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

Lena Hampson, Lauren Heinrich, Janae Lynch, Megan Skalitzky

Department of Biomedical Engineering- University of Wisconsin Madison,
Madison, WI

Summary

Women who are pregnant and choose to undergo radiation therapy risk radiation exposure to their unborn child. In order to shield the fetus from radiation, external shielding can be put over the woman's body but current methods are unsafe or costly. An external shield was designed and tested using SolidWorks. It proved to be mechanically stable in static testing and dynamic testing.

Abstract

Radiation can pose severe health risks to a developing fetus including birth defects and increased likelihood of childhood cancer. Therefore, pregnant patients undergoing radiation therapy 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 methods for reducing fetal radiation dose are either unsafe or cost-prohibitive. The Department of Human Oncology at University Hospital requested that a shield be designed to protect the fetus from leakage from the head of the radiation machine and scattering from the collimators. 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. Over the last two years, the team developed a transportation system, refined the shape of the shield, and added further detail to the lifting/support mechanism. There is now a full model of the shield design with its various components. Static testing of the shield and support system has been completed 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.

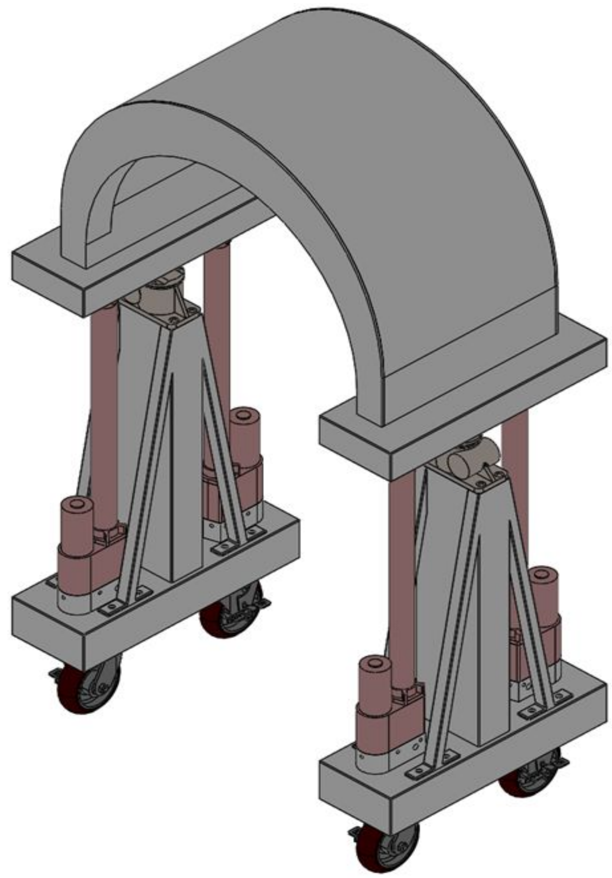


Figure 1: SolidWorks view of the assembled final design. Lipped cylinder (grey), linear actuators (red), and power jacks (green) and transportation system

METHODS AND MATERIALS

The modeling of final prototype and subsequent computer simulations were done with SOLIDWORKS® 2018 Education Edition, 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 was used 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 shape of the body of the shield is a half cylinder with a front lip. 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 with its welded casing mounts were 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). The lip was added to the front of the shield to provide additional protection from horizontal 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 support frames for the screw jacks and the bottom casing mounts that would be the connection between the lifting system and the wheels.

<u>Static Testing: Shield and Shield Casing</u>

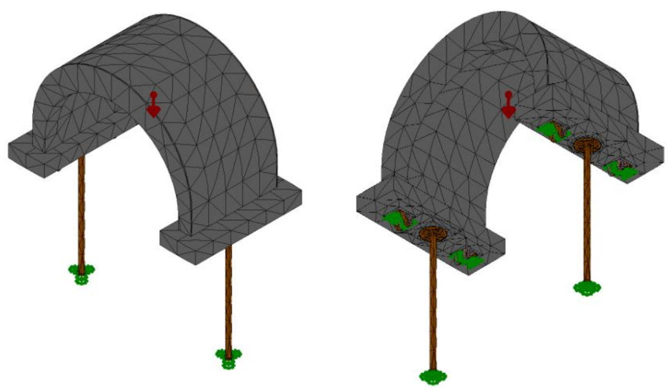


Figure 2: The shield assembly that was subjected to static load testing. Intersecting lines represent nodes, the areas created by those lines represent the elements, the red arrow represents the direction of gravity, the gray parts represent the parts included in the analysis, the brown parts indicate 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 on the casing and the distribution of the weight among the six supports. Due to the heaviness of the lead, it was critical that the steel casing be able to support the lead weight 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 (Figure 3).

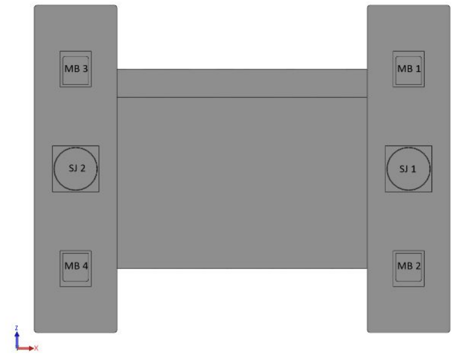


Figure 3: Bottom view of shield casing showing where the linear actuators (four corners) and power screws meet the mounting brackets. Referenced in Table 1.

A separate assembly was made specifically for the static and dynamic tests on the shield: the Top Assembly (Figure 2). The parts included in this assembly were the bottom and top casing, the two casing mounts, the lead shield, the four mounting brackets of the linear actuators, and the two lifting screws from the screw jacks.

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 was bonded to the casing mounts to simulate the effect of welding. The only other component contact applied to the model was global contact that was set as “no penetration”. The bottommost 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 set as coarse as possible. Gravity was applied as -9.81m/s^2 in the downwards direction.

<u>Static Testing: Support Frame</u>

To determine the response of the support frame to the weight of the steel casing and lead, static tests were done on the support frame, which was comprised of the screw jack supports, the bottom casing mounts, and wheel substitutes that were the same size as the wheels (Figure 3). After completing the static load tests on the shield and shield casing, the resultant reaction forces obtained from the points of contact between the casing mounts and lifting mechanisms were applied to the support frame at the places where the lifting parts connect to the bottom casing mounts, and these forces were applied solely in the negative y-direction. While some portion of that resultant force was due to shear forces in the x and z direction, since the majority of the forces were in the y-direction, this was an assumption. In addition to these forces, gravity was also applied to the support frame.

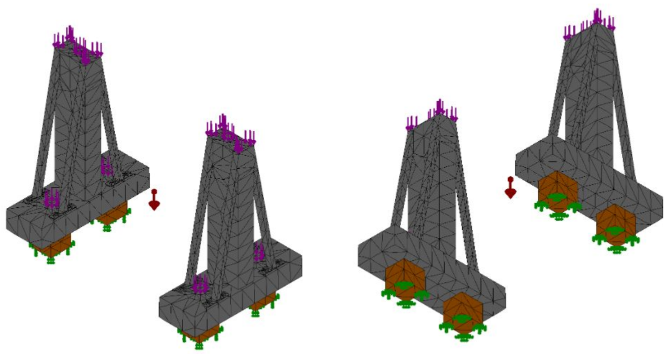


Figure 4: Mesh of static testing of shield casing. Green arrows indicate fixed geometry; red arrows indicate gravity.

The components on each side (the screw jack support, the bottom casing mount, and the two wheel substitutes) were bonded to each other to simulate the effect of the separate parts being permanently attached. The wheels were treated as rigid and fixed since those parts would be purchased from an outside company that has already done their own rigorous testing. All mesh was the SolidWorks default, set to be as coarse as possible.

<u>Dynamic Testing: Shield and Shield Casing</u>

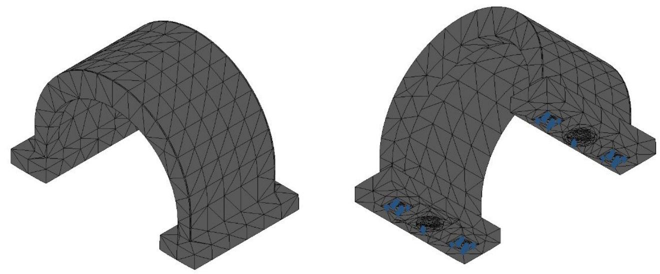


Figure 5 Mesh of dynamic testing on shield casing.

To determine if the stresses induced as a result of the upward and downward velocities contribute significantly to the stresses induced in the shield, dynamic testing was performed on the shield and its casing (Figure 4). The only parts included in this simulation were the bottom casing, casing mounts, top casing, and lead shield, which were bonded together. The only initial conditions present were lifting velocities applied to the points of contact between the casing mounts and lifting mechanisms, which were set as +0.33 in/s for dynamic lifting test and -0.33 in/s for the dynamic lowering test. Mesh was again set as the SolidWorks default, which was defined as coarse as possible.

After running each 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 250 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.

RESULTS AND DISCUSSIONS

Static Testing: Shield and Shield Casing

The weight of the lead shield and its casing was found be 1359 lbs, and the primary aim of the static testing on the shield and casing was to determine the load each support system component would have to bear and if the steel casing would be capable of supporting the weight of the lead.

	F_x (N)	F_y (N)	F_z (N)	$F_{Resultant}$ (N)
CM 1	.01049	1012	-26.23	1012
CM 2	0	897.8	0	897.8
CM 3	1.591	1007	-24.03	1008
CM 4	0	905.0	0	905.0
SJ 1	-163.3	1108	26.27	1120
SJ 2	161.3	1108	24.04	1120

Table 1: Values for the distribution of the weight of the lead shield over where the mounting brackets meet the top casing mounts.

The weight was distributed among the six supports fairly evenly, with the screw jacks bearing 37% of the weight, the front casing mounts (CM 1 and CM 3) bearing 33% of the weight, and the back casing mounts bearing 30% of the weight. The screw jacks likely bear a slightly larger percentage of the weight due to their position in the middle of the casing mount, while the front mounting brackets support a larger load than the back mounting brackets due to the additional lip in the front of the shield.

The areas with the highest stresses were located on the casing mounts, indicating that within the shield and casing subassembly this would be the part most likely to fail. The maximum stresses observed were between 0.6690 MPa and 0.8302 MPa. Comparing those values to the yield strength of A36 steel (250 GPa), the shield casing does approach the point of failure.

Static Testing: Support Frame

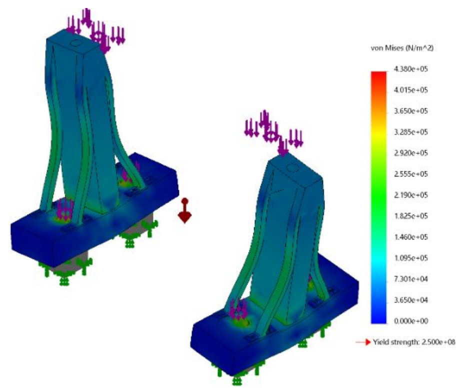


Figure 6: After applying static testing on the support frame, this shows the deformation they received.

The maximum stresses induced on the screw jack supports are 0.2538 MPa (right side) and 0.3387 MPa (left side). The maximum stresses induced on the bottom casing mounts are 0.438 MPa (right side) and 0.4284 MPa (left side). These are far below the yield stress of A36 steel. While the support frame will need to be further modified to accommodate the synchronization system for the six lifting components, these results imply that this is a plausible design for the support frame.

Dynamic Testing: Shield and Shield Casing

The stresses induced on the shield and its steel casing during dynamic analysis never exceeded 200 Pa. Given that the yield strength of A36 steel is 250 MPa, this clearly indicates that the stresses on the steel casing from the acceleration upwards and downwards is negligible.

CONCLUSION

The final design consisted of a half-cylinder shape with a front lip to assist in reducing the levels of radiation that the fetus receives, two power-jack screws, four linear actuators, and four swivel caster caster wheels with brakes. Additionally, the team has made progress in its efforts to create a fabrication plan with Vulcan Global Manufacturing Solutions (Milwaukee, WI). One of the main goals of the past semester was to significantly reduce the price, which was accomplished.

Despite previous successes, there are numerous areas that require improvement. First, further testing in SolidWorks is necessary to ensure safety for the patients. More comprehensive motion analysis testing as well as fatigue testing on the support system and motion analysis of the entire assembly will need to be completed. In addition, the electronic components of the lifting mechanism will need to be determined. This will be important to integrate the power and controls for lifting, as this system is extremely heavy.

The total cost of the shield assembly remains high, however there are places where it can be reduced. One item that will be considered is reducing the price of the power jack screws. This will be done by either finding a new supplier or working with Joyce Dayton to reduce the cost. It is essential to reduce the price is so that there are sufficient funds 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 phantom dosimetry methods at Dr. Wesley Culberson’s lab. The shield will be configured for multiple treatment plans during dosimetry testing. 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 there is no shield.

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. Dosimetry 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 two years, this design has evolved significantly. Now with a design for the whole system, fast progress is being made to complete a safe and effective shield to provide peace of mind for pregnant patients considering undergoing radiation therapy.

REFERENCES

[1] M. Stovell and C. Robert Blackwell, "501 Fetal dose from radiotherapy photon beams: Physical basis, techniques to estimate radiation dose outside of the treatment field, biological effects and professional considerations", *International Journal of Radiation Oncology*Biology*Physics*, vol. 39, no. 2, p. 132, 1997.

[2] A. Owrangi, D. Roberts, E. Covington, J. Hayman, K. Masi, C. Lee, J. Moran and J. Prisciandaro, "Revisiting fetal dose during radiation therapy: evaluating treatment techniques and a custom shield [JACMP, 17(5), 2016]", *Journal of Applied Clinical Medical Physics*, 2017.

[3] M. Islam, F. Saeedi and N. Al-Rajhi, "A simplified shielding approach for limiting fetal dose during radiation therapy of pregnant patients", *International Journal of Radiation Oncology*Biology*Physics*, vol. 49, no. 5, pp. 1469-1473, 2001. Available: 10.1016/s0360-3016(01)01447-x.

[4] M. Josipović, H. Nyström, and F. Kjær-Kristoffersen, “IMRT in a Pregnant Patient: How to Reduce the Fetal Dose?,” *Medical Dosimetry*, vol. 34, no. 4, pp. 301–310, 2009.

[5] M. Mazonakis, A. Tzedakis, & J. Damilakis; Monte carlo simulation of radiotherapy for breast cancer in pregnant patients: How to reduce the radiation dose and risks to the fetus?; *Radiation Protection Dosimetry*, Article vol. 175, no. 1, pp. 10-16, Jun 2017.

APPENDIX:

SolidWorks Modeling

Material Properties

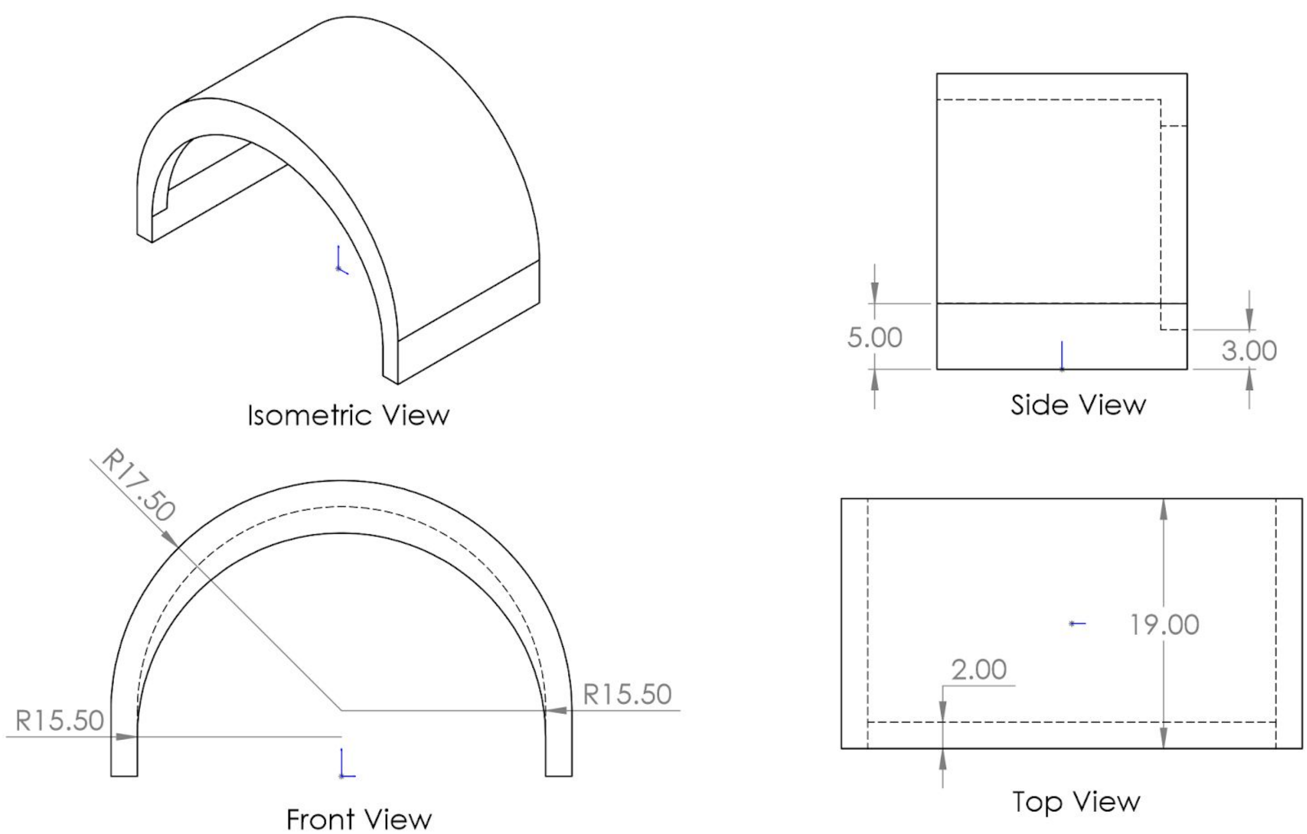
Material: Lead	
Parts/Assemblies	Shield
Source of Properties	SolidWorks Library
Material Properties	
Elastic Modulus	14 GPa
Poisson's Ratio	0.4
Shear Modulus	49 GPa
Mass Density	11000 $\frac{kg}{m^3}$
Tensile Strength	14.5 MPa
Yield Strength	12 MPa
Thermal Expansion Coefficient	5.3×10^{-5} $\frac{1}{K}$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

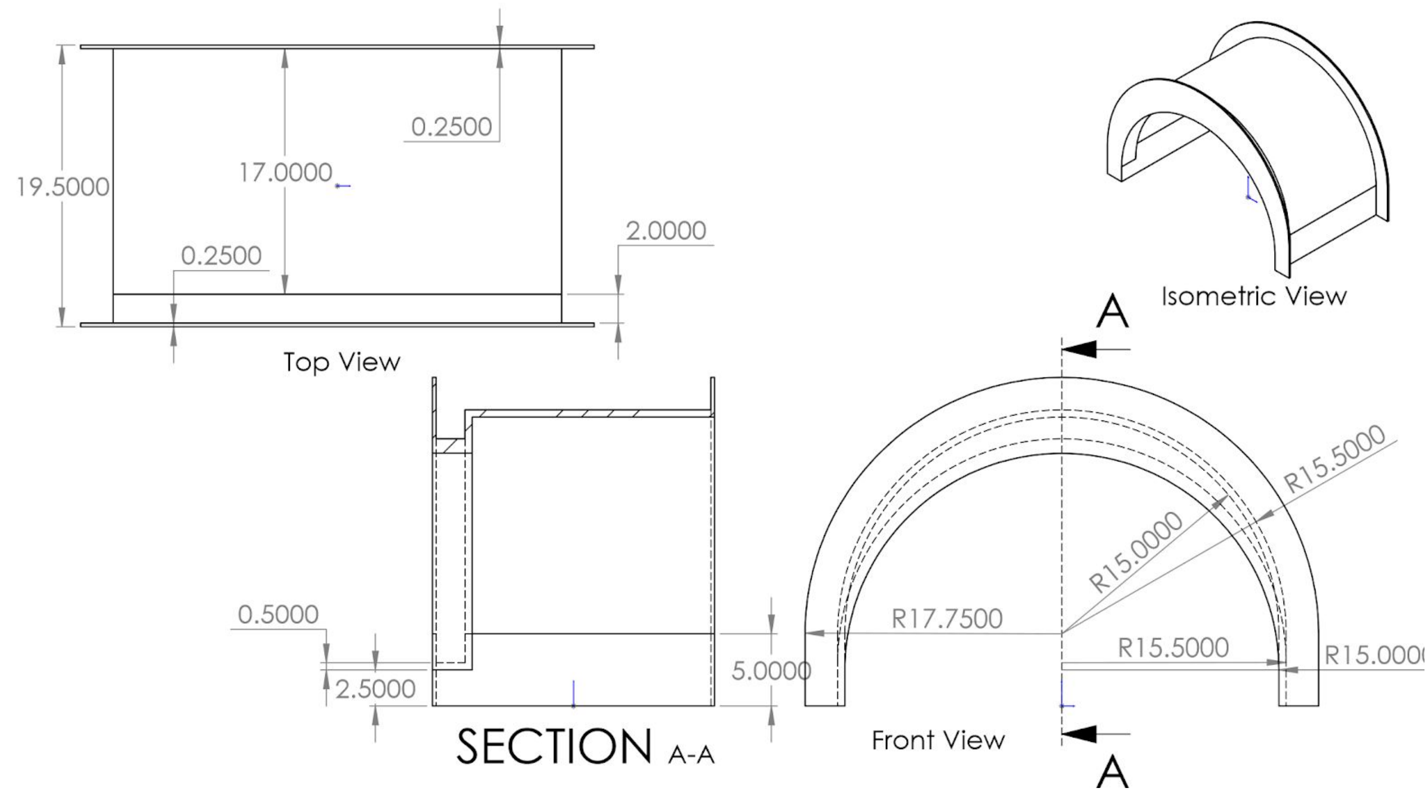
Part Dimensions

SolidWorks Part: Shield



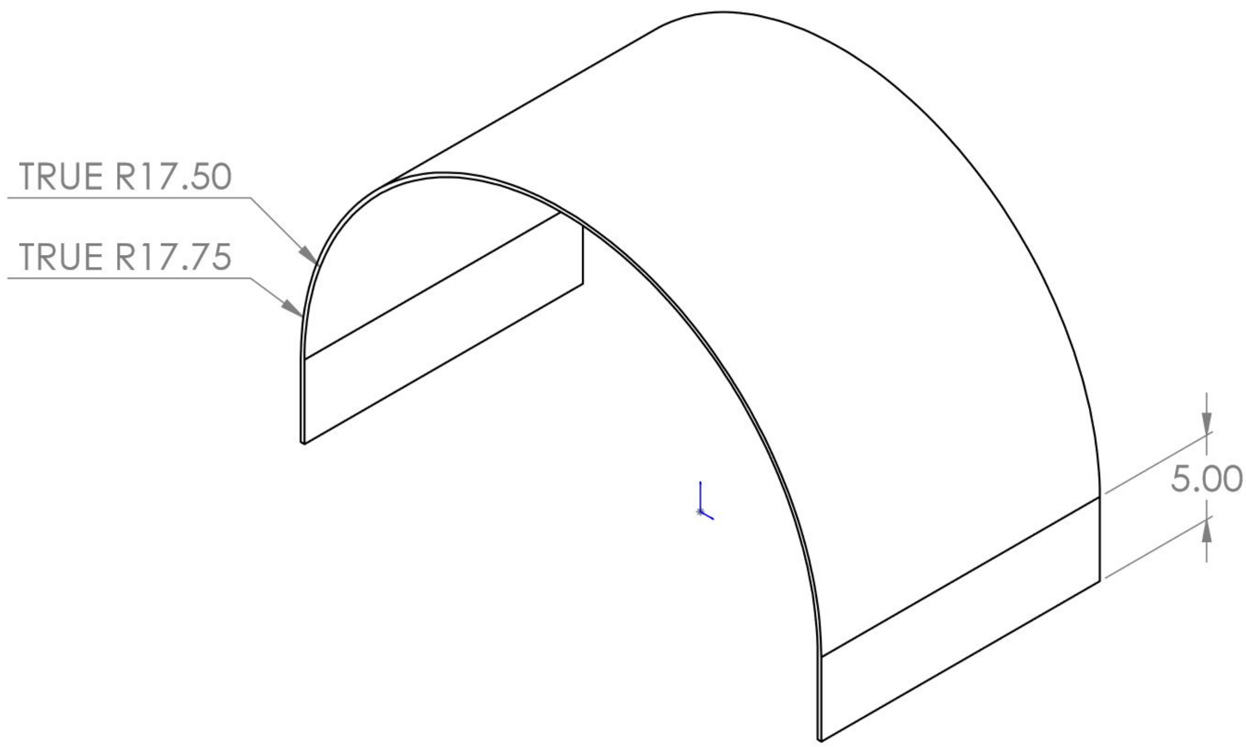
[SolidWorks Drawing] The lead shield that will be placed over the woman to protect the fetus from ionizing radiation. The material will need to be pure lead, and it is expected to weigh roughly ½ ton. Dimensions are in inches

SolidWorks Part: Bottom Casing



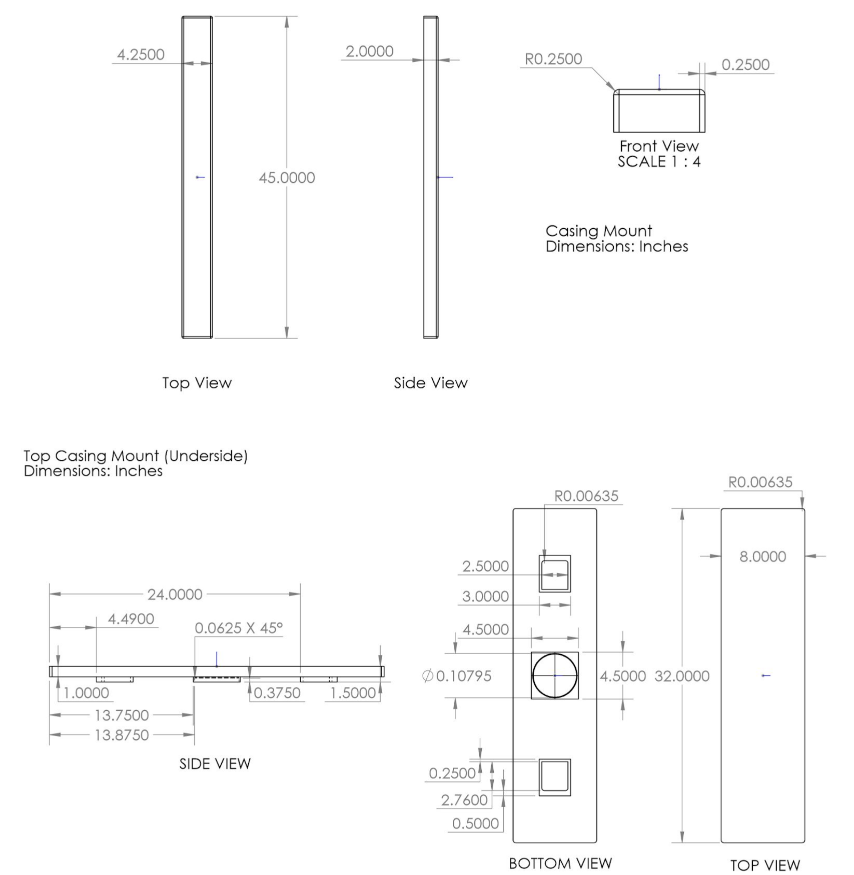
[SolidWorks Drawing] The bottom casing of the shield. It will be welded to the two casing mounts and will bear the brunt of the shield's weight. Dimensions are in inches.

<u>SolidWorks Part: Top Casing</u>



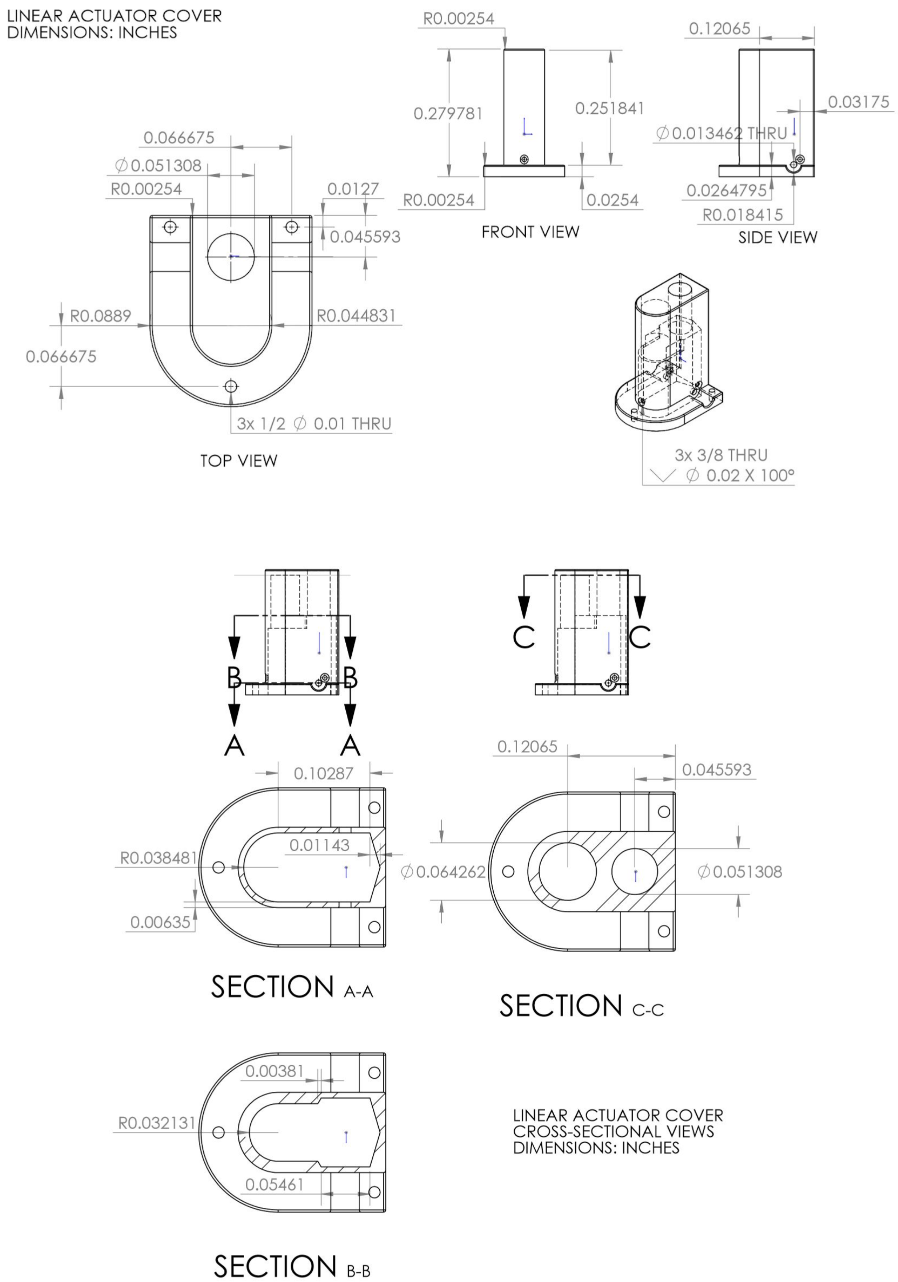
[SolidWorks Drawing] The top shield casing. Its main job is to prevent the lead shield from any accidents that would result in deformation. It will be bolted to the casing mounts via the flange mounts and will rest over the top of the lead shield. Dimensions are in inches.

SolidWorks Part: Casing Mounts



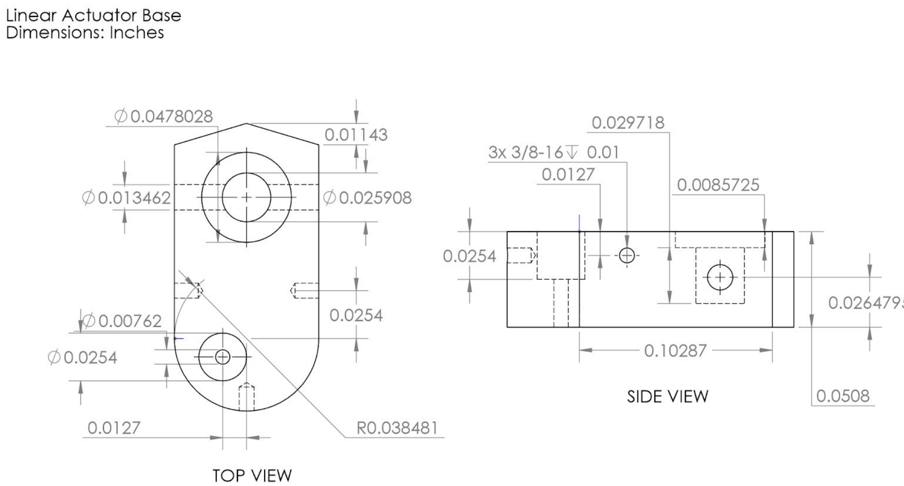
[SolidWorks Drawing] The shield casing mounts that will serve as the connection point between the shield and the lifting mechanism. While there are two, they share the same dimensions because the casing mounts are mirror images of each other.

<u>SolidWorks Part: Linear Actuator Top Cover</u>



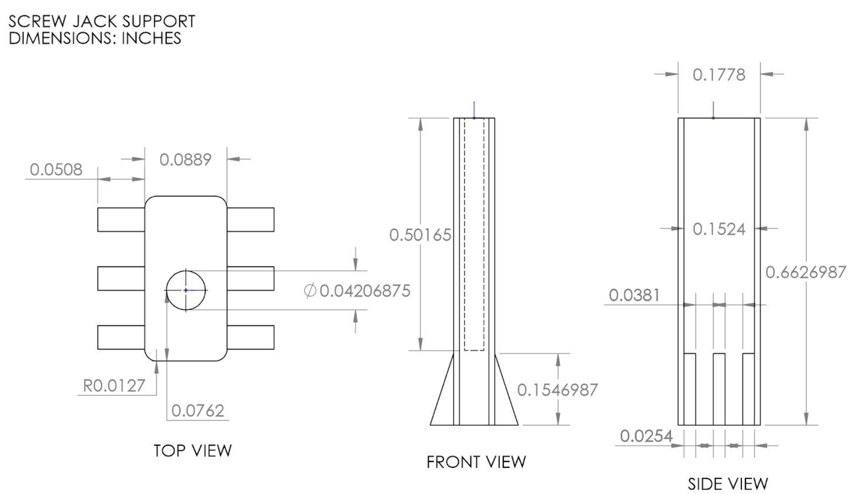
[SolidWorks Drawing] The linear actuator cover that will encase the bottom, bulkier part of the linear actuator.

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..