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COMPARISON OF TUNGSTEN AND DEPLETED URANIUM IN MINIMUM-WEIGHT, LAYERED SHIELDS FOR A SPACE POWER REACTOR

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16. Abstract

The weights of layered spherical shields for a fast spectrum 2.2-megawatt-thermal nuclear space power reactor have been calculated for two candidate gamma shield materials, tungsten and depleted uranium, using natural lithium hydride as the material for neutron shielding. Each shield configuration was optimized to a dose rate constraint of 2 millirem per hour at 20 meters. A one-dimensional discrete ordinates transport program and a steepest-descent method optimization program were used.

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SUMMARY

The weights of layered spherical shields for a spherical reactor equivalent to a fast spectrum 2.2-megawatt-thermal space power reactor have been calculated for two candidate gamma shield materials, tungsten and depleted uranium. Three layers of gamma shield material were placed alternately between four layers of natural lithium hydride for neutron attenuation. The dose rate constraint was 2 millirem per hour at a radius of 20 meters. The reactor core of uranium-235 nitride and tantalum had a radius of 26 centimeters and was reflected by 11 centimeters of molybdenum. A one-dimensional discrete ordinates transport program and a steepest-descent method optimization program were used.

The minimum weight of the seven-layer shield was 28 500 kilograms using tungsten and 25 300 kilograms using depleted uranium. About 70 percent of the 2-millirem-per-hour dose rate for both shields is due to capture gammas produced in metals. For either shield, if the reactor power was increased by a factor of 2, or the dose rate constraint was reduced by a factor of 2, the shield weight increased about 10 percent. A reduction in reactor core radius reduced shield weight about 800 to 1000 kilograms per centimeter.

INTRODUCTION

The radiation shield required for manned space missions that use a nuclear reactor for a heat source will be one of the heaviest components in the space power system (ref. 1). Consequently, the designer of such a shield must strive for weight reductions by proper selection of materials and proper choice of the number, thickness, and arrangement of the shield layers.

For space power reactor shields, lithium hydride is generally considered to be one of the best neutron shield materials. It has a high hydrogen density and a dominant (n,α) reaction in lithium-6. Metallic tungsten and depleted uranium (0.23 percent uranium-235) are candidate high-density gamma-ray shield materials. Both materials generate secondary gamma rays by neutron capture and neutron inelastic scattering reactions (i.e, (n,γ) or (n,n'γ) reactions). A method of reducing the production of these secondary gamma rays is to alternate layers of lithium hydride with layers of metal so as to reduce the magnitude of the neutron flux in successive layers of metal.

Because of the strong effect of geometry on weight, the placement and thickness of the metal layers can be critical. Further, because of the complex relation between neutron flux and the secondary-gamma-ray production rates in layered configurations, detailed neutron transport calculations are required to accurately follow the spatial distribution of the neutron flux and subsequent secondary-gamma-ray transport. To optimize a given layered shield with respect to weight for a particular dose rate constraint (that is, to determine the optimum placement and thickness of the gamma-ray shield layers such that the total shield weight is minimized), an iterative optimization procedure has been used.

The purpose of this report is to compare, on a consistent basis, layers of either tungsten or depleted uranium as gamma-ray shield materials using lithium hydride as the neutron shield material. The criterion used for the comparison is the relative weights of minimum-weight shield configurations for a given dose rate constraint. These weights are determined for initially selected spherical seven-layer shield configurations of tungsten-lithium hydride or uranium-lithium hydride wrapped around a spherical uranium-235 nitride and tantalum core that is 26 centimeters in radius and is reflected by 11 centimeters of molybdenum. The reactor operates at 2.2-megawatt-thermal output. The dose rate constraint is 2 millirem per hour at a radius of 20 meters from the center of the core. Possible shield-cooling requirements were not considered. Also determined are the effects of changes in dose rate constraint, reactor power, and core size on the shield weight.

METHOD OF ANALYSIS

The reactor is represented by a spherical core-plenum-pressure vessel arrangement and is surrounded by a molybdenum reflector and a shield that consists of four spherical layers of natural lithium hydride alternated with three layers of either fully dense tungsten or fully dense depleted uranium. The initial shield-layer thicknesses were selected to give a near-optimum weight, and were based on the results of previous exploratory calculations. A schematic representation of the assembly is shown in figure 1. Increasing the number of shield layers beyond seven did not significantly reduce

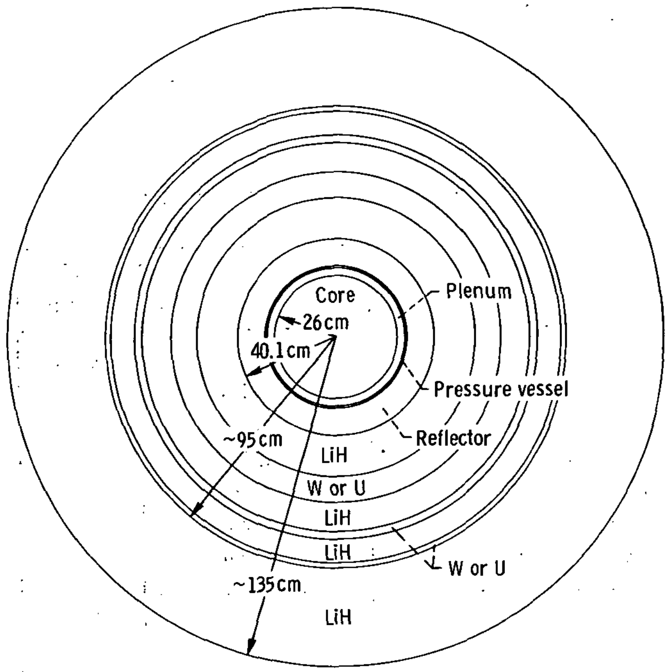

Figure 1. - Schematic representation of layered, spherical assembly. (Approx. to scale.)

the shield weight. The composition of each region or material is given in table I. The initial configurations (layer thicknesses), the dose rates calculated for them, and their weights are listed in table II.

The GAM II (ref. 2) and GATHER II (ref. 3) computer programs were used to obtain a 26-broad group (25 fast, 1 thermal) set of neutron microscopic cross sections and the P_3 downscatter matrix for each of the nuclides in the reactor-shield configurations. Homogeneous resonance calculations were made for the isotopes of tungsten and for uranium-238 mixed with lithium hydride to obtain a conservative estimate of neutron capture cross sections in the resolved resonance region. The neutron energy group boundaries are listed in table III.

The one-dimensional discrete ordinates transport program ANISN (ref. 4) with S_{16} full-range Gauss-Legendre quadrature was used with the P_3 cross sections to obtain the neutron flux distribution by energy group throughout the reactor-shield assembly. The dose rate from core neutrons was obtained from the flux distribution using flux-to-dose-rate conversion factors derived from the fluence-to-kerma factors of reference 5. All of the kerma was assumed to be absorbed locally. This permits direct conversion to absorbed rad dose rate. An average value of 7 was used for the relative biological effectiveness (RBE) to convert the neutron rad dose rate to a rem dose rate.

TABLE I. - COMPOSITION OF MATERIALS

Region and material	Atom density, atoms/barn-cm	Void fraction
Core:		0.109
Lithium-7	0.01158	
Nitrogen	.01316	
Tantalum	.01249	
Tungsten	.002041	
Uranium-235	.012305	
Uranium-238	.000855	
Plenum:		0
Lithium-7	0.022975	
Tantalum	.025590	
Tungsten	.0022385	
Pressure vessel:		0
Tantalum	0.05118	
Tungsten	.004477	
Reflector:		0.100
Lithium-7	0.004595	
Molybdenum	.05763	
Shield:		0
Natural lithium hydride:		
Hydrogen	0.056837	
Lithium-6	.004217	
Lithium-7	.052620	
Depleted uranium:		
Uranium-235	.000109	
Uranium-238	.0472	
Tungsten	.063229	

TABLE II. - SHIELD CONFIGURATIONS AND DOSE RATES

(a) Tungsten gamma shield; total initial shield weight, 35 900 kilograms; total final shield weight, 31 100 kilograms

Region or layer	Initial thickness, cm	Final optimized thickness, cm	Source component	Initial shield thickness	Final optimized shield thickness
				Dose rate from each source, mrem/hr	
Core	[a]26.0	[a]26.0	Neutrons All gammas	0.0243 .0030	0.2927 .0049
Plenum	2.5	2.5	All gammas	.0020	.0031
Pressure vessel	.6	.6	All gammas	.0022	.0035
Reflector	11.0	11.0	Mo(n, γ) Mo(n, n'γ) Total	.2040 .0050 .2090	.2876 .0082 .2958
Lithium hydride-1	17.9	20.6	--	--	--
Tungsten-1	7.0	9.8	W(n, γ) W(n, n'γ) Total	.0921 .0097 .1018	.6000 .0716 .6716
Lithium hydride-2	14.0	12.34	--	--	--
Tungsten-2	5.0	3.0	W(n, γ) W(n, n'γ) Total	.0988 .0278 .1266	.3001 .0707 .3708
Lithium hydride-3	10.0	10.33	--	--	--
Tungsten-3	3.5	2.54	W(n, γ) W(n, n'γ) Total	.2010 .0947 .2960	.2381 .1197 .3578
Lithium hydride-4	59.5	39.3	--	--	--
Total	[a]157.0	[a]138.0		0.765	2.0002

[a]Radius.

TABLE II. - SHIELD CONFIGURATIONS AND DOSE RATES

(b) Depleted uranium gamma shield; initial shield weight, 28 600 kilograms; final shield weight, 27 900 kilograms

Region or layer	Initial thickness, cm	Final optimized thickness, cm	Source component	Initial shield thickness	Final optimized shield thickness
				Dose rate from each source, mrem/hr	
Core	[a]26.0	[a]26.0	Neutrons All gammas	0.4954 .0025	0.3535 .0085
Plenum	2.5	2.5	All gammas	.0016	.0054
Pressure vessel	.6	.6	All gammas	.0019	.0061
Reflector	11.0	11.0	$Mo(n,\gamma)$ $Mo(n,n'\gamma)$ Total	.1590 .0040 .1630	.4599 .0135 .4734
Lithium hydride	19.9	12.0	--	--	--
Uranium-1	9.0	6.27	Neutrons Fission γ $U^{238}(n,\gamma)$ $U^{238}(n,n'\gamma)$ Total	.0186 .0592 .1977 .0323 .3078	.0173 .0666 .2547 .0323 .3709
Lithium hydride-2	12.0	16.78	--	--	--
Uranium-2	3.0	4.48	Neutrons Fission γ $U^{238}(n,\gamma)$ $U^{238}(n,n'\gamma)$ Total	.0049 .0715 .2176 .0377 .3317	.0037 .0846 .2048 .0466 .3397
Lithium hydride-3	10.0	14.66	--	--	--
Uranium-3	2.5	3.16	Neutrons Fission γ $U^{238}(n,\gamma)$ $U^{238}(n,n'\gamma)$ Total	.0043 .1445 .2940 .0695 .5123	.0031 .1371 .2388 .0641 .4431
Lithium hydride-4	40.0	42.58	--	--	--
Total	[a]136.5	[a]141.0		1.8162	2.0006

[a]Radius.

TABLE III. - ENERGY GROUP BOUNDARIES

Energy group	Neutrons, eV	Gammas, MeV
1	1.492×10^{7}	8.0
2	1.221	5.5
3	1.000	5.0
4	8.19×10^{6}	4.5
5	6.07	4.0
6	4.97	3.5
7	4.07	3.0
8	3.01	2.6
9	2.47	2.2
10	2.23	1.8
11	1.83	1.35
12	1.35	.9
13	1.11	.4
14	9.07×10^{5}	.26
15	5.50	.15
16	4.08	.08
17	1.11	
18	1.50×10^{4}	
19	3.35×10^{3}	
20	5.83×10^{2}	
21	1.01	
22	2.90×10^{1}	
23	1.07	
24	3.06×10^{0}	
25	1.13	
26	4.14×10^{-1}	
27	0	

From the multigroup flux distributions and the reaction cross sections for producing secondary gamma rays from GAM II/GATHER II, the number and spatial distribution of capture and inelastic scattering events in each of the nuclides were calculated. The gamma spectra associated with these events (from ref. 6) were then used to define the spatial and energy distribution of secondary gamma sources throughout the assembly. Multigroup gamma cross sections and P_3 downscatter matrices were generated by the computer program GAMLEG (ref. 7), using gamma absorption (photoelectric plus pair production) cross sections from reference 8. The gamma energy group boundaries are listed in table III. ANISN was then used with the S_{16} full-range Gauss-Legendre quadrature to calculate the dose rates from the primary gamma sources in the reactor core and each of the secondary gamma sources. The gamma flux-to-kerma conversion factors were calculated from the mass energy absorption coefficients for muscle from reference 9. All of the kerma was assumed to be absorbed locally.

A separate calculation of dose rate was made for each individual source region and for each type of reaction (capture and inelastic scattering). The dose rate from neutrons and gammas produced by fissions in the depleted uranium of the shield layers was also calculated separately. Separate calculations for each source region are required by the optimization computer program. Separate calculations for the different reactions in a given region are desirable because of the dependence of the respective interaction rates on different portions of the rapidly changing neutron energy spectrum (i.e., the spatial distribution of neutron captures and inelastic scattering reactions are quite different because the reactions primarily involve different neutron energy groups).

The shields were optimized by using the OPEX II computer program described in reference 10. The assumed dose rate-thickness model is of the form

$$D = \sum_i D_i$$

where

$$D_i = C_i \exp\left(-\sum_j \mu_{ij} t_j\right)$$

and D is the total dose rate, D_i is the i^{th} component of the dose rate (i.e., capture gammas from the first layer, . . ., inelastic gammas from the last layer), t_j is the thickness of the j^{th} region, μ_{ij} is an "attenuation coefficient" that describes the effect of a change in the thickness of the j^{th} layer on the i^{th} dose rate component, and C_i is a fitted parameter. To obtain the coefficients for each dose rate component, each layer thickness is systematically perturbed, and dose rates are recalculated; the coefficients are then calculated from the perturbed dose rates (see ref. 10 for details). The transport calculations for the perturbed thicknesses constitute the bulk of the computation effort since approximately $i \cdot j$ calculations are required.

The complete set of coefficients calculated for and used with the initial configuration for each combination of shield materials is shown in table IV. In addition to being used to determine the optimized shield, the coefficients are used to estimate shield weight for other-than-design dose rate constraints. From this model the program first determines a set of thicknesses that meets the dose rate constraint, and then proceeds to minimize the weight by the method of steepest descent. Because the dose rate-thickness model is inexact and the coefficients μ_{ij} are somewhat dependent on layer thickness, a final set of transport calculations is necessary to confirm that the total dose rate from the opti-

TABLE IV. - COEFFICIENTS, μ_{ij}, FOR OPTIMIZATION CALCULATIONS

(a) Tungsten gamma shield

Region or layer	Source component										
	Core neutrons	Core gamma rays	Plenum and pressure vessel secondary gammas	Reflector		Tungsten-1		Tungsten-2		Tungsten-3	
				n, γ	n, n'γ	n, γ	n, n'γ	n, γ	n, n'γ	n, γ	n, n'γ
Lithium hydride-1	0.135	0.0189	0.0147	0.0212	0.0240	0.363	0.230	0.202	0.188	0.184	0.176
Tungsten-1	.248	.774	.772	.805	.795	.272	.181	.239	.254	.254	.258
Lithium hydride-2	.137	.0228	.0204	.0167	.0206	.0210	.0250	.226	.198	.191	.180
Tungsten-2	.232	.770	.766	.790	.781	.798	.827	.178	.126	.205	.237
Lithium hydride-3	.122	.0240	.0220	.0201	.0239	.0187	.0245	.0230	.0250	.223	.181
Tungsten-3	.231	.768	.763	.805	.776	.782	.812	.810	.851	.241	.111
Lithium hydride-4	.119	.0244	.0226	.0196	.0252	.0232	.0286	.0232	.0291	.0231	.0297

(b) Depleted uranium gamma shield

Region or layer	Source component													
	Core neutrons	Core gamma	Plenum and pressure vessel secondary gamma rays	Reflector		Uranium-1			Uranium-2			Uranium-3		
				n, γ	n, n'γ	Fission γ	n, γ	n, n'γ	Fission γ	n, γ	n, n'γ	Fission γ	n, γ	n, n'γ
Lithium hydride-1	0.1238	0.024	0.022	0.021	0.025	0.183	0.2075	0.195	0.167	0.190	0.177	0.153	0.176	0.163
Uranium-1	.2076	.819	.813	.816	.826	.2115	.1266	.127	.211	.158	.206	.221	.207	.222
Lithium hydride-2	.1238	.024	.022	.021	.025	.027	.027	.0235	.181	.245	.197	.156	.194	.169
Uranium-2	.2076	.819	.813	.816	.826	.850	.850	.832	.173	.209	.0723	.212	.164	.208
Lithium hydride-3	.1238	.024	.022	.021	.025	.027	.027	.0235	.028	.028	.024	.160	.212	.175
Uranium-3	.2076	.819	.813	.816	.826	.850	.850	.832	.904	.892	.874	.166	.189	.0676
Lithium hydride-4	.1360	.024	.022	.021	.025	.027	.027	.0235	.028	.028	.024	.030	.030	.025

mized shield arrangement satisfies the constraint. If the total dose rate does not match the constraint, OPEX II is rerun using the dose rates from the final set of transport calculations and the same set of attenuation coefficients. The set of adjusted shield-layer thicknesses that gives a total dose rate of 2 millirem per hour (without further optimization) is then considered to be the optimized configuration. The uncertainties in calculated dose rate are those normally present in any discrete ordinates calculation and include those due to uncertainties in the cross sections themselves, multigroup averages, and the effect of truncation on anisotropic scattering approximations. Although it is beyond the scope of this report to determine the magnitude of the uncertainty in dose rate, a test of the conservativeness of the GAM II capture cross sections for the resonance region is made and discussed in the RESULTS section of this report. The weight penalty associated with a factor of 2 uncertainty is also calculated.

RESULTS

Optimized Configurations

The use of tungsten as the gamma shield material resulted in a total weight of 31 100 kilograms. For depleted uranium the total weight was 27 900 kilograms. The weight of the common core-reflector assembly was 2600 kilograms.

Dose rates from every region and source type are listed in table II for the final, optimized shield configurations. The dose rate from core neutrons was about 15 percent of the total dose rate of 2.0 millirem per hour in both cases. The dose rate from fission neutrons produced in the three depleted uranium shield layers amounted to only about 7 percent of the core neutron dose rate or slightly more than 1 percent of the total. Secondary gammas produced by capture events in the reflector and the heavy layers of the shield account for more than 70 percent of the total for tungsten and 55 percent for depleted uranium. In both cases, about 50 to 75 percent of the neutrons captured in the tungsten or depleted uranium layers have energies between 1 eV and 3 KeV, 20 percent have energies between 3 KeV and 0.9 MeV, and the remainder are either thermal or have energies greater than 0.9 MeV. This distribution is typical of all of the tungsten and uranium shield layers. In the first case, nearly all of the remaining 15 percent of the dose rate is from inelastic scattering events with the tungsten in the shield layers. In the case of the depleted uranium, the remainder is divided between inelastics (10 percent) and fission gammas produced in the shield layers (20 percent). The core gammas amount to less than 0.5 percent of the total dose rate.

The fixed dimensions of the core, plenum, pressure vessel, and reflector, as well as the final thicknesses of the shield layers, total weight, and dose rate components for

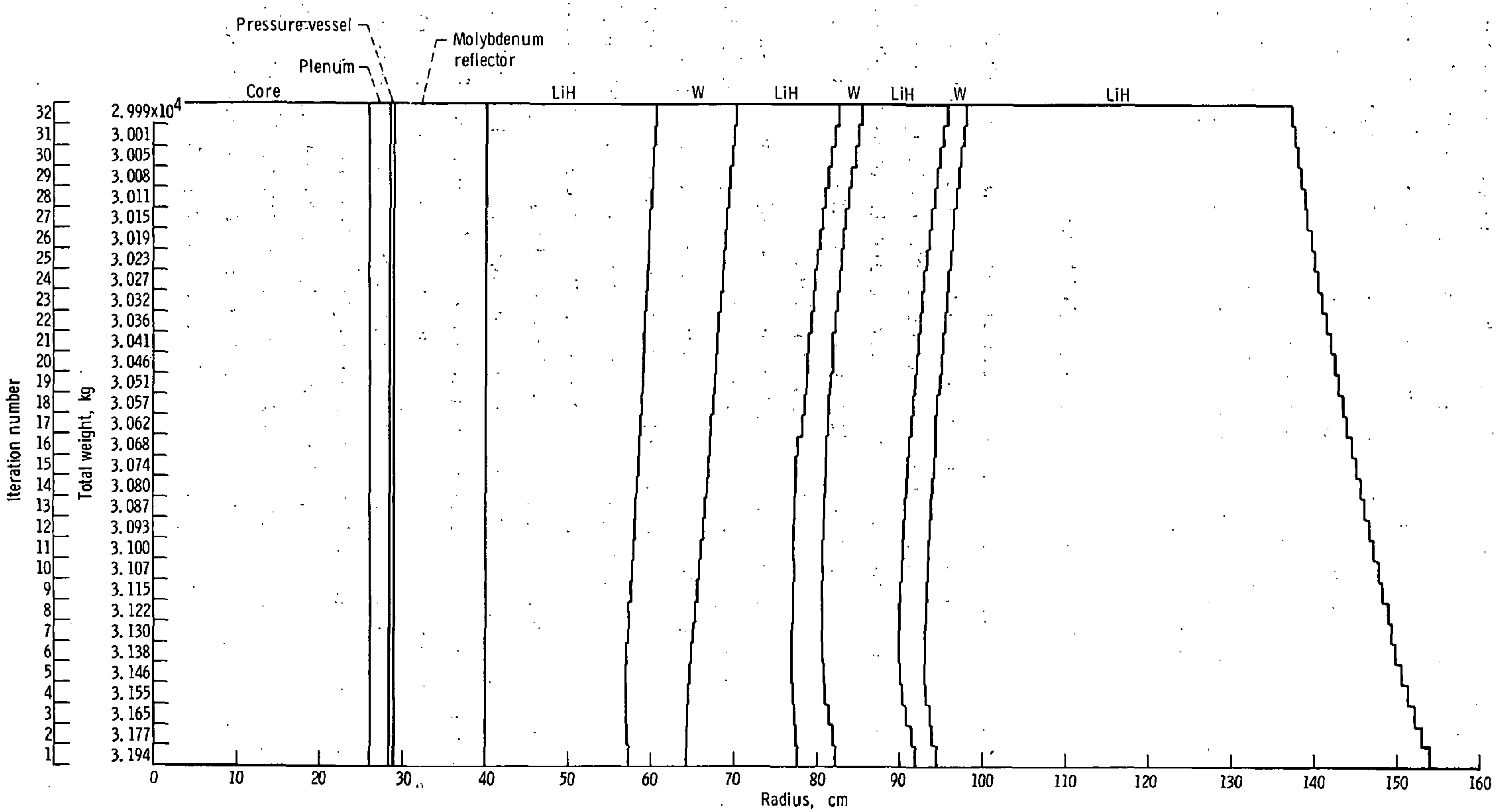

Figure 2. - Results of OPEX-II iterations for tungsten shield case.

the optimized configurations are listed in table II. The thicknesses of the shield layers should not be considered unique. The region of minimum weight for the thick shields considered here is quite broad. Figure 2 illustrates the changes in layer thicknesses for the tungsten case during the course of optimization. Each combination of thicknesses would result in about the same dose rate at the detector (approx. 2 mrem/hr at 20 m), and the weight differences are small when compared to the total weight of a shield that has an optical thickness of 15 to 20 mean free paths. For a dose rate constraint that is higher by 2 or 3 orders of magnitude (i.e., a thinner shield), the minimum weight configuration is more sharply defined.

Estimates of Effects of Some Uncertainties

A transport calculation was also made to determine the importance of the essentially unshielded secondary gammas produced in the outer layer of lithium hydride, which were assumed to be negligible. This calculation considered captures in hydrogen and lithium-7, and inelastic scattering events with lithium-6 and lithium-7. The dose rate at 20 meters was 0.033 millirem per hour, less than 2 percent of the total, justifying the assumption that the secondary gamma rays are negligible.

The conservativeness of the resonance capture cross section from GAM II was tested by estimating the resonance capture rate in the tungsten and uranium layers of the optimized shield configurations shown in table II, using cross sections generated by the code GAROL (ref. 11). This iteration of capture cross section with layer thickness could not have been done in the course of the iteration procedure without unduly lengthening the optimization procedure. In some resonance energy groups the GAROL-calculated capture cross sections were lower than the GAM II values by as much as a factor of 2. This would result in capture rates in the resonance groups that are lower by about 60 percent. And since resonance capture represents 50 to 75 percent of the total number of captures, the total capture rate, and hence to first order, the capture gamma dose rate, would be lower by about 25 percent. This difference was about the same for both the tungsten and uranium shields. Also, since the capture gamma dose rate represents 50 to 70 percent of the total dose rate at the detector, the cross-section correction means, in effect, that the shields were optimized to a dose rate constraint which was 10 to 15 percent lower than 2 millirem per hour. This would not affect the relative shield weight difference as will be shown in the next section of this report.

Variable Parameters

The consequence of a factor of 2 increase in reactor power, or a factor of 2 decrease in the dose rate constraint, or systematic inaccuracies in the dose rate calculations such that they are too low by a factor of 2, is an increase in the shield thickness to produce an additional factor of 2 attenuation. The approximate effect of such an increase in attenuation on the total weight of the configuration was determined by using the optimization program to adjust the thicknesses of the shield layers to meet a dose rate constraint of 1.0 millirem per hour. Using the original set of attenuation coefficients and the layer thicknesses and dose rates from the configuration optimized to 2 millirem per hour, the optimization program adjusted the layer thicknesses to meet the new constraint. The weight of the adjusted configuration was compared to the weight for the 2-millirem constraint. This was done for both tungsten and uranium and was repeated for a constraint of 3 millirem per hour. A change of about 10 percent in shield weight was required to achieve a factor of 2 change in shield attenuation for both tungsten and uranium. These results are shown in figure 3.

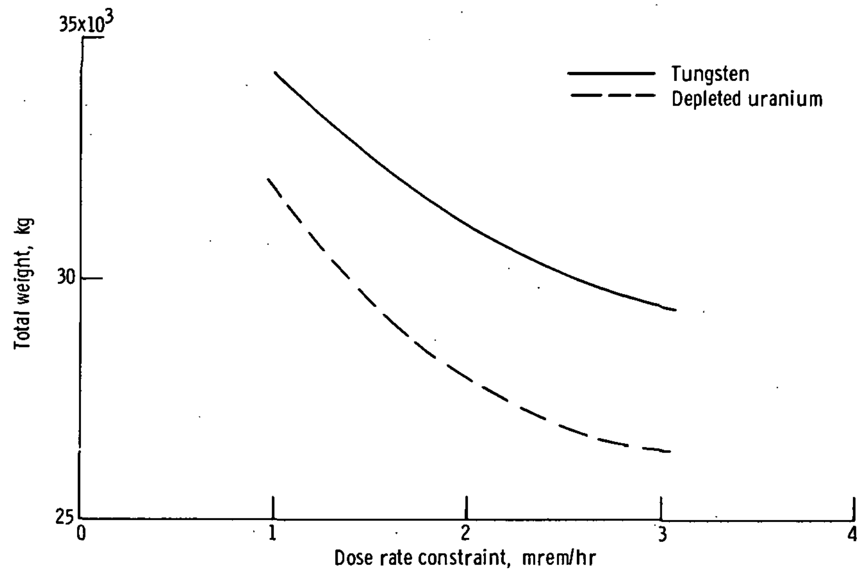

Figure 3. - Variation of total assembly weight with dose rate constraint. Core radius, 26 centimeters.

Over a small range of core radii, it can be assumed that the leakage of neutrons from the core is independent of core radius. To approximate the effect of core radius on the total weight of the configurations, all of the layers outside the core from the configurations optimized to 2 millirem per hour were wrapped around cores with different radii. The thickness of the plenum, pressure vessel, reflector, and each of the shield layers was identical to the thickness from the 2-millirem optimized configuration for that combination of shield materials. The total weight was then calculated for each different core radius. The results are shown in figure 4. Again, the variation was about the same for the tungsten and uranium shields, about 800 to 1000 kilograms per centimeter of core radius.

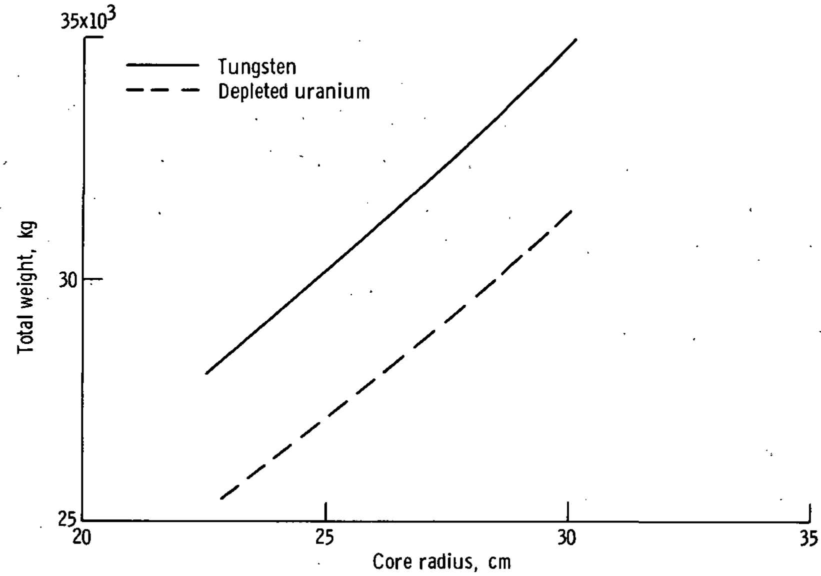

Figure 4. - Variation of total assembly weight with core radius. Dose rate constraint, 2 millirem per hour.

CONCLUSIONS

The use of fully dense depleted uranium layered with lithium hydride in a spherical shield configuration for a nuclear space power reactor with a thermal power of 2.2 megawatts resulted in an optimized shield weight of 25 300 kilograms. The uranium-235 nitride and tantalum core was 52 centimeters in diameter and was reflected by 11 centimeters of molybdenum. The dose rate constraint was 2.0 millirem per hour at a radius of 20 meters. The use of fully dense tungsten with lithium hydride resulted in an optimized shield weight of 28 500 kilograms for the same core-reflector configuration. The thickness of both shields was about 100 centimeters, and each consisted of four layers of lithium hydride alternated with three of uranium or tungsten. Fifteen to 20 percent of the total dose rate was from primary neutrons. Secondary gamma production in the uranium or tungsten layers accounted for the remainder. The primary gamma dose rate was less than 0.5 percent of the total.

The effect on the system weight of variations in the reactor power level, changes in the dose rate constraint, and changes in the core radius were also determined. The consequence of a factor of 2 increase in reactor power or a factor of 2 decrease in the dose rate constraint is an increase of about 10 percent in the total weight. The variation with core radius was 800 to 1000 kilograms per centimeter of core radius.

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Cleveland, Ohio, June 26, 1969,
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