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Proton Therapy Facility Shielding

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NE472 Design Project

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Abstract

Straight beamline gantry-based proton therapy systems have the potential to make highly advanced radiation treatment for cancer patients more accessible in regions that previously could either not afford traditional facilities or did not have the space for them. These facilities would reduce cost and size constraints by requiring only one treatment room, nullifying the need for highly expensive magnetic beam-bending technology. The following report considers the health concerns involved with the operation of such a facility, in particular the dose to patients from spallation neutrons. A CAD design for a functional radiation shield that can be mounted to any ProNova gantry facility is proposed in this report. Experimentally verified Monte Carlo simulation methods have determined that this design is successful in reducing the dose to the patient by approximately 50% with a 4” shield and 65% with a 6” shield.

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Introduction

Team Photograph

Figure 1 Group Members (Left to Right) - Daniel Elkins, Hadyn Daugherty, Alyxandria Wszolek, Isaac Waldschlager, Rachel Gaudet.

Team Acknowledgements

The Proton Therapy senior design group would like to thank certain individuals for their significant involvement and guidance in this design proposal.

- Dr. Matthew Cook was crucial in helping the group create accurate MCNP simulations.
- Dr. Lawrence Heilbronn was invaluable as a mentor in guiding this group through the design process and verifying the results.
- Dr. Ronald Pevey was instrumental in confirming the simulation inputs and outputs from MCNP and helping us implement a more efficient means of retrieving data.

The progress of the project would have been severely hindered without their contributions.

Objectives

The objective of this project is to design a shield for a gantry-based straight beamline proton therapy system that reduces the dose from spallation neutrons while maintaining full functionality and rigidity of the gantry. This project is done in coordination with ProNova, a “company providing unique solutions…to meet the most pressing healthcare challenges, improve patient safety and ensure optimal outcomes” [1]. The mission of ProNova is to redefine cancer therapy with research and development towards cost-effective, compact, and energy efficient proton therapy centers.

ProNova has previously developed traditional proton therapy systems which have a curved beamline that supplies two gantry treatment rooms and one fixed-nozzle treatment room. These facilities are large and their construction is expensive due to the need for magnets to curve the beamline. They have proposed a more cost-effective alternative that employs a straight beamline design that only supplies one treatment room. This design would be valuable to cancer patients that either do not have the space for a large facility or do not have the money required to operate a three-room facility.

As beneficial as such a facility would be, a straight beamline design has yet to be created. Therefore, there was a lack of knowledge on the magnitude of the undesirable neutron radiation produced by protons impacting high-density materials surrounding the treatment room. All beamlines have this effect, but the scatter of neutrons in a direction tangential to the curve of the beamline in a curved system directs the neutrons away from the patient. This additional dose must be shielded without compromising the effectiveness or accuracy of the proton beamline used in treatment. The purpose of this report is to propose a design for a shield that protects the patient from the undesired neutron dose.

Background

Proton Therapy

Proton therapy is a favorable alternative to other current methods of radiation therapy cancer treatment. It offers a significantly decreased risk of damage to healthy human tissue which translates to an “increased probability of cure” [2]. A traditional proton therapy center is shown below in *Figure 2*. The amount of rooms in the facility should be noted along with the curved path of the beamline. Though the advantages of proton therapy are clinically proven, the substantial investment required to construct these facilities poses difficulties in managing the cost-effectiveness of the project.

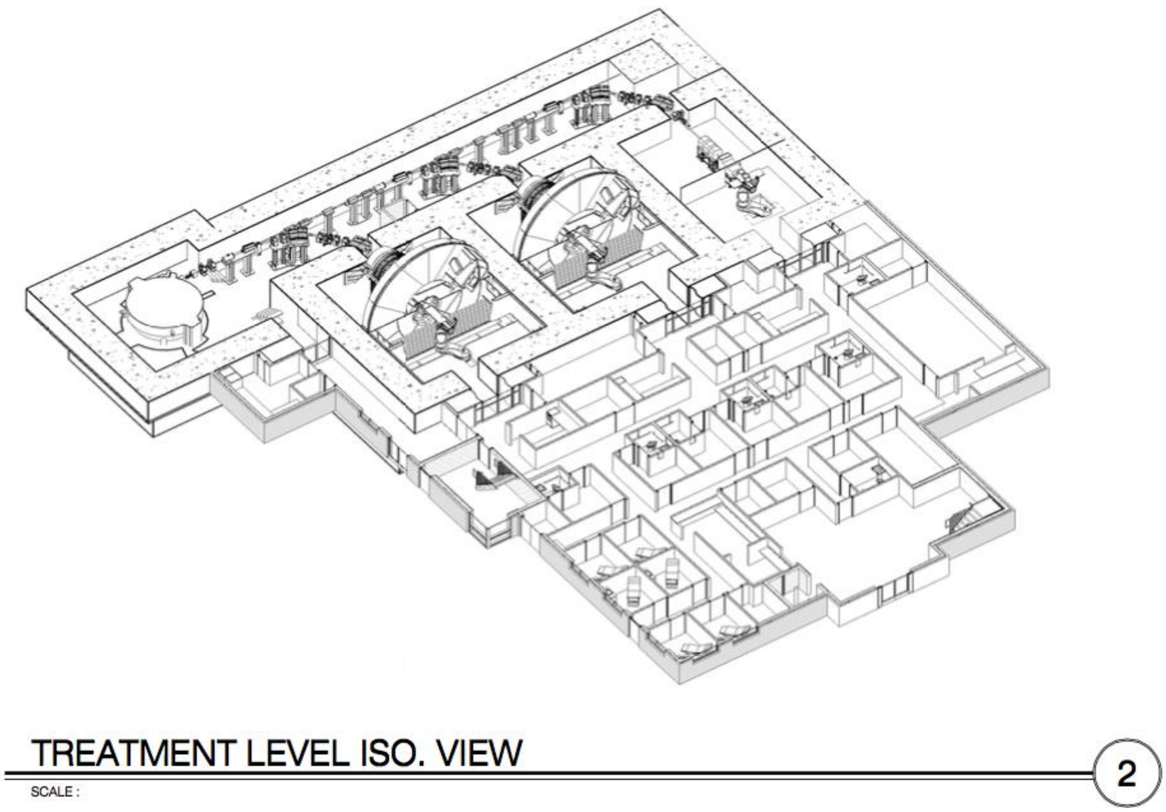

Figure 2 Traditional Proton Therapy Center [1]

The estimated cost of a traditional proton therapy facility can be as high as 62.5 million Euro, or approximately 70 million U.S. dollars [4]. Furthermore, the estimated cost per patient is 14,700 Euro (close to 16,500 dollars). Given the substantial cost (93% more than x-ray therapy), the study resulted in favor of using traditional x-ray therapy [2]. Cost is frequently a hindrance to the use of proton therapy, necessitating an increased effort to find unique solutions to improve the design of proton therapy centers.

Straight Beamline Design

ProNova has proposed a straight beamline orientation to reduce construction and treatment costs. *Figure 3* shows a preliminary aerial view of this compact, straight beamline design. This new design is a single-room system that employs a gantry. This provides the functionality and flexibility required for treating cancer with potentially lower up-front costs. Another picture of the design is shown in *Figure 4*.

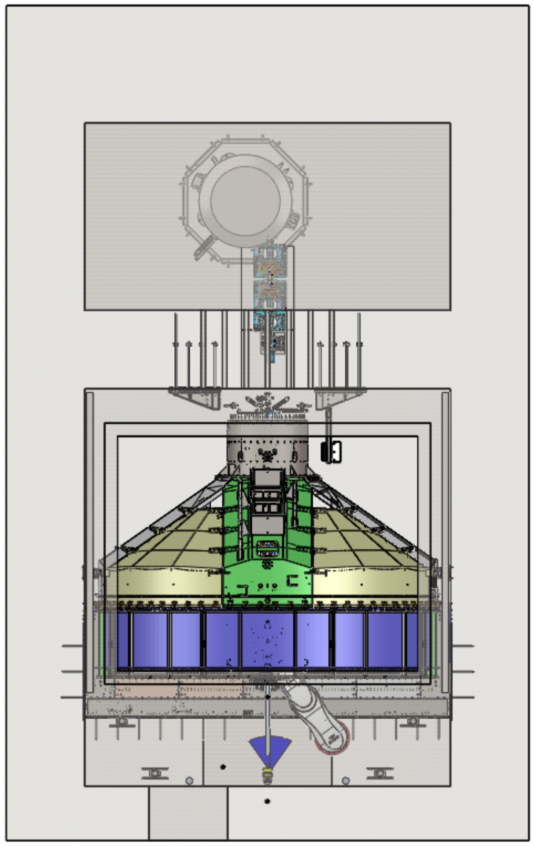

Figure 3 Preliminary Straight-line beam design [1]

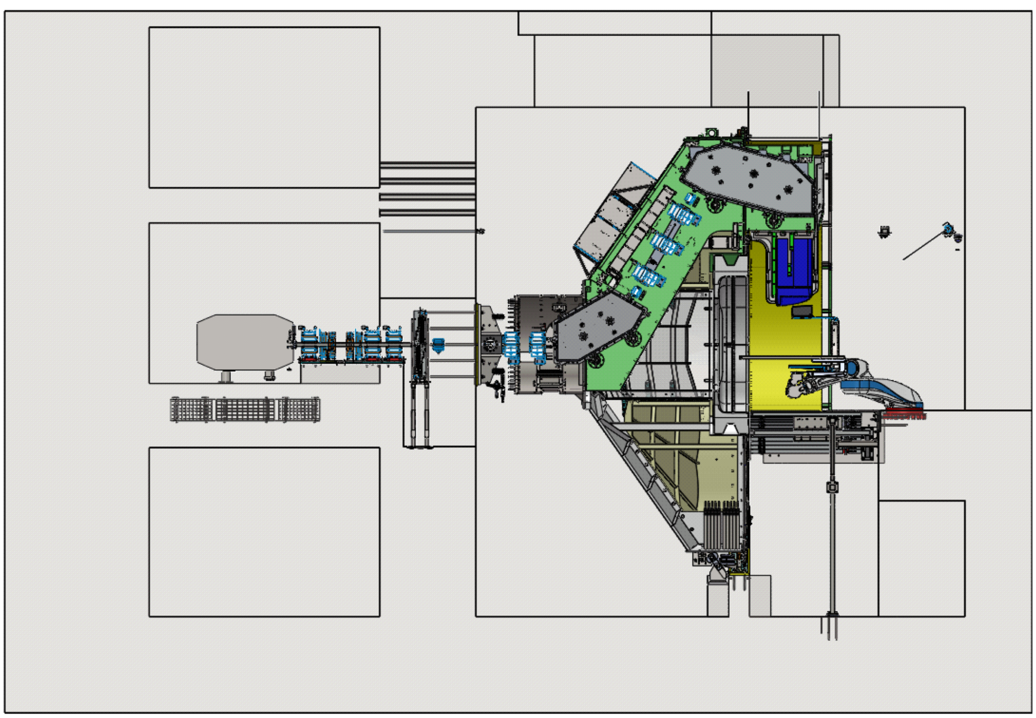

Figure 4 Profile view of preliminary straight-line beam design [1]

Methods

The neutron dose inside the treatment room is due to the 235-MeV proton beam striking various beam diagnostic equipment, radiation safety stops, and the beryllium beam degrader that is used to change the energy of the beam. Neutron radiation is difficult to shield, however, and is a task that has been traditionally accomplished using several feet of concrete. For gantry treatment facilities, a shield of minimal size and weight is necessary to allow the gantry (shown in *Figure 5*) to maintain the sub-millimeter beam accuracy that is required for proton therapy.

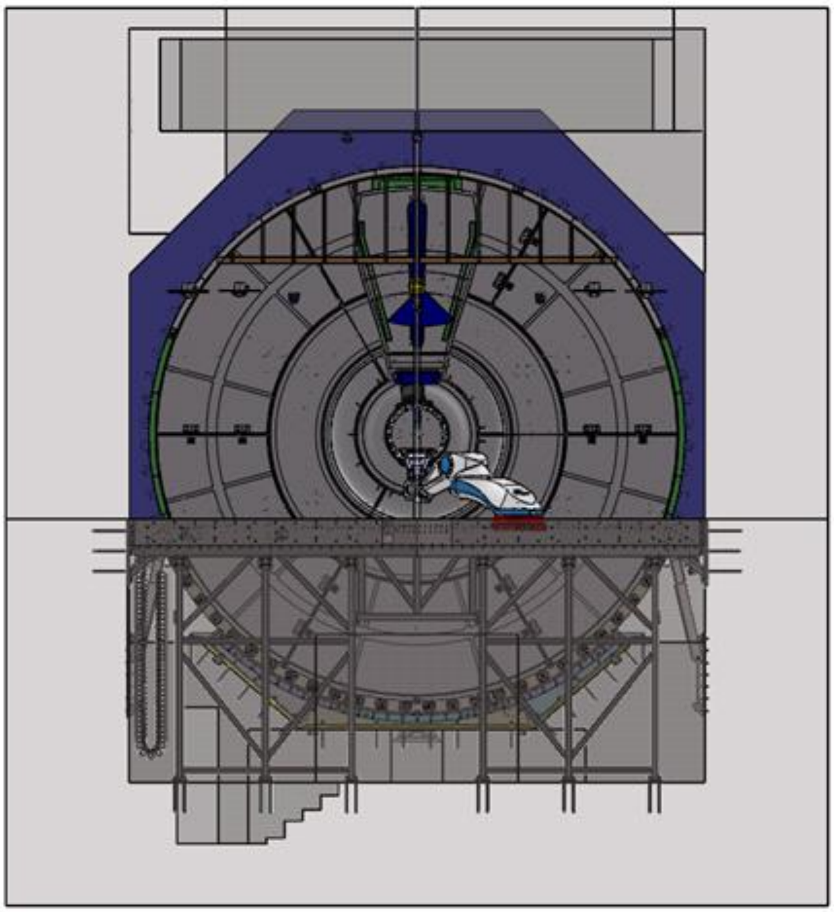

Figure 5 Gantry design in treatment room [1]

The resulting approach to completing this project was:

1) Determine the appropriate methods for calculating the dose;
2) Determine the neutron energy ranges of interest;
3) Verify that the MCNP simulations are accurate via experimentation;
4) Determine the appropriate shielding material and calculate the required shielding thickness;
5) Create a model of the shield to quantify its effectiveness while varying parameters in order to optimize the design;
6) Create a Computer Aided Design (CAD) model of the finalized shield design in order to provide final product specifications, including its size, weight, and method of suspension within the gantry.

Dose Calculation Methods

To calculate dose in MCNP, cell flux mesh tallies were used to provide the flux, ϕ, in particles cm^{-2}. To convert to effective dose, the flux was multiplied by weighting factors corresponding to discrete neutron energies (Equation 1). The effective dose per particle was then multiplied by the source strength to yield results in mSv h^{-1}. For these simulations, International Commission on Radiological Protection (ICRP) data for neutron effective dose per fluence for monoenergetic neutrons was used. This information is provided in Appendix A.

$$\sum_{i=1}^{N} \Phi_i * w_i = H \qquad \text{(Equation 1)}$$

Neutron Energy Ranges of Interest

It was determined via MCNP simulation that neutrons of low energies were not contributing to dose, as can be seen in *Figure 6*. This is due to the fact that thermal and epithermal neutrons are not produced in large enough quantities during the spallation events to have a notable effect on the total dose. All subsequent MCNP runs considered only neutron energies that ranged from 0.03 MeV to 300 MeV.

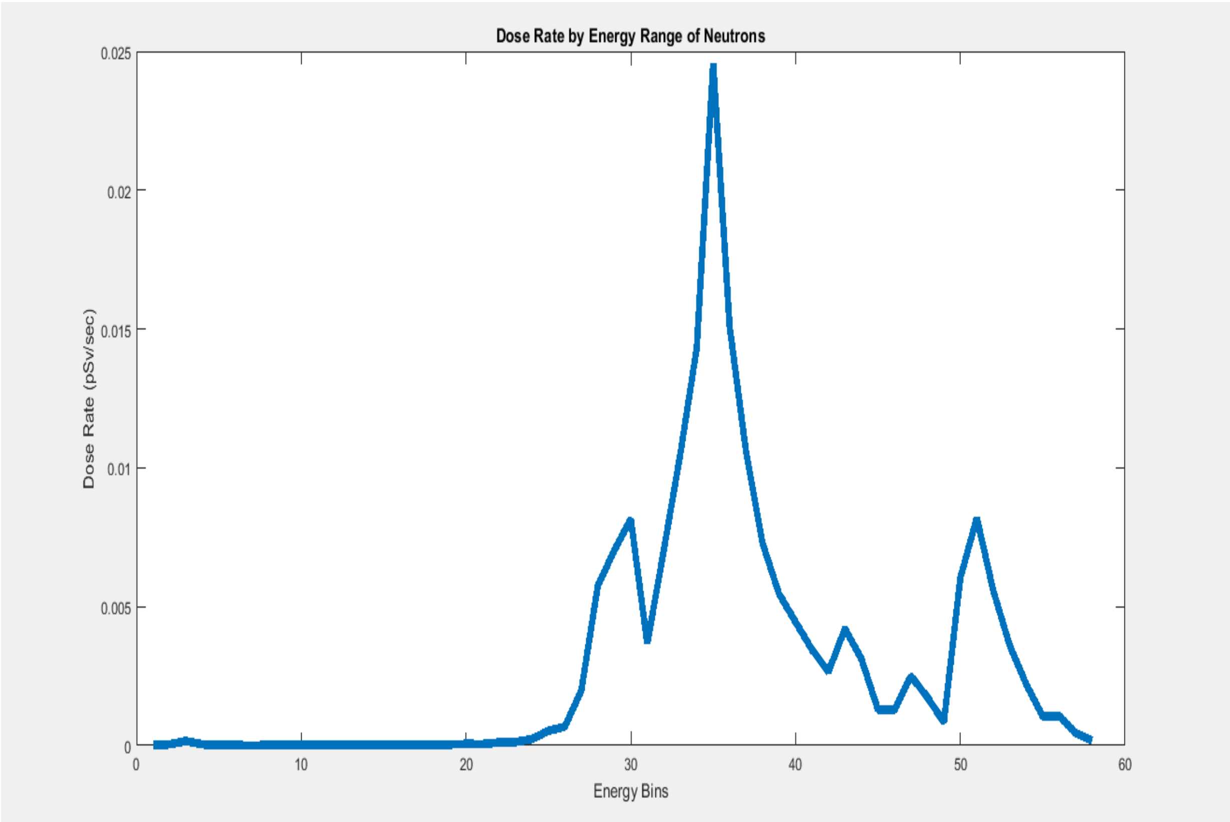

Figure 6 Dose rate as a function of energy bins.

MCNP Verification

In order to verify that the MCNP simulations are accurate, they had to be compared to two simple experiments. The experiments were performed at an experimental traditional facility in a room that did not employ a gantry but rather had a fixed beam path. The beam was fired at a BC-60 Beam Collector Faraday proton measurement device, which is primarily made of copper, placed at isocenter in one experiment and a beryllium target placed at isocenter in the other. The neutron dose rates were taken with a wide-energy neutron detector (WENDI) at three positions: 0, 60, and 90 degrees with respect to the beam vector. Three measurements were taken at each location to provide nine data points per experiment, allowing for decent statistical confidence while minimizing beam time. It is important to note that if this experiment were conducted in a straight beamline orientation, the copper and beryllium equipment would be on the opposite side of the concrete wall. For the experiment and corresponding MCNP model, having the blocks placed at isocenter will provide the most accurate configuration for confirming the simulation with the dose measurements. The results of the experiment are shown in *Table 1* below.

Table 1 Dose Rates of Copper and Beryllium at different angles/distances

Distance	10'	8' right/4'7" away	8' right
Angle (degrees)	0	60 (away/right)	90 (to the right)
Cu	7.4mSv/hr; 7.4mSv/hr; 7.4mSv/hr	7.5mSv/hr; 7.6mSv/hr; 7.7mSv/hr	7.7mSv/hr; 8.3mSv/hr; 6.8mSv/hr
Be	9.0mSv/hr; 9.2mSv/hr; 7.9mSv/hr;	2.6mSv/hr; 2.6mSv/hr; 2.6mSv/hr	2.2mSv/hr; 2.3mSv/hr; 2.2mSv/hr

It is worth noting that there were issues during the beryllium experiment. The WENDI, when placed at 0 degrees, would not measure the high dose rate resulting from the significant amount of neutron production that occurred along the beam axis behind the target. A reading could only be taken 1’ away from the 0-degree line. This phenomenon would also explain the much lower dose rates at the 60 and 90 degree positions. It is also worth noting that these values correspond to changes of up to approximately 10% of beam intensity. These values will all be normalized to the specific beam intensities that they were taken at so they can be better compared to the model.

MCNP was used to create dose map simulations that correspond to each experiment. The MCNP input deck defining the experiment using the copper block is found in Appendix B. The dose map simulating the beryllium experiment is shown in *Figure 7*. Note that the neutron shower effect along the beamline that caused the detector to fail is depicted. The dose map simulating the copper experiment is shown in *Figure 8*.

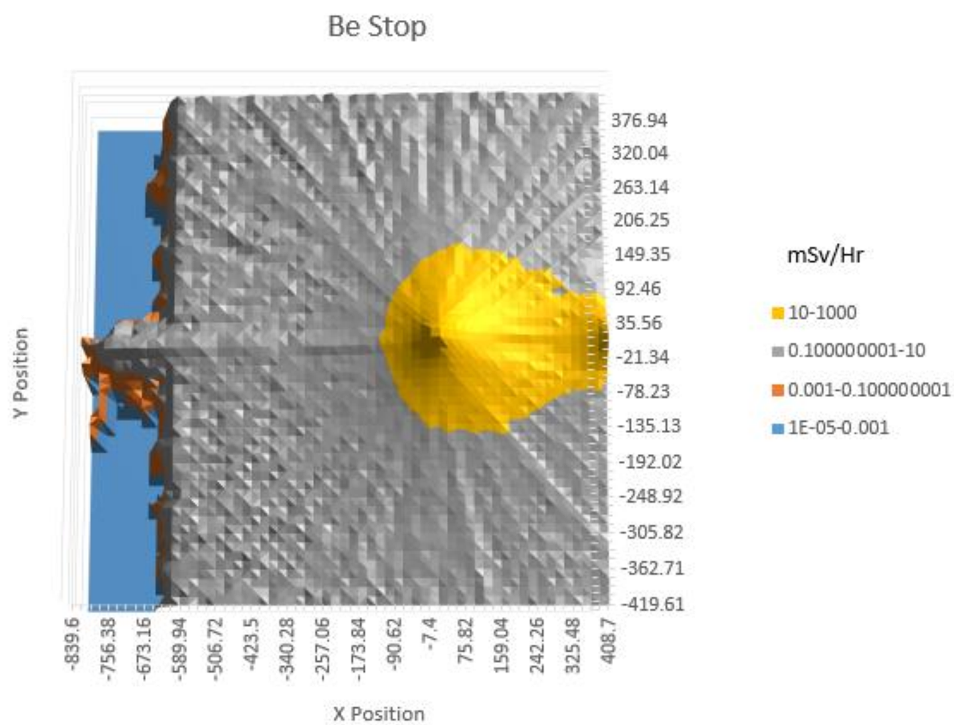

Figure 7 Dose map in treatment room with beryllium stop.

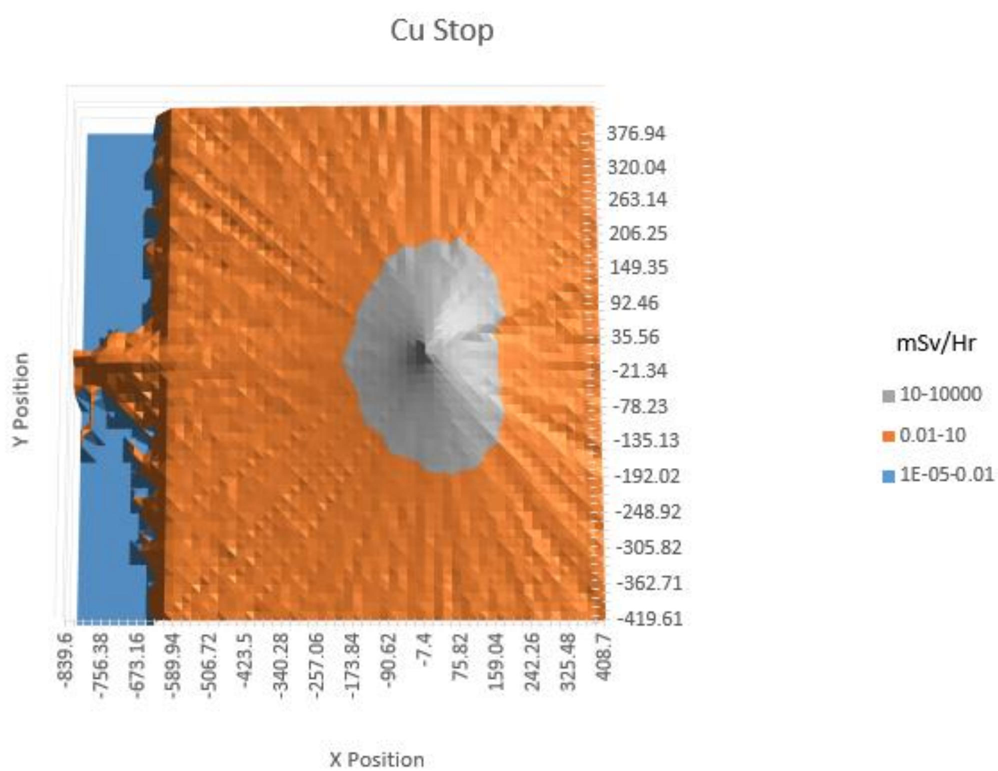

Figure 8 Dose map in treatment room with copper stop.

A comparison of the simulated dose rate values to the experimental data for beryllium and copper is shown in *Table 2* and *Table 3*, respectively. The copper experiment values differed from the simulated ones more than the beryllium experiment values did from theirs because the BC-60 pyramid beam measurement device that was used in the copper experiment was assumed in the simulation to be made of solid copper.

Table 2 Comparison of dose rates resulting from beryllium stop

Detector Orientation	Average Measured Dose Rate for Be Target ($^{mSv}/_{hr}$)	MCNP Simulation ($^{mSv}/_{hr}$)	% diff.
$\mathbf{0^0}$	8.7	8.65	0.6%
$\mathbf{60^0}$	2.6	3.18	22.3%
$\mathbf{90^0}$	2.2	2.55	15.9%

Table 3 Comparison of dose rates resulting from copper stop

Detector Orientation	Average Measured Dose Rate for Cu Target ($^{mSv}/_{hr}$)	MCNP Simulation ($^{mSv}/_{hr}$)	% diff.
$\mathbf{0^0}$	7.4	3.64	50.8%
$\mathbf{60^0}$	7.6	4.95	34.9%
$\mathbf{90^0}$	7.6	4.94	35.0%

Material Selection

All group members researched various properties of materials effective in neutron shielding, along with each material's respective costs, geometries, and design limitations. High-density polyethylene (HDPE) was determined to be the ideal shielding material due to its relatively low cost, low weight, high ease of construction, and ability to thermalize neutrons via inelastic and elastic scattering interactions.

Preliminary Calculations

The shielding thickness calculation was performed at an average energy and intensity for a typical clinical operating mode, or 235 MeV, with a shielding material of HDPE. Assuming that 60% of the initial energy is deposited as heat in the materials [3] (i.e., the copper and beryllium that produce spallation neutrons along the proton beamline), the peak energy of the ejected neutrons is approximately 40% of the initial proton energy (the binding energy in this case is negligible), or ~100 MeV. Assuming that successive elastic scattering off of carbon atoms resulted in an average energy loss, Equation 1 yields an approximate shield thickness of 6" for HDPE.

$$d_{HDPE} = lN_C \quad \text{(Equation 2)}$$

$$l_{100} = \text{pathlength of 100 MeV neutron in HDPE to collision}$$
$$N_C = \text{number of collisions to attain thermal energy}$$
$$d_{HDPE} = \text{approximate required thickness of HDPE}$$

Computational Methodology

An accurate geometric model of the proton beam and all of the materials of interest was developed in MCNP, which was aided by a general layout of the treatment room, given by ProNova, that is shown in Appendix C. The room consists of concrete walls with a single opening (not counting the entrance maze) that allows the proton beam to enter the room. This opening is completely surrounded by a rectangular lead insert. A simulation was created where beryllium and copper were placed behind the concrete wall with the lead insert, and the proton beam was allowed to run. It is important to note that placing the beryllium and copper close to the hole in the lead insert is not realistic, but is rather a conservative estimation that will cause more neutrons to enter the treatment room than will under normal operating conditions.

The resulting neutron current was obtained from a dummy cell with an MCNP surface-crossing tally that was placed on the treatment room side of the lead. The model was then modified multiple times to simulate treatment circumstances with varying shield parameters, including dimensions, composition, and neutron interaction cross-section data for HDPE. The surface tally provided the neutron source strength within the treatment room for a proton beam current of 1.17 nA with an energy of 235 MeV. This simulation allowed for accurate dose estimates with a 6” shield, a 4” shield, and no shield within the room. In order to estimate the dose that would be delivered to the patient, a cylindrical water phantom was placed in the room at isocenter. A cell flux tally was placed on the phantom so Equation 1 could be used to calculate the dose that was delivered to the patient.

Physical Design Methodology

The physical design of the shield is limited by weight, size, material, and mounting availability. Originally, the shield was going to be fabricated as a 12’ diameter cylinder that would be comprised of laminated sheets of HDPE. However, the material was only available from the manufacturer in 4’x8’ rectangular sheets. Determining a method to manufacture a 12’ diameter solid cylindrical mass out of rectangular sheets of HDPE posed a practical problem. In addition to manufacturing complications, it would also be too heavy to install and commission practically, with a 6” thick 12’ cylinder of solid HDPE weighing 3300lbs. It was determined that a better concept would be a rectangular shield of smaller dimensions. The surface area of an 8’x8’ square shield is about 60% as large as that of a 12’ diameter cylindrical shield. There is also an added benefit in that some of the weight saved in manufacturing a smaller 8’x8’ square shield could be reapplied to the center of the shield to more adequately shield a patient’s torso, where most of the vital organs in the body reside. The weighting factors of organs are much higher than those of appendages, so the loss of shielding around the patient's extremities can be neglected.

The shield was designed such that it could be mounted to the existing personnel footbridges. These were chosen due to their axial location within the gantry structure, their inherent strength, and their ability to conveniently accommodate the foot traffic for the rigging, installation, and maintenance of the shield. Furthermore, it was necessary to design for minimal modification of the existing gantry design in order to insure easy compatibility with the gantry. The square tubing that spans the walkway will be strengthened with the addition of four plates welded to the inside face of the tubing and four other brackets welded to the opposite side, such that all-thread could be bolted to the gantry weldment. The rectangular HDPE sheets would simply be sandwiched together with bolts and washers securing them to the walkways. Then, the individual HDPE sheets could be mounted such that assembly and maintenance of the system would only require that personnel be able to lift the sheets off of the shield individually, as opposed to having to move the entire shield as one piece.

The shield was designed with eight fastener points for assembly and mounting. Four of these attachment points secure the shield to the gantry walkways while all eight points hold the HDPE sheets together. In a sense, four of the eight attachment points are pulling double duty. The target weight limit of the shield is 2000 lbs. This target weight is far from exerting enough force on the gantry to inhibit the gantry's ability to operate accurately. It was then determined that each of the four bolts securing the shield to the gantry would have 500 lbs of force contributing to a shearing moment on the bolt. For the design, a 1" steel bolt was chosen for the four main attachments. 1" steel bolts have a tensile strength of about 150,000 psi according to McMaster-Carr, providing a substantial factor of safety. 1", 14 tpi (the standard fine thread measurement for 1" all-thread) all-thread and nuts will be used. Fortunately, the brackets that the all-thread will bolt to require minimal machining and installation and will only require welders to simply weld them on when they build the walkways. Drawings for the brackets can be found in Appendix F.

Gantt Chart Illustrating the Effort of All Group Members

A Gantt Chart was used as a means to organize the individual goals for this project and can be found in Appendix D. It involves an in-depth schedule of weekly progression, outlined to make sure that all objectives for the project would be completed. As the semester progressed and various complications arose, however, working on goals weekly and having an evolving schedule was determined to be the most effective way for the group to operate.

Description of Effort by Each Team Member

The nature of our project made it easy to clearly distribute work to individuals. Contrarily, the initial semester of work was done as a group. First, all team members were tasked to conduct individual research to propose preliminary shield designs based on past research. Throughout the semester team members collectively decided to pursue the HDPE design. Also during the first semester, many members in the group went to take preliminary dose rates to familiarize ourselves with the use of the WENDI detector and acquire an approximate magnitude of the dose rates experienced inside the vault. New measurements were taken to compare current MCNP dose projections to reality. In conclusion, many of our meetings the first semester consisted of brainstorming and group decision-making.

During the second semester, roles were more clearly defined. Isaac Waldschlager worked not only as the group leader, but also translated the optimized shield design to a CAD SolidWorks model. Hadyn Daugherty and Daniel Elkins worked with MCNP to create the previously mentioned models for the experimental setup and for the shield optimization process. This included creating the input decks, running them, and creating the visual interpretations of the data. Rachel Gaudet assisted Alyxandria Wszolek in the creation of the final report. Isaac Waldschlager, Hadyn Daugherty, and Daniel Elkins discussed material compositions and shielding thicknesses, created dose rate maps, verified code, sourced shielding properties for the MCNP simulations, and optimized shield design as all of these parameters changed throughout the modeling process. Group progress was tracked by Isaac Waldschlager using weekly reports defining tasks accomplished and in progress.

Overall contributions were organized as follows:

- Team Lead
    - Waldschlager, Isaac
- Materials Research
    - Daugherty, Hadyn
    - Elkins, Daniel
    - Gaudet, Rachel
    - Waldschlager, Isaac
    - Wszolek, Alyxandria
- Contact Vendors
    - Daugherty, Hadyn
    - Wszolek, Alyxandria
    - Elkins, Daniel
- Presentations
    - Daugherty, Hadyn
    - Elkins, Daniel
    - Waldschlager, Isaac
- Weekly Reports
    - Waldschlager, Isaac
- Drafting Deliverable Reports
    - Wszolek, Alyxandria
- Editing Reports
    - Daugherty, Hadyn

  - Elkins, Daniel
  - Gaudet, Rachel
  - Waldschlager, Isaac
  - Wszolek, Alyx
- MCNP Modeling and Simulations
  - Daugherty, Hadyn
  - Elkins, Daniel
- SolidWorks Modeling
  - Waldschlager, Isaac
- Cost Analysis
  - Waldschlager, Isaac
  - Wszolek, Alyx

Results

MCNP Model of the Treatment Room

The MCNP simulations predicted the dose that a human would receive based on dose measurements in a water phantom. The MCNP input deck for this simulation is provided in Appendix E.

Identical MCNP input decks were ran with a mesh tally applied to the patient treatment room. Three separate conditions were applied to the input deck: the no shield condition (*Figure 9*), a 4" high HDPE shield placed between the sources of neutron spallation and the water phantom (*Figure 10*), and a 6" HDPE shield in the same position (*Figure 11*). The resulting doses to the water phantom are shown in *Table 4*.

Table 4 Dose rate to the water phantom under various shielding conditions from a 1.17nA monoenergetic beam of 235 MeV protons.

	No shield	4" HDPE	6" HDPE
Dose Rate, mSv/h (% err)	11.48 E -04 (±6.11%)	5.57 E -04 (±13.58%)	3.81 E -04 (±14.39%)
Percent Reduction in Dose	--	41.30-60.48%	59.53-73.20%

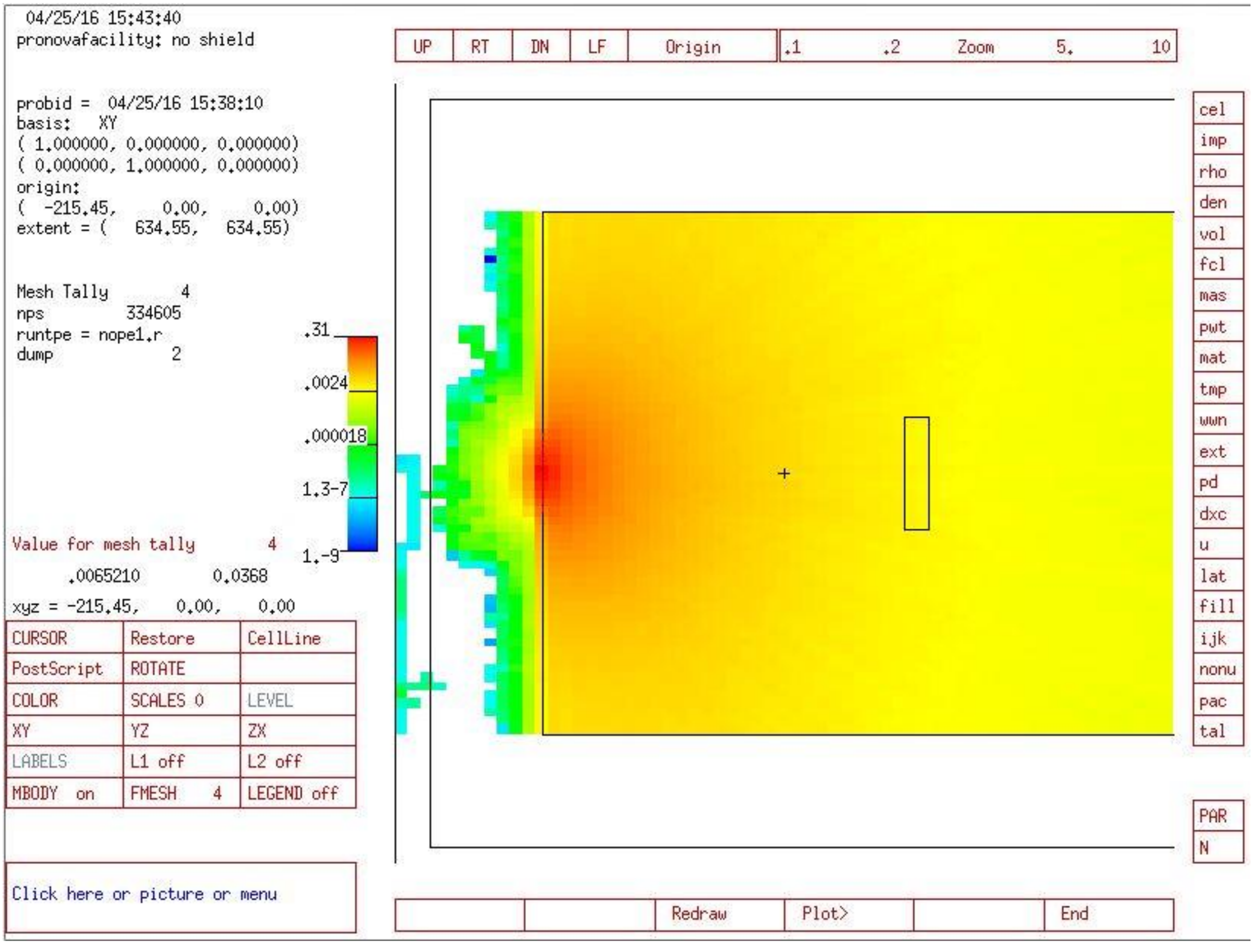

Figure 9 Dose rate (mSv/h) to patient treatment room with neutron shield removed.

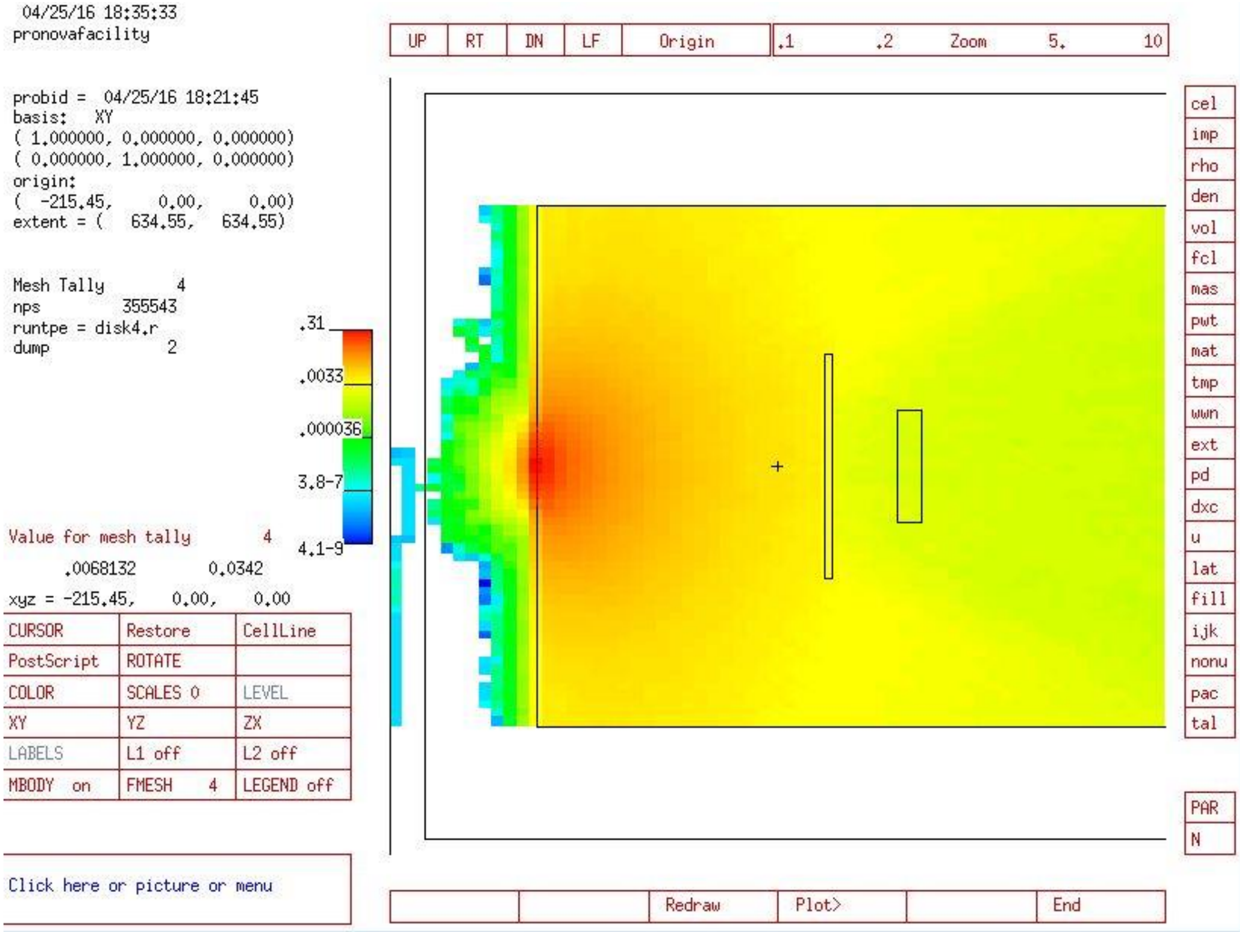

Figure 10 Dose (pSv/particle) to patient treatment room with 4” HDPE shield.

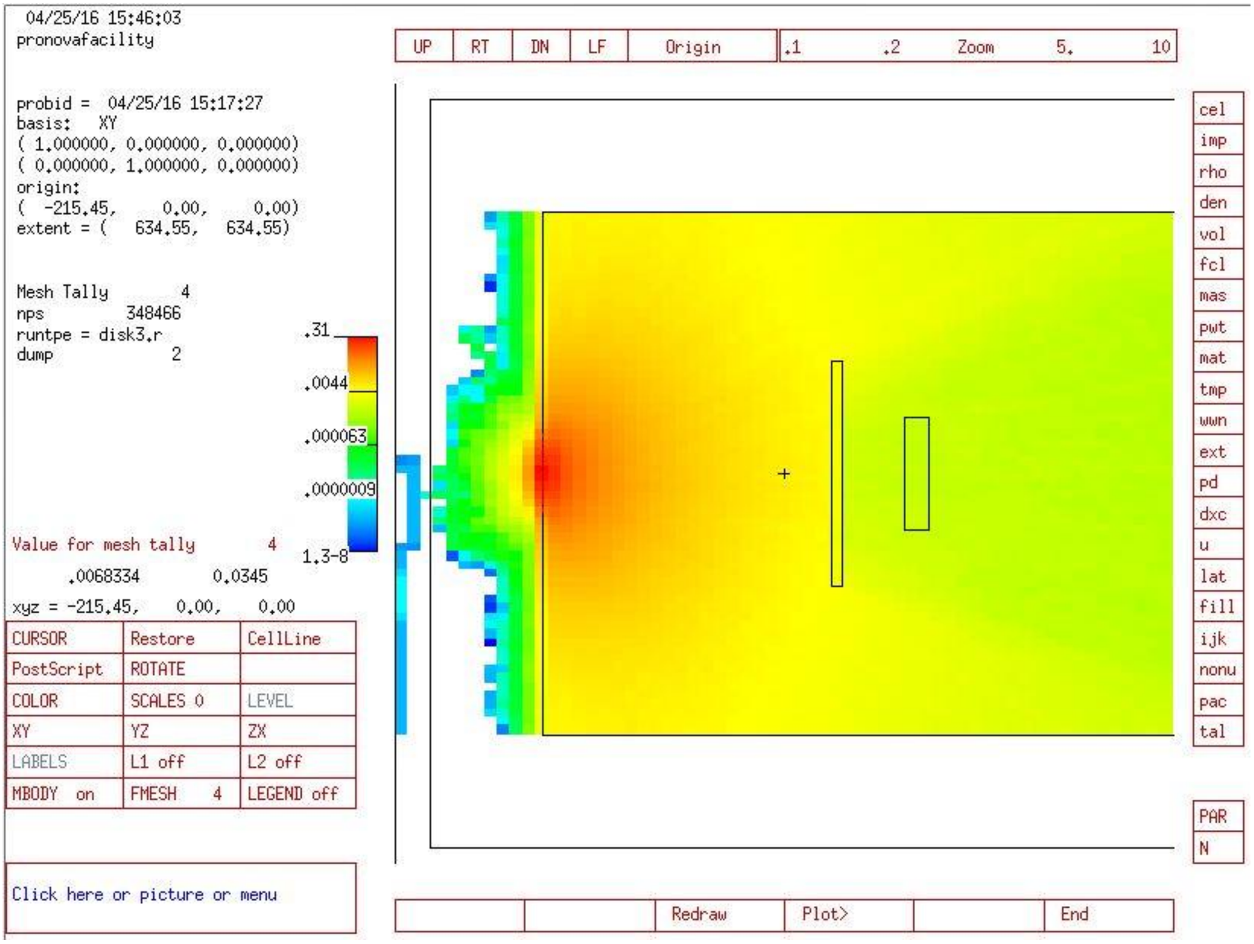

Figure 11 Dose rate (mSv/h) to patient treatment room with 6” HDPE shield.

CAD Model

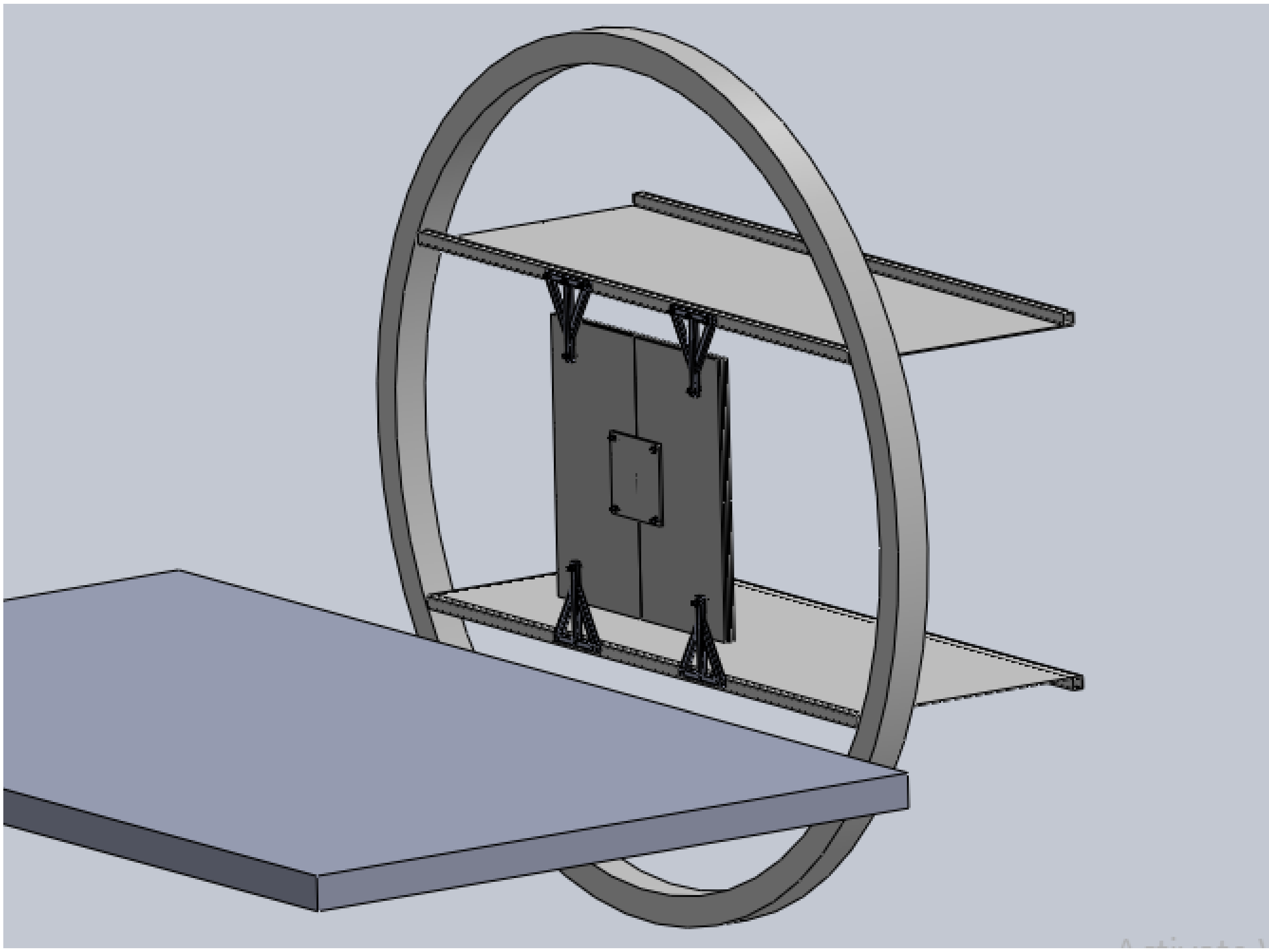

Figure 12 Preliminary design of shield

Material Chart and Cost Comparisons

Table 5 Shielding Materials

Material	Properties	Price
High-density Polyethylene (HDPE)	Density= 0.95 g/cm^3 Thermal neutron cross section= Vendor: http://www.usplastic.com/catalog/item.aspx?itemid=23869	1" x 48" x 96" HDPE Sheet $459.53/sheet ~9 sheets = $4135.77
Fabrication Costs	2" x 3" x 0.25" Tubing Quoted from UTCEE Machine Shop	Machining: $250 Fabrication: $350 Material: $350 Total: $950.00
Hardware	(8) 1"x12" All-Thread Sections (8) 1" Standard Washers (8) 1" ID x 2"OD Oversized Washers (32) 1" Standard Nuts Quoted from McMaster Carr	$82.40/6' $8.53/10pk $8.62/5pk $12.41/10pk Total: $240.21

Conclusions

The deliverable for this project is a design for an HDPE shield that will reduce the dose to the patient by approximately 50% with a 4” shield and 65% with a 6” shield (Table 6) while simultaneously allowing the gantry mechanism to function properly. On top of being fully functional, the shield is lightweight (Approx. 2000lbs), cost-effective (Approx. $6000.00), and easy to install and maintain as needed. All of the preliminary goals that were set for this project were accomplished.

Table 6 Effective dose rate to water phantom (mSv/h) with varying shield conditions.

Shield Condition	Effective Dose Rate ($\times 10^{-4}$ mSv h^{-1})
shield removed	11.48[1]
4” HDPE	5.57[2]
6” HDPE	3.81[3]

Corresponds to dose map in Figure 9[1], 10[2],11[3]

Future Work to Improve Design

For future work optimizing the shield, a full neutron spectrum would be helpful, providing more data for the room. Unfortunately, logistics made this action impossible and we had little to no time to take a better measurement using better detectors and equipment. We also would like the opportunity to use a material called Metamic, which is created specifically for neutron shielding. We were not able to obtain permission from the company that commercially creates the material, and were therefore unable to finish that design. However, if the situation changes, the input deck could easily be adjusted and run to the material properties of Metamic. Additionally, the input deck can be modified using the provided files from the MCNP6 source code that model realistic human phantoms, providing additional data specific to dose rates in organs of interest.

Other references used:
[4] [5] [6] [7]

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APPENDIX A: ICRP 116

Table A.5. Neutrons: effective dose per fluence, in units of pSv *cm2, for monoenergetic particles incident in various geometries.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
1.00E-09	3.09	1.85	1.04	0.893	1.7	1.29
1.00E-08	3.55	2.11	1.15	0.978	2.03	1.56
2.50E-08	4	2.44	1.32	1.12	2.31	1.76
1.00E-07	5.2	3.25	1.7	1.42	2.98	2.26
2.00E-07	5.87	3.72	1.94	1.63	3.36	2.54
5.00E-07	6.59	4.33	2.21	1.86	3.86	2.92
1.00E-06	7.03	4.73	2.4	2.02	4.17	3.15
2.00E-06	7.39	5.02	2.52	2.11	4.4	3.32
5.00E-06	7.71	5.3	2.64	2.21	4.59	3.47
1.00E-05	7.82	5.44	2.65	2.24	4.68	3.52
2.00E-05	7.84	5.51	2.68	2.26	4.72	3.54
5.00E-05	7.82	5.55	2.66	2.24	4.73	3.55
1.00E-04	7.79	5.57	2.65	2.23	4.72	3.54
2.00E-04	7.73	5.59	2.66	2.24	4.67	3.52
5.00E-04	7.54	5.6	2.62	2.21	4.6	3.47
0.001	7.54	5.6	2.61	2.21	4.58	3.46
0.002	7.61	5.62	2.6	2.2	4.61	3.48
0.005	7.97	5.95	2.74	2.33	4.86	3.66
0.01	9.11	6.81	3.13	2.67	5.57	4.19
0.02	12.2	8.93	4.21	3.6	7.41	5.61
0.03	15.7	11.2	5.4	4.62	9.46	7.18
0.05	23	15.7	7.91	6.78	13.7	10.4
0.07	30.6	20	10.5	8.95	18	13.7
0.1	41.9	25.9	14.4	12.3	24.3	18.6
0.15	60.6	34.9	20.8	17.9	34.7	26.6
0.2	78.8	43.1	27.2	23.4	44.7	34.4
0.3	114	58.1	39.7	34.2	63.8	49.4
0.5	177	85.9	63.7	54.4	99.1	77.1
0.7	232	112	85.5	72.6	131	102
0.9	279	136	105	89.3	160	126
1	301	148	115	97.4	174	137
1.2	330	167	130	110	193	153
1.5	365	195	150	128	219	174
2	407	235	179	153	254	203

3	458	292	221	192	301	244
4	483	330	249	220	331	271
5	494	354	269	240	351	290
6	498	371	284	255	365	303
7	499	383	295	267	374	313
8	499	392	303	276	381	321
9	500	398	310	284	386	327
10	500	404	316	290	390	332
12	499	412	325	301	395	339
14	495	417	333	310	398	344
15	493	419	336	313	398	346
16	490	420	338	317	399	347
18	484	422	343	323	399	350
20	477	423	347	328	398	352
21	474	423	348	330	398	353
30	453	422	360	345	395	358
50	433	428	380	370	395	371
75	420	439	399	392	402	387
100	402	444	409	404	406	397
130	382	446	416	413	411	407
150	373	446	420	418	414	412
180	363	447	425	425	418	421
200	359	448	427	429	422	426
300	363	464	441	451	443	455
400	389	496	472	483	472	488
500	422	533	510	523	503	521
600	457	569	547	563	532	553
700	486	599	579	597	558	580
800	508	623	603	620	580	604
900	524	640	621	638	598	624
1000	537	654	635	651	614	642
2000	612	740	730	747	718	767
5000	716	924	963	979	906	1.01E+03
10,000	933	1.17E+03	1.23E+03	1.26E+03	1.14E+03	1.32E+03

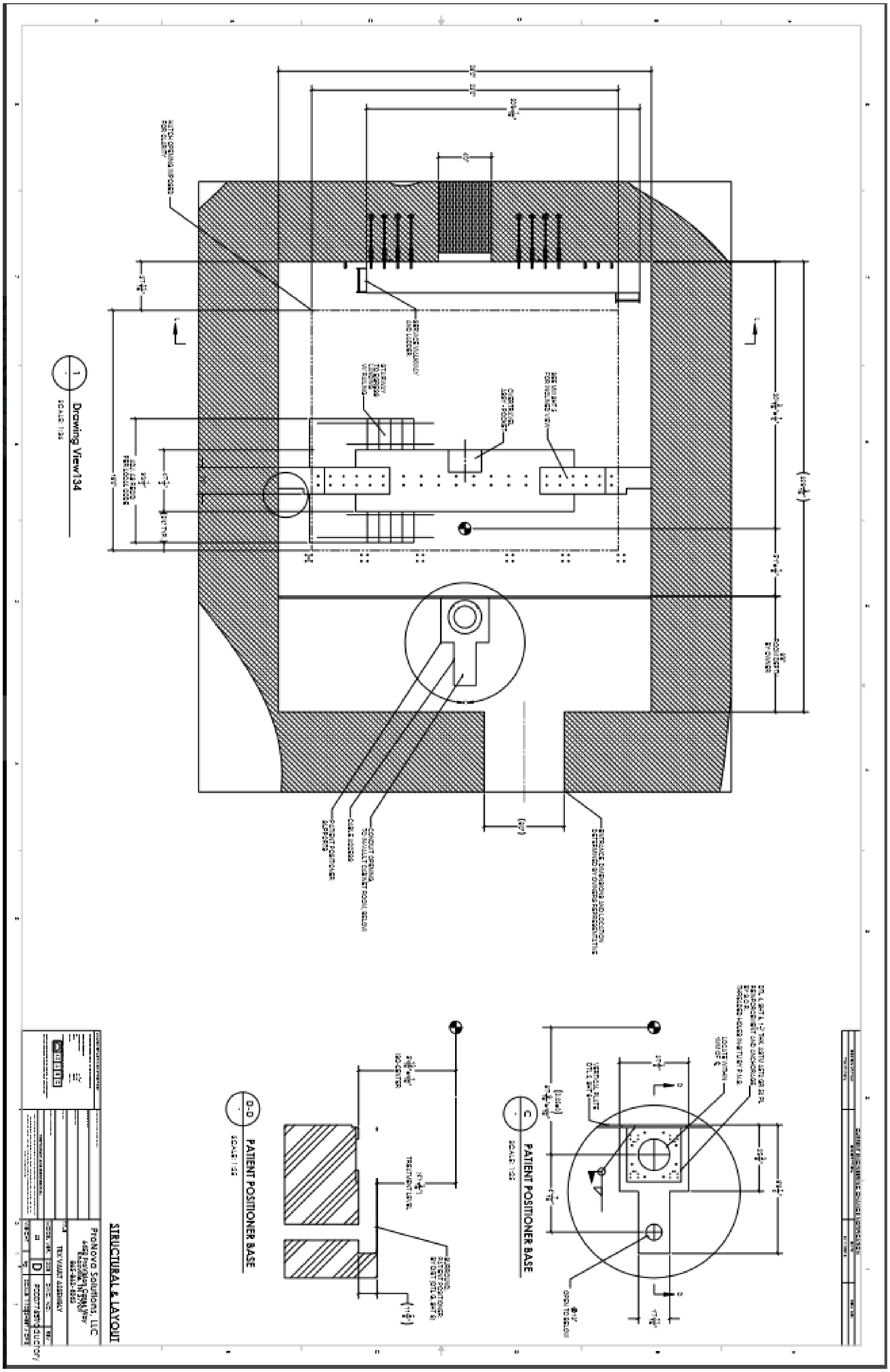
APPENDIX B: MCNP CODE WITH CU BLOCK

```
pronovafacilitynoshield
c ********************************************************************
c
c               Cells
c
c ********************************************************************
1   1 -2.3 -100 101 104 imp:n,h=1 $ concrete walls
2   2 -0.001225 103 (-101:-102) imp:n,h=1 $ inside of room
3   2 -0.001225 100 -99 imp:n,h=1 $ outside of walls
4   3 -8.96 -103 imp:n,h=1 $ Cu block
5   4 -11.342 -104 102 imp:n,h=1 $ Pb insert
999 0  99 imp:n,h=0 $ universe boundary

c ********************************************************************
c
c               Surfaces
c
c ********************************************************************
100 rpp -792.48 601.98 -609.6  609.6  -609.6 609.6 $ outside wall
101 rpp -609.6  419.1  -426.72 426.72 -609.6 609.6 $ inside wall
102 rcc -792.48 0 0 182.88 0 0 7.62 $ hole in beam wall
103 rcc -7.1 0 0 14.2 0 0 3.8 $ Cu block
104 rpp -792.48 -609.6 -60.96 60.96 -60.96 60.96 $ Pb insert
99  rpp -850 850 -850 850 -850 850 $ universe boundary

c ********************************************************************
c
c               Data Cards
c
c ********************************************************************
mode h n
phys:n 300 0 0 3j 0 -1 3j 0 0
phys:h 300 0 -1 j 1 j 0 3j 0 0 0 0.917 $CSDA charge-particle strag
m1 1001 -0.010000 $ concrete
     8016 -0.532000
     11023 -0.029000
         13027 -0.034000
         14000 -0.337000
         20000 -0.044000
     26000 -0.014000
m2 6000 -0.000126 $ air dry near sea level
     7014 -0.76508
         8016 -0.234793
m3 29000 -1 $ Cu
m4 82000 -1 $ Pb
sdef par 9 erg 231 pos -825 0 0 vec 1 0 0 dir 1
```

```
fmesh4:n origin -850 -426.72 -609.6
        imesh 419.1 iints 61
        jmesh 426.72 jints 60
        kmesh 609.6 kints 3
        out ij
de0 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9
         1 1.2 1.5 2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 21
         30 50 75 100 130 150 180 200 300
df0 7.18 10.4 13.7 18.6 26.6 34.4 49.4 77.1 102 126 137 153 174 203
     244 271 290 303 313 321 327 332 339 344 346 347 350 352 353
     358 371 387 397 407 412 421 426 455
ctme 20
```

Appendices

APPENDIX C: TRX VAULT ASSEMBLY PRELIMINARY DESIGN


Drawing View134
PATIENT POSITIONER BASE
PATIENT POSITIONER BASE
STRUCTURAL & LAYOUT
ProNova Solutions, LLC

APPENDIX D: GANTT CHART

Activity	Duration (Days)	Weekday:	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon
		Day:	11	25	1	8	15	22	29	7	14	21	28	4	11	18
		Month:	Jan	Jan	Feb	Feb	Feb	Feb	Feb	Mar	Mar	Mar	Mar	Apr	Apr	Apr
Convert MCNP to straight beam	11															
Generate dose map of facility with new straight-line beam	8															
Measure dose rates to verify the new dose map	6															
Generate report with error for the new code	6															
Alter MCNP model to include copper and Be stops to create neutrons	8															
Create dose map with Cu/Be sources	5															
Aquire quotes for materials from Poly Vendors	5															
Calculate weight using density	6															
Create comparison report with charts, etc to show why we chose what we chose	5															
CAD modelling	10															
Technical Review	3															
Drawings I	6															
Redlines	6															
Drawings II	6															
DFMEA	5															
Estimate for fabrication/machining	6															
MCNP model with shield in place	14															
Generate Dose map (with shield in place)	5															
Make Report	23															
Make Presentation	22															

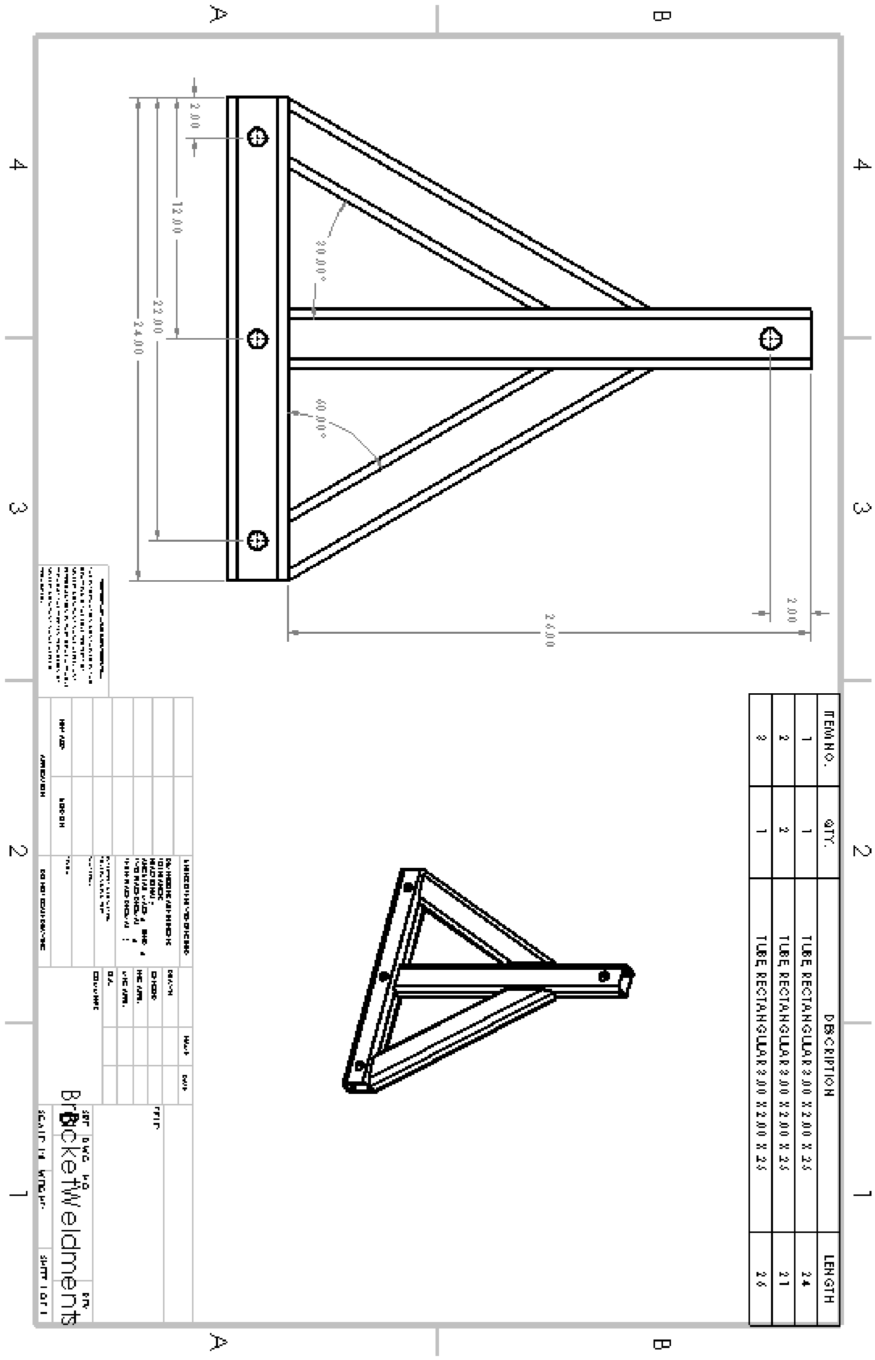
APPENDIX E: MCNP INPUT DECK WITH WATER PHANTOM AT ISOCENTER

```
   pronovafacility: neutron current from 1.17nA 235-MeV proton beam
c *********************************************************************
c
c             Cells
c
c *********************************************************************
4   3  -8.96 -103                    imp:n,h=1  $ Cu block
5   4  -1.85 -104                    imp:n,h=1  $ Be block
6   5  -11.342 -105 102 -115         imp:n,h=1  $ Pb insert
61  5  -11.342 -105 102 115 -125     imp:n,h=10 $ Pb variance red.
62  5  -11.342 -105 102 125 -135     imp:n,h=20
63  5  -11.342 -105 102 135 -145     imp:n,h=40
64  5  -11.342 -105 102 145 -155     imp:n,h=80
65  5  -11.342 -105 102 155 -165     imp:n,h=160
66  5  -11.342 -105 102 165 -175     imp:n,h=320
67  5  -11.342 -105 102 175          imp:n,h=640
7   2  -0.001225 -102                imp:n,h=1  $ hole
8   2  -0.001225  103 104 105 106 -99 imp:n,h=1  $ air in room
9   2  -0.001225 -106                imp:n,h=1  $ air disk
999 0 99                             imp:n,h=0  $ universe boundary

c *********************************************************************
c
c             Surfaces
c
c *********************************************************************
102 rcc -792.48 0 0 182.88 0 0 7.62            $ hole in Pb
103 rcc -808 0 0 14.2 0 0 3.8                  $ Cu block
104 rpp -820.16 -810 -5.08 5.08 -3.81 3.81     $ Be Block
105 rpp -792.48 -609.6 -60.96 60.96 -60.96 60.96 $ Pb insert
115 px  -775                                   $ Pb variance red.
125 px  -750
135 px  -725
145 px  -700
155 px  -675
165 px  -650
175 px  -625
106 rcc -609.5 0 0 0.1 0 0 65                  $ air disk
99  rpp -850 850 -850 850 -850 850             $ universe boundary

c *********************************************************************
c
c             Data Cards
c
c *********************************************************************
mode h n
phys:n 300 0 0 3j 0 -1 3j 0 0
phys:h 300 0 -1 j 1 j 0 3j 0 0 0 0.917 $CSDA charge-particle strag
m2 6000 -0.000126 $ air dry near sea level
     7014 -0.76508
        8016 -0.234793
m3 29000 -1 $ Cu
m4 4000  -1 $ Be
m5 82000 -1 $ Pb
sdef par 9 erg 231 pos -825 0 0 vec 1 0 0 dir 1
f11:n 106.1 106.2 106.3
f21:h 106.1 106.2 106.3
e11 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9
        1 1.2 1.5 2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 21
        30 50 75 100 130 150 180 200 300
ctme 15
```

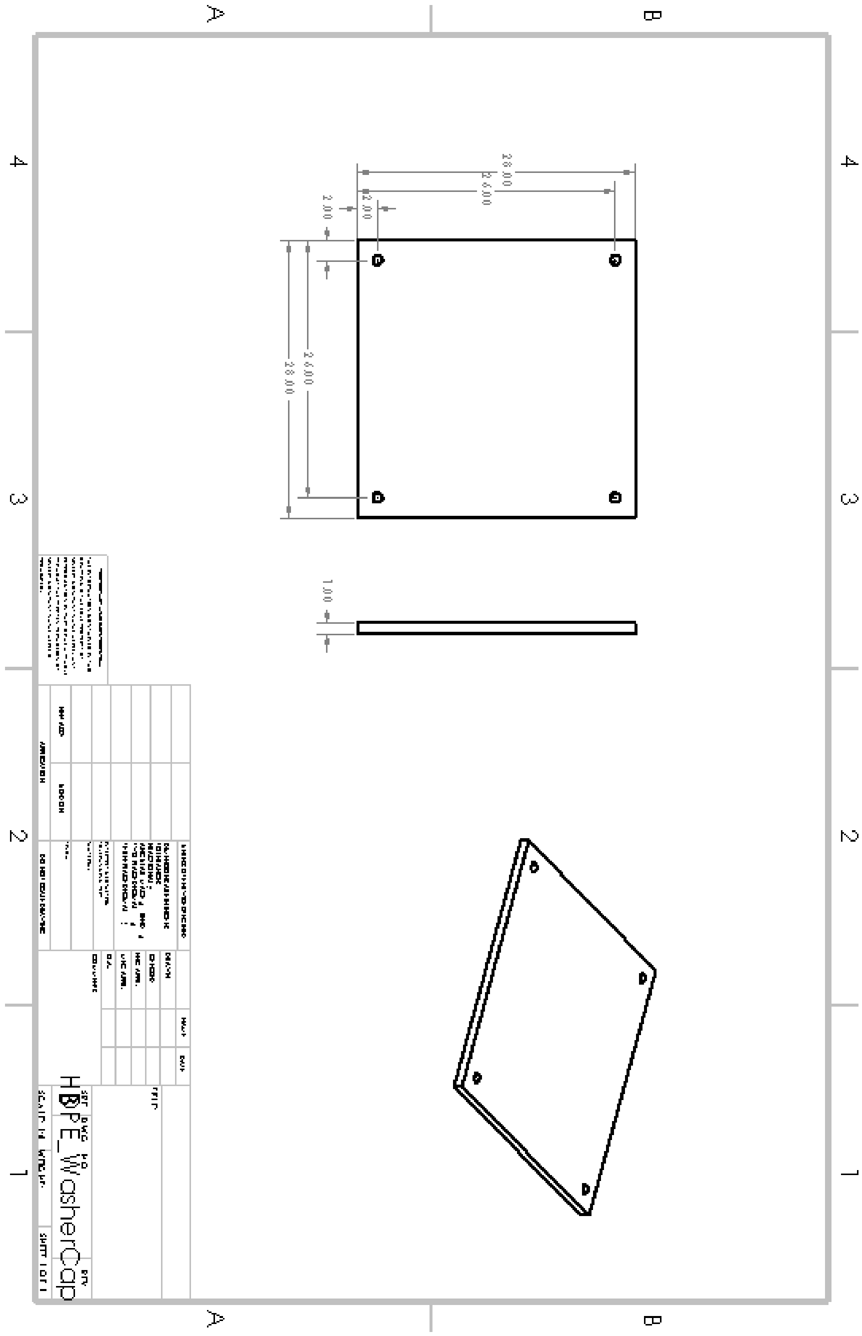
```
pronovafacility: neutron disk source (from input deck 1) and dose maps
c ****************************************************************************
c
c              Cells
c
c ****************************************************************************
1   1  -2.3 -100 101        imp:n,h=1 $ concrete walls
2   2  -0.001225 -101 55 51 imp:n,h=1 $ inside of room
3   2  -0.001225 100 -99    imp:n,h=1 $ outside of walls
4   0  -106                 imp:n,h=0 $ disk source
51  51 -0.95 -51            imp:n,h=1 $ Shield
55  53 -0.9982 -55          imp:n,h=1 $ Person
999 0   99                  imp:n,h=0 $ universe boundary

c ****************************************************************************
c
c              Surfaces
c
c ****************************************************************************
51 rcc -137.16 0 0 10.16 0 0 182.88                $ 4- or 6-inch shield
55 rcc  0 -91.44 0 0 182.88 0 20.32                $ person
100 rpp -792.48 601.98 -609.6  609.6  -609.6 609.6 $ outside wall
101 rpp -609.6  419.1  -426.72 426.72 -609.6 609.6 $ inside wall
106 rcc -609.5 0 0 0.1 0 0 65                      $ air disk
99 rpp -850 850 -850 850 -850 850                  $ universe boundary

c ****************************************************************************
c
c              Data Cards
c
c ****************************************************************************
mode n
phys:n 300 0 0 3j 0 -1 3j 0 0
m1 1001 -0.010000 $ concrete
     8016 -0.532000
     11023 -0.029000
        13027 -0.034000
        14000 -0.337000
        20000 -0.044000
     26000 -0.014000
m2 6000 -0.000126 $ air dry near sea level
     7014 -0.76508
        8016 -0.234793
m51 1001 -0.1437258942 6000 -0.8562741058 $ Polyethylene
m53 1001 -0.1119042597 8016 -0.8880957403 $ Water
sdef par 1 erg d1 pos -609.5 0 0 rad d3 axs 1 0 0 ext d2
si1 0 0.03 0.05 0.07 0.10 0.15 0.20 0.30 0.50 0.70 0.90 1.00 1.20 1.50
     2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 12.00 14.00 15.00
     16.00 18.00 20.00 21.00 30.00 50.00 75.00 100.00 130.00 150.00
     180.00 200.00 300.00
sp1 0 0.00218869 0.000190433 0.000133554 0.00019002 0.000269249 0.000226244
     0.000358164 0.000627393 0.000316655 0.000184112 6.85958E-05 7.55183E-05
     6.89942E-05 7.58393E-05 0.000114072 2.29994E-05 4.56329E-06 9.23104E-06
     6.83002E-06 9.22947E-06 2.30778E-06 9.11756E-06 1.15381E-05 6.81665E-06
     4.46384E-06 0 2.30778E-06 2.30778E-06 2.30778E-06 9.23114E-06 3.00012E-05
     1.61545E-05 1.61545E-05 2.07701E-05 0 2.07701E-05 1.38467E-05 1.38467E-05
si2 0 0.1
sp2 0 1
si3 0 65
sp3 0 1
fmesh4:n origin -850 -426.72 -609.6
       imesh 419.1 iints 61
       jmesh 426.72 jints 60
```

```
       kmesh 609.6 kints 3
       out ij
f14:n 55
de0 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9
        1 1.2 1.5 2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 21
        30 50 75 100 130 150 180 200 300
df0 7.18 10.4 13.7 18.6 26.6 34.4 49.4 77.1 102 126 137 153 174 203
     244 271 290 303 313 321 327 332 339 344 346 347 350 352 353
     358 371 387 397 407 412 421 426 455
fm4 130.19 $ particles-mSv/pSv-h
fm14 130.19 $ particles-mSv/pSv-h
ctme 5
```

APPENDIX F: DRAWINGS



2.00
12.00
22.00
24.00
30.00°
60.00°
26.00
2.00
ITEM NO.
QTY.
DESCRIPTION
LENGTH
1
1
TUBE, RECTANGULAR 2.00 X 2.00 X .25
24
2
2
TUBE, RECTANGULAR 2.00 X 2.00 X .25
21
3
1
TUBE, RECTANGULAR 2.00 X 2.00 X .25
26
BracketWeldments


HDPE_WasherCap