Conf-830406--50

Paper to be presented at the Fifth ANS Topical Meeting on the Technology of Fusion Energy, April 26-28, 1983, Knoxville, TN

CONF-830406--50

DE83 011752

EBT-P GAMMA-RAY-SHIELDING ANALYSIS*

by

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* Work supported by the U.S. Department of Energy.

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ABSTRACT

First, a one-dimensional scoping study was performed for the gamma-ray shield of the ELMO Bumpy Torus proof-of-principle device to define appropriate shielding material and determine the required shielding thickness. The dose-equivalent results are analyzed as a function of the radiation-shield thickness for different shielding options. A sensitivity analysis for the pessimistic case is given. The recommended shielding option based on the performance and cost is discussed. Next, a three-dimensional scoping study for the coil shield was performed for four different shielding options to define the heat load for each component and check the compliance with the design criterion of 10 watts maximum heat load per coil from the gamma-ray sources. Also, a detailed biological-dose survey was performed which included: a) the dose equivalent inside and outside the building, b) the dose equivalent from the two mazes of the building, and c) the skyshine contribution to the dose equivalent.

I. INTRODUCTION

An elaborate study[1,2] was performed for the coil and biological shield of the ELMO Bumpy Torus Proof of Principle (EBT-P) device for four different operating scenarios. First, a one-dimensional scoping study was carried out to define appropriate shielding materials and determine the required shielding thickness. The main objective of the radiation shield is to achieve a dose equivalent of 0.25 mrem/hr during operation outside the outer shield wall of the EBT-P device. The scoping study considered several different shielding options, but a detailed analysis was performed for only three of the options. The shielding materials for these options are: a) ordinary concrete, b) heavy concrete, and c) ordinary concrete with a layer of iron-scrap based concrete. Next, three-dimensional scoping study for the coil shield was performed for four different shielding options to define the heat load for each component and check the compliance with the design criterion of 10 watts maximum heat load per coil from the gamma ray source. Also, a detailed biological dose survey was performed which included: a) the dose equivalent inside and outside the building, b) the dose equivalent from the two mazes of the building, and c) the skyshine contribution to the dose equivalent.

In order to perform this study, two different three-dimensional models for the EBT-P device including the building were developed. The first model utilizes the symmetry of the torus around the Z axis (36 cavities) by considering a half-cavity sector. The second model describes the whole device (36 cavities, ring support structure, floors, roof, walls, mazes, etc.) in detail. The MCNP general Monte Carlo code for neutrons and photon transport was used to perform all the photon transport[3] calculations. The energy and spatial distribution of the gamma ray source were used explicitly in the calculation with a continuous energy representation for the gamma ray interaction cross sections.

In this paper, the dose equivalent results are analyzed as a function of the radiation shield thickness from each shielding option, the geometrical model and calculational method are described, a sensitivity analysis for the pessimistic case is presented, and the recommended shielding option is discussed based on the performance and cost. Also, the heat load in each component in the system and the dose equivalent rates at various locations are given.

II. GEOMETRICAL MODELS AND CALCULATIONAL METHODS

EBT-P is a toroidal array of 36 magnetic mirrors (36 cavities). The gamma ray source in each cavity consists of three rings, two scattered sources from the limiter and one direct source. A one-dimensional model based on the geometrical configuration was developed to perform the scoping study. The gamma ray source was approximated by a one toroidal ring to get the source strength per unit length of the torus. The one-dimensional model consists of an infinite cylinder with a ring source as shown in Fig. 1. The ring source has a 20 cm internal radius and 2.5 cm thickness. The first wall of the cavity has a 39.5 cm internal radius and 0.5 cm thickness. The shielding material has an internal radius of 350 cm to simulate the torus wall. This model was developed to give a conservative estimate for the dose equivalent outside the shield. The analysis was performed for four different sources[1,4] corresponding to the following operating scenarios: 1) Upgrade configuration with aluminum limiters, assuming a 1 MeV ring temperature with 1% aluminum impurity. 2) Baseline configuration with a stainless steel vacuum vessel, assuming a 1 MeV ring temperature without impurities. 3) Upgrade configuration with aluminum limiters, assuming a 2 MeV ring temperature with 2% aluminum purity. 4) Baseline configuration with a stainless steel vacuum vessel, assuming a 1 MeV ring temperature with 1% iron impurity. Table 1 gives the source strength per cavity for the third source in a 21 energy group structure.[1] The photon transport calculations for this model were performed with the one-dimensional discrete ordinates code ANISN. A 21 gamma ray group cross section data set from the CTR Library (DLC-41C) was used for the calculations.

Fig. 1. One-dimensional geometrical model used for the dose equivalent analysis.

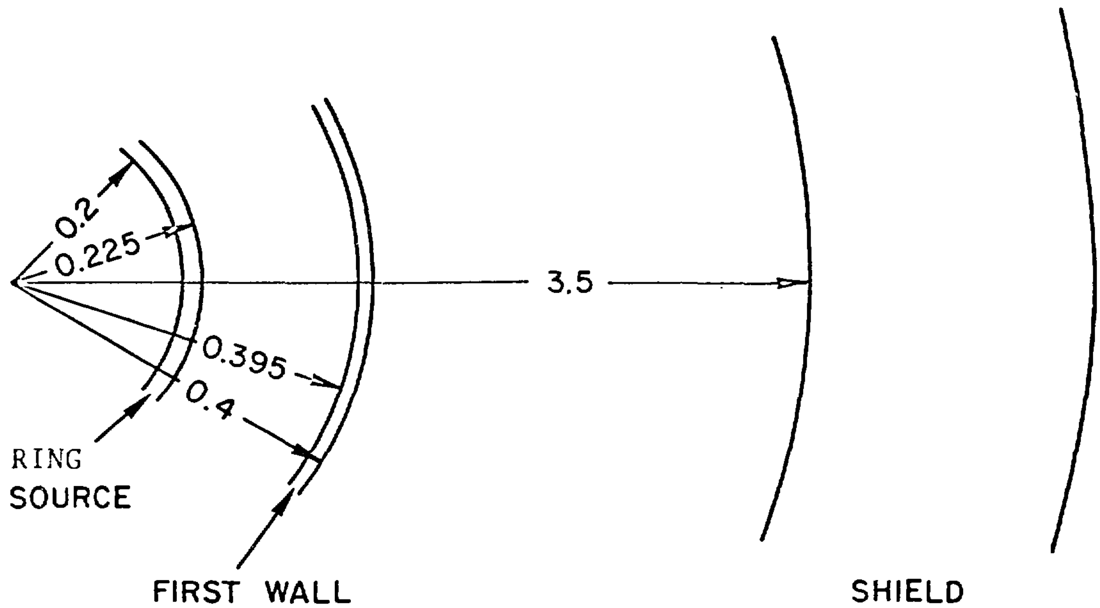
Two different three-dimensional geometrical models were developed for the EBT-P. The first model was used to study and determine the following quantities: a) The dose equivalent inside the building. b) The dose equivalent outside the building and through the concrete shield. c) The skyshine dose equivalent. d) The photon energy deposition in the different components. The second model was developed to determine the dose equivalent from the two mazes of the building.

Table 1. GAMMA RAY SOURCE STRENGTH PER CAVITY IN 21 ENERGY GROUP STRUCTURE FOR SOURCE NO. 3

Group Energy (Mid-Pt.) (MeV)	Old Source		Updated Source	
	Total Power (Watts)	Gamma Source (#/S)	Total Power (Watts)	Gamma Source (#/S)
0.055	4.569+00	5.704+14*	4.124+00	4.680+14
0.150	4.497+00	1.871+14	4.039+00	1.681+14
0.300	7.911+00	1.646+14	7.069+00	1.471+14
0.700	1.866+01	1.664+14	1.651+01	1.472+14
1.250	1.198+01	5.983+13	1.049+01	5.236+13
1.750	9.858+00	3.516+13	8.549+00	3.049+13
2.250	8.269+00	2.294+13	7.107+00	1.971+13
2.750	7.016+00	1.592+13	5.973+00	1.356+13
3.250	5.993+00	1.151+13	5.050+00	9.700+12
3.750	5.139+00	8.554+12	4.282+00	7.128+12
4.250	4.414+00	6.483+12	3.633+00	5.336+12
4.750	3.749+00	4.985+12	3.079+00	4.046+12
5.250	3.259+00	3.875+12	2.604+00	3.095+12
5.750	2.797+00	3.036+12	2.194+00	2.382+12
6.250	2.396+00	2.393+12	1.842+00	1.839+12
6.750	2.050+00	1.895+12	1.539+00	1.423+12
7.250	1.750+00	1.506+12	1.278+00	1.100+12
7.750	1.491+00	1.200+12	1.054+00	8.490+11
9.000	4.020+00	2.788+12	2.568+00	1.781+12
11.000	2.035+00	1.155+12	9.338-01	5.299+11
13.000	9.996-01	4.800+11	1.463-01	7.023+10
TOTALS	1.129+02	1.272+15	9.406+01	1.086+15

* 5.704+14 reads 5.704×10^{14}

The first three-dimensional model makes use of the symmetry of the torus around the Z-axis (36 cavities) by considering a half cavity sector. This sector includes all the major components of the EBT-P device as shown in figures 2 and 3. The model uses a 1.5 and 2.4 m of ordinary concrete for the roof and vertical wall thickness, respectively. The floor thickness between the upper and lower levels in the machine room is 0.15 m of ordinary concrete with a central hole of 1.83 m radius. The machine floor thickness is 2.70 m of ordinary concrete. The concrete ring has a rectangular cross section of 1.22 x 0.61 m.



DIMENSIONS IN m

Fig. 2. Vertical cross section for the first three-dimensional geometrical model used in the calculations.

Fig. 3. Horizontal cross section of the cavity in the first three-dimensional geometrical model.

The model represents the different cavity components explicity. The second model describes the whole device (36 cavities, ring support structure, floors, roof, walls, mazes, etc.) as given in the blueprints of the EBT-P device. This model uses 1293 surfaces to describe 536 zones included in the geometry. The main purpose of the second model is to determine the dose equivalent rate at the exit of the two mazes. Ordinary concrete is used in both models. Air environment and soil outside the building are included to account for any photons scattered back around the building. The environment outside the building extends to 1100 m in the radial and axial directions.

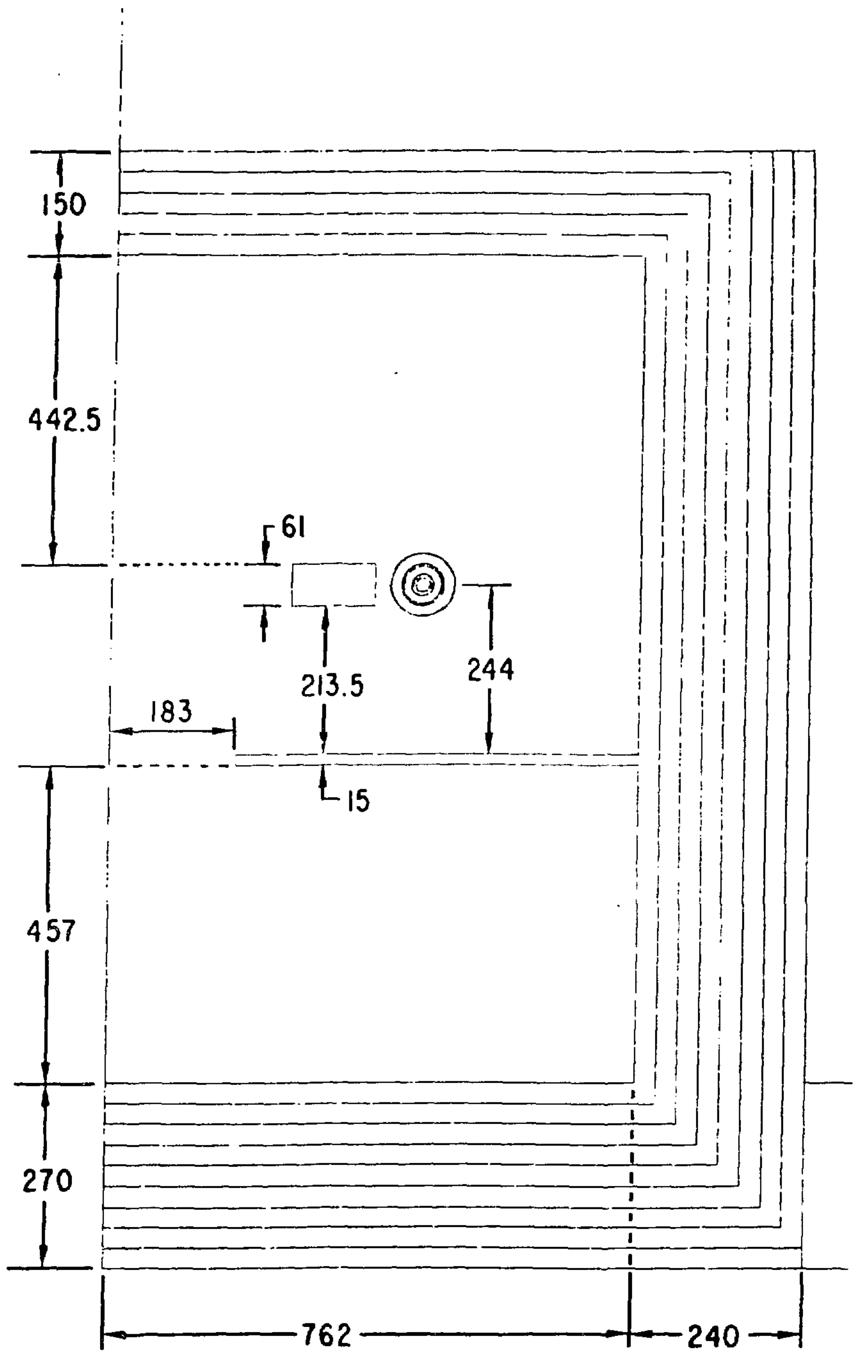
The calculations were performed with MCNP general Monte Carlo code for neutron and photon transport.[3] The photon interaction cross sections with a continuous energy representation from the MCPLIB library were used.[3] The photon transport was performed with a detailed physics treatment that accounts for fluorescent photons after photoelectric absorptions.

The dose equivalent was calculated from the gamma fluxes using the flux- to- dose conversion factor of the American National Standard ANSI/ANS-6.1.1-1977.

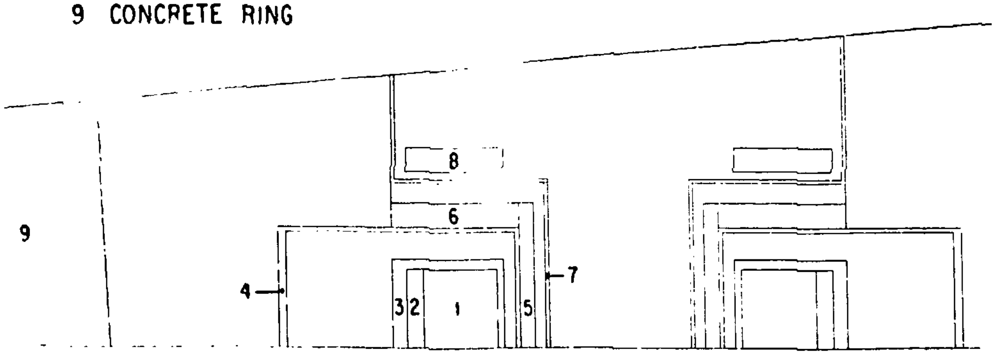
The gamma ray source from the upgrade configuration with aluminum limiters, 2 MeV ring temperature, and 2% aluminum impurity[2] was used in the three-dimensional analysis. The gamma ray source spatial and energy distribution were used in the calculations without approximations. The source used in the three-dimensional analysis is an update from the one used in the one-dimensional analysis reflecting the expected operating mode of the EBT-P device,[2,4] both sources are listed in Table 1.

III. DOSE EQUIVALENT ANALYSES FOR THE DIFFERENT SHIELDING OPTIONS

The dose equivalent was calculated as a function of the shield thickness for ordinary concrete, heavy concrete (magnetite type), and ordinary concrete with 30 cm internal layer of iron-scrap concrete. The use of a high-Z material such as lead, tungsten or tantalum was excluded from the scoping study for the following reasons: a) The high-Z materials have a high photoneutron cross section. For example, lead has about 500 mb (γ,xn) cross section at 14 MeV photon energy. For the lead shield option, the photoneutrons and the secondary photons produced by these neutrons


150
442.5
61
213.5
244
183
15
457
270
762
240

1 SUPERCONDUCTOR
2 LIQUID HELIUM
3 SUPERCONDUCTOR CASE
4 MAGNET DEWAR
5 MAGNET SHIELD (TUNGSTEN OR LEAD)
6 MAGNET SHIELD (LEAD)
7 FIRST WALL
8 LIMITER
9 CONCRETE RING



increase the dose equivalent by two to three orders of magnitude during operation.[5] b) The photoneutrons generate radioactive materials in the different components which affects the hand-on maintenance and accessibility of the torus area after shutdown. c) The unit cost of the high-Z materials is excessive compared to the concrete. The calculations were carried out with ANISN code using S_8P_5 approximations. The order of angular quadrature (S_n) and Legendre expansion of the scattering cross section (P_L) for the calculations will be examined later. Table 2 gives the key results for the two types of concrete for each gamma ray source. Three conclusions have been reached based on these calculations: a) Source No. 3 gives the highest dose equivalent. b) The shield thickness required for Source No. 3 is 261 cm of ordinary concrete to reduce the dose equivalent to 0.25 mrem/hr. c) The use of heavy concrete saves ~ 0.4 of the required ordinary concrete shield thickness to achieve an 0.25 mrem/hr dose equivalent.

The use of intermediate-Z materials (iron-scrap based concrete) between two layers of ordinary concrete is motivated by several factors: a) The reduction in the total shield thickness is a factor of two compared to the ordinary concrete option. b) The use of intermediate-Z materials after thick layer of ordinary concrete reduces the photoneutron generation rate by orders of magnitude. c) The cost of an ordinary concrete shield with a layer of iron-scrap based concrete is low compared to the heavy concrete.

The results in Table 2 show that all the maximum heating rates in the concrete are lower than the 1 mW/cm^3 design criterion.[1] This design criterion protects the concrete against loss of water, temperature effects, radiation absorption effects, and stress conditions.

The sensitivity of the results to the different approximations in the calculational procedure are examined in this section for the ordinary concrete shield. The calculations were performed with 1 cm mesh size in the shielding materials. This choice of 1 cm mesh with a 5 cm average mean free path in the concrete eliminates the effect of the mesh size on the results. All the scoping calculations were performed with P_5 approximations for the scattering cross section and S_8 angular quadrature set. The dose equivalent calculations for Source No. 3 (the pessimistic case) were recalculated with P_0S_8, P_1S_8, P_3S_8 and P_5S_8 to study the effect of the different scattering order. The results show that the convergence is achieved by P_5, and the results obtained by P_3 approximation at 0.25 mrem/hr biological dose are ~ 0.6% less than P_5. In order to check the adequacy of S_8 quadrature set for the calculations, the dose equivalent from Source No. 3 was recalculated with P_5S_6, P_5S_8, and P_5S_{12}. The results from P_5S_8 and P_5S_{12} show a good agreement, with a difference of ~ 0.7% at 0.25 mrem/hr dose equivalent. The effect of the cutoff energy for the photon source was examined. The results show that the change in the dose equivalent at 0.25 mrem/hr is 2% when the cutoff energy is changed from 10 to 14 MeV. Also, the source strength drops very fast with energy above 10 MeV which indicates the adequacy of the 14 MeV cutoff energy.

In order to recommend a specific shielding option for EBT-P, the cost of each option was calculated. The unit cost for a specific type of concrete varies greatly depending on the location, type of forms, and construction method. Table 3 gives the installed cost per cubic yard for the different concrete types, and compiles data from the calculations to give the cost of the shield per square yard for Source No. 3. The unit cost for the magnetite concrete is three times the ordinary concrete, which requires more than a factor of three reduction in the shield to make the magnetite concrete an attractive option. The reduction achieved in the shield thickness for Source No. 3 is only 41% which makes the ordinary concrete shield option more attractive. The use of ordinary concrete with a layer of iron scrap based concrete results in less cost compared to the magnetite type; however, the cost is still 78% more than the ordinary concrete option. This analysis concludes that the ordinary concrete is the most attractive shielding option for EBT-P.

IV. COIL SHIELD

A three-dimensional scoping study for the coil shield was carried out to choose a shielding material and determine its thickness. The main function of the coil shield is to reduce the nuclear heat load below 10 watts per coil. The one-dimensional analysis for the nuclear heat load in the coil was avoided due to the large approximation of the photon source locations relative to the coil. Also, the need for an accurate assessment did promote the use of three dimensional analysis for this study. The analysis was performed for four different options with aluminum first wall. The first option has 1.9 cm of tungsten shield in the throat area and 3.2 cm of lead

Table 2. HEATING RATE IN THE FIRST WALL, MAXIMUM HEATING RATE IN THE ORDINARY CONCRETE SHIELD, DOSE EQUIVALENT AT 240 cm OF ORDINARY CONCRETE, AND SHIELD THICKNESS TO ACHIEVE 0.25 MREM/HR

	Source Number			
	I	II	III	IV
First Wall Heating Rate (mW/cm^3)	1.48	0.15	1.32	0.52
Maximum Heating Rate in the Ordinary Concrete (mW/cm^3)	0.057	0.005	0.059	0.020
Biological Dose at 240 cm of Ordinary Concrete Shield (mrem/hr)	0.078	0.004	0.803	0.028
Ordinary Concrete Shield Thickness to Achieve 0.25 mrem/hr Dose Equivalent (cm)	222	178	261	206
Heavy Concrete Shield Thickness to Achieve 0.25 mrem/hr Dose Equivalent (cm)	136	110	155	126

Table 3. THICKNESS AND COST OF THE SHIELD FOR SOURCE NO. 3

Concrete Type	Shield Thickness for 0.25 mrem/hr (cm)	Cost/Square Yard of the Shield ($)
Ordinary ($300/Cu.Yd)	261	856
Magnetite ($900/Cu.Yd)	155	1526
Ordinary ($300/Cu.Yd) and Iron Scrap Based (1560/Cu.Yd)	120 + 50	1247

shield on each side of the coil as shown in Fig. 3. The second option has lead instead of tungsten to save on the shield cost. The third option reduces the shield thickness around the coil by a factor of two from the second option. The last option does not have any shield for the coil. The calculations were performed with the Monte Carlo method without any variance reduction technique. The track length estimator technique was used to calculate the nuclear heating in each component.

Two cooling systems are used for each coil, a liquid helium system for the superconductor region including the magnet case and a liquid nitrogen system for the magnet drawer. The design criterion of 10 watts maximum heat load per coil applies to the liquid helium system. The results show that the heat load for the liquid helium system without shield is 13 watts, which exceeds the 10 watts design limit. This result clearly indicates that a shielding material is essential to reduce the heat load in the liquid helium below the design limit. The use of tungsten or lead shield reduces the heat load below the design limit. The difference between the heat loads from the tungsten and lead shield options is small. The tungsten shield option (Option 1) deposits ~ 1.9 watts in the liquid helium system, while the lead shield option (Option 2) deposits ~ 2.3 watts. However, the cost of the tungsten material promotes the lead shield design. The third option deposits 5.3 watts in the liquid helium system, with 0.95 cm of lead in the throat area and 1.6 cm of lead on each side of the coil. This analysis results in three main conclusions: a) The lead shield option is a conservative design with respect to the heat load in the liquid helium system; the resulting heat load is 2.3 watts. b) The results from the third option indicate that it is possible to replace the lead shield in the second option with stainless steel and keep the heat load below 5 watts to reduce the photoneutron generation rate. c) The tungsten or lead shield option has a similar performance, however, the tungsten material is more expensive. The heat load for the reference design is 1.6 watts in the liquid helium system with type 316 stainless steel first wall and lead shield. The reference lead shield thickness is 1.5 and 3.8 cm in the throat area and on the sides, respectively.

V. DOSE EQUIVALENT ANALYSES INSIDE AND OUTSIDE THE BUILDING

The dose equivalent inside the building was calculated on a spatial grid covering the upper and lower level. The track length estimator technique was used to calculate the dose equivalent, and the photon flux averaged over 58 small spheres of 15 cm radius each. The dose equivalent peaks on the center lines of the torus below the 15 cm concrete floor because this area has the largest solid angle to the source relative to any other point in the lower level. The dose equivalent varies from 400 to 8800 rem/hr in the lower level. The concrete ring causes the dose equivalent to have a minimum of ~ 567 rem/hr at Z = 2.44 m on the center line of the torus. The maximum dose equivalent is 17500 rem/hr around the first wall. The dose equivalent parallel to the vertical wall indicates that the dose equivalent reaches a maximum value on the midplane of the torus at Z = 2.44 m.

The dose equivalent through and outside the concrete shield including the contribution from the photons scattered back by collisions with air nuclei (skyshine) were analyzed. The calculations were performed with the same technique used in calculating the dose equivalent inside the building. The track length estimator technique was used to calculate the dose equivalent and the photon flux in 49 cylinder. These cylinders were arranged in a specific pattern to get the dose equivalent and the photon fluxes in five different planes: a) lower level at Z = -3.67 m, b) upper level at Z = 2.44 m, c) vertical plane perpendicular to the roof, d) vertical plane parallel to the outer surface of the 2.4 m concrete shield wall, and e) through the 2.4 m concrete shield at Z = 2.44 m. The dose equivalent in the upper and lower levels are defined as a function of the distance from the outer concrete shield surface every 100 m including the skyshine contribution. At each point, the dose equivalent was calculated as an average over a cylindrical volume of 1 m radius. The center lines of these cylinders exists in the upper or lower plane parallel to the concrete surface. The upper level was taken at Z = 2.44 m based on the dose equivalent analysis inside the building from the previous analysis to get the maximum dose equivalent outside the concrete shield. The results show that the dose equivalent at the surface of the concrete shield in the upper level is 0.30 mrem/hr. The corresponding value from the one-dimensional model used before is 0.48 mrem/hr. The one-dimensional model over-estimates the dose equivalent because it does not account for the coil and its shield.

The dose equivalent on the roof is 68.8 mrem/hr compared to 0.3 mrem/hr maximum dose equivalent around the machine. The skyshine contribution is ~ 6% of the 0.3 mrem/hr dose equivalent. The dose equivalent analysis for the two mazes of the machine room shows that the use of "U" shape maze of 0.9 m width for personnel access reduces the dose equivalent to 0.25 mrem/h at the exit. The large maze with 18 m width and "L" shape requires shielding door to reduce the dose equivalent from 87 to 0.25 mrem/hr.

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Work supported by McDonnell Douglas Astronautics Company and U.S. Department of Energy.