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PRELIMINARY EARTH BERM SHIELDING CALCULATIONS FOR THE ACCELERATOR PRODUCTION OF TRITIUM 1700-MeV ACCELERATOR

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ABSTRACT

We have performed calculations using the LAHET Code System (LCS) to obtain an estimation of the amount of earth berm shielding that will be required for the 1700-MeV proton accelerator proposed for the Accelerator Production of Tritium (APT) Project.

A source scenario of 10 nA/m beam loss along the beam line was used to calculate the dose values above a 6-m earth berm from high-energy neutrons, low-energy neutrons, and photons. LAHET, a Monte Carlo based particle transport code, was used to transport 1700-MeV protons from the beam along a divergence path of 1° from the original beam direction and impacting representative beampipe material along a 300-m beamline. LAHET was then used to track all high-energy neutron production until the neutrons either escape the berm shield, or scatter down in energy to 20 MeV, where their parameters were then written to a source file for MCNP. Photon production data was also written to a source file used by MCNP. MCNP transported all neutrons and photons from the LAHET source file until they (1) were absorbed, scattered down to an energy cutoff, or (3) escaped from the system. Doses were calculated from surface flux tallies obtained from LAHET and MCNP. These doses were then compared to earlier Moyer model calculations.

I. INTRODUCTION

Early in the scoping phase of design of the 1700-MeV APT accelerator, the requirement was put forth to determine the thickness of earth required to reduce the dose rate at the top of the accelerator tunnel to 0.25 mrem/h. Drawings were being made for preliminary tunnel designs, and the earth berm shielding was an integral part of the design planning.

The initial estimate[1] was done using the Moyer model[2,3] for accelerator beam line shielding. The preliminary working model of the accelerator design was modeled in the LAHET™ Code System (LCS)[4] to validate assumptions used in the Moyer model calculations. LCS calculations were done for a model with 6 m of soil above the accelerator beamline to obtain doses at the surface of the berm. Calculations were also done with a berm thickness of 10 m to compare data with albedo effects to the data from the 6-m calculations. The calculations for the 6- and 10-m berms were done at proton beam energies of 500, 750, 1000, 1250, 1500, and 1700 MeV, to look at the energy dependence of the doses.

II. LAHET/MCNP MODEL

The LAHET Code System is a descendent of the HETC code[5] originally developed at Oak Ridge National Laboratory (ORNL) in the 1960's. Unless otherwise noted, the default settings, as reported in the LCS user's guide,[4] were used in the LAHET calculations in this report. The exceptions are shown in Table 1. With these settings, the Bertini[6] model is used to simulate the intranuclear cascade phase. The multi-stage pre-equilibrium model[7] is then invoked prior to the evaporation phase. The Rutherford-Appleton[8] (RAL) fission model is used to simulate high-energy fission in tungsten and lead. The Fermi[9] breakup model replaces the Dresner[10] evaporation model for the de-excitation of light nuclei. LAHET version 2.83[11] was used, including the new neutron and proton elastic scattering treatment.

The model was developed from a preliminary conception of the accelerator tunnel design. Figure 1 shows an MCNP[12] geometry plot of the model used. The accelerator walls are composed of 1-m thick concrete,

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surrounded by soil representative of that found at the Savannah River Site (SRS). The soil is also composed of 20% water by weight. The accelerator tunnel was 9.3 m in width and 11 m high at its highest point. The beampipe was located slightly off-center, 2.55 m above the tunnel floor. The beampipe was composed of 5-cm i.d. copper pipe, of 1 cm thickness. Copper is chosen as a target material because any beam spill impinging on accelerator magnets will interact with the copper windings of the magnet.

Table 1. Non-default physics model settings in the LAHET input deck.

Line	Record	Setting	Description
4	12	IPREQ = 1	use pre-equilibrium model following the intranuclear cascade Default: no pre-equilibrium model will be used
5	1	NBERTP = -1	nucleon-pion-muon transport Default: nucleon-pion transport only
6	1	NSPRED = -5	step size for the multiple scattering treatment is reduced by a factor of 1/5 of the default for both primary and secondary particles Default: calculate multiple scattering for primary charged particles
6	9	ICPT = 1	transport heavy charged particles Default: do not transport heavy charged particles

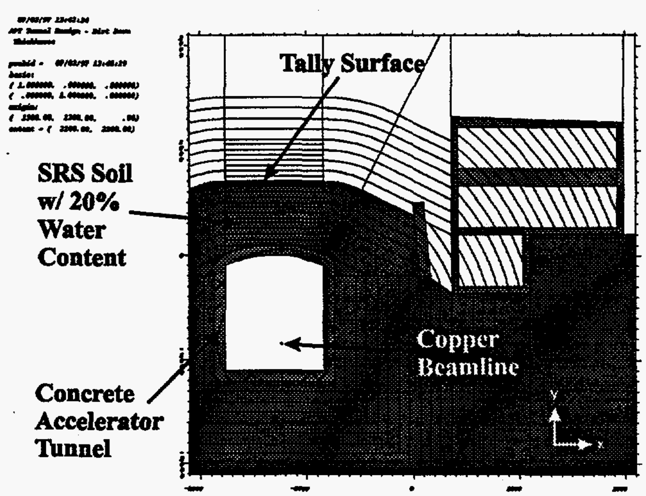


Figure 1. Elevation view of the LCS geometry model showing the accelerator tunnel and earth berm shielding on top.

The proton source in the calculation is a cylindrical source of diameter 4.999 cm, centered in the copper beampipe. Protons were launched in LAHET from the cylinder at an angle of 1° measured from the direction of the travel of the beam. These protons would then interact with the surrounding materials, the copper in the beampipe and the concrete in the tunnel walls, and create the neutron spectrum, to be transported in the codes.

Calculations were done for each of the beam energies of 500, 750, 1000, 1250, 1500, and 1700 MeV. The beam energy of the final APT accelerator design will be 1700 MeV. The other calculations allow for determination of the energy dependence on the results.

The model included extensive division of the concrete and soil cells to allow for the use of a variance reduction technique in LAHET and MCNP, called importance sampling. As a particle travels from one region to another of higher importance, it is split into an integer number of particles, determined by the ratio of importances of the two cells, with the weight of each particle adjusted accordingly to conserve total particle weight. Each particle is then transported separately. In this manner, any loss of particles from attenuation through the material can be offset through the splitting of incident particles. This allows a constant population of particles to be present throughout the material, as opposed to the decreasing populations normally seen from attenuation.

III. DOSE CALCULATIONS

All charged particle transport, and high-energy neutron transport (E > 20 MeV), is done in LAHET. When a neutron's energy falls below the 20-MeV cutoff, the neutron's parameters are then written to a source file to be used by MCNP. All parameters for created photons are also written to a source file for MCNP to transport. MCNP and LAHET both tally particles as they cross a defined surface in the model. The tally surfaces in the calculation were planes in the berm above the top of the tunnel. Tally surfaces were placed at increments of 50 cm throughout the berm depth. As a neutron or photon passes a tally surface, an energy-dependent flux to dose conversion factor is used to tally the resultant dose.

The flux-to-dose conversion factors used in MCNP for the photons and low energy neutrons were from standards referenced in Appendix H of the MCNP manual. The neutron flux-to-dose conversion factors were from NCRP-38, ANSI/ANS-6.1.1-1977,[13] and the photon flux-to-dose conversion factors were taken from ANSI/ANS-6.1.1-1977.[14]

The high-energy neutron flux-to-dose conversion factors encompass the range from 20 to 800 MeV, and reference to their origin can be found in reference 15. These conversion factors are shown in Table 2, and are shown graphically in Figure 2. Unfortunately, the analysis was done with conversion factors up to 800 MeV in energy, which is the nominal energy for the accelerator located at LANSCE. This underestimates the dose above 800 MeV, because the 800-MeV flux-to-dose conversion factor is used for all neutrons of energy greater that 800 MeV, as opposed to factors obtained by extrapolating the curve to higher energies. However, we feel that this effect will be negligible, and are currently performing calculations to verify this.

IV. MOYER MODEL CALCULATIONS

The Moyer model uses several empirical formulas to estimate the dose through a shield from a proton accelerator. Tesch[16] has explored many of these in detail, and Pitcher used this treatise for the original Moyer model calculations.[1]

Table 2. High-energy neutron flux-to-dose conversion factors used in the LAHET calculation, taken from Reference 15.

High-Energy Neutron Flux-to-Dose Conversion Factors	
Energy (MeV)	**DF(E) ((mrem/h)/(n/cm^2-s))**
20	1.54E-01
25:119	1.55E-01
31.623	1.57E-01
39:811	1.61E-01
50.119	1.64E-01
63.096	1.67E-01
79.433	1.72E-01
100	1.77E-01
125.89	1.82E-01
158.49	1.89E-01
199.53	1.97E-01
251.19	2.07E-01
316.23	2.21E-01
398.11	2.41E-01
501.19	2.67E-01
575	2.94E-01
650	3.17E-01
725	3.39E-01
800	3.60E-01

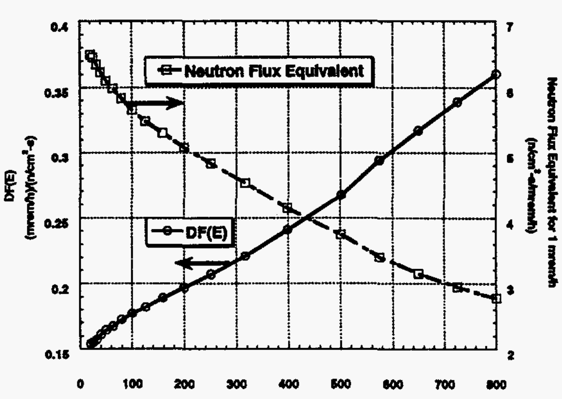


Figure 2. High-energy (E > 20 MeV) neutron flux-to-dose conversions.[15]

Tesch compiled experimental data for the energy-dependent dose-equivalent attenuation length for concrete at 90° to the proton beam. He then fit a curve to this data, which is represented in Figure 3 along with the compiled experimental data points. The curve fit to Tesch's data is the empirical function

$$\rho\lambda = 110\frac{g}{cm^2}\left[1-\exp\left(-\frac{E^{0.714}}{42}\right)\right]. \qquad (1)$$

As reported by Fasso, et. al.,[17] this can also be applied to soil. Using this assumption, an attenuation length for the Savannah River Site (SRS) soil can be derived for the Moyer model calculation. Figure 3 also shows the attenuation length values from the LCS calculation. These values agree quite well with the empirical function, validating this assumption.

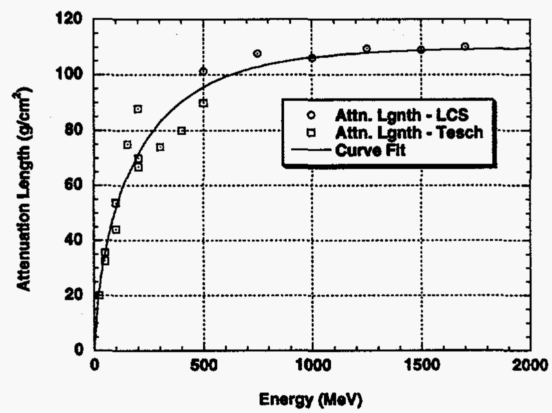


Figure 3. Dose attenuation length for concrete (Tesch data[16]), and Savannah River Site Soil used in the LCS calculation (LCS data).

The dose-rate source term used for the Moyer model calculation was developed from the data compiled by Tesch for the dose equivalent per proton at 90° from a copper target. Therefore, a copper beampipe was used for the LCS calculations. Since the superconducting option has since been chosen for the APT accelerator, the target material would be niobium, and would represent a 20 – 30% increase in source term over that of copper.[1]

V. LCS - MOYER MODEL COMPARISONS

The Moyer model was used to calculate the amount of earth required above the beamline tunnel to achieve a dose rate of 0.25 mrem/h assuming a uniform 10-nA/m beam loss along the beamline. A transcendental equation, derived from equations presented by Tesch, was solved to produce the curve shown in Figure 4.

For the LCS calculation, a model was developed with 10 m of berm shielding above the tunnel. Dose was then calculated through the earth in 50 cm intervals. This dose is shown in Figure 5. Neglecting the first and last three data points to eliminate end effects, a fit to the data was used to determine the exact depth at which 0.25 mrem/h occurs. The values of the attenuation length λ for Figure 3 were also found from this fit to calculated data.

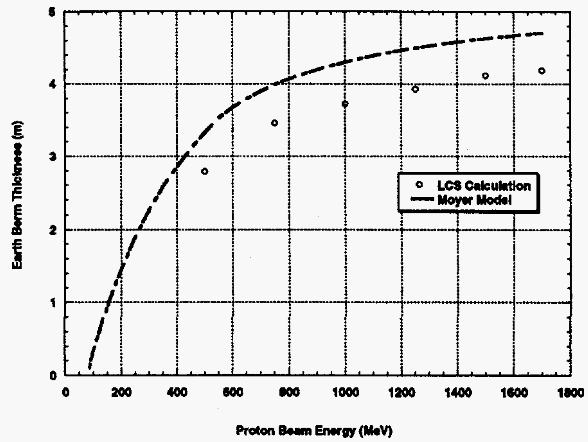


Figure 4. Thickness of SRS earth berm required for a 0.25 mrem/h dose rate at surface of a 1700 MeV proton accelerator berm shield for a 10 nA/m beam spill along the accelerator beamline, as predicted by the Moyer model and calculated by LCS.

The comparison between the Moyer model predictions, and the LCS calculated results are shown in Table 3.

Table 3. Comparison of amount of earth berm required to reduce the surface dose to 0.25 mrem/h, as predicted by the Moyer model and calculated by LCS.

Proton Beam Energy (MeV)	Moyer Model Estimate (m)	LCS Calculation (m)	(Moyer-LCS) / LCS
500	3.33	2.79	19.5%
750	3.99	3.46	15.3%
1000	4.31	3.73	15.7%
1250	4.50	3.93	14.5%
1500	4.63	4.13	12.2%
1700	4.71	4.19	12.3%

VI. ALBEDO EFFECTS

Having both a 6- and 10-m model allows for the examination of the albedo effects caused by the presence of earth above the 6-m mark, as opposed to air. The albedo effects can be seen on the components of the dose in Figure 7. The absence of earth above the 6-m mark allows for the increase in the high-energy fraction of total dose. This albedo effect can also be seen in the comparison between the 6- and 10-m calculations. The presence of the earth above the 6-m mark in the 10-m calculation increases the total dose at the 6-m mark by 31% to 0.008 mrem/h. The albedo effect increases the high-energy neutron dose by 15%, the low-energy neutron dose by 58%, and the photon dose by 60%.

VII. SURFACE DOSE AT 6 METERS OF BERM

The results of the LCS calculation of surface dose at 6 m of SRS soil above the accelerator tunnel are shown in Figure 6. The calculation shows that the dose at the surface of a 6 m berm for a 1700 MeV proton beam spilling 10 nA/m would be 0.006 mrem/h. Of this, dose from high energy neutrons (E > 20 MeV) comprises approximately 77%, whereas photon dose only comprises 1% of the total dose. The components of the 1700 MeV dose through the berm are shown in Figure 7.

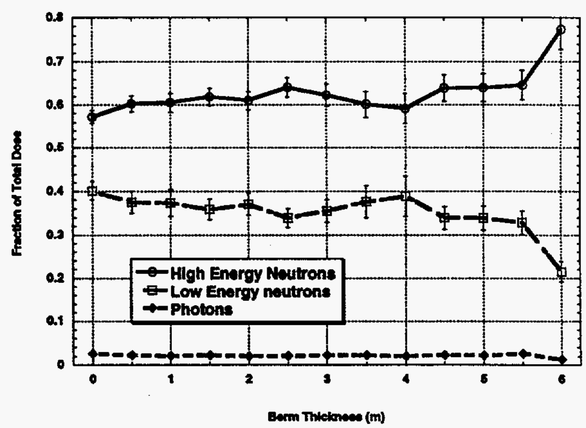


Figure 7. Components of the 1700-MeV proton beam dose through 6 m of SRS earth berm.

VIII. CONCLUSIONS

Using both the Moyer model for accelerator shielding and LAHET Code System calculations, it was determined that 6 m of SRS earth berm was sufficient to shield a 1700 MeV proton accelerator with a 10 nA/m beam loss on copper. LCS calculated that the dose at the surface of a 6-m berm would be 0.006 mrem/h, well below the target dose rate of 0.25 mrem/h. The Moyer model, which uses many assumptions to simplify the problem, produced a value which is within 12% of this result.

With the choice of a superconducting accelerator, the source term will change, but surface dose rates will be able to increase over an order of magnitude before approaching the target dose rate, whereas the source term is only estimated to increase 20 – 30%.[1]

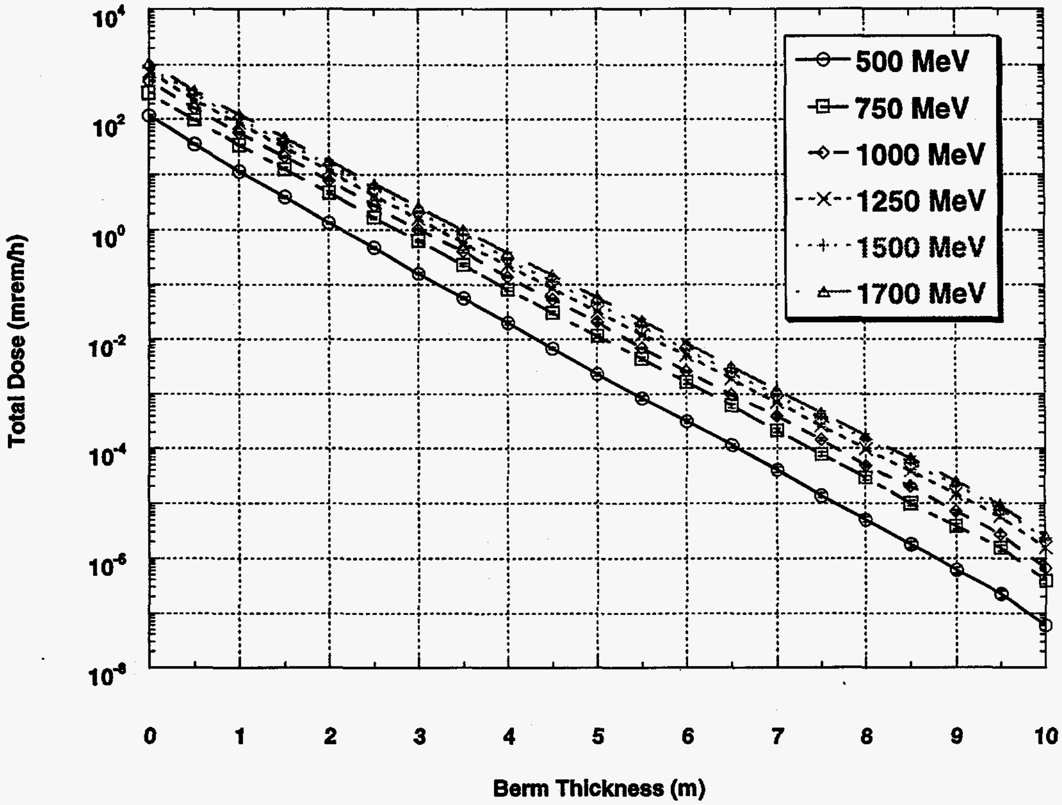
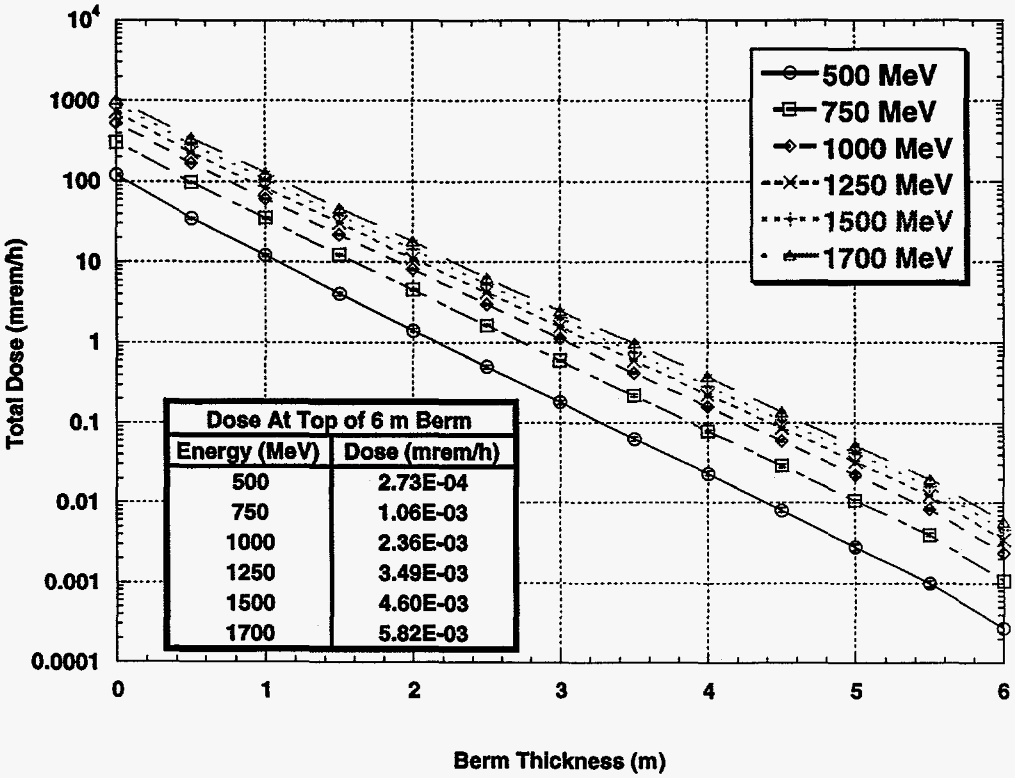


Figure 5. LCS calculation of dose through 10 m of earth berm above the APT accelerator beamline for 6 different proton beam energies.



Dose At Top of 6 m Berm	
Energy (MeV)	Dose (mrem/h)
500	2.73E-04
750	1.06E-03
1000	2.36E-03
1250	3.49E-03
1500	4.60E-03
1700	5.82E-03

Figure 6. LCS calculated dose through 6 m of SRS soil on top of the accelerator tunnel.

Since the total dose is largely dose from high-energy neutrons (60-70%), the lack of flux-to-dose conversion factors above 800 MeV probably causes LCS to underestimate the total dose. This should not significantly affect the final dose, and will only decrease the difference between the Moyer model estimation of dose, and the LCS calculation.

ACKNOWLEDGEMENTS

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