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Shielding Considerations for the 750-MeV Electron Accelerator at the University of Illinois

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Abstract

Shielding calculations for the proposed 750-MeV electron accelerator at the University of Illinois are presented and discussed.

Shielding Considerations for the 750-MeV Electron Accelerator at the University of Illinois

T. A. Gabriel, R. A. Lillie, and B. L. Bishop

I. INTRODUCTION

This report summarizes some of the calculations that were carried out to provide shielding data for the proposed 750-MeV electron accelerator at the University of Illinois.[1] All of the results described herein were obtained for a 300-MeV and/or 750-MeV electron beam. All calculations deal with doses produced by the particle beam during operation and do not include secondary radiation sources, i.e., induced radioactivity. The dose equivalents were obtained as a function of shield thickness so that various accident scenarios could be considered, i.e., various percentages of beam loss during operation.

The calculated results that were considered included: 1) the earth shielding thickness (and iron door) surrounding the accelerator vault, 2) the earth shielding thickness around the beam transport tunnel, 3) an estimate of the thickness and composition of the movable shielding door in the general purpose electron beam experimental area, 4) the shield thickness around the beam dump in the bremsstrahlung irradiation facility, 5) skyshine dose from some of the experimental areas, and 6) dose rates inside and outside the tagged photon facility.

The programs and cross section data bases used in the calculations, as well as the source neutron spectra calculations, are presented in Section II. The results of the dose calculations are presented and discussed in Section III.

II. PROGRAMS/CROSS SECTION DATA BASES AND SOURCE CALCULATIONS

A list of the programs and cross section data bases used for these analyses are given in Table 1[2-7] along with a brief description of the purpose of the program or data base. All of the programs and data bases are state-of-the-art for use in radiation transport and analysis. The composition of the materials used in the calculations are given in Table 2. The soil was taken to be the same as that at the Fermi National Accelerator Laboratory[8] and the concrete was taken to be the same as that at the Tower Shielding Facility.[9]

The EGS[2] code was used to obtain the photon track length ($T(E_\gamma)$) produced by 300 and/or 750 MeV electrons incident on infinite iron and aluminum targets. The track length data are given in Fig. 1. These track lengths were used in the PICA[3] code to obtain neutron source spectra ($d^2Y/d\Omega dEe^-$) for use in the radiation transport codes ANISN[4] and DOT.[5] The angle integrated (0-180°) neutron source spectra are given in Fig. 2. For the 750-MeV iron case, 9.76×10^{-3} neutrons/electrons are produced above 15 MeV; for the 300-MeV iron case, 1.78×10^{-3}; and for the 750-MeV aluminum case, 1.30×10^{-2}. Only neutrons above 15 MeV are needed in the source definition because only the high-energy source neutrons contribute significantly to the dose at large depths, i.e., greater than five mean free paths of penetration. For several of the dose calculations, the particle production data generated by the PICA code was analyzed using angular intervals suitable for use with an S_8 quadrature. The

Table 1

Programs and Cross Section Data Bases Used in the Shielding Analysis

Program/Data Base	Purpose
EGS[2]	Electron/gamma shower transport code for calculating the photon track length (flux)
PEGS[2]	Generates cross sections for use in EGS
PICA[3]	An intranuclear cascade code for high energy ($E_\gamma \geq 20$ MeV) photonuclear collisions
MECCAN[3]	Analyses data generated by the PICA code so that doubly differential (energy/angle) particle spectra can be obtained
ANISN[4]	One-dimensional discrete ordinates code for neutron/gamma ray transport
DOT[5]	Two-dimensional discrete ordinates code for neutron/gamma ray transport
AXMIX[6]	Processes cross sections for use in the ANISN or DOT codes
HILO[7]	Coupled neutron ($E_N \leq 400$ MeV)/gamma ray ($E_\gamma \leq 15$ MeV) cross section library for use with ANISN or DOT

Table 2

Composition of Materials Considered in the Shielding Calculations (atom/b·cm)

Element	Soil (ρ=1.8 gm/cm^3)	Concrete (ρ=2.35 gm/cm^3)	Fe (ρ=7.86 gm/cm^3)
H		1.33-2*	
C	3.00-3	2.05-2	
O	3.73-2	3.55-2	
Mg	1.11-3	1.86-3	
Al	2.21-3	6.00-4	
Si	8.82-3	1.70-3	
Ca	1.79-3	1.13-2	
Fe	5.65-4	1.90-4	8.47-2

*Read as 1.33×10^{-2}.

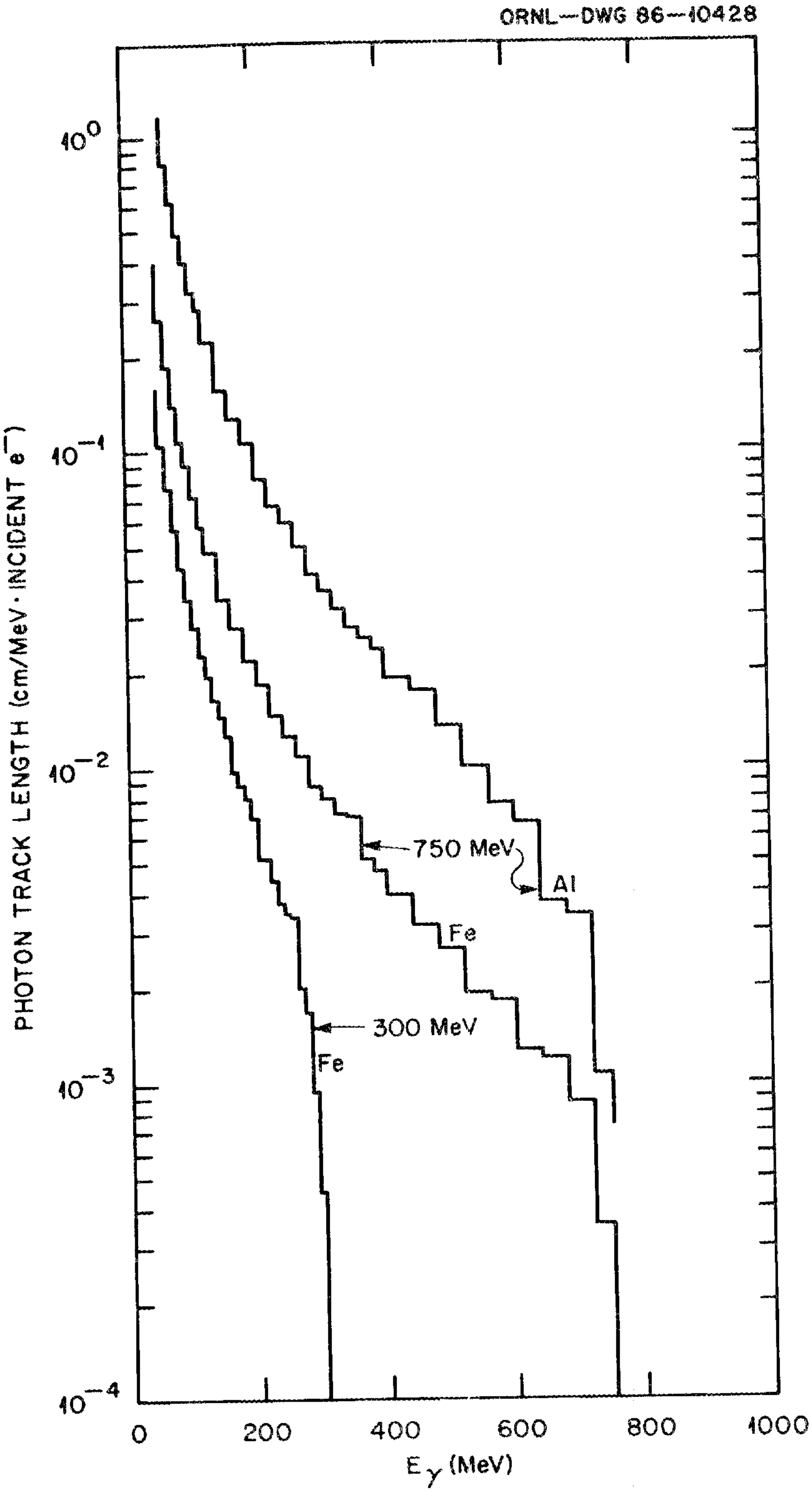

Fig. 1. Photon track lengths in infinite Al and Fe targets for 300- and 750-MeV incident electrons.

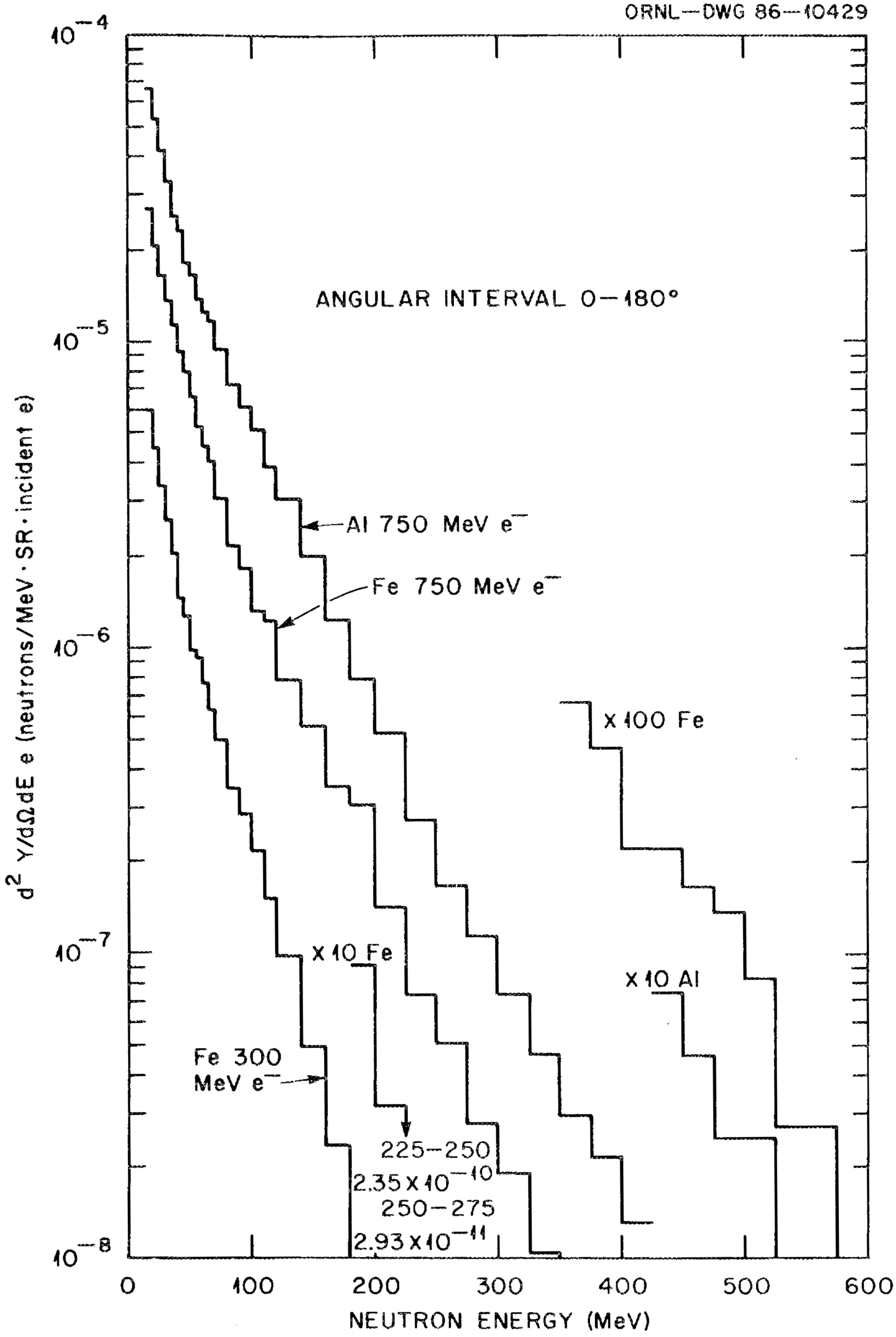

Fig. 2. Neutron production in infinite Al and Fe targets by incident 300- and 750-MeV electrons.

neutron source which had energies above the 400-MeV neutron limit in the HILO[7] neutron and gamma ray transport library were placed in the energy group interval 375-400 MeV by conserving energy, i.e., the weight of each of these neutrons was increased by $E_n/387.5$.

The flux-to-dose conversion factors are given in Table 3 for the HILO group structure.

III. RESULTS OF THE DOSE CALCULATIONS

In the accelerator room and down the beam transport tunnel, electrons will be lost and will produce neutrons which must be shielded. The neutron spectra presented in Section II, and the one-dimensional ANISN code, in conjunction with the HILO neutron/gamma ray transport library have been used to obtain the radiation dose profiles presented in Figs. 3-5. All data have been normalized to 1% of beam power, i.e., 0.75 kW, unless otherwise noted. For the transport tunnel calculation, this 1% loss is assumed to be distributed uniformly over a distance of 50 meters. The one-dimensional geometric models used in the calculations were made to correspond as closely as possible to those described in the accelerator manual.[1] The data in Fig. 4 were used to determine the thickness of the iron door in the accelerator room. It can be seen from Figs. 4 and 5 that if a substantial amount of beam loss is on Al, slightly more shielding will be required to reduce the dose to acceptable levels.

One-dimensional and two-dimensional calculations have been carried out to determine the shielding requirements around the beam dump in the general purpose electron beam and electron spectrometer room. These results are also applicable for the shield thickness around the beam plug just before the tagged photon facility. The results of the one-dimensional spherical calculations are given in Fig. 6. The 750-MeV e^- produced neutron source is located at the center of an iron sphere surrounded by soil. The variation of soil thickness required to reduce the dose rate to 0.025-, 0.25-, and 2.5 mr/hr as a function of iron thickness is given. Using these results as a guide, two-dimensional r-z calculations were carried out to determine the dose profiles around the beam dump. These results are shown in Fig. 7. By comparing the data in Fig. 6 with the more realistic data in Fig. 7, the accuracy of the one-dimensional data becomes apparent. In this application, the one-dimensional analysis is fairly accurate and could be used to optimize the design.

The results of the two-dimensional calculations to obtain the required thickness of the iron door in the general purpose electron beam and electron spectrometer room are shown in Fig. 8 in the form of dose profiles. The one-dimensional results indicated an iron thickness of approximately 1.25 m was required. The two-dimensional dose profiles verified this thickness. In the two-dimensional calculation, the full width of the iron door was extended 2.5 m past the hall opening and 0.75 m of the door thickness was extended 3.5 m past the hall opening. The two-dimensional profiles shown in Fig. 8 indicate that these values may be reduced by $\sim$1.0 m.

In addition to the required door thickness, the two-dimensional dose profiles indicate directly the soil thickness and indirectly the concrete thickness required because of backscatter from the iron beam dump that might be needed between experimental rooms. At 750 MeV

Table 3

Flux-to-Dose Conversion Factors for the HI-LO Group Structure

Upper Group Energy (MeV)	Flux-to-Dose (mr/hr/n or γ/cm$^2\cdot$sec)	Upper Group Energy (MeV)	Flux-to-Dose (mr/hr/n or γ/cm$^2\cdot$sec)	Upper Group Energy (MeV)	Flux-to-Dose (mr/hr/n or γ/cm$^2\cdot$sec)	Upper Group Energy (MeV)	Flux-to-Dose (mr/hr/n or γ/cm$^2\cdot$sec)
400*	2.494-1$^+$	25.0	1.621-1	1.50-2	3.600-3	7.00	6.984-3
375	2.382-1	22.5	1.617-1	7.10-3	3.586-3	6.50	6.696-3
350	2.284-1	20.0	1.612-1	3.35-3	3.636-3	6.00	6.336-3
325	2.198-1	17.5	1.608-1	1.58-3	3.672-3	5.50	5.976-3
300	2.124-1	14.9	1.530-1	4.54-4	4.068-3	5.00	5.580-3
275	2.061-1	13.5	1.523-1	1.01-4	4.248-3	4.50	5.184-3
250	2.007-2	12.2	1.508-1	2.26-5	4.320-3	4.00	4.788-3
225	1.963-1	10.0	1.498-1	1.07-5	4.356-3	3.50	4.356-3
200	1.912-1	8.19	1.498-1	5.04-6	4.428-3	3.00	3.924-3
180	1.872-1	6.70	1.498-1	1.50-2	3.600-3	2.50	3.449-3
160	1.836-1	5.49	1.498-1	7.10-3	3.586-3	2.00	2.930-3
140	1.793-1	4.49	1.483-1	3.35-3	3.636-3	1.50	2.311-3
120	1.771-1	3.68	1.465-1	1.58-3	3.672-3	1.00	1.508-3
110	1.753-1	3.01	1.447-1	1.58-3	3.672-3	4.00-1	7.560-4
100	1.740-1	2.46	1.400-1	4.54-4	4.068-3	2.00-1	3.816-4
90	1.723-1	2.02	1.332-1	1.01-4	4.248-3	1.00-1	2.761-4
80	1.707-1	1.65	1.267-1	2.26-5	4.320-3		
70	1.694-1	1.35	1.210-1	1.07-5	4.356-3		
65	1.686-1	1.11	1.159-1	5.04-6	4.428-3		
60	1.678-1	9.07	9.936-2	2.38-6	4.500-3		
55	1.669-1	7.43-1	7.992-2	1.12-6	4.428-3		
50	1.661-1	4.98-1	5.688-2	4.14-7	4.176-3		
45	1.652-1	3.34-1	3.852-2	14.0†	1.170-2		
40	1.644-1	2.24-1	2.840-2	12.0	1.019-2		
35	1.635-1	1.50-1	2.207-2	10.0	8.748-3		
30	1.629-1	8.65-2	9.900-3	8.00	7.812-3		
27.5	1.625-1	3.18-2	4.752-3	7.50	7.452-3		

*Start neutron groups.
$^+$Read as 2.494×10^{-1}.
†Start gamma-ray groups.

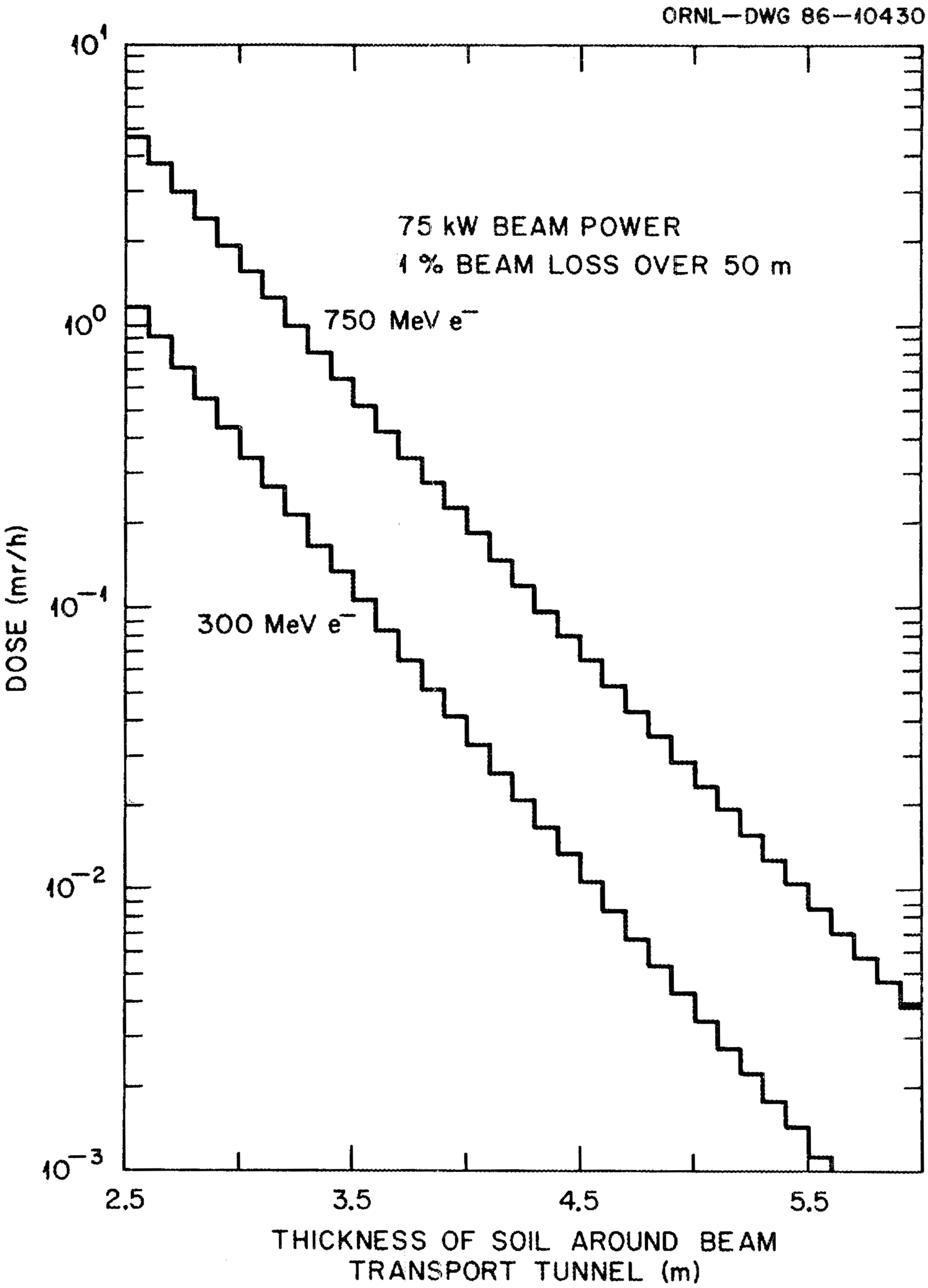

Fig. 3. Dose vs. thickness of soil surrounding the beam transport tunnel.

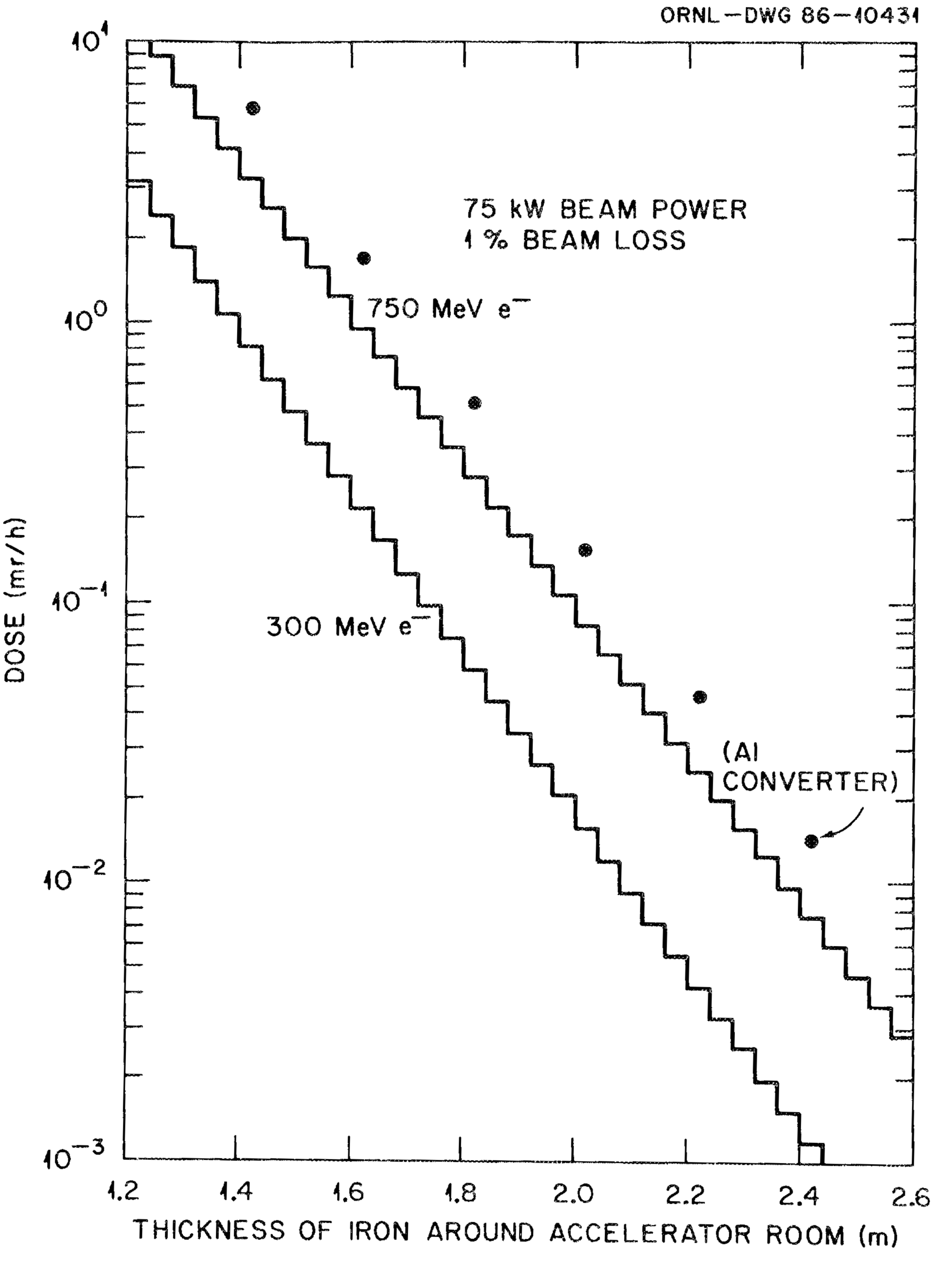

Fig. 4. Dose vs. thickness of iron surrounding the accelerator room.

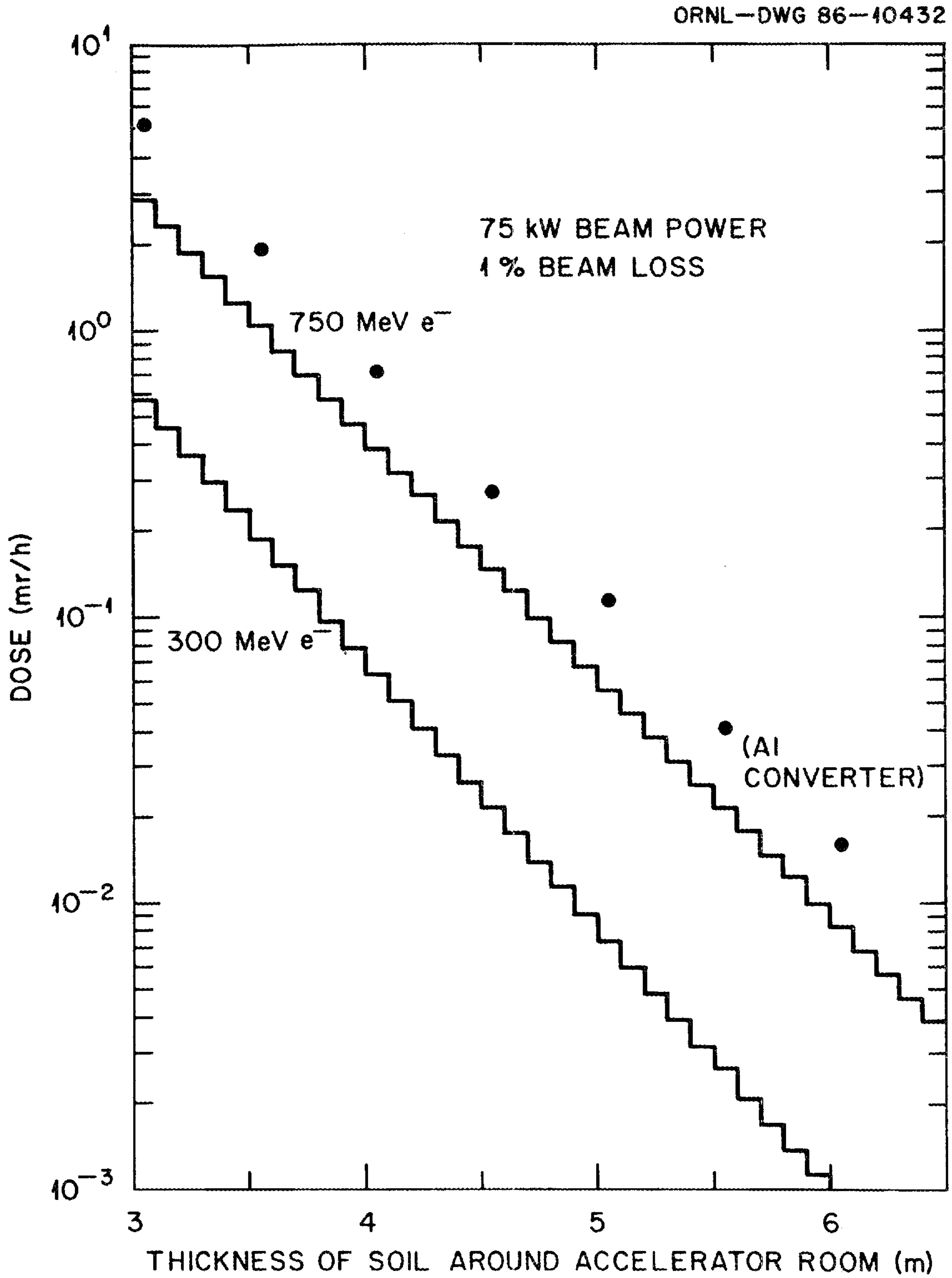

Fig. 5. Dose vs. thickness of soil surrounding the accelerator room.

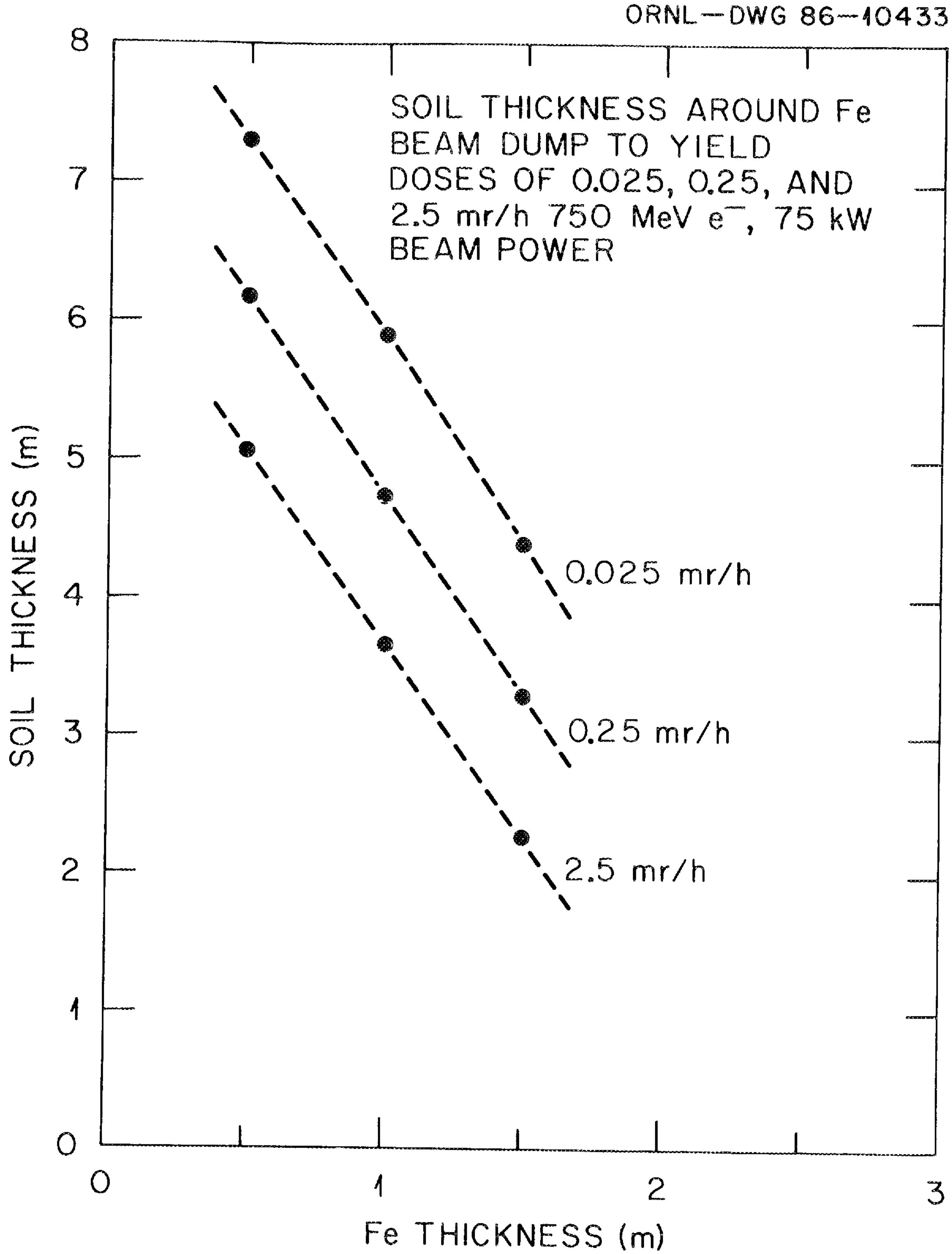

Fig. 6. One-dimensional analysis of the beam dump.

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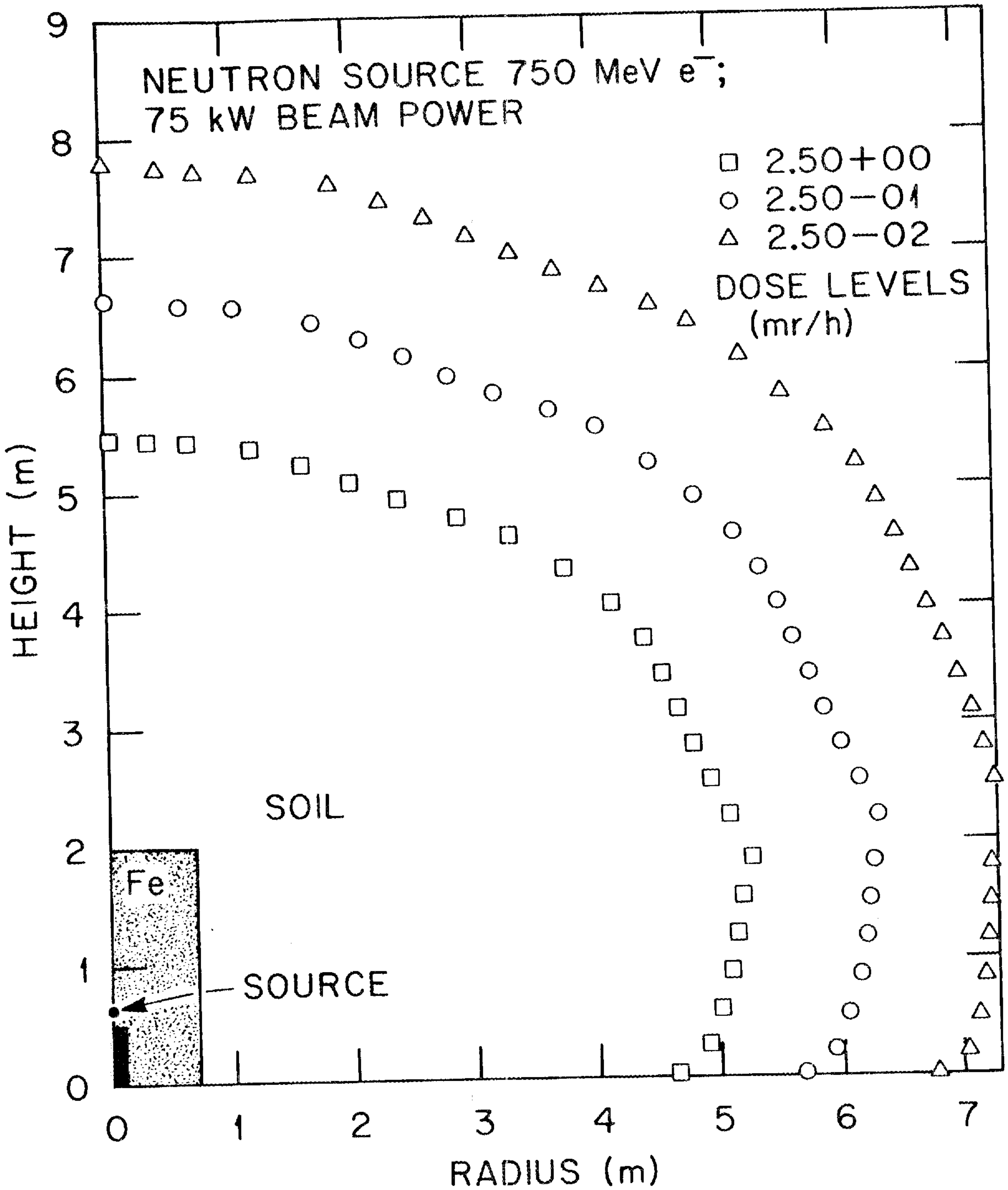

Fig. 7. Dose profiles surrounding the beam dump.

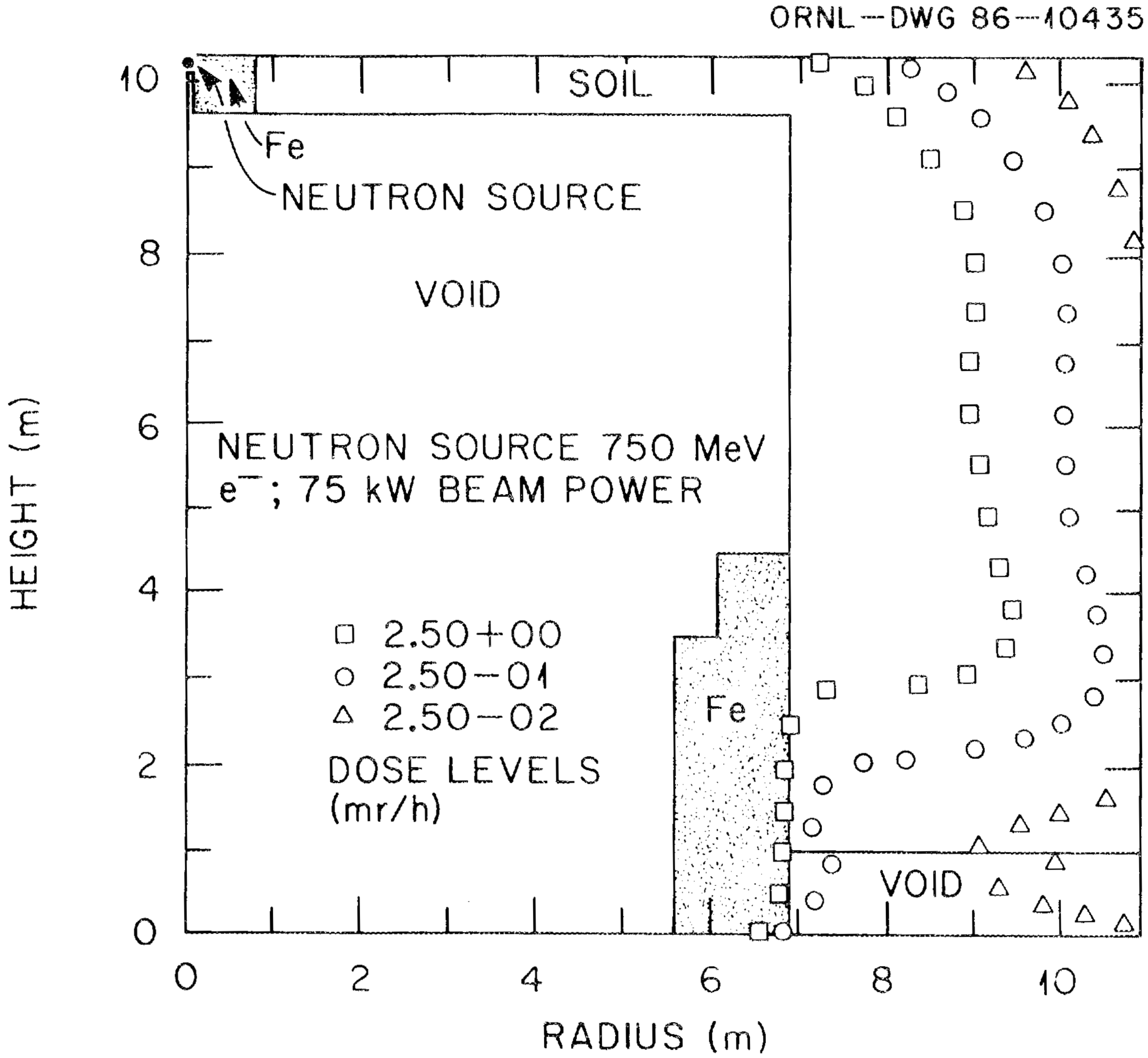

Fig. 8. Dose profiles surrounding the iron shielding door.

and 75 kW beam power, approximately 2 m of earth wall shielding is needed to obtain 2.5 mr/hr. To obtain 0.25 mr/hr, approximately 3.2 m of earth wall shielding is required. For concrete, equivalent gram thicknesses would be approximately 1.5 m and 2.5 m, respectively.

Estimates of the biological dose rates resulting from skyshine due to the photoneutron sources in the bremsstrahlung irradiation facility and estimates of the biological dose rates outside the tagged photon facility have been obtained. In all cases, the appropriate neutron fluxes or neutron currents required to estimate the various dose rates were generated by performing a number of one-dimensional radiation transport calculations. Two-dimensional calculations were not required since skyshine neutron importance functions had been previously generated.[10]

For the bremsstrahlung irradiation facility, skyshine biological dose rates will be primarily due to photoneutrons produced near the bending magnets and by those produced in the beam dump. The dose rates resulting from skyshine due to a worst case total beam loss at the bending magnets were 25,000, 87.7, and 2.0 mr/hr with no shielding, 1.0 m and 2.5 m of concrete, respectively, surrounding the bending magnets. However, under normal operating conditions, substantially lower dose rates will exist since beam losses less than 1% should prevail. The dose rate due to skyshine from the photoneutrons produced in the beam dump was calculated to be 4.83 mr/hr. This last value which could be 2 to 10 times too high because of the one-dimensional approximations was obtained assuming a bremsstrahlung power of 750 watts incident on the beam dump. All of these dose rates represent dose rates due to skyshine at a distance of 11 m from the respective source.

The dose rates at the inner and outer surfaces of the one-foot thick concrete wall surrounding the tagged photon facility due to a 1% beam loss at the converter and due to the photons incident on the beam dump have also been calculated. In all previous calculations, the photoneutron source consisted only of those neutrons produced above 14.9 MeV since fairly large shielding thicknesses were considered. Because only one foot of concrete surrounds the tagged photon facility, a low energy, i.e., below 14.9 MeV, evaporation tail was added to the existing high energy, i.e., above 14.9 MeV, neutron sources. For a 1% beam loss at the converter, dose rates of 18.2 and 2.38 mr/hr were obtained at the inside and outside surfaces, respectively, of the concrete wall. For 0.75 watts of photon power incident on the beam dump, the corresponding dose rates are 5.7 and 0.20 mr/hr. At the inside surface, approximately 90% of the dose rate for both sources is due to the low energy source neutrons whereas at the outer surface this value drops to approximately 70%.

All of the above results were obtained for a 750-MeV electron beam. For a 300 MeV electron beam normalized to the same current, the dose rates reported above and those reported previously may be reduced by approximately a factor of 13 provided the shielding is not changed. To obtain dose rates with the 300-MeV electron beam equivalent to those obtained with the 750-MeV electron beam, soil thicknesses may be reduced by approximately 1.5 m or iron thicknesses, e.g., doors, may be reduced by approximately 0.4 m, or concrete thicknesses by approximately 1.2 m. These thicknesses yield dose attenuations of approximately 13 in the respective materials. Thus, for the same current 300-MeV electron beam, the total shield thicknesses required for the 750-MeV electron beam may be reduced by approximately 2.5 mean free paths.

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