Fetal Radiation Shield
Limiting dosage of high-energy radiation to the developing fetus

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Summary

Women who are pregnant and choose to undergo radiation therapy risk putting their child at risk of radiation exposure. In order to shield from radiation, external shielding can be put over the woman's body but can be unsafe and in some cases, costly. An external shield was designed and tested using SolidWorks. It proved to be mechanically stable in static testing with dynamic testing to be completed Spring 2019.

Abstract

Radiation can be extremely dangerous to a developing fetus, with risks including birth defects and increased likelihood of childhood cancer. Pregnant patients undergoing radiation therapy, therefore, require modification of treatment plans in order to reduce the fetal radiation dose. Currently, there exists no universal product to physically shield the fetus from oncoming radiation. Existing apparatuses for this purpose are either unsafe or cost-prohibitive for most institutions. The Department of Human Oncology at University Hospital requests that a shield be designed specifically to protect the fetus from leakage from the head of the radiation machine and scatter off of the patient. This will be accomplished with a lead shield that is five centimeters thick and: safe for the patient and medical personnel, mobile for storage outside the treatment room, capable of raising and lowering to accommodate different treatment plans, and shields 50% of stray radiation capable of reaching the fetus. Throughout the last semesters, the team developed a transportation system, refined the shape of the shield, and added further detail to the lifting/support mechanism. The team now has a full model of the shield design with its various components. With the full model completed, the team completed static testing in SOLIDWORKS®. The top arch of the shield, which is the part located directly over the patient, does not appear to exceed 100 kPa. There are no significant stress concentrations on the casing mounts, and the areas with the highest stress occur on the edges of the recesses that accomodate the mounting brackets and screw jack load pads. Implementation of the apparatus in University Hospital will provide more treatment options for pregnant patients throughout the state of Wisconsin.

Key Terms: Fetal radiation, Leakage radiation, Pregnant women, Radiation shield

INTRODUCTION

Each year, nearly 4,000 pregnant women are treated with radiation therapy in the United States and this number is increasing due to more cancer diagnoses and an increase in average childbearing age [1,2]. Radiation therapy is most often considered when treatment cannot be delayed until after childbirth, especially in young women with either brain or breast cancer [1]. When a woman chooses to undergo radiation therapy while pregnant, measures are made to limit to limit fetal dose to an acceptable level.

The main sources of radiation risk to the fetus include photon leakage through the head of the machine and collimators, and radiation scattered within the patient from the treatment beams [3]. There is no preventative measure that can be taken to reduce the radiation dose due to scatter within the patient, however, external measures can be take to reduce radiation as a result of the machine leakage.

To limit as much radiation exposure to the fetus as possible, the patient may be repositioned for treatment or the physician may resort to stacking lead bricks on a bridge that is placed over the patient and treatment couch [4]. This method is not favorable due to the safety risk posed to the patient and medical personnel [1]. The University of Michigan's Medical Innovation Center developed an external U-shaped lead shield which included a sophisticated locking system and hydraulic motors [2]. Although the shield was effective at blocking 50% of the peripheral dose (PD) to the fetus, the design proved far too expensive and led to the bankruptcy of the manufacturing company [2][5]. As such, there is no commercially-available shield.

The Department of Human Oncology at the University of Wisconsin Hospital has developed this project and we have designed and completed theoretical mechanical testing on a shield designed to reduce fetal radiation. Here, we describe the components of the shield and the mechanical testing that has been completed.

METHODS AND MATERIALS

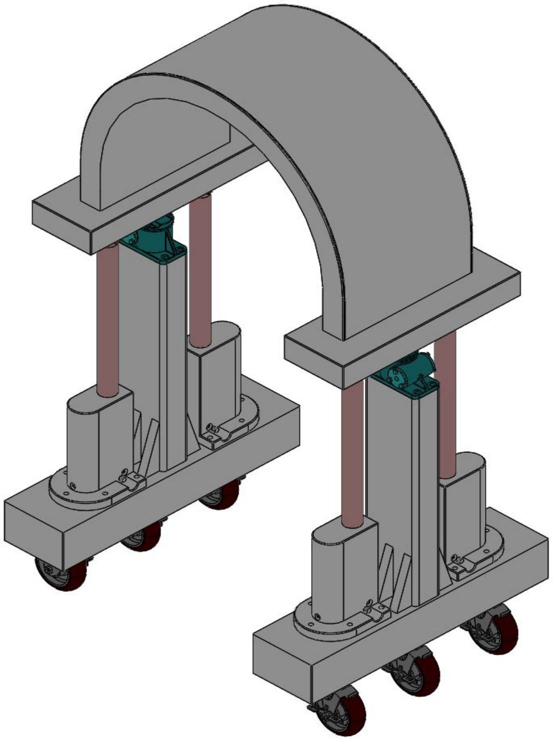

Figure 1: SolidWorks view of the assembled final design. Lipped cylinder (grey), linear actuators (red), and power jacks (green) and transportation system

The modeling of final prototype and subsequent computer simulations were all done with SOLIDWORKS® 2018 Education Edition, which is purchased through the College of Engineering at the University of Wisconsin-Madison. The software is the property of the SolidWorks Corporation, which is headquartered in Waltham, MA, and it is published through the French-based Dassault Systèmes. SOLIDWORKS® Student Premium was used to create a 3D model of the design while SOLIDWORKS® Simulation Premium allowed us to run various tests on the final model.

The entire device was modeled in a top-down assembly design, starting with the shield and its casing before fitting it with the supports (Figure 1). Individual subassemblies were created for the shield and its casing, the linear actuators, and the backup screw jack mechanism respectively, while the bottom frame that supports the entire system was created as its own part before adding it to the assembly. Since all parts and materials would be purchased/manufactured by US-based companies, the SolidWorks templates for the parts, assemblies, and drawings utilized the IPS (inch, pound, second) unit system, with all the decimals customized to the ten thousandths place. Since every component has yet to be manufactured, the materials that were applied to individual parts were based on the proposed materials. For all parts that would be custom made, the materials were customized using the properties provided by the manufacturer or, if the manufacturer's material properties were not available, using the preprogrammed properties from the SolidWorks library of materials.

The main body of the shield is in the shape of a half cylinder. Since the lead shield must fit over a treatment table with a width of 21" (53.34 cm) and a translational movement of up to 5" (12.7 cm), the inner width of the steel casing was set to be 28" (71.12 cm). This allows the lead shield and its steel casing to fit over the treatment table with an additional cushion of 1" (2.54 cm) on either side. The most important constraint that the team worked with was that the lead shield must be at least 5 cm thick in all places. However, since the parts that the team planned on purchasing would be based on the Imperial system, this lead thickness was rounded up to 2" (5.08 cm). An additional lip was added to the front of the shield to provide additional protection from radiation scatter originating from patient's body.

The SolidWorks files of the linear actuators and the associated mounting brackets were uploaded into SOLIDWORKS® via Progressive Automations. For the simulations, the inner cylinder was separated from the rest of the linear actuator and added to the device assembly as an independent part. A bottom anchor was made to snugly fit around the ends of the linear actuators, with dimensions rounded to easy-to-work with values, such as whole numbers. The top cover was also made to closely fit to the motor and base of the linear actuator, with numerous bolt holes added to anchor it to both the bottom anchor and the bottom frame. To ensure that the top cover would be capable of easily sliding over the linear actuator, the series of holes (starting from the top) were extended all the way to the bottom of the cover or extended until they reached an outer face of the linear actuator. This ensured that when the cover is placed over the actuator, there are no ends sticking out that would prevent the cover from fully covering the actuator. The linear actuator was connected to the base and top cover via a mounting rod. For animation purposes, the inner cylinder and the rest of the linear actuator were split into two SolidWorks parts that would be mated together in the full assembly.

The SOLIDWORKS® file of the mechanical screw jack that will be purchased from Joyce/Dayton was downloaded from Dassault Systemes 3DContentCentral website. The configuration of the 2 Ton Machine Screw Jack from Joyce/Dayton was a 6-to-1 worm gear ratio, upright configuration, translating design, type 2 (load pad) end condition, reverse base base type, single lead type, standard shaft input for both the left and right shaft, an A95 design anti-backlash, a bellows boot, and a rise of 20.00 inches. The screw jack support was modeled in SolidWorks to contain the entirety of the protection tube while still connecting it to the bottom casing mount. For animation purposes, the bearing cap was not inserted into the full SolidWorks assembly, and the input shaft was separated from the jack housing and created as a separate SolidWorks part.

The frame consisted of top and bottom casing mounts that would connect the shield to the lifting system and the lifting system to the wheels attached to the bottom casing mount. The top casing mount was split into two sections that would be welded together.

To create the full assembly, all the individual SOLIDWORKS® parts were inserted such that no interferences occured. Since the team did not do any dynamic testing this semester, there were no subassemblies inserted into the final assembly. Each part was inserted individually.

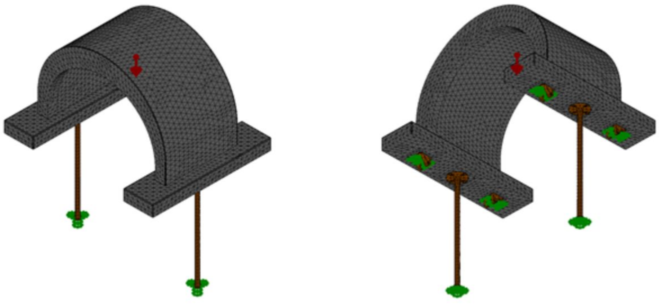

Figure 2: The shield assembly that was subjected to static load testing. Intersecting lines represent nodes, the areas created by those lines represent the elements, the red arrow represents the direction of gravity, the gray parts represent the parts included in the analysis, the brown parts indicate the parts made rigid, and the green arrows point to the faces that were kept fixed

Static load testing of the shield and its casing was completed in SolidWorks to determine the effect that the weight of the lead had the casing and the distribution of the weight among the six supports (Figure 2). Due to the heaviness of the lead, it was critical that the steel casing be able to support the weight of the lead and not exceed its yield strength. This would ensure that the shield would not collapse on the patient. The stresses and reaction forces that were induced as a result of the weight of the shield casing being distributed among the six supports would give an accurate representation of how much of the load each support bore.

Since SOLIDWORKS® was limited by the computer's memory and capabilities, the fetal radiation shield assembly had to be simplified before simulations could be run on it. All mates used in the animation were suppressed and each individual part was set to float. This ensured that the measured stresses would come from surface-to-surface contact and closely resemble how the parts would act in the physical world. Since the team was mainly interested in the results from the steel casing, all parts that were not in direct contact with the steel casing were suppressed, which left the machine screw, the mounting brackets, and the lead shield. Since the mounting brackets and machine screw have already been subjected to rigorous testing by their respective companies, those parts were made rigid in the analysis. The bottom casing and lead shield were bonded to the top casing mounts and underside of the top casing mounts to accurately simulate the effect of welding. The only other component contact applied to the model was global contact that was set as no penetration.

The bottomost flat faces of the machine screws and mounting brackets were fixed in space to accurately represent the summation of weight on the parts closer to the ground. Mesh was applied to each part individually and the SolidWorks default mesh was used, which created an element size of 1.0575 in and a ratio of 1.5 on all parts involved in the simulation. Gravity was applied as -32.19 ft/s^2 in the downwards direction.

After running the simulation, the von Mises stresses on each node of the steel casing were compared to yield strength of A36 steel, which is accepted to be 200 GPa (Appendix 1). If the maximum von Mises stress exceeded the yield strength, then failure due to static loading would occur, and if the maximum von Mises stress was below the yield strength, then the design factor of safety would be acquired. To determine the resultant forces of the support system on the casing mounts, the free body forces of all faces on the underside of the top casing mounts for each mounting bracket and machine screw were determined.

Summary statistics were calculated for the data collected through gravity simulation and weight distribution tests performed in SolidWorks using Matlab R2016b. From weight distribution analysis, the mean, maximum and standard deviation for the stress and strain in each member of the support assembly was determined. Gravity simulation data analysis was performed to determine the mean, maximum and standard deviation for the stress and strain at the contact faces of each component of the shield and steel encasement assembly. Lastly, the mean and standard deviation of the highest 10% of stress values recorded at the nodes during weight distribution testing in SolidWorks were calculated for each support assembly member to assess if yield stress was exceeded.

RESULTS AND DISCUSSIONS

The weight of the lead shield was found be 958.99 lbs and the steel casing 550.09 lbs, for a total of 1509.08 lbs. The primary aim of the weight distribution testing was to determine the load each support system component would have to bear.

The largest portion of the shield weight was collectively over the linear actuators, whereas the highest individual loads were supported by the power screws. The four linear actuators altogether support 547.37 lbs (2,434.8 N), while the power screws support 532.31 lbs (2,367.8 N) (Figure 3 and Table 1). The mounting brackets directly below the shield lip bear a marginally larger load than in the back.

The highest areas of stress on the bottom casing are located at the edges closest to the casing mounts (Figure 4). The top arch of the shield, which is the part located directly over the patient, does not appear to exceed 100 kPa. There are no significant stress concentrations on the casing mounts, and the areas with the highest stress occur on the edges of the recesses that accomodate the mounting brackets and screw jack load pads. All other areas appear to have negligible stress.

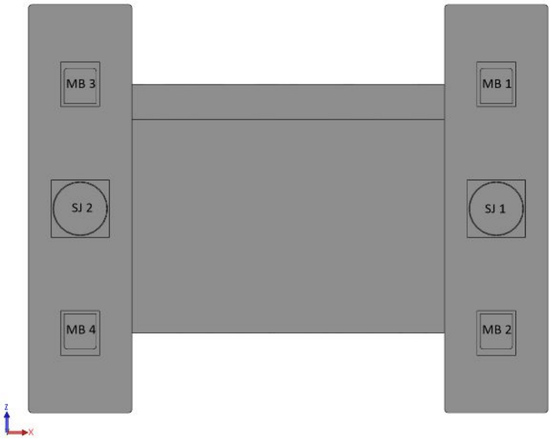

Figure 3: Bottom view of shield casing showing where the linear actuators (four corners) and power screws meet the mounting brackets. Referenced in Table 1.

Part	Unit	Resultant Force (lbs)
Power Jackscrew	1	319.32
	2	319.46
	Average ± Std.	319.39± 0.10
Linear Actuator	1	231.58
	2	211.95
	3	230.77
	4	212.70
	Average ± Std.	221.75 ± 10.89
Total		1525.76

Table 1: Values for the distribution of the weight of the lead shield over where the support components meet the steel bottom casing.

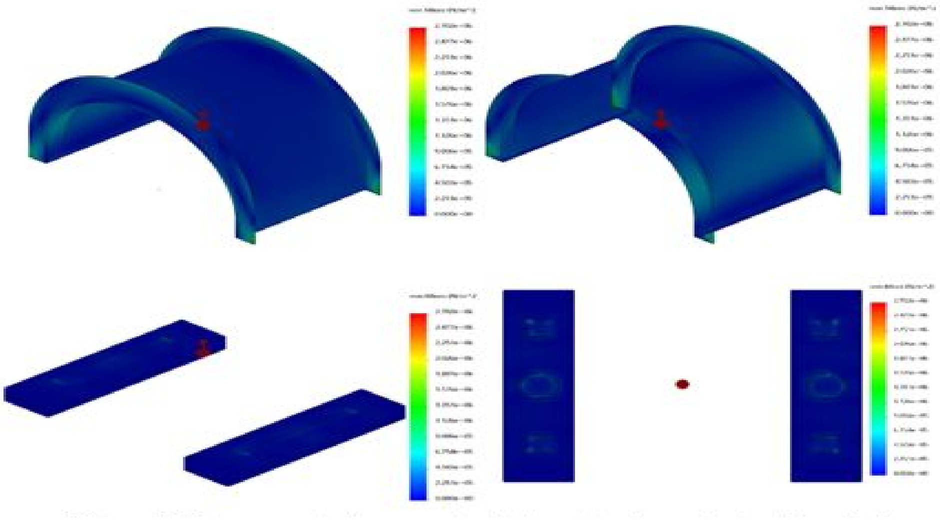

Figure 4: The stress on the bottom casing in the top front isometric view (Upper Left), the stress on the bottom casing in the bottom back isometric view (Upper Right), the stress on the casing mounts in the top isometric view (Lower Left), and the stress on the casing mounts in the bottom view (Lower Right). Scales in each picture are relative to maximum stress felt and not indicative of a certain value.

CONCLUSION

Last semester, the team primarily focused on the transportation system with refining the designs for both the shield shape and the power screw design. Ultimately, the team decided on utilizing four swivel caster caster wheels with brakes attached and two ball transfer units. The new shield has a half-cylinder shape with a front lip to assist in reducing the levels of radiation that the fetus receives. Additionally, the team has made progress in its efforts to create a fabrication plan with Vulcan Global Manufacturing Solutions (Milwaukee, WI). With respects to the lifting/ support mechanism, the team looked into power jack screw from Joyce/Dayton instead of having this be costume made for this device. One of the large goals of the past semester was to significantly reduce the price, which was accomplished.

Even though the team has made success throughout the semesters, there a numerous area that still need work. First, the team wants to complete further testing in SolidWorks to ensure safety for the patients. Stress testing of shield on all supports, dynamic testing, and fatigue testing and some of the

SolidWork tests that will need to me completed. In addition, the electronic component of the lifting mechanism will need to be put in place. This will be important to integrate the power and controls for lifting, as this system is extremely heavy.

As the system is still over budget, it will be necessary to find areas where the cost can be reduced. One item that will be considered is reducing the price of the power jack screws by either finding a new company or working with Joyce Dayton to reduce the cost. The reason why it is essential to reduce the price is so there is room in the budget for physical prototyping to ensure the design is compatible with the treatment room before manufacturing the final product.

In terms of manufacturing and assembly, once the shield shape, support, and mobility systems are fully defined and approved, the shield will be manufactured by Vulcan Global Manufacturing Solutions (Milwaukee, WI). The electric components of the lifting mechanism, including linear actuators and motors, will be ordered from Progressive Automations (Blaine, WA). Final assembly of the shield will occur at Vulcan Global Manufacturing and the shield will then be transported to UW Hospital by methods still to be determined.

Extensive testing will be conducted on the final prototype. Actuators and screw jacks will be tested individually to ensure their ability to support the shield on their own. The efficacy of the shield in blocking fetal dose will be tested using a phantom at Dr. Wesley Culberson's lab, at which time the shield will be placed over the phantom for multiple treatment plans. The capacity of the shield to attenuate fetal radiation dose will be measured by comparing the percentage of radiation reaching the abdomen of the phantom when the shield is in place compared to when no shield is used.

Finally, the shield will need to be incorporated into a general treatment protocol for use by University Hospital. Workflow will need to be assessed and medical staff trained on how to use the shield. Phantom testing will also be used to inform the appropriate placement of the shield for the different treatment options. This will likely be conducted over the course of several months after final fabrication and involve coordination between staff and other users as well as the design team.

In the past semesters, this design had been greatly extended. Now, with an overall design for the whole system, the team is well on its way to completing a safe and effective shield to provide peace of mind for pregnant patients considering undergoing radiation therapy.

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APPENDIX:

SolidWorks Modeling

Material Properties

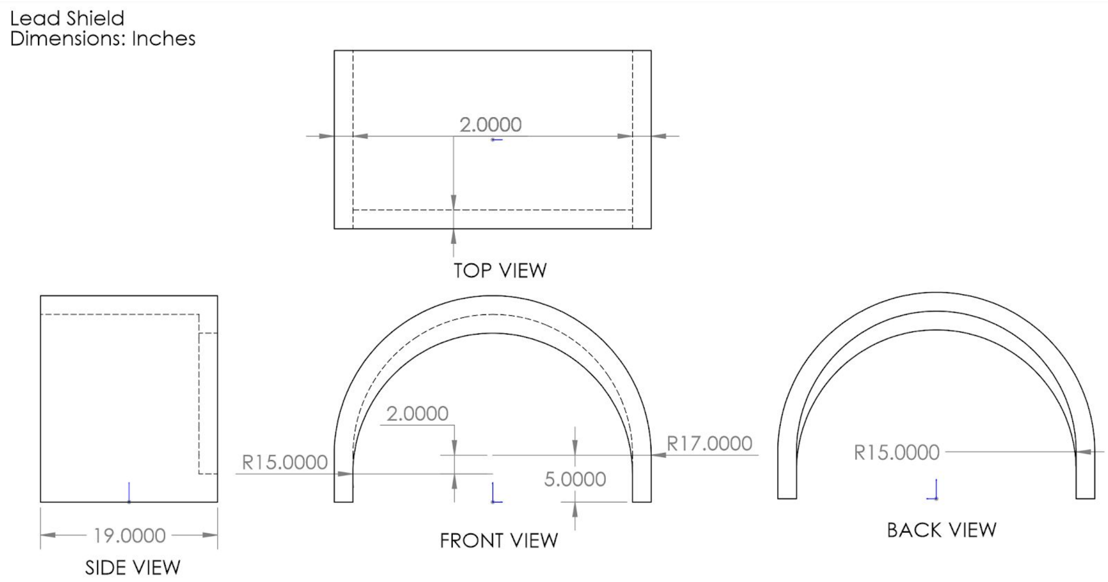
Material: Lead	
Parts/Assemblies	Shield
Source of Properties	SolidWorks Library
Material Properties	
Elastic Modulus	14 GPa
Poisson's Ratio	0.4
Shear Modulus	49 GPa
Mass Density	11000 $\frac{kg}{m^3}$
Tensile Strength	14.5 MPa
Yield Strength	12 MPa
Thermal Expansion Coefficient	$5.3 \times 10^{-5}\ \frac{1}{K}$
Thermal Conductivity	35 $\frac{W}{m*K}$
Specific Heat	130 $\frac{J}{kg*K}$

Material: A36 Steel	
Parts/Assemblies	Bottom Casing Top Casing Top Casing Mounts (Top and Underside) Bottom Casing Mounts Linear Actuator Base Linear Actuator Cover Mounting Rod Screw Jack Support

Source of Properties	SolidWorks Library
Material Properties	
Elastic Modulus	200 GPa
Poisson’s Ratio	0.26
Shear Modulus	79.3 GPa
Mass Density	7850 $\frac{kg}{m^3}$
Tensile Strength	400 MPa
Yield Strength	250 MPa

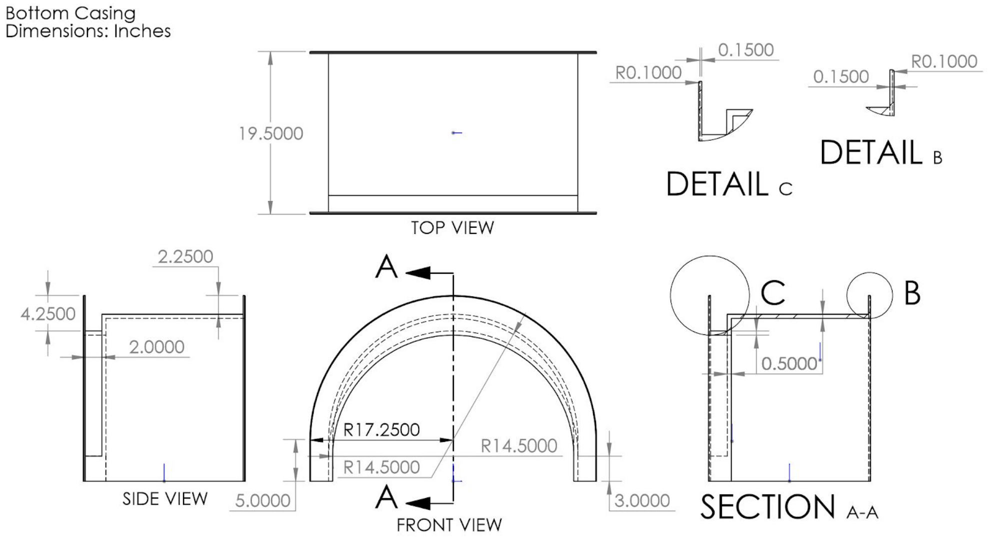
Part Dimensions

<u>SolidWorks Part: Shield</u>



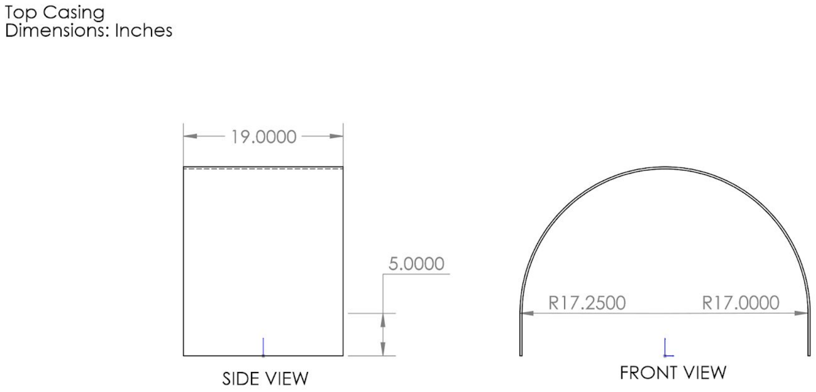
[SolidWorks Drawing] The lead shield that will be placed over the woman to protect the fetus from ionizing radiation. The material will need to be pure lead, and it is expected to weigh roughly ½ ton.

SolidWorks Part: Bottom Casing



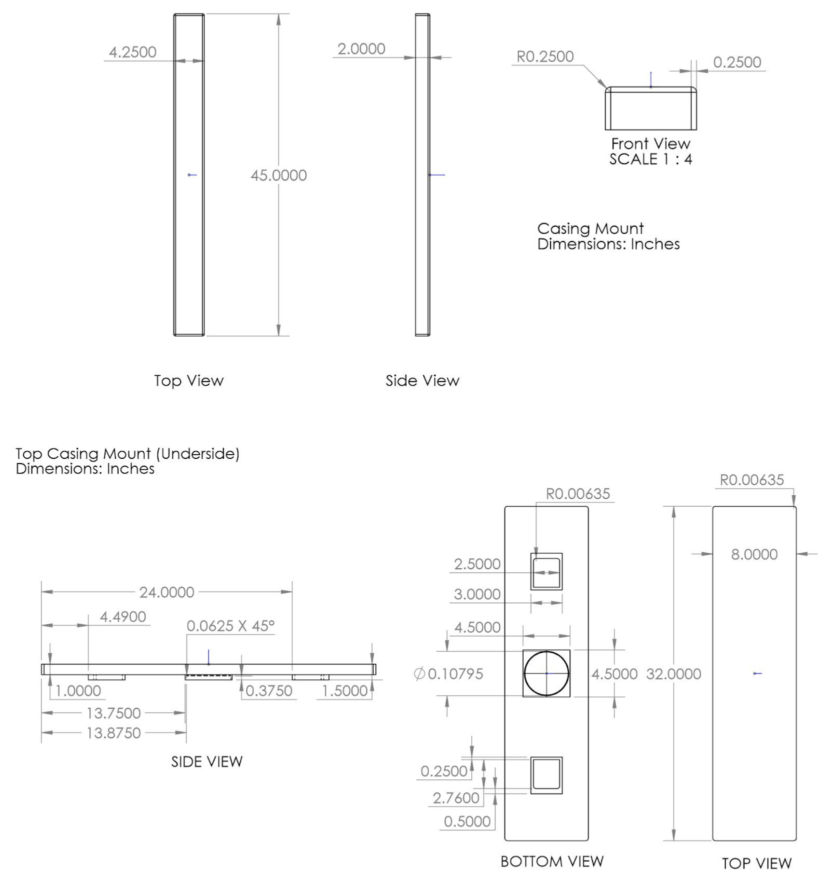
[SolidWorks Drawing] The bottom casing of the shield. It will be welded to the two casing mounts and will bear the brunt of the shield's weight.

SolidWorks Part: Top Casing



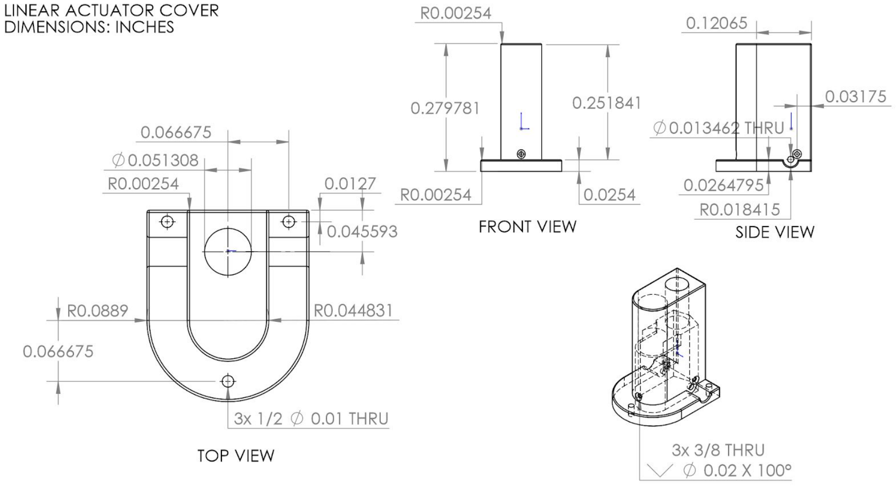
[SolidWorks Drawing] The top shield casing. Its main job is to prevent the lead shield from any accidents that would result in deformation. It will be bolted to the casing mounts via the flange mounts and will rest over the top of the lead shield.

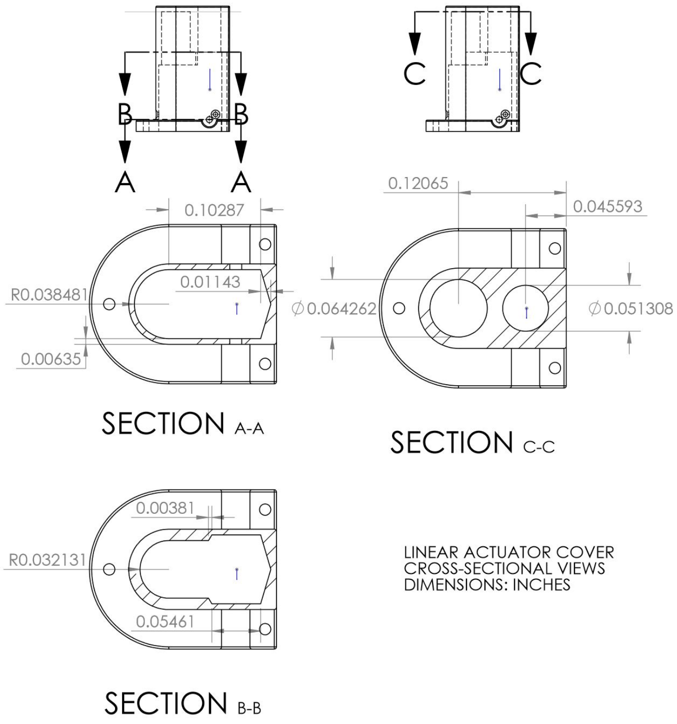
SolidWorks Part: Casing Mounts



[SolidWorks Drawing] The shield casing mounts that will serve as the connection point between the shield and the lifting mechanism. While there are two, they share the same dimensions because the casing mounts are mirror images of each other.

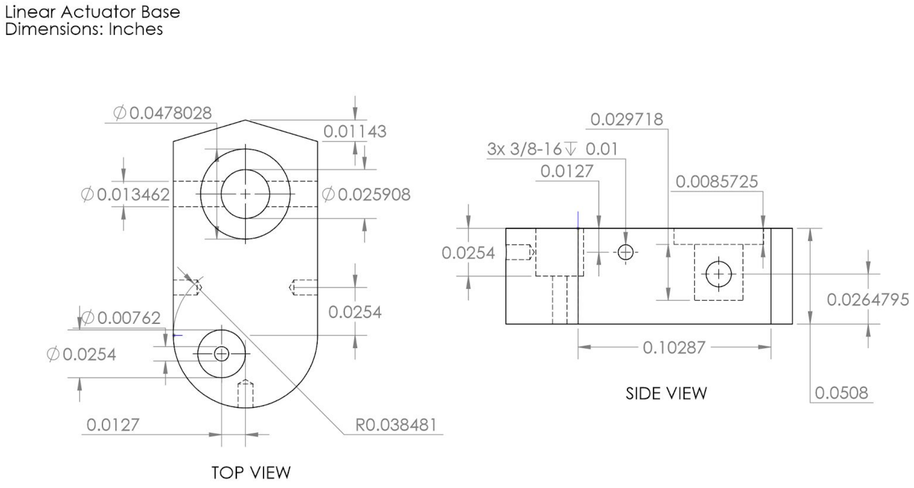
SolidWorks Part: Linear Actuator Top Cover





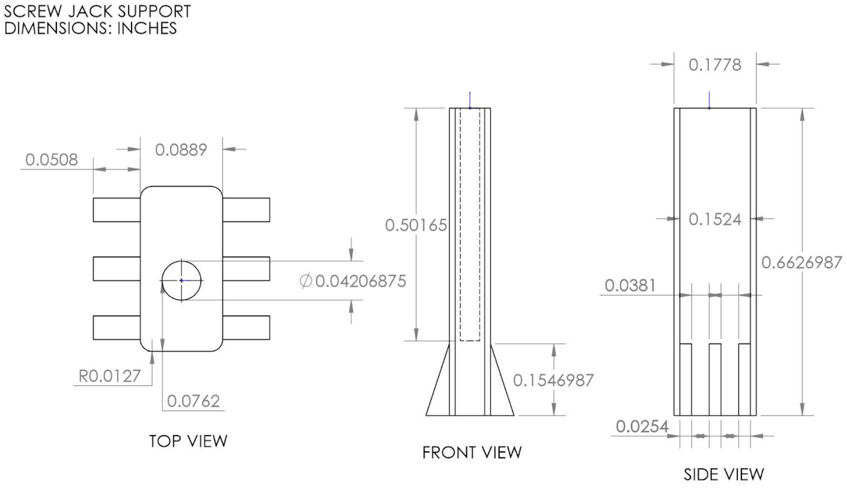
[SolidWorks Drawing] The linear actuator cover that will encase the bottom, bulkier part of the linear actuator.

SolidWorks Part: Linear Actuator Bottom Cover



[SolidWorks Drawing] The bottom part of the linear actuator cover that will bear the brunt of the weight and will serve as a connector to anchor the linear actuator to the bottom frame.

SolidWorks Part: Screw Jack Support



[SolidWorks Drawing] The screw jack support for the mechanical screw jack..