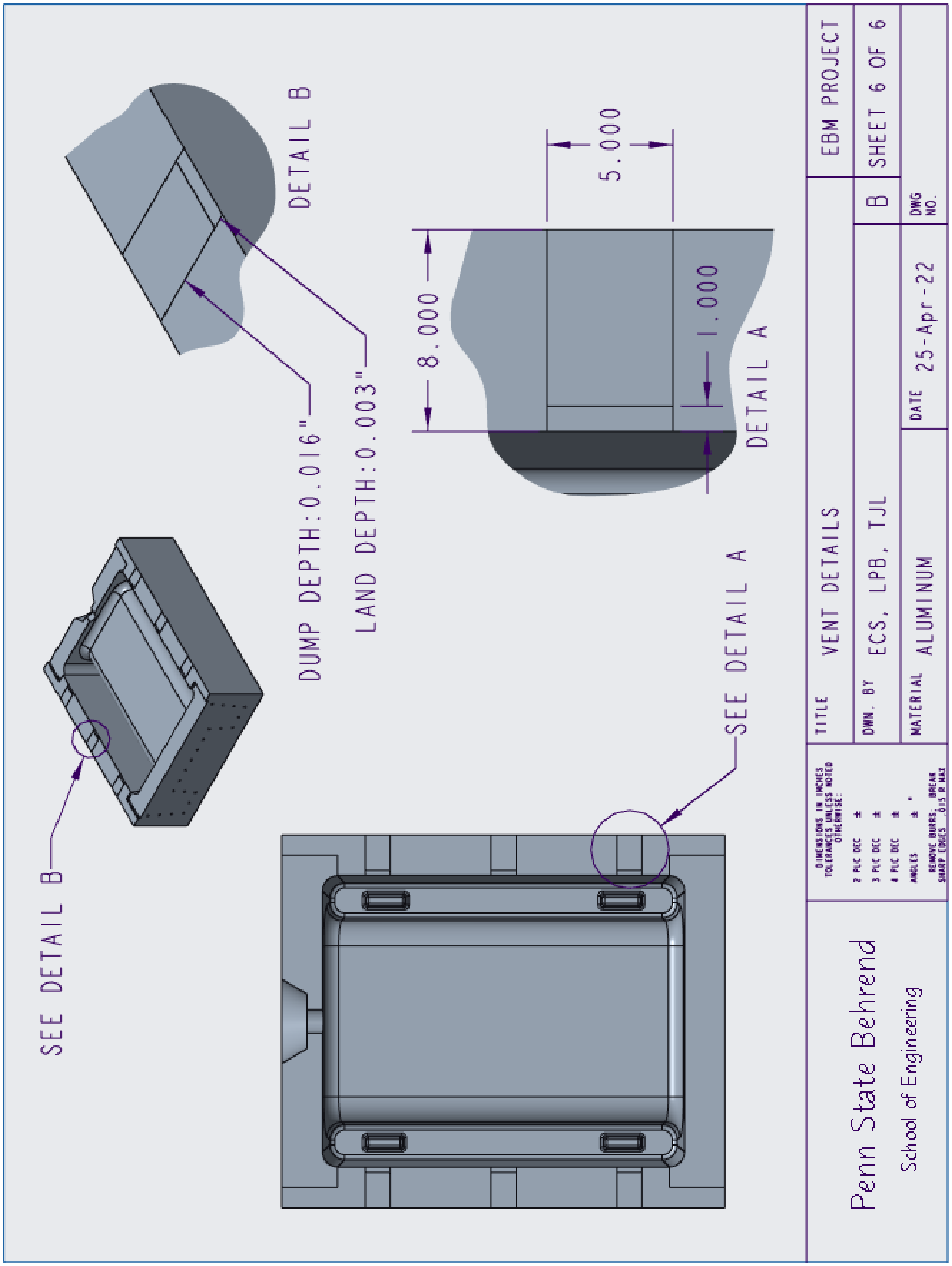
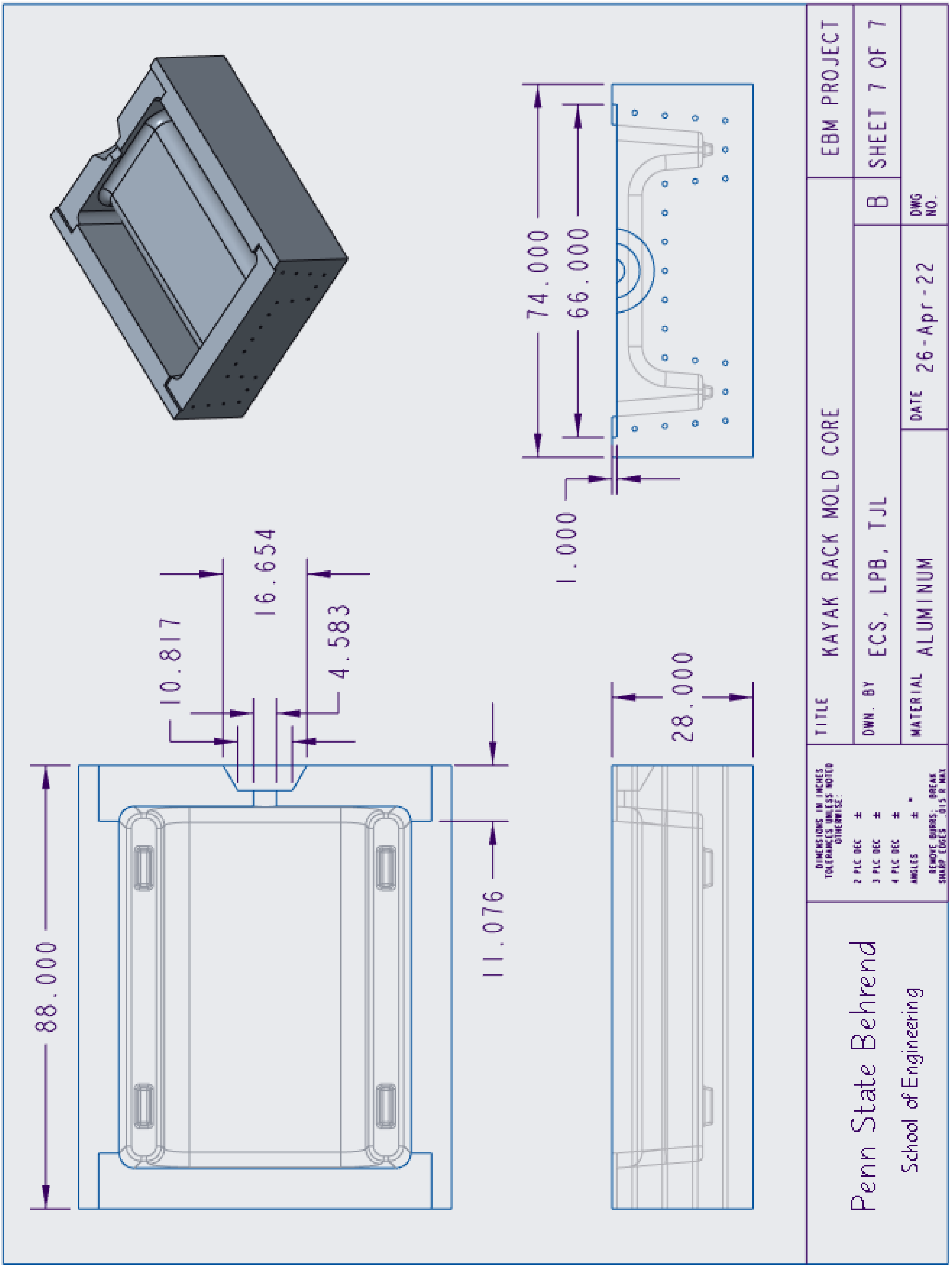
School of Engineering

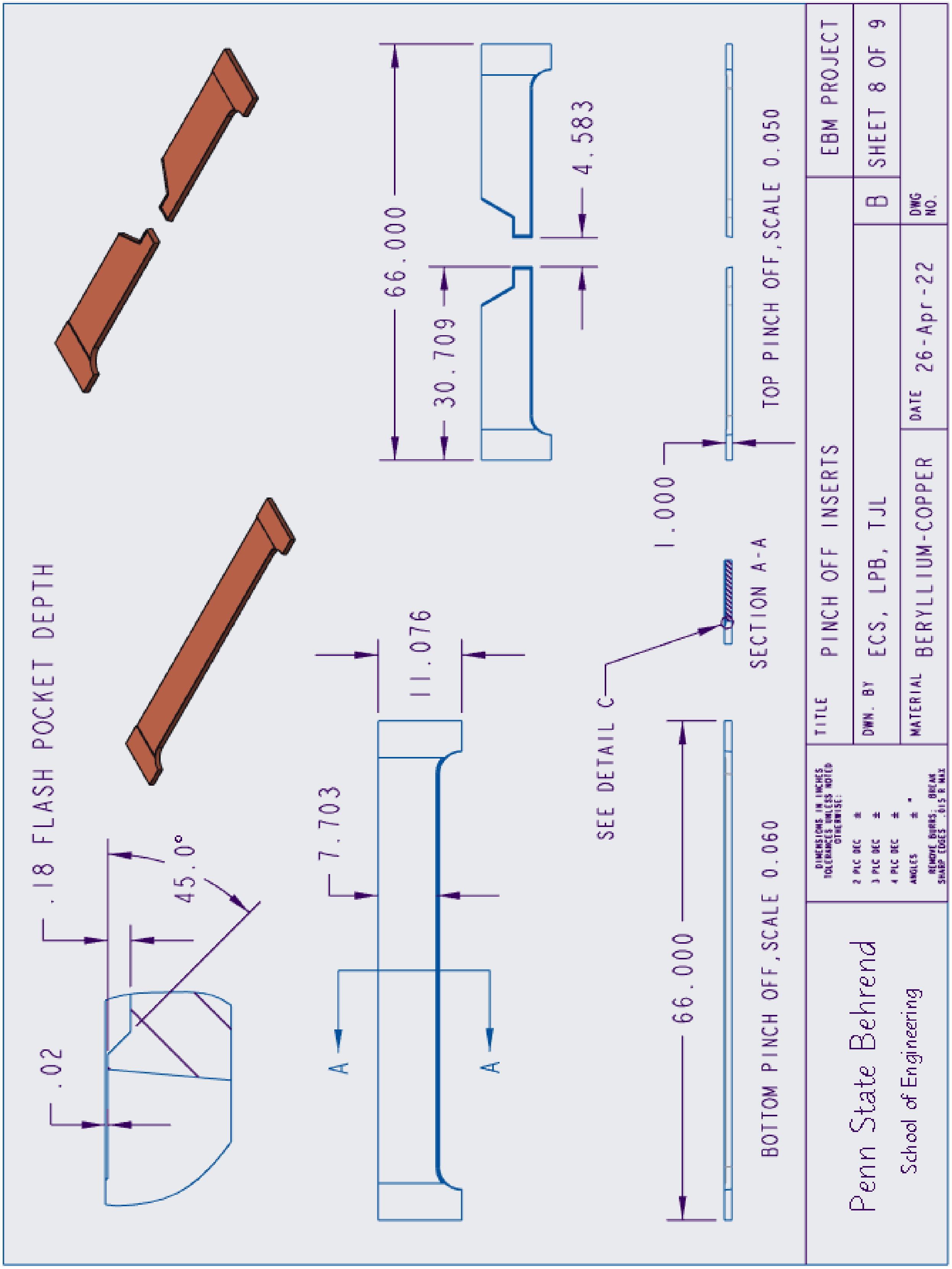
Vent Details



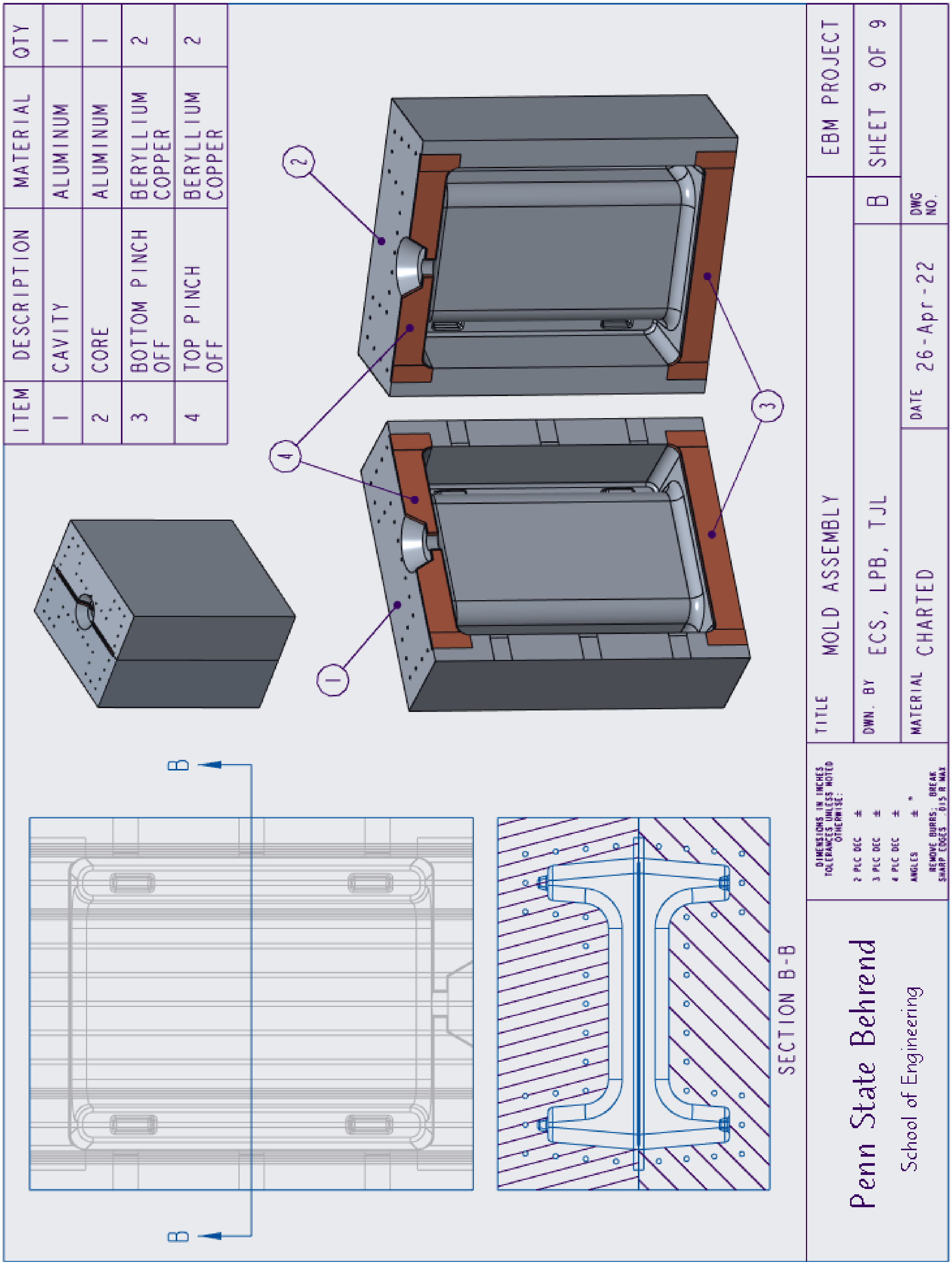
Mold Core


EBM PROJECT
SHEET 7 OF 7
B
KAYAK RACK MOLD CORE
TITLE
DWN. BY
ECS, LPB, TJL
DATE
26-Apr-22
MATERIAL
ALUMINUM
DWG NO.
Penn State Behrend
School of Engineering
88.000
74.000
66.000
1.000
28.000
11.076
10.817
16.654
4.583

Pinch Off Inserts



Assembly



ITEM | DESCRIPTION | MATERIAL | QTY
1 | CAVITY | ALUMINUM | 1
2 | CORE | ALUMINUM | 1
3 | BOTTOM PINCH OFF | BERYLLIUM COPPER | 2
4 | TOP PINCH OFF | BERYLLIUM COPPER | 2
1
2
3
4
B
B
SECTION B-B
Penn State Behrend
School of Engineering
TITLE
MOLD ASSEMBLY
DWN. BY
ECS, LPB, TJL
MATERIAL
CHARTED
DATE
26-Apr-22
EBM PROJECT
B
SHEET 9 OF 9
DWG NO.

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