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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

EBT-P GAMMA-RAY SHIELDING SYSTEM*

by

Y. Gohar

Fusion Power Program

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LIST OF FIGURES

<u>Number</u>		<u>Page</u>
1	Vertical cross section for the first three-dimensional geometrical model used in the calculations.....	3
2	Section AA of the first three-dimensional geometrical model used in the calculations.....	4
3	Part of section AA of the first three-dimensional geometrical model showing the different components in the cavity.....	6
4	Vertical cross sections for the second geometrical model used in the calculations.....	7
5	Section A-A of the second three-dimensional geometrical model used in the calculations.....	8
6	Section B-B of the second three-dimensional geometrical model used in the calculations.....	9
7	Vertical cross section showing the different components in the cavity.....	10
8	Section C-C of the second three-dimensional geometrical model showing the whole torus.....	11
9	Section D-D of the second three-dimensional geometrical model showing a section of the torus.....	12
10	Section of the second three-dimensional geometrical model showing the small maze.....	13
11	Section of the second three-dimensional geometrical model showing the large maze.....	14
12	Cross section of the cavity showing the gamma ray source locations.....	22
13	Grid points and directions for the dose equivalent calculations.....	29
14	Grid points for the dose equivalent calculations.....	30
15	Iso-dose equivalent contours in the lower floor of the machine room (rem/hr).....	31

LIST OF FIGURES (Cont.)

<u>Number</u>		<u>Page</u>
16	The dose equivalent in the vertical direction inside the machine room at the points 1 to 12.....	33
17	The dose equivalent in the vertical direction inside the machine room at the points 13 to 25.....	34
18	The dose equivalent in the vertical direction inside the machine room at points 26 to 37.....	35
19a	Photon flux at point no. 1 of Fig. 13.....	36
19b	Photon flux at point no. 5 of Fig. 13.....	37
19c	Photon flux at point no. 13 of Fig. 13.....	38
19d	Photon flux at point no. 17 of Fig. 13.....	39
19e	Photon flux at point no. 26 of Fig. 13.....	40
19f	Photon flux at point no. 30 of Fig. 13.....	41
20	Dose equivalent rates for the old and current source as a function of shield thickness based on the one-dimensional calculations.....	43
21	Dose equivalent in A direction outside the concrete shield.....	45
22	Skyshine dose equivalent in A direction outside the concrete shield.....	46
23	Dose equivalent in B direction outside the concrete shield.....	47
24	Skyshine dose equivalent in B direction outside the concrete shield.....	48
25	Dose equivalent in C direction above the roof.....	51
26	Total and skyshine dose equivalent in D direction parallel to the concrete shield.....	53
27	Dose equivalent in B direction through the concrete shield.....	55
28a	Photon flux at the intersection of direction A with the shield on Fig. 13.....	56

LIST OF FIGURES (Cont.)

<u>Number</u>		<u>Page</u>
28b	Photon flux at the intersection of direction B with the shield on Fig. 13.....	57
28c	Photon flux at the intersection of direction C with the roof on Fig. 13	58
29	Dose equivalent at the entrance of the small maze.....	60
30	Dose equivalent at the exit of the small maze.....	61
31	Dose equivalent at the entrance of the large maze.....	62
32	Dose equivalent at the exit of the large maze.....	63
33	Photon flux at the exit of the large maze at $Z = 2.44M$	65

LIST OF TABLES

<u>Number</u>		<u>Page</u>
1	Atomic density for EBT-P materials.....	15
2a	Gamma ray source strength per cavity as a function of the gamma ray energy.....	17
2b	Gamma ray source strength per cavity in 21 energy group structure.....	23
3	Heating rate in each component per cavity.....	25
4	Heating rate in each component per cavity for the reference design.....	27
5	Dose equivalent inside the machine room.....	28
6	Dose equivalent in A, B-directions as a function of the distance from the concrete surface.....	44
7	Dose equivalent in C-direction as a function of the distance from the roof.....	50
8	Average dose equivalent in D-direction as a function of height parallel to the concrete shield surface.....	52
9	Average dose equivalent in the concrete shield.....	54
10	Average dose equivalent at the entrance and exit of the small maze.....	66
11	Average dose equivalent at the entrance and exit of the large maze.....	67

ABSTRACT

An elaborate study was carried out for the coil and biological shield of the ELMO Bumpy Torus proof-of-principle (EBT-P) device. 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 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 machine room, and c) the skyshine contribution to the dose equivalent.

In order to perform this study, two different three-dimensional geometrical models for EBT-P including the building were developed. The MCNP general Monte Carlo code for neutrons and photon transport was used to perform all the photon transport 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 report, the geometrical models, calculational method, and gamma ray source are described. The heat loads in each component from the different coil shield options and the reference design are presented. Also, the dose equivalent rates at various locations and directions are given.

1. INTRODUCTION

An elaborate study was carried out for the coil and biological shield of the ELMO Bumpy Torus Proof-of-Principle device (EPT-P). The gamma ray source from the upgrade configuration with aluminum limiter, 2 MeV ring temperature, and 2% aluminum impurity was used for the calculations.

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 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 machine room, and c) the skyshine contribution to the dose equivalent.

In order to perform this study, two different three-dimensional geometrical models for EBT-P 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 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 report, the geometrical models, calculational method, and gamma ray source are described. The heat loads in each component from the

different coil shield options and the reference design are presented. Also, the dose equivalent rates at various locations and directions are given.

2. EBT-P GEOMETRICAL MODELS AND CALCULATIONAL METHOD

Two different three-dimensional geometrical models for EBT-P were developed to perform this study. The first model was used to study and determine the following quantities:

- a) The dose equivalent inside the machine room.
- b) The dose equivalent outside the machine room 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 machine room.

The first 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 EBT-P. Figures 1 and 2 show a vertical and horizontal cross section of the model, respectively. 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 level of 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

Fig. 1. Vertical Cross Section for the First Three-Dimensional Geometrical Model Used in the Calculations.

(Dimensions in cm)

Fig. 2. Section AA of the First Three-Dimensional Geometrical Model Used in the Calculations

1.22 x 0.61 m. Figure 3 shows a section of the model which gives a cross section for the cavity. The different components of cavity, first wall, limiter, magnet and magnet shield are considered explicitly in the model.

The second model describes the whole device (36 cavities, ring support structure, floor, roof, walls, mazes, etc.) as given in the blueprints of EBT-P and the modifications provided by McDonnell Douglas Astronautics Co. [1] at the time of the study. This model uses 1293 surfaces to describe 536 zones included in the geometry. Figures 4 through 11 give different geometrical cross sections in the model to show the different components. 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, except in the small maze area where a heavy concrete (magnetite-type) wall is used to save space as shown in Fig. 10. Air environment and soil outside the machine are included to account for any photons scattered back as shown in Figs. 1 and 4. The environment outside the machine extends to 1100 m in the radial and axial directions. Table 1 gives the composition and density of the materials used in the analysis. It should be noted that the first wall material was changed during the course of this study from aluminum to steel structure.

The calculations were performed with MCNP general Monte Carlo code for neutron and photon transport. [2] The photon interaction cross sections with a continuous energy representation from the MCPLIB library were used. [2] The photon transport was performed with a detailed physics treatment that accounts for fluorescent photons after photoelectric absorptions. Different variance reduction techniques were

- 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

Fig. 3. Part of Section AA of the First Three-Dimensional Geometrical Model Showing the Different Components in the Cavity.

- 1 CONCRETE RING
- 2 SUPPORT COLUMN
- 3 CONCRETE FLOOR
- 4 AIR
- 5 CONCRETE SHIELD
- 6 SOIL

Fig. 4. Vertical Cross Section for the Second Geometrical Model Used in the Calculations.

Fig. 5. Section A-A of the Second Three-Dimensional Geometrical Model Used in the Calculations.

Fig. 6. Section B-B of the Second Three-Dimensional Geometrical Model Used in the Calculations.

Fig. 7. Vertical Cross Section Showing the Different Components in the Cavity.

Fig. 8. Section C-C of the Second Three-Dimensional Geometrical Model Showing the Whole Torus.

Fig. 9. Section D-D of the Second Three-Dimensional Geometrical Model Showing a Section of the Torus.

(Dimensions in cm)

Fig. 10. Section of the Second Three-Dimensional Geometrical Model Showing the Small Maze.

(Dimensions in cm)

Fig. 11. Section of the Second Three-Dimensional Geometrical Model Showing the Large Maze.

Table 1
Atomic Density for EBT-P Materials.

Zone	Material	Density gm/cm ³	Atomic Density
First Wall	Al	2.699	Al 0.06024
First Wall	50% Type 316 SS	7.86	Cr 0.00760
	50% H ₂ O	1.0	Mn 0.00061
			Fe 0.02731
			Ni 0.00560
			Me 0.00070
			H 0.00335
			O 0.00167
Magnet Shield	W	19.2	W 0.06289
Magnet Shield	Pb	11.34	Pb 0.03348
Steel Structure	Type 316 SS	7.86	Cr 0.01520
			Mn 0.00123
			Fe 0.05462
			Ni 0.01121
			Mo 0.00140
Liquid Helium	He	0.122	He 0.01836
Superconductor	71.1% Cu	8.96	Cu 0.06039
Region	2.6% He	0.122	He 0.00048
	23.7% NbTi	6.54	Nb 0.00658
	2.6% epoxy	1.147	Ti 0.00672
			H + 0.00123
			O 0.00019
			C 0.00095
Ordinary Concrete		2.258	H 0.00418
			O 0.03855
			Si 0.01567
			Ca 0.00481
			Fe 0.00195
Heavy Concrete		3.6	H 0.015056
(Magnetite Type)			O 0.046622
			Si 0.001695
			Ca 0.003567
			Fe 0.021780
Air		1.2929 x 10 ⁻³	N 4.1968 x 10 ⁻⁵
			O 1.1300 x 10 ⁻⁵
			A 2.5858 x 10 ⁻⁷
Soil	90% SiO ₂ , 10% H ₂ O	1.8	H 0.01206
			O 0.03851
			Si 0.01624

used during the course of this study. Geometry splitting with Russian roulette were used for several problems. In short, if the photons go through a splitting process as they migrate away from the source in an important direction, they are increased in number to provide better sampling. However, if they go in the opposite direction, unbiased Russian roulette is exercised to save on the computer time. Energy splitting with Russian roulette technique was used for the second geometrical model only. Basically, energy splitting builds up the photon population at the high energy to get better sampling, while the Russian roulette controls the population from excessive increase. Source energy biasing was used to increase the number of the high energy tracks while correcting the distribution by altering the weights assigned to these tracks. The corrected weight of the photon in a particular energy bin is determined by the ratio of the actual distribution divided by the fictitious distribution to conserve the total weight of photons started in this energy range.

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

3. GAMMA RAY SOURCE

The gamma ray source from the upgrade configuration with aluminum limiters, 2 MeV ring temperature, and 2% aluminum impurity [1] was used in the calculations of this study. The gamma ray source consists of two components for each cavity (i.e., the direct component from the plasma and the scatter component at the edge of the limiters) as shown in Fig. 12. Table 2a lists the source distribution as a function of the photon energy

Table 2a
Gamma Ray Source Strength per Cavity as a Function
of the Gamma Ray Energy

Energy (MeV)	Direct Source (#/s·MeV)	Scattered Source (#/s·MeV)	Total Source (#/s·MeV)
1.000e - 01	1.593e + 15	1.072e + 15	2.665e + 15
2.000e - 01	7.483e + 14	4.492e + 14	1.198e + 15
3.000e - 01	4.716e + 14	2.617e + 14	7.332e + 14
4.000e - 01	3.358e + 14	1.751e + 14	5.109e + 14
5.000e - 01	2.560e + 14	1.266e + 14	3.826e + 14
6.000e - 01	2.039e + 14	9.617e + 13	3.000e + 14
7.000e - 01	1.674e + 14	7.563e + 13	2.430e + 14
8.000e - 01	1.406e + 14	6.101e + 13	2.016e + 14
9.000e - 01	1.202e + 14	4.192e + 13	1.704e + 14
1.000e + 00	1.042e + 14	3.546e + 13	1.461e + 14
1.100e + 00	9.132e + 13	3.031e + 13	1.268e + 14
1.200e + 00	8.081e + 13	2.613e + 13	9.822e + 13
1.300e + 00	7.209e + 13	2.269e + 13	8.744e + 13
1.400e + 00	6.475e + 13	1.984e + 13	7.833e + 13
1.500e + 00	5.849e + 13	1.743e + 13	7.055e + 13
1.600e + 00	5.312e + 13	1.540e + 13	6.385e + 13
1.700e + 00	4.845e + 13	1.366e + 13	5.803e + 13
1.800e + 00	4.438e + 13	1.216e + 13	5.295e + 13
1.900e + 00	4.078e + 13	1.216e + 13	4.847e + 13
2.000e + 00	3.223e + 13	8.749e + 12	4.450e + 13
2.100e + 00	2.995e + 13	7.882e + 12	4.098e + 13
2.200e + 00	3.223e + 13	7.117e + 12	3.500e + 13
2.300e + 00	2.995e + 13	6.439e + 12	3.245e + 13
2.400e + 00	2.788e + 13	5.838e + 12	3.014e + 13
2.500e + 00	2.601e + 13	6.439e + 12	2.805e + 13
2.600e + 00	2.430e + 13	5.838e + 12	3.014e + 13
2.700e + 00	2.275e + 13	5.301e + 12	2.805e + 13
2.800e + 00	2.132e + 13	4.822e + 12	2.614e + 13
2.900e + 00	2.001e + 13	4.393e + 12	2.440e + 13
3.000e + 00	1.880e + 13	4.008e + 12	2.281e + 13
3.100e + 00	1.769e + 13	3.661e + 12	2.135e + 13
3.200e + 00	1.666e + 13	3.348e + 12	2.001e + 13
3.300e + 00	1.570e + 13	3.065e + 12	1.877e + 13
3.400e + 00	1.481e + 12	2.809e + 12	1.762e + 13
3.500e + 00	1.399e + 13	2.577e + 12	1.656e + 13
3.600e + 00	1.322e + 13	2.366e + 12	1.558e + 13
3.700e + 00	1.250e + 13	2.174e + 12	1.467e + 13
3.800e + 00	1.182e + 13	1.999e + 12	1.382e + 13
3.900e + 00	1.119e + 13	1.840e + 12	1.230e + 13
4.000e + 00	1.050e + 13	1.695e + 12	1.161e + 13
4.200e + 00	9.526e + 12	1.440e + 12	1.097e + 13
4.300e + 00	9.035e + 12	1.329e + 12	1.036e + 13
4.400e + 00	8.573e + 12	1.227e + 12	9.800e + 12

Table 2a (Cont.)
Gamma Ray Source Strength per Cavity as a Function
of the Gamma Ray Energy

Energy (MeV)	Direct Source (#/s·MeV)	Scattered Source (#/s·MeV)	Total Source (#/s·MeV)
4.500e + 00	8.137e + 12	1.133e + 23	9.270e + 12
4.600e + 00	7.727e + 12	1.047e + 12	8.773e + 12
4.700e + 00	7.339e + 12	9.677e + 11	8.306e + 12
4.800e + 00	6.972e + 12	8.949e + 11	7.867e + 12
4.900e + 00	6.626e + 12	8.279e + 11	7.454e + 12
5.000e + 00	6.298e + 12	7.662e + 11	7.064e + 12
5.100e + 00	5.987e + 12	7.093e + 11	6.697e + 12
5.200e + 00	5.693e + 12	6.568e + 11	6.350e + 12
5.300e + 00	5.415e + 12	6.084e + 11	6.023e + 12
5.400e + 00	5.150e + 12	5.637e + 11	5.714e + 12
5.500e + 00	4.899e + 12	5.224e + 11	5.422e + 12
5.600e + 00	4.661e + 12	4.842e + 11	5.146e + 12
5.700e + 00	4.435e + 12	4.489e + 11	4.884e + 12
5.800e + 00	4.221e + 12	4.162e + 11	4.637e + 12
5.900e + 00	4.017e + 12	3.860e + 11	4.403e + 12
6.000e + 00	3.823e + 12	3.580e + 11	4.181e + 12
6.100e + 00	3.638e + 12	3.321e + 11	3.970e + 12
6.200e + 00	3.463e + 12	3.080e + 11	3.771e + 12
6.300e + 00	3.296e + 12	2.858e + 11	3.581e + 12
6.400e + 00	3.137e + 12	2.651e + 11	3.402e + 12
6.500e + 00	2.986e + 12	2.460e + 11	3.231e + 12
6.600e + 00	2.841e + 12	2.282e + 11	3.070e + 12
6.700e + 00	2.704e + 12	2.117e + 11	2.916e + 12
6.800e + 00	2.574e + 12	1.964e + 11	2.770e + 12
6.900e + 00	2.449e + 12	1.822e + 11	2.631e + 12
7.000e + 00	2.330e + 12	1.690e + 11	2.499e + 12
7.100e + 00	2.217e + 12	1.568e + 11	2.374e + 12
7.200e + 00	2.109e + 12	1.454e + 11	2.255e + 12
7.300e + 00	2.007e + 12	1.348e + 11	2.142e + 12
7.400e + 00	1.909e + 12	1.250e + 11	2.034e + 12
7.500e + 00	1.815e + 12	1.159e + 11	1.931e + 12
7.600e + 00	1.726e + 12	1.074e + 11	1.834e + 12
7.700e + 00	1.641e + 12	9.951e + 10	1.741e + 12
7.800e + 00	1.560e + 12	9.218e + 10	1.652e + 12
7.900e + 00	1.483e + 12	8.537e + 10	1.568e + 12
8.000e + 00	1.409e + 12	7.903e + 10	1.488e + 12
8.100e + 00	1.339e + 12	7.314e + 10	1.412e + 12
8.200e + 00	1.271e + 12	6.767e + 10	1.339e + 12
8.300e + 00	1.207e + 12	6.258e + 10	1.270e + 12
8.400e + 00	1.146e + 12	5.784e + 10	1.204e + 12
8.500e + 00	1.088e + 12	5.345e + 10	1.141e + 12
8.600e + 00	1.032e + 12	4.936e + 10	1.082e + 12
8.700e + 00	9.790e + 11	4.556e + 10	1.025e + 12

Table 2a (Cont.)
Gamma Ray Source Strength per Cavity as a Function
of the Gamma Ray Energy

Energy (MeV)	Direct Source (#/s·MeV)	Scattered Source (#/s·MeV)	Total Source (#/s·MeV)
8.800e + 00	9.284e + 11	4.203e + 10	9.704e + 11
8.900e + 00	8.800e + 11	3.874e + 10	9.187e + 11
9.000e + 00	8.338e + 11	3.570e + 10	8.695e + 11
9.100e + 00	7.898e + 11	3.287e + 10	8.227e + 11
9.200e + 00	7.478e + 11	3.024e + 10	7.780e + 11
9.300e + 00	7.077e + 11	2.779e + 10	7.355e + 11
9.400e + 00	6.694e + 11	2.553e + 10	6.950e + 11
9.500e + 00	6.329e + 11	2.343e + 10	6.564e + 11
9.600e + 00	5.981e + 11	2.147e + 10	6.196e + 11
9.700e + 00	5.649e + 11	1.967e + 10	5.846e + 11
9.800e + 00	5.332e + 11	1.799e + 10	5.512e + 11
9.900e + 00	5.030e + 11	1.644e + 10	5.194e + 11
1.000e + 01	4.741e + 11	1.500e + 10	4.891e + 11
1.010e + 01	4.466e + 11	1.367e + 10	4.603e + 11
1.020e + 01	4.204e + 11	1.244e + 10	4.328e + 11
1.030e + 01	3.954e + 11	1.130e + 10	4.067e + 11
1.040e + 01	3.715e + 11	1.024e + 10	3.817e + 11
1.050e + 01	3.487e + 11	9.274e + 09	3.580e + 11
1.060e + 01	3.271e + 11	8.379e + 09	3.354e + 11
1.070e + 01	3.064e + 11	7.553e + 09	3.139e + 11
1.080e + 01	2.867e + 11	6.794e + 09	2.935e + 11
1.090e + 01	2.679e + 11	6.095e + 09	2.740e + 11
1.110e + 01	2.500e + 11	5.453e + 09	2.554e + 11
1.120e + 01	2.329e + 11	4.864e + 09	2.378e + 11
1.130e + 01	2.167e + 11	4.325e + 09	2.210e + 11
1.140e + 01	1.864e + 11	3.382e + 09	2.050e + 11
1.150e + 01	1.724e + 11	2.971e + 09	1.754e + 11
1.160e + 01	1.590e + 11	2.598e + 09	1.616e + 11
1.170e + 01	1.463e + 11	2.260e + 09	1.486e + 11
1.180e + 01	1.342e + 11	1.954e + 09	1.361e + 11
1.190e + 01	1.226e + 11	1.678e + 09	1.243e + 11
1.200e + 01	1.117e + 11	1.430e + 09	1.131e + 11
1.210e + 01	1.012e + 11	1.207e + 09	1.024e + 11
1.220e + 01	9.131e + 10	1.010e + 09	9.232e + 10
1.230e + 01	8.187e + 10	8.342e + 08	8.270e + 10
1.240e + 01	7.289e + 10	6.797e + 08	7.357e + 10
1.250e + 01	6.436e + 10	5.447e + 08	6.491e + 10
1.260e + 01	5.626e + 10	4.278e + 08	5.669e + 10
1.270e + 01	4.856e + 10	3.276e + 08	4.889e + 10
1.280e + 01	4.125e + 10	2.429e + 08	4.149e + 10
1.290e + 01	3.430e + 10	1.727e + 08	3.448e + 10
1.300e + 01	2.771e + 10	1.159e + 08	2.783e + 10
1.310e + 01	2.146e + 10	7.142e + 07	2.153e + 10

Table 2a (Cont.)
 Gamma Ray Source Strength per Cavity as a Function
 of the Gamma Ray Energy

Energy (MeV)	Direct Source (#/s·MeV)	Scattered Source (#/s·MeV)	Total Source (#/s·MeV)
1.320e + 01	1.553e + 10	3.845e + 07	1.557e + 10
1.330e + 01	9.907e + 09	1.608e + 07	9.923e + 09
1.340e + 01	4.577e + 09	3.528e + 06	4.580e + 09
Totals	5.327e + 15	2.742e + 15	8.052e + 15

for both components. In each cavity, the gamma source consists of three rings as shown in Fig. 12. The photon source spatial and energy distribution were used without approximations in this study. In the calculations, the angular distribution of the gamma ray source was considered isotropic for both components.

The gamma ray source strength used in this study is different from the one used in an earlier one dimensional analysis. [3] The current source is an update from the old source reflecting the expected operating mode of EBT-P. Table 2b gives both versions of the same source in 21 energy groups. The current source power is 94.06 watts compared to 112.9 watts for the old source. Also, the source distribution as a function of the gamma ray energy is different.

4. 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 in the superconductor region. 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 first geometrical model discussed in the previous section was used in this study. The analysis was performed for four different options. The first option has 1.9 cm of tungsten shield in the throat area and 3.2 cm of lead shield on each side of the coil as shown in Fig. 12. The second option has lead instead of

Fig. 12. Cross Section of the Cavity Showing the Gamma Ray Source Locations.

Table 2b
Gamma Ray Source Strength Per Cavity
In 21 Energy Group Structure

GROUP ENERGY (Mid-Point) (MeV)	OLD SOURCE		CURRENT SOURCE	
	TOTAL POWER (WATTS)	GAMMA SOURCE (#/S)	TOTAL POWER (WATTS)	GAMMA SOURCE (#/S)
5.500e - 02	4.569E + 00	5.704E + 14	4.124e + 00	4.680e + 14
1.500e - 01	4.497E + 00	1.871E + 14	4.039e + 00	1.681e + 14
3.000e - 01	7.911E + 00	1.646E + 14	7.069e + 00	1.471e + 14
7.000e - 01	1.866E + 01	1.664E + 14	1.651e + 01	1.472e + 14
1.250e + 00	1.198E + 01	5.983E + 13	1.049e + 01	5.236e + 13
1.750e + 00	9.858E + 00	3.516E + 13	8.549e + 00	3.049e + 13
2.250e + 00	8.269E + 00	2.294E + 13	7.107e + 00	1.971e + 13
2.750e + 00	7.016E + 00	1.592E + 13	5.973e + 00	1.356e + 13
3.250e + 00	5.993E + 00	1.151E + 13	5.050e + 00	9.700e + 12
3.750e + 00	5.139E + 00	8.554E + 12	4.282e + 00	7.128e + 12
4.250e + 00	4.414E + 00	6.483E + 12	3.633e + 00	5.336e + 12
4.750e + 00	3.749E + 00	4.985E + 12	3.079e + 00	4.046e + 12
5.250e + 00	3.259E + 00	3.875E + 12	2.604e + 00	3.095e + 12
5.750e + 00	2.797E + 00	3.036E + 12	2.194e + 00	2.382e + 12
6.250e + 00	2.396E + 00	2.393E + 12	1.842e + 00	1.839e + 12
6.750e + 00	2.050E + 00	1.895E + 12	1.539e + 00	1.423e + 12
7.250e + 00	1.750E + 00	1.506E + 12	1.278e + 00	1.100e + 12
7.750e + 00	1.491E + 00	1.200E + 12	1.054e + 00	8.490e + 11
9.000e + 00	4.020E + 00	2.788E + 12	2.568e + 00	1.781e + 12
1.100e + 01	2.035E + 00	1.155E + 12	9.338e - 01	5.299e + 11
1.300e + 01	9.996E - 01	4.800E + 11	1.463e - 01	7.023e + 10
TOTALS	1.129E + 02	1.2722 + 15	9.406e + 01	1.086e + 15

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. The calculations were performed with 10^5 source photons for each option. Table 3 gives the heating rate in each component per cavity for the four options.

Two cooling systems are used for each coil, a liquid helium system for the superconductor region including the magnet case a liquid nitrogen system for the magnet dewar. The design criterion of 10 watts maximum heat load per coil applies to the liquid helium system. The results in Table 3 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 in 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 difference in the unit cost of each 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 four main conclusions:

Table 3
Heating Rate In Each Component Per Cavity.

Components	Option							
	1		2		3		4	
	Heating Rate (W)	Fractional Standard Deviation	Heating Rate (W)	Fractional Standard Deviation	Heating Rate (W)	Fractional Standard Deviation	Heating Rate (W)	Fractional Standard Deviation
Superconductor region	0.9016	0.042	1.1965	0.036	2.6715	0.025	6.2236	0.016
Liquid Helium	0.0043	0.066	0.0045	0.063	0.0100	0.044	0.02447	0.027
Magnet case	0.9825	0.026	1.1596	0.024	2.6174	0.016	6.6940	0.010
Magnet dewar	4.4536	0.010	4.6048	0.010	6.0573	0.008	10.7290	0.006
Tungsten on lead shield	7.0596	0.015	6.1626	0.015	4.7104	0.014	--	--
Lead shield	15.9768	0.009	16.1755	0.009	12.1320	0.008	--	--
First wall (Al design)	3.8773	0.003	3.7161	0.003	3.9476	0.004	4.2146	0.004
Limiter	13.1218	0.006	13.1367	0.006	13.2070	0.006	13.7161	0.006
Concrete ring	4.5621	0.020	4.5618	0.020	4.6841	0.020	5.0221	0.019
Concrete wall (roof, wall, and floor)	32.2562	0.007	32.2701	0.007	33.0220	0.006	35.4400	0.006
Concrete between the upper and lower floor	10.1694	0.010	10.1794	0.010	10.4240	0.009	11.2350	0.009

- 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 case 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.
- d) The heat load for the reference design is 1.6 watts in the liquid helium system as shown in Table 4. The lead shield thickness is 1.5 and 3.8 cm in the throat area and on the sides, respectively.

5. DOSE EQUIVALENT INSIDE THE MACHINE ROOM

The first geometrical model was used to calculate the dose equivalent inside the machine room on a spatial grid covering the upper and lower level. The Monte Carlo method with two variance reduction techniques was employed for this calculation. Geometry splitting with Russian roulette and source energy biasing were implemented to improve the sampling of the high energy photons at the mazes. The track length estimator technique was used to calculate the dose equivalent, and the photon flux averaged over 44 small spheres of 15 cm radius each. Figures 13 and 14 show the grid used for the calculation where the centers of these spheres are located. Table 5 gives the dose equivalent and standard deviation at each point. Figure 15 gives the iso-dose equivalent contours in the lower floor of the machine based on data from Table 5. The dose equivalent

Table 4
Heating Rate In Each Component Per Cavity For The Reference Design.

Component	Heating Rate (W)	Fractional Standard Deviation
Superconductor region	0.8436	0.014
Liquid helium	0.0003	0.030
Magnet case	0.7905	0.012
Magnet dewar	4.1610	0.010
Lead shield (throat area)	5.4740	0.012
Lead shield (side area)	14.7700	0.007
First wall (type 316 SS designs)	8.2430	0.007
Limiter	16.3100	0.006
Air (machine room)	0.6652	0.005
Concrete ring	3.2290	0.013
Concrete wall	29.6686	0.004
Concrete between the upper and lower floor	9.7060	0.007

Table 5
Dose Equivalent Inside the Machine Room.

	Grid Point Number and Location			Dose (rem/hr)	Standard Fractional Deviation
	X	Y	Z		
1	218.60	9.54	-452.0	7.84×10^2	0.066
2	218.60	9.54	-308.0	1.27×10^3	0.050
3	218.60	9.54	-164.0	2.14×10^3	0.051
4	218.60	9.54	- 20.0	9.98×10^2	0.055
5	218.60	9.54	35.0	8.11×10^3	0.039
6	218.60	9.54	139.5	6.92×10^3	0.041
7	218.60	9.54	244.0	5.67×10^2	0.098
8	218.60	9.54	334.6	5.45×10^3	0.044
9	218.60	9.54	425.2	6.94×10^3	0.036
10	218.60	9.54	515.8	6.81×10^3	0.039
11	218.60	9.54	606.4	5.69×10^3	0.038
12	218.60	9.54	697.0	5.18×10^3	0.044
13	438.97	18.23	-452.0	1.02×10^3	0.052
14	438.97	18.23	-308.0	1.30×10^3	0.053
15	438.97	18.23	-164.0	1.51×10^3	0.046
16	438.97	18.23	- 20.0	9.42×10^2	0.043
17	438.97	18.23	35.0	6.94×10^3	0.031
18	438.97	18.23	139.5	1.14×10^4	0.026
19	438.97	18.23	179.0	1.74×10^4	0.021
20	438.97	18.23	309.0	1.75×10^4	0.021
21	438.97	18.23	334.6	1.25×10^4	0.025
22	438.97	18.23	425.2	7.36×10^3	0.031
23	438.97	18.23	515.8	5.85×10^3	0.032
24	438.97	18.23	606.4	4.71×10^3	0.036
25	438.97	18.23	697.0	4.24×10^3	0.040
26	746.16	44.91	-452.0	6.43×10^2	0.065
27	746.16	44.91	-308.0	5.79×10^2	0.061
28	746.16	44.91	-164.0	4.11×10^2	0.062
29	746.16	44.91	- 20.0	2.80×10^2	0.089
30	746.16	44.91	35.0	2.93×10^3	0.047
31	746.16	44.91	139.5	3.17×10^3	0.053
32	746.16	44.91	244.0	3.15×10^3	0.050
33	746.16	44.91	334.6	3.16×10^3	0.049
34	746.16	44.91	425.2	2.94×10^3	0.046
35	746.16	44.91	515.8	2.53×10^3	0.050
36	746.16	44.91	606.4	2.63×10^3	0.050
37	746.16	44.91	697.0	2.12×10^3	0.052
38	520.00	20.00	244.0	5.70×10^3	0.036
39	633.60	20.00	244.0	3.98×10^3	0.043
40	747.00	20.00	244.0	2.89×10^3	0.050
41	576.20	25.16	244.0	4.55×10^3	0.038
42	689.59	30.11	244.0	3.02×10^3	0.041
43	518.00	25.32	244.0	5.74×10^3	0.052
44	631.96	35.21	244.0	3.89×10^3	0.047

Fig. 13. Grid Points and Directions for the Dose Equivalent Calculations.

Fig. 14. Grid Points for the Dose Equivalent Calculations.

Fig. 15. Iso-Dose Equivalent Contours in the Lower Floor of the Machine Room (rem/hr).

peaks at $Z = -1.7$ m on the center line of the torus because this point has the largest solid angle to the source relative to any other point in the lower level. The dose equivalent varies from 400 to 2300 rem/hr in the lower level. The dose equivalents in three vertical directions, shown in Fig. 13, are plotted in Figs. 16 through 18. The dose equivalent in A-direction shows the effect of the concrete ring and the 15 cm concrete floor between the upper and lower level of the machine on the dose equivalent for $Z < 0$, causing a peak at $Z = -1.7$ m. Also, 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. Figure 17 shows the dose equivalent reaching a maximum of ~ 1750 rem/hr around the first wall. Figure 18 indicates that the dose equivalent reaches a maximum value on the midplane of the torus at $Z = 2.44$ m. The photon flux distributions at different points inside the machine room are given in Fig. 19.

6. DOSE EQUIVALENT OUTSIDE THE MACHINE ROOM

The main function of the concrete shield around the EBT-P device is to achieve a dose equivalent rate ≤ 0.25 mrem/hr during operation. Again, the first geometrical model was used to analyze the dose equivalent through and outside the concrete shield including the contribution from the photonsscattered back by collisions with air nuclei (skyshine). The calculations were performed with the same technique used in calculating the dose equivalent inside the machine room. The track length estimator technique was used to calculate the dose equivalent and the photon flux in 49 cylinders. These cylinders were arranged in a specific pattern to get the dose equivalent and the photon fluxes in five different planes: a)

Fig. 16. The Dose Equivalent in the Vertical Direction
Inside the Machine Room at the Points 1 to 12.

Fig. 17. The Dose Equivalent in the Vertical Direction
Inside the Machine Room at Points 13 to 25.

Fig. 18. The Dose Equivalent in the Vertical Direction Inside the Machine Room at Points 26 to 37.

Fig. 19-a. Photon flux at point No. 1 of Fig. 13.

Fig. 19-b. Photon Flux at point No. 5 of Fig. 13.

Fig. 19-c. Photon flux at point No. 13 of Fig. 13.

Fig. 19 - d. Photon flux at point No. 17 of Fig. 13.

Fig. 19-e. Photon flux at point No. 26 of Fig. 13.

Fig. 19-f. Photon flux at point No. 30 of Fig. 13.

lower level, b) upper level, 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, as shown in Fig. 13.

The dose equivalent in the upper and lower levels are given 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 exist 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 machine in the previous section 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 including the skyshine component (0.02 mrem/hr). The corresponding value from the one-dimensional model used in an earlier study [3] is 0.48 mrem/hr with the current photon source. Figure 20 gives the dose equivalent as a function of the concrete shield thickness for the old [3] and current photon source. The one-dimensional model over-estimates the dose equivalent because it does not account for the coil and its shield.

The skyshine and the total dose equivalent were calculated at the same time in one problem. During the tracking process at each tally (dose equivalent or photon flux) two different counters are used. The first counter accounts for total tally from all the photons, while the second counter considers only the photons crossing the roof level ($Z = 8.67$ m) to calculate the skyshine contribution. Table 6 and Figs. 21 through 24 give

Fig. 20. Dose Equivalent Rates for the Old and Current Source as a Function of Shield Thickness Based on the One-Dimensional Calculations.

Table 6
Dose Equivalent In A,B-Directions As A Function
Of The Distance From The Concrete Surface.

Distance from Concrete Shield (m)	Total		Skyshine	
	Dose Equivalent (mrem/h)	Fractional Standard Deviation	Dose Equivalent (mrem/h)	Fractional Standard Fraction
<u>Lower Level: Z = 3.67 m</u>				
1	2.65×10^{-2}	0.063	1.17×10^{-2}	0.049
100	7.60×10^{-3}	0.029	6.03×10^{-3}	0.032
200	1.66×10^{-3}	0.049	1.41×10^{-3}	0.056
300	4.91×10^{-4}	0.055	4.02×10^{-4}	0.060
400	1.72×10^{-4}	0.075	1.30×10^{-4}	0.071
500	5.42×10^{-5}	0.104	3.80×10^{-5}	0.122
600	3.96×10^{-5}	0.143	2.75×10^{-5}	0.180
700	8.59×10^{-6}	0.148	4.80×10^{-6}	0.194
800	3.95×10^{-6}	0.263	2.41×10^{-6}	0.368
900	1.02×10^{-6}	0.295	4.82×10^{-7}	0.461
1000	4.48×10^{-7}	0.352	1.95×10^{-7}	0.459
<u>Upper Level: Z = 2.44 m</u>				
1	3.02×10^{-1}	0.029	1.76×10^{-2}	0.051
100	8.33×10^{-3}	0.028	6.84×10^{-3}	0.032
200	1.86×10^{-3}	0.038	1.57×10^{-3}	0.043
300	5.73×10^{-4}	0.050	4.79×10^{-4}	0.056
400	1.77×10^{-4}	0.074	1.43×10^{-4}	0.084
500	6.70×10^{-5}	0.132	5.09×10^{-5}	0.163
600	3.16×10^{-5}	0.117	2.24×10^{-5}	0.148
700	1.23×10^{-5}	0.169	8.05×10^{-6}	0.228
800	9.04×10^{-6}	0.325	6.42×10^{-6}	0.443
900	2.56×10^{-6}	0.242	8.31×10^{-7}	0.393
1000	1.61×10^{-6}	0.307	9.46×10^{-7}	0.434

Fig. 21. Dose Equivalent in A Direction Outside the Concrete Shield.

Fig. 22. Skyshine Dose Equivalent in A Direction Outside the Concrete Shield.

Fig. 23. Dose Equivalent in B Direction Outside the Concrete Shield.

Fig. 24. Skyshine Dose Equivalent in B Direction Outside the Concrete Shield.

the skyshine and the total dose equivalent with standard deviation. The skyshine contribution increases as the dose equivalent drops to very low values. The dose equivalent in the vertical planes was calculated using the same technique for the horizontal planes. The dose equivalent as a function of the distance above the roof (1.5 m of concrete) is given in Table 7 and Fig. 25. The dose equivalent at the roof is 68.8 mrem/hr compared to 0.30 mrem/hr maximum dose equivalent around the shield. Also, the dose equivalent outside the 2.4 m concrete shield as a function of the height is given in Table 8 and Fig. 26. The results in Table 8 show that the skyshine contribution is ~ 6% and 25% at the maximum and minimum dose equivalent, respectively. Again, the maximum dose equivalent occurs around $Z = 2.44$ m as shown in Fig. 26.

The dose equivalent in the concrete shield was calculated at different points as an average over a small cylindrical volume of 0.15 m radius. The center lines of these cylinders are in the horizontal plane of $Z = 2.44$ m, parallel to the concrete shield surface. Table 9 and Fig. 27 give the dose equivalent in the concrete shield and standard deviation. Photon fluxes at different points are given in Fig. 28.

7. DOSE EQUIVALENT AT THE TWO MAZES OF THE MACHINE ROOM

The machine room has two mazes for access with different configurations, as shown in Fig. 5. The small maze shown in Fig. 10 has a "U" shape at the exit. A heavy concrete is used for the central part of the "U" shape to save on the space requirement and keep the dose equivalent at the exit less than 0.25 mrem/hr. The large maze is

Table 7
Dose Equivalent In C-Direction As A Function
Of The Distance From The Roof

Distance from the Roof (m)	Dose Equivalent (mrem/hr)	Fractional Standard Deviation
1	68.80	0.031
10	30.20	0.036
20	15.20	0.047
30	8.32	0.057
60	5.85	0.069
50	3.58	0.083
60	2.58	0.092
20	1.93	0.112
80	1.38	0.108
90	1.18	0.124

Fig. 25. Dose Equivalent in C Direction Above the Roof.

Table 8
Average Dose Equivalent In D-Direction As A Function Of Height Parallel
To The Concrete Shield Surface.

Height (M) From To		Dose Equivalent (mrem/hr)	Fractional Standard Deviation	Skyshine Dose Equivalent (mrem/hr)	Fractional Standard Deviation
-4.67	-2.67	2.64×10^{-2}	0.063	1.17×10^{-2}	0.048
-2.56	-0.56	5.16×10^{-2}	0.037	1.13×10^{-2}	0.051
-0.56	1.44	1.98×10^{-1}	0.031	1.59×10^{-2}	0.049
1.44	3.44	3.06×10^{-1}	0.029	1.75×10^{-2}	0.051
3.44	5.44	2.01×10^{-1}	0.029	1.96×10^{-2}	0.048
5.44	7.23	1.04×10^{-1}	0.034	2.527×10^{-2}	0.047

Fig. 26. Total and Skyshine Dose Equivalent in D-Direction Parallel to the Concrete Shield.

Table 9
Average Dose Equivalent In The Concrete Shield.

Distance from the Inner Surface of the Concrete Shield (m)	Dose Equivalent (mrem/hr)	Fractional Standard Deviation
0.15	3.550×10^5	0.033
0.45	3.359×10^4	0.042
0.75	4.444×10^3	0.047
1.05	6.342×10^2	0.051
1.35	9.737×10^1	0.055
1.65	1.622×10^1	0.063
1.95	2.777×10^0	0.071
2.25	4.819×10^{-1}	0.078

Fig. 27. Dose Equivalent in B Direction Through the Concrete Shield.

Fig. 28-a. Photon flux at the intersection of Direction A with the shield on Fig. 13.

Fig. 28-b. Photon flux at the intersection of Direction B with the shield on Fig. 13.

Fig. 28-c. Photon flux at the intersection of Direction C with the roof on Fig. 13.

envisioned to be used during the maintenance for moving the equipment in and out. The width of the large maze is 1.82 m without any enhancement for the concrete shield.

The second geometrical model was used to assess the dose equivalent from the two mazes. The calculation was performed to get the dose equivalent at the entrance and exit of each maze averaged over a small surface area. The surface area of each maze is divided into 11 segments. The segment height is 0.5 m and 0.6 m in the upper and lower levels, respectively. The variance reduction techniques discussed in the model section were employed in this calculation.

The average dose equivalent at the entrance and exit of the small maze is given in Table 10. The dose equivalent at the entrance of the small maze is shown in Fig. 29. The dose equivalent at the upper level is about one order of magnitude higher than the dose equivalent at the lower level due to the concrete floor (the concrete floor thickness is 0.15 m of ordinary concrete). The maximum dose equivalent is 1.15×10^6 mrem/hr as shown in Fig. 29. The maximum dose equivalent at the exit of the small maze is 0.25 mrem/hr as shown in Fig. 30. At the exit, the dose equivalent shows a small change in the vertical direction because the model does not include the concrete floor between the upper and lower levels in the maze area. This result indicates that the small maze does not require additional shield during operation.

Similar results for the large maze are given in Table 11 and Figs. 31 and 32. The dose equivalent at the entrance is six times higher than the corresponding dose equivalent for the small maze. However, the exit dose has a maximum of 87 mrem/hr, which is higher than the design limit. This

Fig. 29. Dose Equivalent at the Entrance of the Small Maze.

Fig. 30. Dose Equivalent at the Exit of the Small Maze.

Fig. 31. Dose Equivalent at the Entrance of the Large Maze.

Fig. 32. Dose Equivalent at the Exit of the Large Maze.

indicates that an additional shield equivalent to 1 m of ordinary concrete is required to reduce the dose to the permissible level at the exit of the large maze. The photon flux at several locations in the two mazes is given in Fig. 33.

8. CONCLUSIONS AND RECOMMENDATIONS

The EBT-P gamma ray shielding results for the upgrade configuration are briefly summarized as follows:

- 1) A 2.4-m thick shield of ordinary concrete reduces the maximum dose equivalent to 0.3 mrem/hr including the skyshine contribution.
- 2) A 1.5-m thick shield of ordinary concrete for the roof reduces the skyshine dose equivalent to ≤ 0.025 mrem/hr.
- 3) The heat load per coil is 1.6 watts for the reference design with the lead shield. The use of type 316 stainless steel instead of lead for the shield with the same dimensions increases the heat load to ~5 watts per coil, which satisfies the design criterion of 10 watts maximum heat load per coil and significantly reduces the photoneutron generation rate.
- 4) The small maze does not require additional shield; it has a maximum dose equivalent of 0.25 mrem/hr at the exit.
- 5) The large maze requires additional shield; it has a maximum dose equivalent of 87 mrem/hr at exit.
- 6) The dose equivalent in the lower level of the machine has a hot spot at $Z = -1.7$ m on the center line of the torus.
- 7) The maximum dose equivalent near the first wall is 1.75×10^7 mrem/hr.

Fig. 33. Photon flux at the exit of the
Large Maze at $Z = 2.44M$.

Table 10
Average Dose Equivalent At The Entrance And Exit Of The Small Maze.

Height (M) From To		Entrance Dose (mrem/hr)	Fractional Standard Deviation	Exit Dose (mrem/hr)	Fractional Standard Deviation
-4.72	-3.54	1.560×10^5	0.203	0.1823	0.663
-3.54	-2.36	1.286×10^5	0.252	0.2157	0.601
-2.36	-1.18	1.243×10^5	0.224	0.1642	0.750
-1.18	0.00	7.874×10^4	0.194	0.2563	0.665
0.00	0.98	1.095×10^6	0.129	0.2031	0.622
0.98	1.96	1.086×10^6	0.115	0.2070	0.377
1.96	2.94	1.152×10^6	0.127	0.2472	0.495
2.94	3.92	1.145×10^6	0.178	0.1686	0.459
3.92	4.90	1.117×10^6	0.121	0.1805	0.343
4.90	5.88	9.201×10^5	0.126	0.1156	0.488
5.88	7.17	1.047×10^6	0.109	0.0822	0.334

Table 11
Average Dose Equivalent At The Entrance And Exit Of The Large Maze.

Height (M) From	To	Entrance Dose (mrem/hr)	Fractional Standard Deviation	Exit Dose (mrem/hr)	Fractional Standard Deviation
-4.72	-3.54	2.351×10^5	0.121	33.30	0.223
-3.54	-2.36	1.409×10^5	0.132	45.48	0.234
-2.36	-1.18	1.310×10^5	0.123	55.84	0.255
-1.18	0.00	1.411×10^5	0.146	62.68	0.239
0.00	0.98	1.047×10^6	0.087	73.74	0.251
0.98	1.96	1.085×10^6	0.090	74.74	0.258
1.96	2.94	1.224×10^6	0.102	84.39	0.243
2.94	3.92	1.170×10^6	0.080	82.51	0.233
3.92	4.90	1.206×10^6	0.096	87.41	0.223
4.90	5.88	1.242×10^6	0.081	76.56	0.246
5.88	7.17	1.124×10^6	0.078	64.59	0.289

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