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**ONE-DIMENSIONAL GAMMA-RAY SHIELDING ANALYSIS
FOR EBT-P***

by

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ABSTRACT

A one-dimensional scoping study was performed for the gamma ray shield of the ELMO Bumpy Torus proof-of-principle (EBT-P) device. The objective was to define appropriate shielding material and determine the required shielding thickness for EBT-P. The dose equivalent results as a function of the radiation shield thickness for different shielding options are presented. A sensitivity analysis for the pessimistic case is given. The recommended shielding option based on the performance and cost is discussed.

1. INTRODUCTION

A one-dimensional scoping study was performed for the gamma ray shield of the ELMO Bumpy Torus proof-of-principle device (EBT-P) for four different operating scenarios. The emphasis in this study was to define appropriate shielding materials and determine the required shielding thickness for EBT-P. The main objective of the EBT-P radiation shield is to achieve a dose equivalent of 0.25 mrem/hr during operation outside the outer shield wall of the 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) iron-scrap-based concrete. In this report, the dose equivalent results as a function of the radiation shield thickness from each shielding option are presented, the geometrical model and calculational method are described, a sensitivity analysis for the pessimistic case is presented, and the recommended shielding option based on the performance and cost is discussed.

2. GEOMETRICAL MODEL AND CALCULATIONAL METHOD

EBT-P is a toroidal array of 36 magnetic mirrors (36 cavities). Figure 1 shows a vertical cross section of the torus area, while Fig. 2 gives the details for one of these cavities. The gamma ray source in each cavity consists of three rings, two scattered sources from the limiter and one direct source, as shown in Fig. 2. A one-dimensional model based on the geometrical configuration shown in Figs. 1 and 2 was used to perform the scoping study. The photon source was approximated by a 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. 3. This model was

Figure 1. Vertical cross section for torus area.

Figure 2. Cross section of the cavity showing the gamma ray source locations.

Figure 3. One-dimensional geometrical model used for the dose equivalent analysis.

developed to give a conservative estimate for the dose equivalent outside the shield.

The analysis was performed for four different sources [1] 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 four sources in a 21 energy group structure. [1]

The photon transport calculations were performed with the one-dimensional discrete ordinates code ANISN. [2] The photon interaction cross section data were obtained from DLC-41C library. [3] A 21 gamma ray group cross section data library was used for the calculations. The dose equivalent was calculated from the gamma flux using the flux to dose conversion factor of the American National Standard ANSI/ANS-6.1.1-1977. The atomic densities for the different materials used in the scoping study are listed in Table 2.

3. DOSE EQUIVALENT RESULTS FOR THE DIFFERENT SHIELDING OPTIONS

The photon sources listed in Table 1 were used to calculate the dose equivalent as a function of the shield thickness. The geometrical model has a ring source of 20 cm internal radius and 2.5 cm thickness simulating the three ring sources in the cavity. The photon source was treated as an isotropic

Table 1

Gamma Ray Source Strength Per Cavity from the Four Different Operating Scenarios

Source No.	1		2		3		4	
Group Energy (Mid-Point) (MeV)	Total Power (Watts)	Gamma Source (Photon/s)	Total Power (Watts)	Gamma Source (Photon/s)	Total Power (Watts)	Gamma Source (Photon/s)	Total Power (Watts)	Gamma Source (Photon/s)
5.000E-02	5.367E+00	1.169E+15	1.118E+00	1.396E+14	4.569E+00	5.704E+14	3.268E+00	4.080E+14
1.500E-01	8.084E+00	3.364E+14	8.993E-01	3.742E+13	4.497E+00	1.871E+14	2.819E+00	1.173E+14
3.000E-01	1.276E+01	2.655E+14	1.341E+00	2.791E+13	7.911E+00	1.646E+14	4.447E+00	9.253E+13
7.000E-01	2.531E+01	2.257E+14	2.429E+00	2.166E+13	1.866E+01	1.664E+14	8.820E+00	7.865E+13
1.250E+00	1.339E+01	6.685E+13	1.150E+00	5.743E+12	1.198E+01	5.983E+13	4.665E+00	2.330E+13
1.750E+00	9.396E+00	3.351E+13	7.396E-01	2.638E+12	9.858E+00	3.516E+13	3.276E+00	1.169E+13
2.250E+00	6.716E+00	1.863E+13	4.890E-01	1.357E+12	8.269E+00	2.294E+13	2.344E+00	6.503E+12
2.750E+00	4.827E+00	1.096E+13	3.284E-01	7.454E+11	7.016E+00	1.592E+13	1.687E+00	3.829E+12
3.250E+00	3.468E+00	6.661E+12	2.226E-01	4.276E+11	5.993E+00	1.151E+13	1.213E+00	2.330E+12
3.750E+00	2.483E+00	4.133E+12	1.517E-01	2.526E+11	5.139E+00	8.554E+12	8.698E-01	1.448E+12
4.250E+00	1.768E+00	2.597E+12	1.037E-01	1.523E+11	4.414E+00	6.483E+12	6.202E-01	9.108E+11
4.750E+00	1.252E+00	1.645E+12	7.092E-02	9.319E+10	3.794E+00	4.985E+12	4.395E-01	5.776E+11
5.250E+00	8.810E-01	1.047E+12	4.847E-02	5.763E+10	3.259E+00	3.875E+12	3.096E-01	3.681E+11
5.750E+00	6.162E-01	6.689E+11	3.309E-02	3.592E+10	2.797E+00	3.036E+12	2.167E-01	2.353E+11
6.250E+00	4.284E-01	4.279E+11	2.254E-02	2.251E+10	2.396E+00	2.393E+12	1.508E-01	1.506E+11
6.750E+00	2.962E-01	2.739E+11	1.532E-02	1.416E+10	2.050E+00	1.895E+12	1.044E-01	9.651E+10
7.250E+00	2.038E-01	1.754E+11	1.038E-02	8.938E+09	1.750E+00	1.506E+12	7.183E-02	6.184E+10
7.750E+00	1.394E-01	1.123E+11	7.018E-03	5.652E+09	1.491E+00	1.200E+12	4.919E-02	3.962E+10
9.000E+00	2.323E-01	1.611E+11	1.146E-02	7.951E+09	4.020E+00	2.788E+12	8.203E-02	5.689E+10
1.100E+01	4.736E-02	2.687E+10	2.278E-03	1.292E+09	2.035E+00	1.155E+12	1.675E-02	9.507E+09
1.300E+01	9.191E-03	4.413E+09	4.353E-04	2.090E+08	9.996E-01	4.900E+11	3.255E-03	1.563E+09
TOTALS	1.017E+02	2.144E+15	9.195E+00	2.351E+14	1.129E+02	1.272E+15	3.547E+01	7.480E+14

Table 2
Densities of Candidate Materials

Material (gm/cm³)	Density	Atom/cm³ x 10²⁴	
Type 316 SS	7.86	Cr	0.01520
		Mn	0.00123
		Fe	0.05462
		Ni	0.01121
		Mo	0.00140
Ordinary Concrete	2.26	H	0.00418
		O	0.03855
		Si	0.01567
		Ca	0.00481
		Fe	0.00195
Heavy Concrete (Magnetite Type)	3.60	H	0.01506
		O	0.04662
		Si	0.00169
		Ca	0.00357
		Fe	0.02178

volume source. 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. Three different shielding options were analyzed: a) ordinary concrete shield, b) heavy concrete shield (magnetite type), and c) ordinary concrete with internal layer of iron (type 316 steel punchings).

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. The photoneutrons and the secondary gamma rays produced by these neutrons increase the dose equivalent by two to three orders of magnitude for the lead shield option. [4]
- b) The photoneutrons generate radioactive materials in the different components of EBT-P which affects the hand-on maintenance and accessibility of the torus area.
- 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 sections (P_L) for the calculations will be examined later.

The dose equivalent from each photon source as a function of the ordinary concrete shield thickness is presented in Fig. 4. Similar results for the heavy concrete are given in Fig. 5. Table 3 gives the required shield thickness for each source to achieve an 0.25 mrem/hr dose equivalent. Three conclusions have been reached based on these calculations:

- a) Source No. 3 gives the highest dose equivalent.

Figure 4. Dose equivalent rates for the different sources as a function of the ordinary concrete shield thickness.

Figure 5. Dose equivalent rates for the different sources as a function of the heavy concrete shield thickness.

- b) The shield thickness required for Source No. 3 to reduce the dose equivalent to 0.25 mrem/hr is 261 cm of ordinary concrete.
- 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.

Figure 6 gives the dose equivalent rate from a three-layered shield. The arrangement consists of ordinary concrete, type 316 stainless steel, and an ordinary concrete layer. The calculations did use a type 316 stainless steel for the second layer of the shield instead of the iron-scrap-based concrete. The use of intermediate-Z materials (type 316 stainless steel) 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 between two thick layers of ordinary concrete reduces the photoneutron generation rate by orders of magnitude.
- c) The unit cost of an ordinary concrete shield with a layer of type 316 stainless steel is low compared to the heavy concrete.

The use of such a concept requires more analysis which is beyond the scope of this study although the merits are recognized.

4. GAMMA RAY FLUXES AND HEATING RATES

Figure 7 shows the gamma ray fluxes at 240 cm of ordinary concrete shield for the four different sources. The dose equivalent at this particular thickness is listed in Table 3 for each source. Also, the gamma ray heating rates in the first wall and the maximum heating rates in the concrete are given in Table 4. All the maximum heating rates in the concrete are lower than the concrete design criteria [5] as shown in Table 5. These design criteria protect the concrete against loss of water, temperature effects, radiation absorption effects, and stress conditions.

Figure 6. Dose equivalent rates for the different sources as a function of the shield thickness.

Figure 7. Gamma ray fluxes at 240 cm of ordinary concrete shield.

Table 3

Shield Thickness for 0.25 $\mu\text{rem/hr}$ Dose Equivalent
from the Different Photon Sources

Source Number	Shield Thickness (cm)	
	Ordinary Concrete	Heavy Concrete
I	222	136
II	178	110
III	261	155
IV	206	126

Table 4

Heating Rate in the First Wall, Maximum Heating Rate in the
Ordinary Concrete Shield, and Dose Equivalent at 240 cm
of Ordinary Concrete Shield

	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 ($\mu\text{rem/hr}$)	0.078	0.004	0.803	0.028

Table 5

Design Criteria for the Concrete Shield with Gamma Ray Source

Maximum Internal Temperature	177°C
Maximum Ambient Air Temperature	149°C
Maximum Heat Generation Rate	1 mW/cm^3
Maximum Temperature Gradient through the Shield	$dt/dx = 1^\circ\text{C/cm}$

5. SENSITIVITY ANALYSIS

The sensitivity of the results to the different approximations in the calculational procedure are examined in this section. The calculations in the previous section 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 on the results. Figure 8 shows 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 biological dose for Source No. 3 was recalculated with P_5S_6 , P_5S_8 , and P_5S_{12} , and the results are displayed in Fig. 9. 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.

Figure 10 gives the biological dose from Source No. 3 with two different cutoffs for the gamma ray source. The results show that the change in the biological dose at 0.25 mrem/hr is 2% when the cutoff energy is changed from 14 to 10 MeV. Also, the source strength drops very fast with energy above 10 MeV which indicates the adequacy of the 14 MeV cutoff energy.

6. CONCLUSIONS

In order to recommend a specific shielding option for EST-P, the cost of each option was calculated subject to the 0.25 mrem dose equivalent design criteria. However, the unit cost for a specific type of concrete varies

Figure 8. Dose equivalent rates from Source No. 3 for different P_L approximations.

Figure 9. Dose equivalent rates for Source No. 3 for different S_n approximations.

Figure 10. Biological dose rates from Source No. 3 with two different cutoff energies.

greatly depending on the location, type of forms, and construction method. Table 6 gives the installed cost per cubic yard for the different concrete types. Table 7 compiles data from the previous tables and figures 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. However, the reduction in the shield thickness for Source No. 3 is 41% which makes the ordinary concrete shield option more attractive. The use of the laminated shield option of ordinary and iron-scrap 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.

Table 6
Typical Installed Cost for Concrete

Concrete Type	Installed Cost Per Cu. Yd. for 1970 (\$)	Installed Cost Per Cu. Yd for FMJT(6) (\$)
Ordinary	154	300
Magnetite	430	900
Iron Scrap Based	780	1560*

*Estimated from 1970 Cost

Table 7
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	261	856
Magnetite	155	1526
Ordinary and Iron- Scrap Based	120 + 150	1247

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