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MMW SHIELDING DESIGN AND ANALYSIS

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Arne P. Olson

Applied Physics Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
(312) 972-4873

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Author running head: Arne P. Olson

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Address all correspondence to: Dr. Arne P. Olson

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MMW SHIELDING DESIGN AND ANALYSIS

Arne P. Olson
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

ABSTRACT

Reactor shielding for multimagawatt (MMW) space power must satisfy a mass constraint as well as performance specifications for neutron fluence and gamma dose. A minimum mass shield is helpful in attaining the launch mass goal for the entire vehicle, because the shield comprises about 1% to 2% of the total vehicle mass. In addition, the shield internal heating must produce tolerable temperatures. The analysis of shield performance for neutrons and gamma rays is emphasized. Topics addressed include cross section preparation for multigroup 2D S_n-transport analyses, and the results of parametric design studies on shadow shield performance and mass versus key shield design variables such as cone angle, number, placement, and thickness of layers of tungsten, and shield top radius. Finally, adjoint methods are applied to the shield in order to spatially map its relative contribution to dose reduction, and to provide insight into further design optimization.

INTRODUCTION

Reactor shielding for multimegawatt (MMW) space power must satisfy a mass constraint as well as performance specifications for neutron fluence and gamma dose. A minimum mass shield is helpful in attaining the launch mass goal for the entire vehicle, because the shield comprises about 1% to 2% of the total vehicle mass. In addition, the shield internal heating must produce tolerable temperatures. Finally, the shield materials must remain physically and chemically stable for the lifetime of the vehicle.

Performance guidelines for the shield back were arbitrarily selected:

- Neutron fluence $\leq 3 \times 10^{15}$ n/cm^2 (for E_n > 111 keV) and

- Gamma dose to silicon $\leq 2 \times 10^7$ rads.

This work emphasized shield performance for neutrons and gammas. The derived heating rates are essential inputs for auxiliary calculations to predict temperature profiles, thermal expansion, thermal stresses, and structural strength. Topics to be addressed include cross section preparation for multigroup 2D S_n-transport analyses, and the results of parametric design studies on shadow shield performance and mass versus key shield design variables such as cone angle, number, placement, and thickness of layers of tungsten, and shield top radius. Finally, adjoint methods were applied to the shield in order to spatially map its relative contribution to dose reduction, and to provide insight into further design optimization.

CROSS SECTION PREPARATION

Energy deposition in a nuclear reactor consists of a primary component from fission product recoil, plus smaller contributions from neutron slowing down (neutron heating), from photon slowing down (photon heating), and from stopping of charged particles such as β^-, β^+, and α. Fortunately, the micrometer-scale range of fission products and heavy charged particles makes for an accurate approximation that such heating is deposited locally, at the site of its production. Energy deposition in a shield is simpler, in principle, because it has no fission products. In practice, it may be difficult to compute accurately because of the sensitivity to particle transport effects, or because of limitations in basic cross section data.

Cross section data of ENDF/B-V (Kinsey 1978) were processed by NJOY, (MacFarlane et al. 1982) followed by space and energy dependent collapsing over asymptotic spectra via MC^2-2/SDX (Wade 1975 and 1978 and Henryson et al. 1976). Various multigroup structures were prepared in order to study shield performance at several levels of detail. Any analysis is a compromise between selecting sufficient detail in space, energy, and scattering angle, within the limits of computer memory available and cost-effectiveness. Final heating rates were mostly obtained from a 9 neutron/8 gamma group library, using the TWODANT code (Alcouffe et al. 1984) (S_4-P_1 quadrature) in R-Z geometry. The energy group structures used are given in Table 1. Portions of DIF3D (Derstine 1984) were used for reaction rate summaries.

Although gamma transport data for energies less than 0.1 MeV are available, the photon cross sections become very large below this energy. As a consequence the S_n transport mesh interval requirements become impractically large. Cross section sets were initially prepared in 9 neutron by 9 gamma group form, having a single extra gamma group from 10^5 eV down to 10^3 eV. This library caused massive convergence difficulties in TWODANT (and only in group 9).

Spatial detail surveys were also conducted, using as many as 48 x 285 mesh intervals, through relaxing the energy detail down to 5 neutron and 5 gamma groups. Results shown in Tables 2 and 3 indicate silicon dose predictions of at least a factor of 4 higher when 5N x 5G was used, as opposed to 9N x 8G. Because the neutron fluence data only change by 20 to 25%, it is clear that gamma transport effects (longer mean free paths) from few-group averaging must be largely responsible for the inaccuracy of the silicon gamma dose predictions obtained using 5N x 5G.

GEOMETRICAL MODEL OF MMW CORE AND SHIELD

Figure 1 is a schematic of a reactor core, control drums, shield, and power conditioning equipment. Cone angles of 30° and 25° were assumed in preparing the geometrical model. This model included 12 control drums, 3 core zones, axial reflector and plenum zones, void spaces around the drums, and all shield layers. The power conditioning equipment (PCE) was homogenized into two uniform truncated conical segments.

S_n-P_ℓ transport calculations were carried out with TWODANT using various R-Z or slab representations. A symmetry plane was assumed to be located at the core axial midplane.

Correlations of gamma dose (rads) to silicon versus total tungsten thickness (t) were approximately fitted to the TWODANT S_n transport results for four shield designs (see Figure 2). All four shield designs used the same first two layers of B_4C and TZM.

1. <u>Three-Layer Shield of Be_2C and W</u>

   Including PCE reflection effects following the shield, and three tungsten layers of thickness ratios 4:2:1, and $t=t_1 + t_2 + t_3 > 0$:

$$\text{dose} = 2.662 \times 10^7 \exp(-0.440\ t) + 1.459 \times 10^8 \exp(-1.288\ t);$$

2. <u>Two-Layer Shield of Be_2C and W</u>

   Assuming a first layer fixed at 3 cm, ignoring PCE enhancement, and $t = 3 + t_2 > 3$:

$$\text{dose} = 1.224 \times 10^9 \exp(-0.7539t);$$

3. <u>One-Layer Shield of Be_2C and W</u>

   Assuming $t = t_1 > 0$, ignoring PCE enhancement:

$$\text{dose} = 6.94 \times 10^8 \exp(-0.1423\ t);$$

4. <u>Three-Layer Shield of LiH and W</u>

   Including PCE reflection effects for three tungsten layers of thickness ratios 4:2:1, and $t = t_1 + t_2 + t_3 > 0$:

$$\text{dose} = 8.64 \times 10^8 \exp(-0.505\ t) + 1.9 \times 10^9 \exp(-1.3\ t).$$

RESULTS AND FINDINGS FROM S_n TRANSPORT ANALYSIS

Shield design and performance parametric studies are plotted in Figure 2. The shield in all cases consists of two light neutron moderators (95% LiH + 5% B_4C, or 95% Be_2C + 5% B_4C) separated by up to three layers of tungsten.

Layer	Thickness	Material
1	t_1	W
2	50 cm	neutron moderator
3	t_2	W
4	50 cm	neutron moderator
5	t_3	W

When not parameters, R_o and θ are held at 31.5 cm and 25°, respectively. Basic results on gamma dose and neutron fluence are given in Table 2. Consider first, the use of Be_2C with B_4C as a neutron attenuator. It is clear that the photon source in the shield itself (following the tungsten in layer 1) is of sufficient magnitude to prevent a single-layer W shield from coming close to acceptance, if all of the W is in layer 1. Of course it could all be in layer 5 - but the volume of layer 5 is so much greater than that of layer 1 as to make this configuration noncompetitive on the basis of mass.

A two-layer shield (tungsten in layers 1 and 5) is much more effective than a shield having just one tungsten layer. The result given in Figure 2 for two layers does not include flux and dose enhancement caused by the presence of the PCE, and so it compares to the "3-layer, without PCE" curve in this figure. The parameter survey yields a satisfactory shield design consisting of 3 + 4.4 cm tungsten, with a mass ~2690 kg.

A three-layer shield is substantially more effective, especially when the tungsten layers are in the thickness ratio: 4:2:1. A total tungsten thickness of 2.12 cm, in a shield of mass ~1530 kg, meets the design silicon gamma dose objective.

Complete substitution of Be_2C by LiH is impractical in a passively cooled shield due to LiH dissociation at high temperatures. Hence, the shield would lose its structural integrity and its performance would be impaired unless its various materials are physically stable and chemically compatible at design temperatures for the life of the system. Nevertheless, if a means of stabilizing the LiH (or encapsulating it in a matrix of some other material) is developed, it is of interest to ascertain whether or not the shield mass can be significantly reduced. From Figure 2, the nominal shield mass is ~1550 kg for a three-layer tungsten shield of total thickness 7.93 cm. It is concluded that while there is no inherent shield mass advantage with respect to the silicon gamma dose design limit, there is a fast neutron fluence advantage from using LiH instead of Be_2C.

A final study of a shield of <u>both</u> Be_2C and LiH in the sequence: $W/Be_2C/W/LiH/W$, was carried out; the LiH being placed where the heating rate is substantially reduced. From Figure 2, correlation E, the optimal composite shield uses ~2.99 cm of tungsten and weighs 1305 kg (r_o = 31.5 cm, θ = 25°). The fast neutron dose goal of 3×10^{15} n/cm^2 is almost precisely met, as is the dose to silicon goal of 2×10^7 rads. This composite shield is the lightest and is recommended subject to verification of satisfactory peak temperatures (and peak power densities) in the LiH.

It is always helpful to know the limitations of a given analysis procedure. The 2D S_n transport calculations are too demanding in computer resources to permit a direct assessment of higher-order S_n or P_n effects. Consequently a suitable 1D model was set up for 3 tungsten layers, in a total thickness of 2.63 cm, for the Be_2C shield configuration comparable to case BE-1 in Table 2. This problem was analyzed using a variety of group structures, S_n orders, and P_n orders. The results are given in Table 3. It is found that the 9N x 8G analysis results in 1D have uncertainties from low S_n order of 5% for fluence and ~16% for silicon dose. It is reasonable to assume similar errors apply to the 2D results of Table 2. Also it is clear that the 5-gamma-group results are subject to substantial error factors for predicted gamma dose to silicon. The large change in fast neutron fluence from 27N down to 9N is not fully understood Since the core center fast neutron fluences agree to within 3%, it is believed that the difference is a neutron transport (coupled with transverse leakage) effect. Because transverse leakage is so highly important to the 1D model's predicted fluence, it is believed to be an effect which is magnified in 1D versus 2D. An uncertainty of ±25% is arbitrarily assigned to the 9N 2D fluences. The highest-energy neutrons generally have very low total cross sections and thus are most likely to escape from the shield via leakage. Group-averaging of total cross sections is performed using spectral weighting which tends to favor the lower-energy neutrons, thus diminishing the penetrating power of those neutrons having the lowest total cross section. In principle, the 1D model should have used group-dependent extrapolation lengths for calculating transverse leakage. But the leakage representation is difficult, at best, making such a refinement unwarranted.

Also given in Table 3 are silicon dose data for prompt gammas alone. It is shown that the dose rate at the bottom of the shield is virtually unchanged when a gamma production matrix omitting delayed gammas at infinite irradiation was used. Doses to silicon at core center do show the effect of delayed gammas: 1.8166×10^{13} rads versus 1.2865×10^{13} rads. However, the delayed gammas have a much softer spectrum than that of the prompt gammas and so the shield is much more effective for them. The gamma heating in the half-core changes from 1.94 MW out of 27.77 MW, to 2.93 MW out of 29.72 MW, when delayed gammas are included.

SHIELD MASS OPTIMIZATION

Final optimization of the shield consists of finding a modified, lighter shield having a more complex geometry. For example, the nominal truncated conical section could be modified by rounded or beveled corners. But one needs an elaborate analysis or experimental test program in order to verify that removed shielding material is truly redundant. Analytically, one would like a "worth map" of the relative importance of each volume element to the silicon gamma dose response, for a number of dose points (on-axis, and at various radial positions). If any material is removed, one must still verify the shield's performance.

This "worth map" was derived by an adjoint flux calculation. Axial and radial "worth" traverses were computed for a silicon gamma detector.

Tungsten is an excellent gamma-attenuating medium, because of its high Z and high density. But in a neutron flux, it also is a strong source of photons via (n; gamma) reactions. The axial worth profiles clearly demonstrated the large sources inside the tungsten layers. A similar phenomenon was observed to occur inside Be_2C. The radial worth maps indicated a significant low-Z scattering pathway via the control drums: photons born in the core could bypass portions of the upper shield and return to the lower shield.

It is concluded that the described adjoint worth methodology is, in fact, a useful means to understand how a given shield is performing. Further study would be necessary in order to confirm its worth for shield optimization. In this simple example, it has identified a gamma pathway through the shield via the low-Z control drum, indicating that a fully-optimized shield would use more tungsten at large radii, and less at small radii.

CONCLUSIONS

A shield design with a cone angle of 25° incorporating three discrete tungsten layers, was found optimal with regard to performance requirements on neutron fluence and gamma dose at a measurement plane at the back of the shield. These requirements were:

- neutron fluence $\leq 3x10^{15}$ n/cm^2 (En > 111kev)
- gamma dose to silicon $\leq 2x10^7$ rods.

The payload will be located many meters away, in the "shadow" of the shield. Geometrical attenuation will assure that much more restrictive dose and fluence limits to payload can be met by simply choosing sufficient separation.

Acknowledgments

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Table 1 Neutron and Gamma Ray Group Structures.

Group	9 Neutron eV	8 Gamma eV	5 Neutron eV	5 Gamma eV
1	1.419 + 7	2.000 + 7	1.419 + 7	2.000 + 7
2	2.231 + 6	8.000 + 6	2.231 + 6	8.000 + 6
3	4.979 + 5	6.000 + 6	4.979 + 5	6.000 + 6
4	1.111 + 5	4.000 + 6	1.111 + 5	4.000 + 6
5	2.479 + 4	2.500 + 6	5.531 + 3	1.500 + 6
6	5.531 + 3	1.500 + 6	0.	1.000 + 5
7	1.234 + 3	7.000 + 5		
8	2.754 + 2	3.000 + 5		
9	1.371 + 1	1.000 + 5		
	0.			

Table 2 S_n Transport Calculations in R-Z Geometry (R_o=31.5cm; θ=25°).

Case No.	No. of Groups Neut.	Gamma	Mesh Intervals	Shield Tungsten Thickness (cm)	Silicon Dose 10^7 rads	Fluence 10^{15}n/cm^2	Total Power MW	PCE Included?	Moderator
LI-1	9	8	48 × 193	1.50+0.75+0.38=2.63	28.6	1.85	29.60	yes	LiH
LI-2				2.86+1.43+0.71=5.00	7.16	1.56			
LI-3				4.57+2.29+1.14=8.00	1.53	1.26			
LI-3R				4.57+2.29+1.14=8.00	1.56	1.93		yes	
BE-1				1.50+0.75+0.38=2.63	1.344	3.69			Be_2C
BE-2				2.86+1.43+0.71=5.00	0.320	2.67			
BE-2R				2.86+1.43+0.71=5.00	0.315	4.24		yes	
BE-3			48 × 170	1.50+0.75+0.38=2.63	0.307	3.04		no	
BE-4				2.29+1.14+0.57=4.00	0.144	2.59			
BE-5				2.86+1.43+0.71=5.00	9.14-2	2.19			
BE-6				3.40+1.70+0.90=6.00	5.87-2	2.16			
BE-7				4.0+2.0+1.0=7.0	3.94-2	1.74			
BE-8			48 × 145	4.0	39.3	3.72			
BE-9				7.0	25.6	2.66			
BE-10				2.0+4.0=6.0	0.759	2.36			
BE-11				3.0+1.0=4.0	6.06	2.67			
BE-12				3.0+3.0=6.0	1.31	2.30			
BE-13				3.0+4.0=7.0	0.624	2.09			
BE-14				4.0+1.0=5.0	5.18	-			
BE-15	5	5	48 × 170	See BE-6	5.91	2.15	28.87	no	Be_2C
BE-16				See BE-7	3.84	1.73			
BE-17			48 × 285	2+4	1.48	2.84		yes	
BE-18				3+1	17.3	3.19			
BE-19				3+3	5.73	2.97			
BE-20				3+4	1.22	2.58			
BE-21			48 × 145	See BE-14	23.0	2.25		no	
LIBE-1	9	8	48 × 193	See LI-2	0.676	1.503	29.60	yes	
LIBE-2				See LI-2	0.655	2.406		yes	
LIBE-3				See LI-1	2.62	3.154		yes	

Table 3 Parametrics in S_n - P_ℓ Order from 1D Transport.

No. of Groups		Fast n Fluence (n/cm^2)		Silicon Dose Into PCE (rads)	S_n Order		P_n Order[a]
Neutron	Gamma	Core Center	Into PCE		Neutron	Gamma	Gamma
		10^{23}	10^{15}	10^6			
27	18	0.4315	6.381	5.978 (6.005)[b]	4	4	1
27	18	0.4314	6.658	7.103 (7.096)[b]	12	12	3
9	8	0.4201	1.622	7.395	4	4	1
9	8	0.4200	1.703	8.544	12	12	3
5	5	0.4126	1.593	34.05	4	4	1
5	5	0.4124	1.672	36.20	12	12	3

[a]All neutron flux calculations use P_1 cross sections.
[b]Prompt gammas alone, no infinite-irradiation delayed gammas.

Figure Captions

Figure 1 Core and Shield Configuration.

Figure 2 Parametric Performance of MMW Shield (R_o = 31.5cm; θ = 25°).

Table Captions

Table 1 Neutron and Camma Ray Group Structures.

Table 2 S_n Transport Calculations in R-Z Geometry (R_o = 31.5 cm; θ = 25°).

Table 3 Parameters in S_n-P_1 Order from 1D Transport.

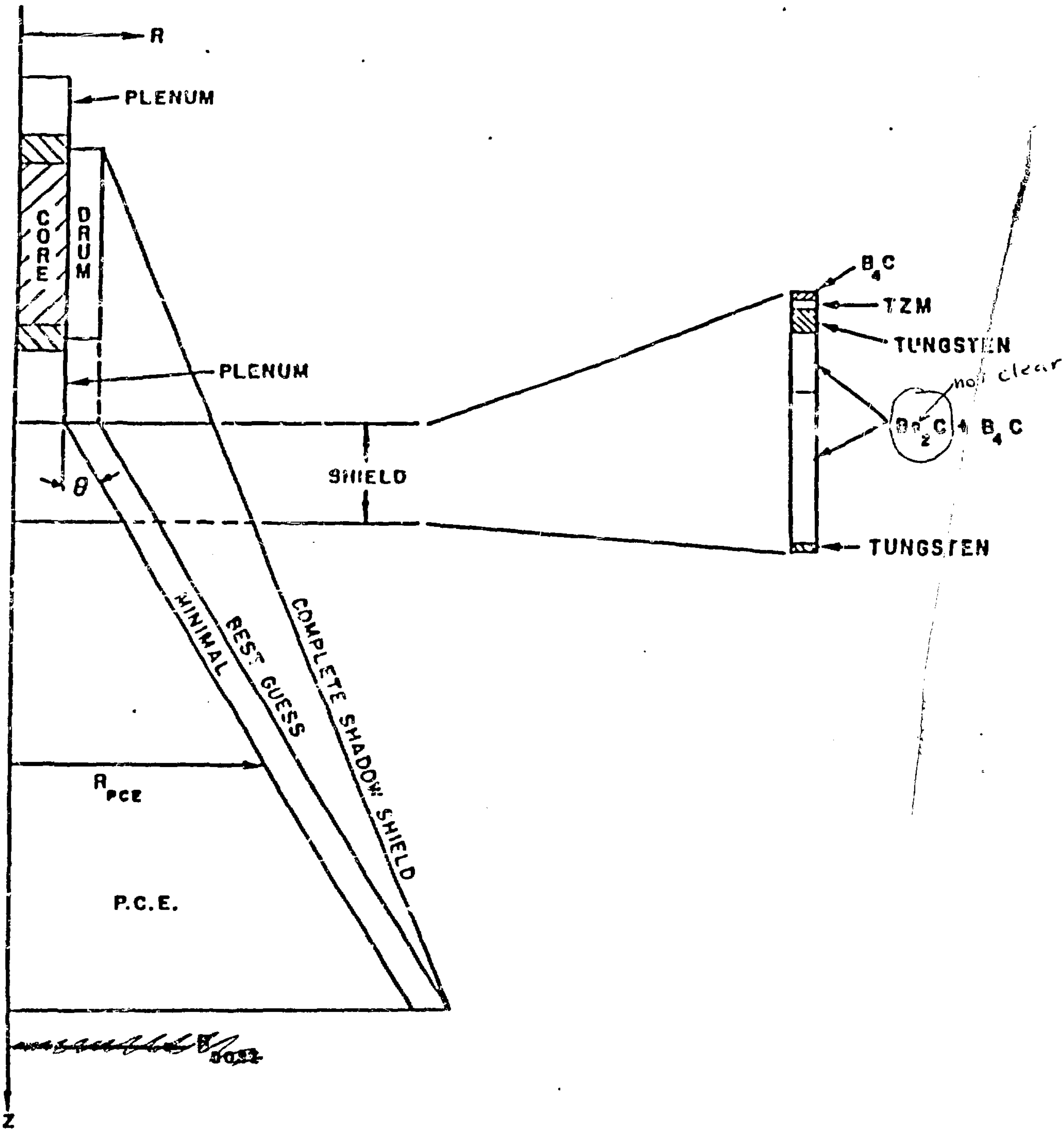

Figure 1. Core and Shield Configuration($R_0 = 31.5cm$; $\theta \sim 25°$).

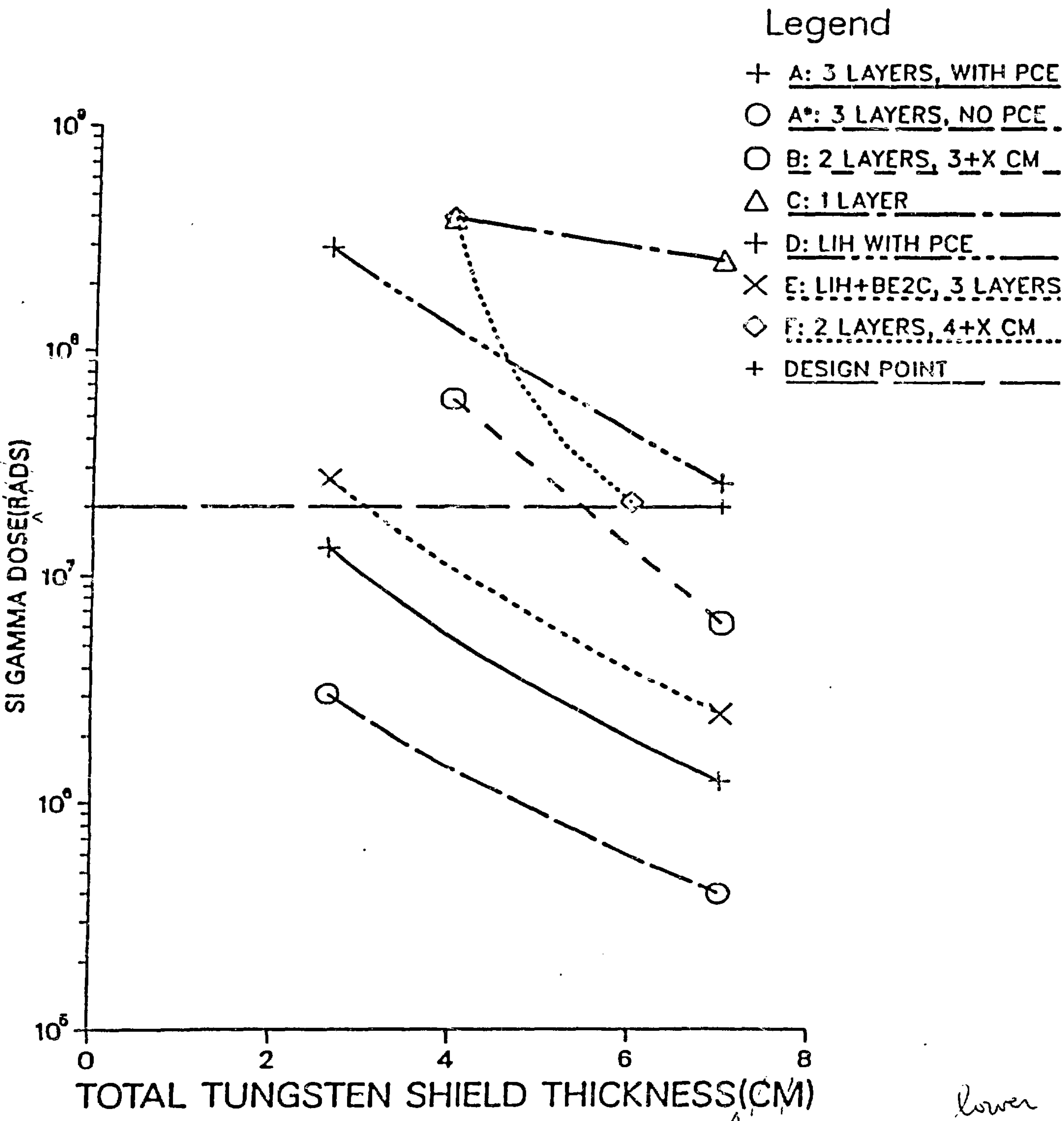

Figure 2. Parametric Performance of MMW Shield.

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Caption: Parametric Performance of MMW Shield (R_o = 31.5cm; θ = 25^o).

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Organization: Argonne National Laboratory

Address: 9700 S. Cass Avenue

Argonne, IL 60439, USA

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