Evaluating radiological hazards at proposed additions to MIRP using Monte Carlo simulation

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Abstract

The proposed 600 MeV linac addition to the Medical Isotope Research and Production greatly exceeds current 200 MeV facilities. The REF tunnel below Michelson Street where 400 MeV particles will enter and the target station where protons will reach 600 MeV need assessment for radiological hazards of exposure in the event of a beamline fault, and soil activation around linac structures. Using transport code MCNP6.2, we created two models and simulated particles at 400 MeV and 600 MeV respectively via Linux cluster at Brookhaven National Laboratory to obtain a ~20.1 mrem maximum instantaneous dose above the tunnel, and maximum possible extent of a ground cap. Results indicate that Michelson Street should not require Controlled Area classification, and that internal shielding cannot safely mitigate high neutron fluxes along the beampipe due to rebounding particles from the target, so a ground cap will need to cover the linac until the first tunnel bend. The simulation process ensures radiation safety, enabling BNL to construct and operate valuable facilities like CLIP, and has added MCNP6.2 and Linux parallel processing to my technical skills.

1) Introduction

The Medical Isotope Research and Production Program (MIRP) at Brookhaven National Laboratory (BNL) produces radioactive isotopes used for medical radiation therapy, which are in short supply due to the high-energy particle accelerator facilities needed to produce them.[1] Demand for the alpha-emitter Ac-225 is particularly high and cannot be met by current United States facilities. A proposed extension of MIRP, called the Center for Linac Isotope Production (CLIP), will operate with proton energies up to 600 MeV and beam currents up to 200 μA, compared to the current respective maximums of 200 MeV and 165 mA, allowing for greatly increased production of Ac-225. A couple cavity linac (CCL) will be constructed as an extension of the existing 200 MeV proton linear accelerator. This CCL will provide a 400 MeV energy gain from the current 200 MeV energy to produce the final 600 MeV proton energy reached when the beam encounters the target array. These extensions will be made in existing REF and NBTF tunnels, with the 400 MeV CCL section in the REF tunnel beneath Michelson Street, and a new target station will need to be constructed for the target array where particles collide at 600 MeV.[2] The location of these extensions is shown in Figure 1.

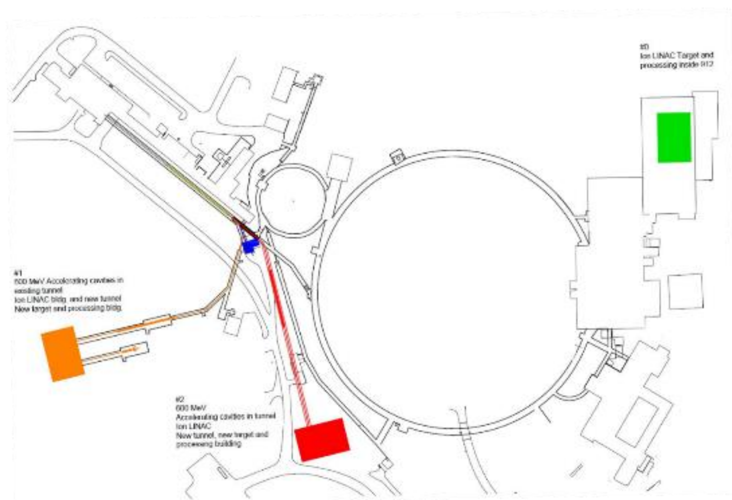

Figure 1: Current MIRP facilities with locations of extensions indicated at left

This dramatically increased proton beam energy will entail greater amounts of radioactive byproducts around the accelerator structures, including radionuclides produced at 600 MeV in the target room which enter soil and pose a risk to the public via groundwater leaching, as well as radiation doses experienced by people standing above the 400 MeV tunnel, such as someone standing or driving on Michelson Street. MCNP simulations are needed to determine the amount and materials of shielding required around the target room to be within 5% of the drinking water standard for activated soil, and to determine the extent of activated soil around the target room so that a properly sized cap can be constructed above it.[3] Simulations are also required to estimate the instantaneous dose received by someone standing above the REF tunnel in the ~0.75 seconds that it would take for an interlock system to stop the beam in the event of a fault, in order to ensure that this dose is within the design criterion of 25 mrem to satisfy the BNL Administrative Control Level of 25 mrem/year for an untrained person.[4, 5]

2) Methods

2.1 Simulation

The Monte Carlo transport code MCNP6.2 was used to model the geometry of the 400 MeV and 600 MeV accelerator sections, then simulate with their respective beam energies and both with 200 μA current via a parallel processing Linux cluster. Detectors placed within each model, known as tally designators, provide results for each simulation by reporting the estimated neutron flux at the tally location.[6] From these results, we identified areas of interest based on the purpose of each model. In the 600 MeV study, our primary interest was the amount and extent of soil activation occurring around the target room. Simulation results were used to determine the extent of soil activation that results given a minimal amount of concrete shielding necessary around the target room, which would allow us to determine the maximum necessary size of the cap used above linac structures to prevent rainwater leaching of this soil. The 400 MeV study primarily intends to determine if the amount of radiation experienced by a person standing or driving on Michelson Street, above the REF tunnel, in the approximately 0.75 seconds it would take for the interlock system to activate in the event of a worst-case-scenario fault in the beamline is within the BNL Administrative Control Level of 25 mrem/year for an untrained person. We compare two positions of a valve assembly belonging to the interlock system to examine if the assembly's position with respect to the road is consequential to this determination.

2.1.1 Modelling Geometry

Tunnels used in various sections of CLIP are largely uniform and given that both additions will connect to existing sections of CLIP, both models used the same dimensions for approximate tunnel diameter and height which were obtained from scale analysis of survey images by Matthew Ilardo.[7] Both use the same common beampipe height within the tunnel of approximately 5 feet above the floor, leaving approximately 1 meter distance from the beampipe to the ceiling. Both beampipes are centered in the tunnel, which may differ from their eventual construction, but this choice was made because centering the beampipes provides the least amount of shielding vertically above the beampipe and therefore provides conservative results. The cross-sectional survey images used to obtain tunnel dimensions, along with their respective models and the axes orientation common to both, are shown in Figure 2.

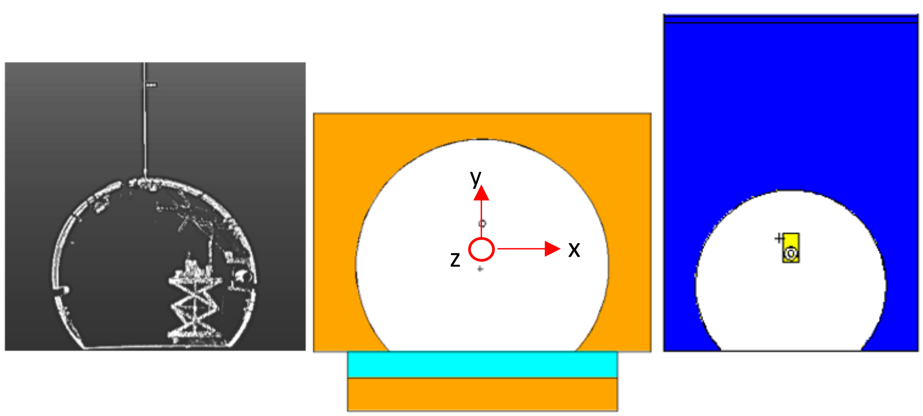

Figure 2: Survey scan of a standard tunnel cross section with the same dimensions and profile seen used in the 600 MeV and 400 MeV models (not to scale)

2.1.2 600 MeV Section Geometry

The 600 MeV model features the concrete-walled target room itself as well as the beampipe, target array, and water tank surrounding it. The thorium, inconel, copper, and water target array designed by Dmitri Medvedev to stop the 600 MeV beam and maximize Ac-225 production, shown in Figure 3, was modelled using initial dimensions and materials as specified.[8]

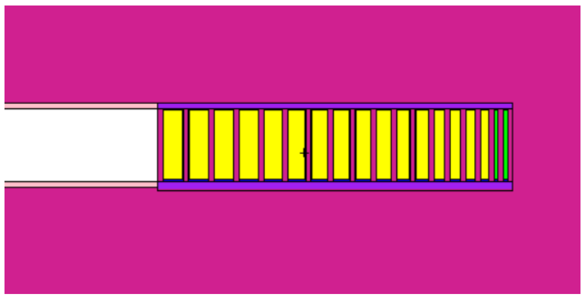

Figure 3: Model of D. Medvedev's target array design consisting of thorium, Inconel, water, and copper layers

The water tank with 1in steel casing provides additional shielding around the array, the most radiologically active part of the linac, and allows the target to be removed and replaced easily from aboveground. Its 1m diameter is centered at the midpoint of the array's length, extending 1 meter above and below its width, all dimensions based similarly on existing structures in BLIP.

Concrete walls of the target room, which play a significant role in radiation shielding, were first modelled using an assumed 1ft dimension, which is common and reasonable in construction, with the intent to evaluate and adjust based on results. Images of the XY, ZX, and ZY views of the model in MCNP are provided by Figure 4, with common features between views indicated.

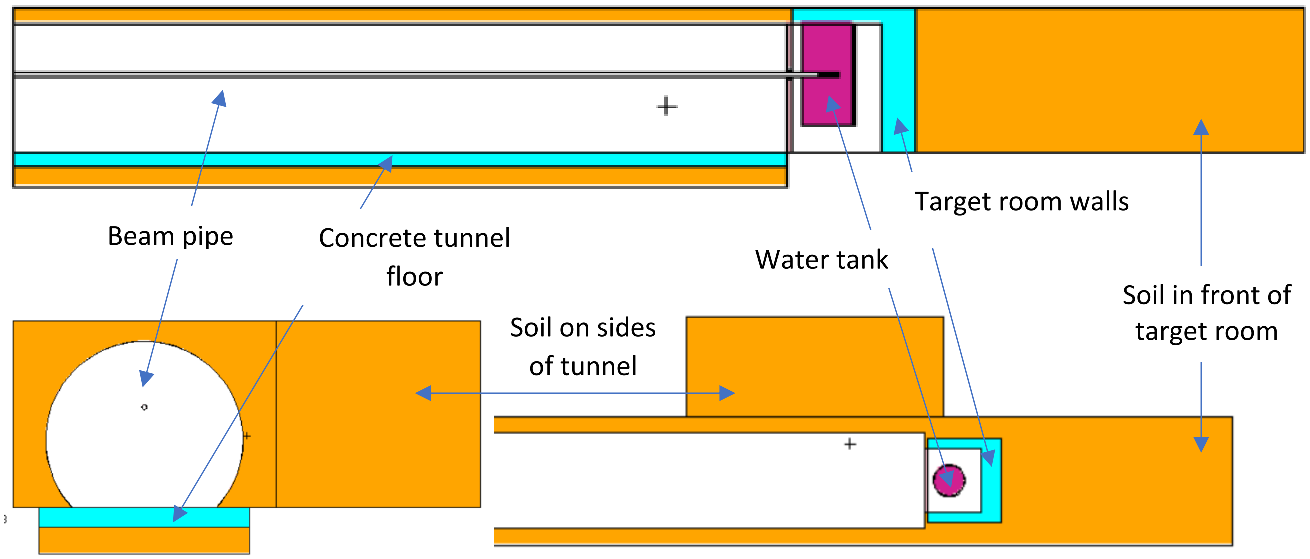

Figure 4: Views of the 600 MeV model provided by MCNP software

2.1.3 400 MeV Section Geometry

A feature unique and consequential to the 400 MeV model is the valve assembly, shown in Figure 5, belonging to the interlock system that identifies and stops a fault. Dimensions and assembly structure of the valve components were obtained from an existing MCNP model created by Shannon Gray of the last accelerator tank of the existing linac.[4] The location of the valves along the beampipe was explored to determine if the shielding provided by the ground and hills on either side of the road significantly affects the dose experienced by a person on the road. This was done in a version of the REF tunnel that modelled the road as soil, and in a version that replaced the top 4in of the soil more realistically as concrete to explore the effect of this difference as well.

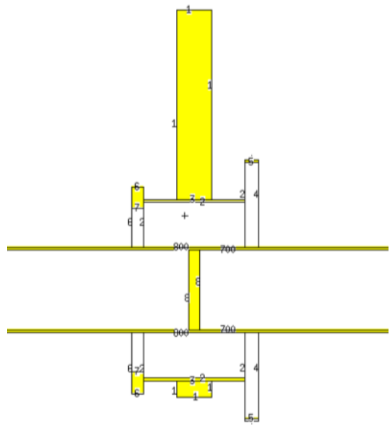

Figure 5: Valve components around the beampipe, with one flange inside the pipe

Natural features are a unique and important aspect in this model given the interest in valve location. Its simplicity otherwise afforded the computing power to simulate more detailed surfaces, so the hills and ground around the road, as well as its surface unevenness, were modelled as accurately as possible. The distance from the top of the tunnel to the road surface, the deviation across the road surface, and the profile of the ground and hills on either side were provided directly by survey images.[7] Dimensions of the hills and ground were obtained using scale analysis of the cross-sectional survey image profiles, shown with the corresponding model cross section in Figure 6.

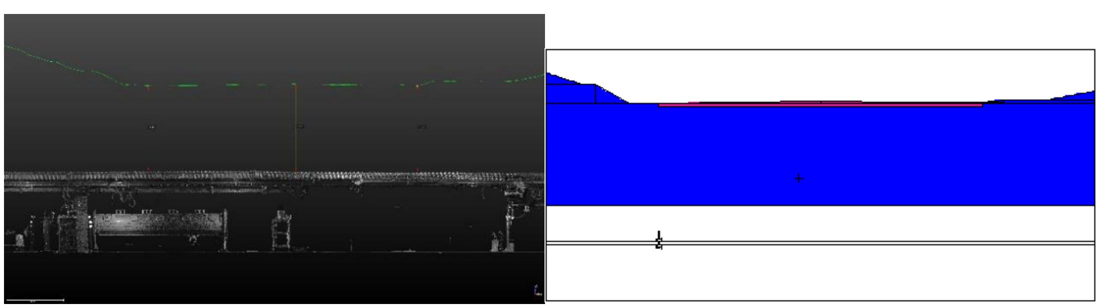

Figure 6: Survey scan of the existing REF tunnel below Michelson Street, and the natural geometry translated into the 400 MeV model

2.2 Empirical Radiological Hazard Evaluation

2.2.1 600 MeV Soil Activation Estimation

Simulation results from tally designators provide the neutron flux at each tally's specific location, giving us results in units of neutrons/cm^2 per incident proton. For the 600 MeV model, we use these results to determine the amount of soil activation surrounding the target room. The shielding materials and geometry of the target room were modified and simulation repeated until results indicate that soil activation levels are within 5% of the drinking water standard that allows for concentrations of the contaminant radionuclide, H^3, up to 1000 pCi/L.[3, 9]

2.2.2 400 MeV Instantaneous Dose Estimation

For the 400 MeV model, we use MCNP to convert tally results to rem per proton, allowing us to calculate the approximate dose of radiation that a person standing above the REF tunnel would receive in the 0.75 seconds before the interlock system activates. To convert the tally results to mrem in 0.75 seconds, the following calculation is performed with an example dose value used to demonstrate:

$$tally\ result\ (dose) * normalization\ factor * time$$

$$\left(2.44 * 10^{-17}\left(\frac{rem}{proton}\right)\right) * \left(\frac{200\mu A}{1.602 * 10^{-19}\ C}\right) * (0.75\ seconds) = 22.8\ mrem$$

3) Results

3.1 600 MeV Section

The 600 MeV study intends to demonstrate the general extent and distribution of soil activation around the accelerator structures that would result given the minimum wall shielding throughout, with the aim of estimating the smallest possible ground cap that would be required using these thicknesses. The values of 1ft and 2ft of concrete shielding were chosen on the assumption that they are reasonably achievable and realistic parameters. Final design of shielding structures, including the ground cap and various wall thicknesses and materials, will be determined after further evaluation and discussion with the BNL staff responsible as plans progress.

Results of the first design iteration using 1ft concrete walls around the target room, shown in Figure 7, support the assumption that maximum flux would occur along the direction of the beam, which is oriented positively along the z-axis. Based on this, the initial wall dimensions were adjusted to determine that 1ft was sufficient on the x-sides of the target room, while the z-forward wall required 2ft due to the greater flux in this direction.

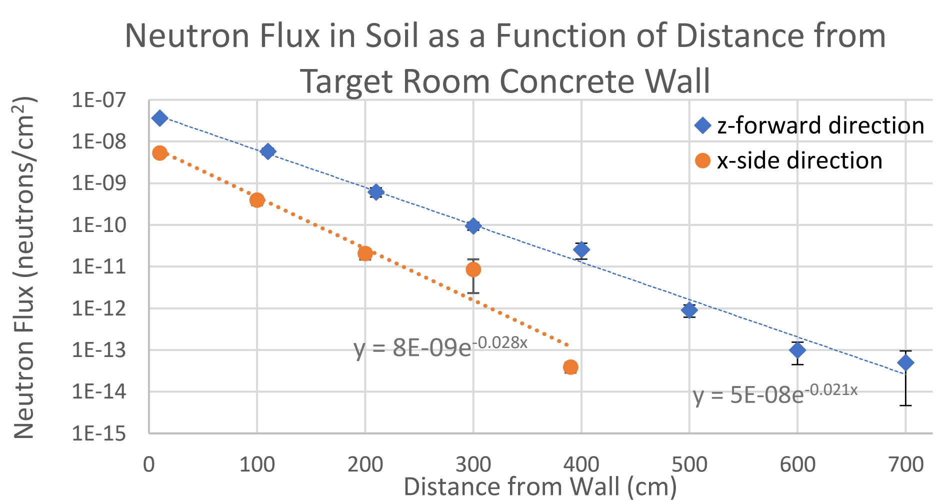

Figure 7

The inside of the tunnel leading to the target room was explored to understand activated soil outside tunnel walls. Figure 8 shows fluxes in the x-direction sides of the tunnel at two points roughly equidistant lengthwise exhibit similar sharply decreasing trends from the tunnel wall until the extent of the soil at 4 meters.

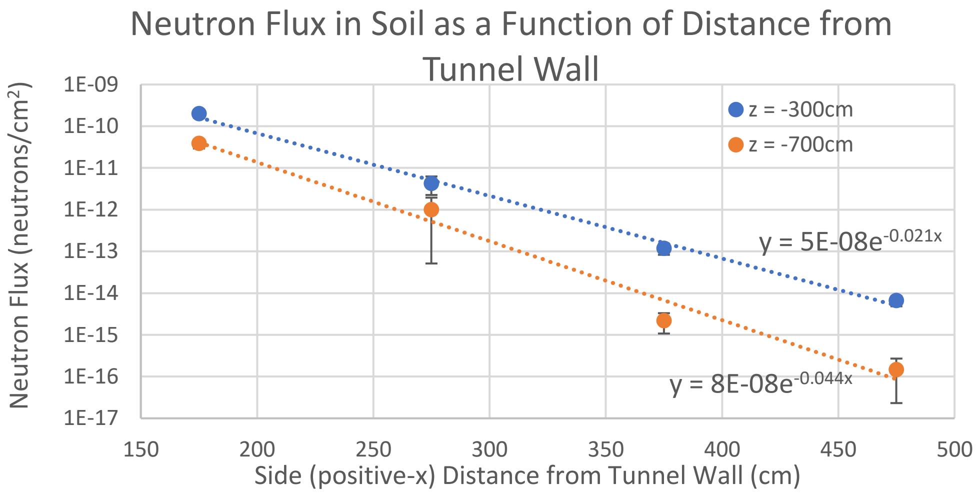

Figure 8

Figure 9 shows fluxes in the z-direction from the target room entrance (z=-60cm) to the tunnel end (z=-1460cm), measured beneath the 1ft concrete tunnel floor, which were high as expected given the directionality. We increased the tunnel length, initially 200cm, to 1400cm to examine the effect of greater z-distances, but results showed fluxes to remain consistently high along the beampipe. In an effort to reduce neutron fluxes in the backward direction, the 10cm steel door shown in Figure 10 was constructed between the target room entrance and tunnel, with a circular opening around the beampipe allowing sufficient clearance to accommodate mechanical components. This approach was unsuccessful, and it was concluded that fluxes around the beampipe are too concentrated and centralized to its diameter to be effectively addressed by a door with an opening in this highly active location.

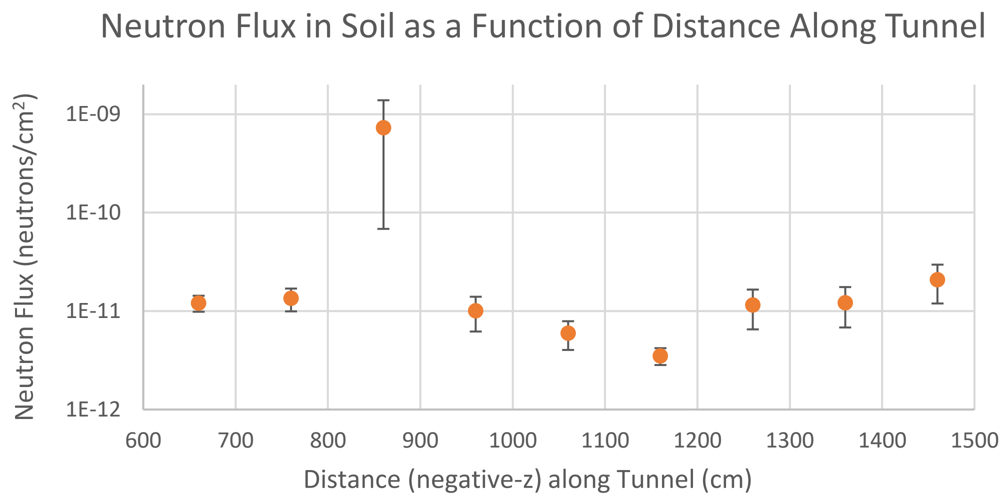

Figure 9

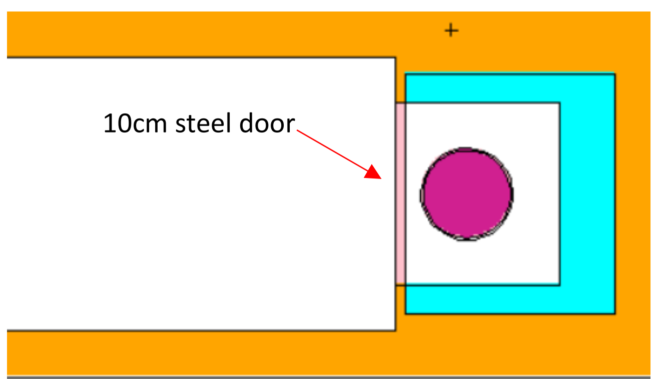

Figure 10: Steel door constructed between target room and tunnel, shown in light pink

Given that the 600 MeV model uses a minimal amount of internal shielding, it can be assumed that the ground cap obtained from this study is the maximum possible size that could be necessary, meaning that the finalized ground cap should be within the size determined here (also due to final designs likely employing greater shielding). To satisfy the design criterion of soil activation within 5% of the drinking water standard, fluxes in the surrounding area must be below $3.22466*10^{-13}$ neutrons/cm², after which the 5% limit is exceeded.[10] From Figures 7, 8, and 9 that show fluxes at various locations around the accelerator structures, the ground cap estimate is easily determined to be any area with greater than ~3.22466 $*10^{-13}$ neutrons/cm². The coordinate bounding this limit is identified from each plot, and we obtain a general approximation for the extent of ground cap necessary above the structure shown in Figure 11.

Point	Location (cm) with flux of ~3.22466 $*10^{-13}$ neutrons/cm²
1	(0, 0, ~575)
2	(~375, 0, 0)
3	(~350, 0, -300)
4	(~275, 0, -700)
5	(0, 0, -1460)

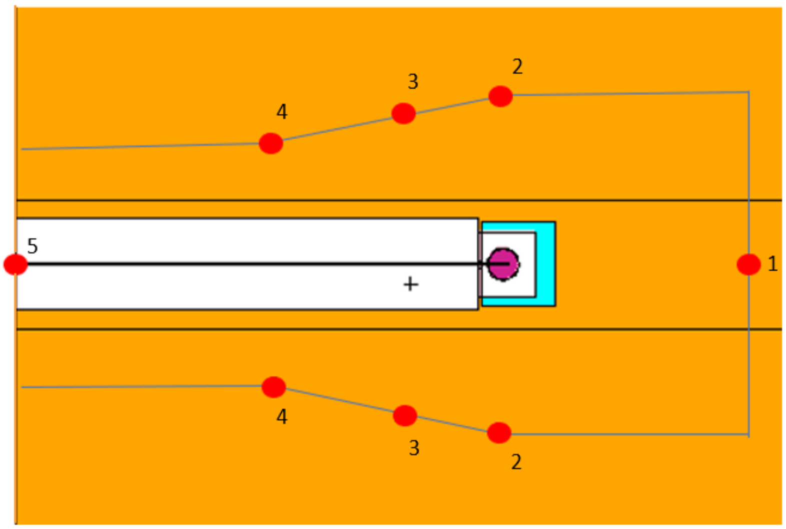

Figure 11: Approximate maximum extent of ground cap necessary for 600 MeV model, obtained using MCNP

A notable caveat of our results applies to Point 5 in Figure 11, due to limitations of the model's z-directional extent, the negative end of which is marked by Point 5 but has flux of $2.08094*10^{-11}$ neutrons/cm². We've demonstrated that backward fluxes concentrated along the direction of the beampipe, caused by high energy particles rebounding from collisions with the target, cannot be addressed with internal shielding along the straight section of tunnel or within the target room. This tells us that the ground cap in the backwards direction along the tunnel will need to extend until there is a turn in the accelerator tunnel, which scale analysis of Figure 1 indicates to be about ~391.4ft from the target room entrance.

3.2 400 MeV Section

The REF tunnel study explores instantaneous exposure to a person standing or driving on Michelson Street by placing tally detectors along the length of the tunnel at 1 meter above the road, estimated to be about waist level. In both the concrete paved and unpaved models, the valve assembly's position was changed to determine its effect on dose results, and the effect of natural shielding provided by surrounding hills. The fluxes at each detector location along the road for both valve positions are shown for the unpaved and paved models in Figures 12 and 13. The unpaved model with the assembly below the hill (z = -100cm) and at the start of the road (z = 0cm) showed maximum dosages of 22.8 mrem and 21.0 mrem respectively. The paved model comparing the two valve positions in the same way resulted in maximum dosages 20.1 mrem and 19.8 mrem respectively. In the context of interpreting and applying results to real-world scenarios, the maximum dosage value used is 20.1 mrem resulting from the paved model, due to this being the more realistic model of the two.

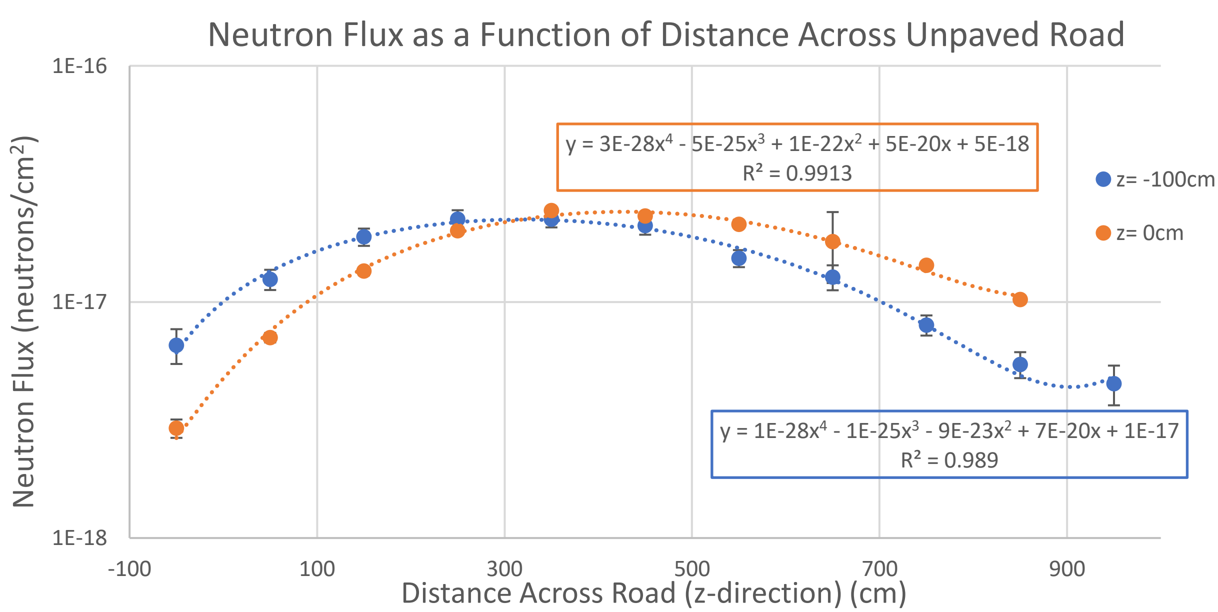

Figure 12

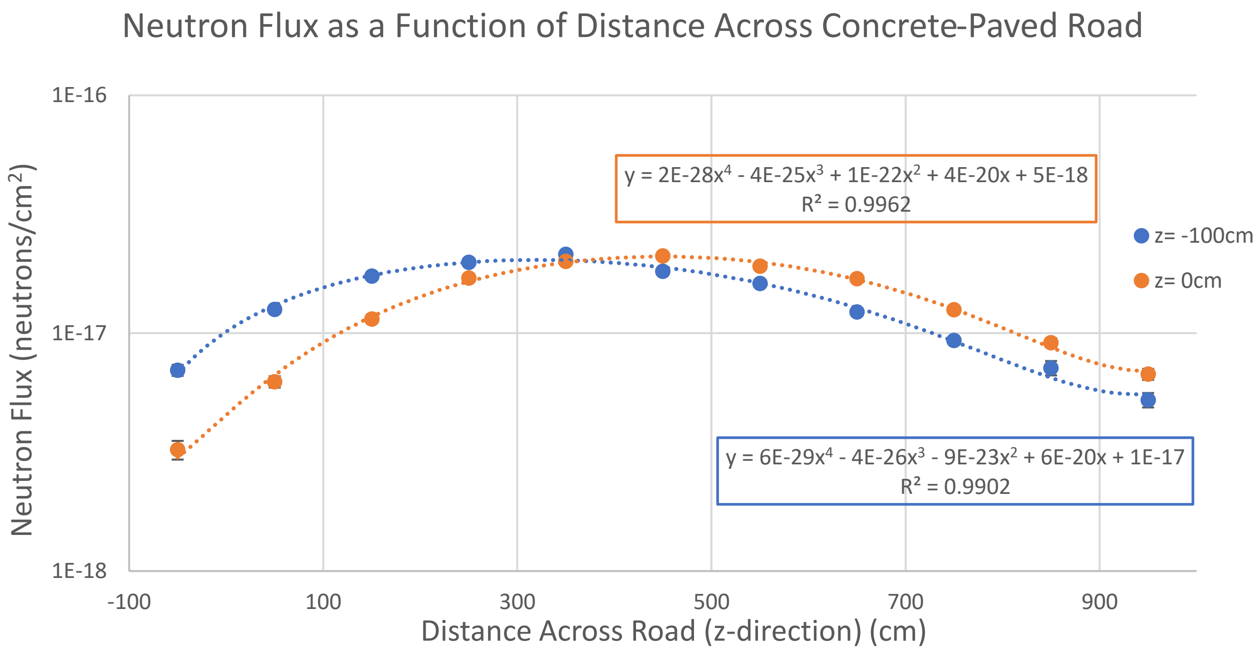

Figure 13

Figures 12 and 13 demonstrate that the different positions of the valve assembly shift the distribution of varying doses, but the maximums between the two positions do not differ significantly within either model. It also shows that the natural shielding above the z = -100cm valves is less effective than 4in of concrete above the z = 0cm position. Comparison between the unpaved and paved models reveals that this simplification does not significantly affect results, with the respective maximum flux (in units of neutrons/cm^2) at z = -100cm being 2.24272 $*10^{-17}$ versus 2.1454 $*10^{-17}$, and 2.43569 $*1010^{-17}$ versus 2.10981 $*10^{-17}$ for valves at z = 0cm.

Assuming reasonably that such a beam fault would not occur more than once in a year to any untrained person including guests, visitors, and minors, all the design iterations simulated result in an instantaneous dose during a fault of less than the BNL Administrative Control Level of 25 mrem/year.[5] These preliminary results indicate that the area of Michelson Street above the REF tunnel would likely not need to be designated a Controlled Area, though further studies and consultations with the scientists and engineers responsible for its design will be needed to verify.

4) Conclusion

Simulations performed on models of various design iterations of the proposed 600 MeV extension of CLIP were used to examine the extent of soil activation that would result around the 600 MeV target room section when a minimal amount of concrete shielding is used internally, and the instantaneous dose an untrained person standing above the 400 MeV section would receive in the event of a beam fault. Results of the 600 MeV model are most consequential for soil activation in the direction away from the target room, indicating that a ground cap will be needed until the first turn in the accelerator tunnel is reached ~391.4 feet from the target room entrance, due to high neutron fluxes concentrated backwards along the beampipe which cannot be sufficiently addressed by internal shielding. The 400 MeV model demonstrated that Michelson Street should not require Controlled Area designation, with the maximum ~20.1 mrem dose experienced by a person standing or driving above the REF tunnel in the event of a fault being within the BNL Administrative Control Level of 25 mrem/year for an untrained person. As CLIP plans progress, both 600 MeV and 400 MeV studies will require further evaluation and discussion among those at BNL responsible for its design and construction.

5) Acknowledgements

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