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OPTIMIZED 4π SPHERICAL-SHELL DEPLETED URANIUM-WATER SHIELD WEIGHTS FOR 200- TO 550-MEGAWATT REACTORS

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16. Abstract

Optimization calculations to determine minimum 4π spherical-shell shield weights were performed at 200-, 375-, and 550-megawatt-thermal reactor power levels. Monte Carlo analyses were performed for a reactor power level corresponding to 375 megawatts. Power densities for the spherical reactor model used varied from 64.2 to 256 watts per cubic centimeter (1.81 to 7.25 MW/ft^3). The dose rate constraint in the optimization calculations was 0.25 mrem per hour at 9.14 meters (30 ft) from the reactor center. The resulting shield weights were correlated with the reactor power levels and power densities by a regression analysis. The correlation equation is $W_s = 44100P^{(0.473-0.0539 \ln \rho_P)}$ where W_s is the shield weight in pounds, P the core power level in megawatts, and ρ_P the power density in megawatts per cubic foot. The optimum shield weight for a 375-megawatt, 160-watt-per-cubic-centimeter (4.53-MW/ft^3) reactor was 202 000 kilograms (445 000 lb).

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by Millard L. Wohl, Jack Celnik,* and Robert D. Schamberger*

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SUMMARY

Parametric studies were performed to determine weight-optimized 4π spherical-shell uranium-water shield configurations for 200-, 375-, and 550-megawatt spherical reactors. Power densities were 64.2, 160, and 256 watts per cubic centimeter (1.81, 4.53, and 7.25 MW/ft^3).

Neutron and gamma-ray Monte Carlo transport analyses were performed for the 375-megawatt, 160-watt-per-cubic-centimeter (4.53-MW/ft^3) reactor shield. Neutron and gamma-ray attenuation parameters and secondary gamma-ray production parameters were determined from the results of these Monte Carlo analyses. These parameters were used as input variables for the optimization code UNAMIT.

UNAMIT was then used to perform the optimization analyses for a dose rate constraint of 0.25 mrem per hour at 9.14 meters (30 ft) from the reactor center. The optimized shield weights generated with UNAMIT were correlated with the reactor power levels and power densities by a regression analysis. The correlation is

$$W_s = 44100P^{(0.473-0.0539 \ln \rho_P)}$$

where W_s is the shield weight in pounds, P the core power level in megawatts, and ρ_P the power density in megawatts per cubic foot. The optimum shield weight for the 375-megawatt, 160-watt-per-cubic-centimeter (4.53-MW/ft^3) case was 202 000 kilograms (445 000 lb).

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INTRODUCTION

Minimum weight shield configurations are desirable in most mobile nuclear powerplant applications. Examples of these are powerplants for nuclear aircraft, air-cushion vehicles, other ocean-going vehicles, and many spacecraft modules.

Previous studies have established parametric 4π-spherical minimum shield weights for nuclear reactors in the 150- to 350-megawatt range (ref. 1). These studies considered various shield material combinations - heavy and light hydrides, heavy hydrides and water, lead and water, and tungsten and water.

One isolated analysis of a depleted uranium-water shield indiated that lower weight shields might be obtained with this combination of materials. The chief advantage of depleted uranium lies in its lower neutron capture rate (than, e.g., tungsten) and its correspondingly lower secondary gamma production rate due to its lower average capture cross section.

As a result the depleted uranium-water material combination was selected for the present parametric optimized shield weight studies for power levels in the range of 200 to 550 megawatts. Powerplants in this power range would have application to nuclear aircraft, air-cushion vehicles, and some ocean-going vehicles. The purpose of this report is to provide parametric depleted uranium-water shield weights for mission planners.

The analysis consisted of the following calculations: A Monte Carlo calculation was made for a reactor-shield configuration at 375 megawatts and a power density of 160 watts per cubic centimeter (4.53 MW/ft^3) to generate the parameters for the optimization code UNAMIT. UNAMIT optimization calculations were performed at power levels of 200, 375, and 550 megawatts for power densities of 64.2, 160, and 256 watts per cubic centimeter (1.81, 4.53, and 7.25 MW/ft^3). The dose rate constraint was 0.25 mrem per hour at 9.14 meters (30 ft) from the reactor center.

ANALYSIS

The purpose of the analysis performed is to generate 4π optimum unit shield weights in the 200- to 550-megawatt power range and the 35- to 350-watt-per-cubic-centimeter (1- to 10-MW/ft^3) power density range. This is done by applying a combination of Monte Carlo neutron and gamma-ray transport codes (SANE 2M and SAGE 4) and the shield optimization code UNAMIT (ref. 2).

This study differs from previous NASA parametric shield optimization studies (e.g., ref. 1) significantly because of the much lower external dose rate constraint. The allowed external dose rate was reduced from the previous specification of 2.5 millirem per hour at 39.6 meters (130 ft) from the reactor center to 0.25 millirem per hour at 9.14 meters (30 ft). All dose rates refereenced in this report are at the 9.14-meter (30-ft) distance.

Geometry

The standard depleted uranium-water shield consisted of 23 spherical shield layers surrounding the reflected reactor core, as shown in table I. This multilayered configuration, determined from experience with a previously analyzed tungsten-water shield

TABLE I. - STANDARD 375-MW REACTOR-SHIELD CONFIGURATION

Physical region	Type		Outer radius, cm
1	Core		82.38
2	Be reflector	Mix 1	90.0
3	Uranium		93.0
4	Water		100.0
5	Uranium		103.0
6	Water		110.0
7	Uranium		113.0
8	Water		120.0
9	Uranium		123.0
10	Water		130.0
11	Uranium	Mix 2	132.0
12	Water		140.0
13	Uranium		142.0
14	Water		150.0
15	Uranium		152.0
16	Water		160.0
17	Uranium		162.0
18	Water		170.0
19	Uranium	Mix 3	172.0
20	Water		190.0
21	Uranium		192.0
22	Water		210.0
23	Uranium		212.0
24	Water		230.0
25	Water		320.0
26	Air		1000.0

(ref. 1), is the one upon which the Monte Carlo analysis is performed. To account for a 250-fold reduction in the dose rate constraint as compared with the work of reference 1, approximately five additional fast-neutron mean free paths of water and an additional five high-energy gamma-ray mean free paths of depleted uranium were included.

The depleted uranium shield layers for the Monte Carlo analysis were of 2- to 3-centimeter thickness to allow the benefit of self-shielding effects, and also to limit the total number of layers considered to a reasonable number. The water layer thicknesses were selected so as to yield homogenized uranium-water mixture densities, for the optimization calculations, in the nominal range of 3 to 6.5 grams per cubic centimeter. To cover this range, three mixtures were considered, called Mix 1, Mix 2, and Mix 3, as indicated in table I. Mix 1 consists of 30 percent depleted uranium plus 70 percent borated water, yielding a homogenized density of 6.4 grams per cubic centimeter. Mix 2 is 20 percent depleted uranium plus 80 percent borated water, giving a mixture density of 4.6 grams per cubic centimeter. Mix 3 is 10 percent depleted uranium plus 90 percent borated water, giving a mixture density of 2.8 grams per cubic centimeter. The elemental composition of the reactor, reflector, shield, and surrounding air is shown in table II.

TABLE II. - MATERIAL COMPOSITIONS

Element	Region							
	Core	Reflector	Depleted uranium shield	Mix 1 (heavy) shield	Mix 2 (medium) shield	Mix 3 (light) shield	Borated water shield	Air
	Atom density, atoms/cm^3							
Hydrogen	1.976×10^{22}	0	0	4.51×10^{22}	5.16×10^{22}	5.80×10^{22}	6.45×10^{22}	0
Oxygen	1.184	↓	↓	2.26	2.58	2.90	3.37	9.0×10^{18}
Aluminum	5.120	↓	↓	0	0	0	0	0
Zirconium	1.744	↓	↓	↓	↓	↓	↓	↓
Uranium-235	9.79×10^{20}	↓	↓	↓	↓	↓	↓	↓
Beryllium	0	1.20×10^{23}	↓	↓	↓	↓	↓	↓
Uranium-238	7.80×10^{19}	0	4.82×10^{22}	1.446×10^{22}	9.64×10^{21}	4.82×10^{21}	↓	↓
Boron-10	0	↓	0	1.17×10^{20}	1.33×10^{20}	1.49×10^{20}	1.73×10^{20}	↓
Boron-11	0	↓	0	5.28	6.02	6.77	7.85	↓
Nitrogen	0	↓	0	0	0	0	0	4.17×10^{19}

Monte Carlo Calculations for Base Case

A Monte Carlo neutron transport calculation was run with the code SANE-2M to determine the external neutron dose rate. A 10 000 history problem, requiring 50 minutes on the CDC-1604A computer, yielded a neutron dose rate 9.14 meters (30 ft) from the core center of 9.99×10^{-3} millirem per hour for a core power level of 375 megawatts. The statistical uncertainty of this calculation was about ±10 percent.

A second SANE-2M neutron calculation was run to yield secondary gamma-ray sources from each of the shield layers. In order to obtain reasonable statistical accuracy (10 to 30 percent) on the neutron flux in each of the energy bins, a 12 000 history problem was run. This calculation yielded an external neutron dose rate of 8.94×10^{-3} millirem per hour with a statistical uncertainty of ±15 percent.

Secondary gamma-ray sources were calculated for all shield regions using the SANE-2M code. Then, the secondary gamma-ray transport calculations were run at six discrete energies ranging from 1 to 6 MeV. Contributions to the external dose rate from all the secondary gamma-ray source regions were determined for purposes of obtaining the proper slopes of dose-rate-against-radius curves. These, in turn, were used to get attenuation parameters for input to the UNAMIT optimization code (ref. 1). The Monte Carlo-determined contributions to the external dose rate from each shield region for the 375-megawatt shield with homogenized depleted uranium-water mixes is shown in table III.

TABLE III. - SECONDARY GAMMA-RAY DOSE RATE

Region	Material	Inner radius, cm	Outer radius, cm	6-MeV gamma source	Intermediate gamma source (3 to 5 MeV)	2.2-MeV gamma source
				Dose rate,[a] rem/hr/source neutron/sec		
1	Depleted uranium	90.0	93.0	2.53×10^{-30}	1.55×10^{-25}	0
2	Mix 1	96.5	126.5	3.88×10^{-28}	8.40×10^{-27}	0
3	Mix 2	126.5	166.0	1.92×10^{-26}	4.96×10^{-26}	0
4	Mix 3	166.0	221.0	1.47×10^{-25}	1.17×10^{-25}	2.24×10^{-26}
5	Water	221.0	320.0	5.94×10^{-26}	2.18×10^{-28}	2.10×10^{-27}

[a] At 9.14 meters from core center.

The core gamma-ray Monte Carlo transport calculations were also performed in six discrete source energy groups ranging from 1 to 6 MeV. The core gamma-ray contribution was 3.70×10^{-28} rem per hour per source neutron per second. The total gamma-ray dose rate from the standard shield was 4.26×10^{-25} rem per hour per neutron per second or 0.0124 millirem per hour for a core power of 375 megawatts. When this was added to the total neutron dose rate of 0.010 millirem per hour, the total dose rate was 0.0224 millirem per hour, or about a factor of 10 lower than the required dose rate constraint of 0.25 millirem per hour. This will not have a significant effect on input parameters for the optimization calculations in very thick shields such as those considered here.

UNAMIT Optimization Calculations

All optimization calculations were performed with the code UNAMIT (ref. 2). It has a general multicomponent dose rate structure for handling the dose rate contributions of both neutrons and gamma rays. Using the geometric description of an initial shield configuration and source and attenuation parameters, the code varies radii of successive spherical shells, searching for shield layer radii which satisfy the dose rate constraint and yield minimum shield weights. It can reduce layer thicknesses to zero, but cannot physically interchange or add layers. The UNAMIT code requires input parameters for attenuation of primary neutrons, primary gamma rays, and secondary gamma rays and source, or production, parameters for secondary gamma rays.

The neutron attenuation parameters appropriate for the external neutron dose rate are based on removal cross sections taken from Goldstein (ref. 3). An exception to this are parameters for the outer water layer. Since this layer is followed by air, rather than a hydrogenous medium, removal theory does not apply; so the Monte Carlo-determined fast dose rate falloff was used for this layer. This resulted in a value of $0.100\ \text{cm}^{-1}$ compared with a removal cross section of $0.0945\ \text{cm}^{-1}$, which is within the uncertainty of the removal cross section.

Analysis of (1) the slopes of the secondary gamma-ray source strengths as a function of radial distance (ref. 2) and (2) the slopes of the resultant leakage through the separate shield materials as determined by the Monte Carlo calculations led to a classification of three main gamma-ray source types. These are a 6 MeV gamma ray, an intermediate-energy (3- to 5-MeV) gamma ray, and a 2.2-MeV hydrogen capture gamma ray. The 2.2-MeV gamma ray contributes to the leakage mostly from the outermost uranium-water mix region (mix 3) and the outer water layer.

The Monte Carlo-determined secondary radiation attenuation parameters are tabulated in table IV(a). The attenuation parameters and source parameters in tables IV

TABLE IV. - ATTENUATION PARAMETERS

(a) Attenuation parameters pertinent to secondary radiation

Shield range	Material	6-MeV gamma source		Intermediate gamma source (3 to 5 MeV)		2.2-MeV gamma source	
		Attenuation parameter, cm^{-1}					
		μ_n	μ_γ	μ_n	μ_γ	μ_n	μ_γ
1	Uranium	0.15	0.44	0.273	0.90	0.273	0
2	Mix 1 (heavy)	.15	.31	.273	.30	.273	0
3	Mix 2 (medium)	.133	.23	.15	.22	.15	0
4	Mix 3 (light)	.115	.13	.13	.124	.13	.18
5	Water	.097	.048	.097	.050	.099	.040

(b) Primary radiation attenuation parameters

Shield range	Material	Attenuation parameter, cm^{-1}	
		μ_n	μ_γ
1	Depleted uranium	0.1735	0.90
2	Mix 1 (heavy)	.118	.30
3	Mix 2 (medium)	.110	.22
4	Mix 3 (light)	.102	.13
5	Water	.100	.05

TABLE V. - SECONDARY GAMMA-RAY DOSE RATE BY SOURCE TYPE FOR 375-MW SHIELD

Shield region	Material	6-MeV gamma source	Intermediate gamma source (3 to 5 MeV)	2.2-MeV gamma source
		Dose rate, mrem/hr		
1	Uranium	1.620×10^{6}	7.456×10^{7}	0
2	Mix 1 (heavy)	5.374×10^{5}	2.579×10^{8}	0
3	Mix 2 (medium)	3.725	1.529	0
4	Mix 3 (light)	3.317	8.632×10^{7}	1.827×10^{7}
5	Water	2.493	4.260×10^{5}	1.901×10^{6}

and V may be described as follows (ref. 4): The assumed dose rate - thickness model is of the general form

$$\dot{D} = \sum_{i} \dot{D}_i$$

where

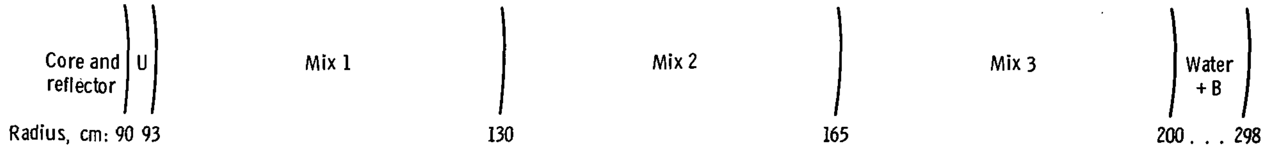
$$\dot{D}_i = C_i \exp\left(-\sum_{j=1}^{i-1} \mu_{ij}t_j\right) \exp\left[-(\mu_{n,ii} + \mu_{\gamma,ii})\right] \exp\left(-\sum_{j=i+1}^{k} \mu_{ij}t_i\right)$$

and $\dot{D}$ is the total dose rate; $\dot{D}_1$ is the dose rate from the first layer; $\dot{D}_2$ is the dose rate from the second layer, and so forth; t_j is the thickness of the j^{th} region; μ_{ij} is a gamma-ray 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 source parameter. In table IV(a), the gamma-ray attenuation coefficients in a specific region apply to gamma-ray sources in that region and all the shield regions internal to the specific region. The primary radiation attenuation parameters used in the UNAMIT calculations are shown in table IV(b). The secondary gamma-ray dose rates, by source, used in the UNAMIT calculations are shown in table V. These correspond to the C_i in the previous equation. The dose rate sources listed in table V in the 6-MeV and 3- to 5-MeV columns for shield region 5, or the outer water region, are sources due to inelastic scattering of neutrons in oxygen. The primary neutron dose rate source term used in the UNAMIT calculations was 3.372×10^{8} millirem per hour. The primary gamma-ray dose rate source term was 1.820×10^{12} millirem per hour.

UNAMIT Optimization Results

The parameters for input to UNAMIT are generated from the 375-megawatt, 160-watt-per-cubic-centimeter (4.53-MW/ft^3) reactor shield. In performing the UNAMIT shield optimization calculations, two types of calculations were made:

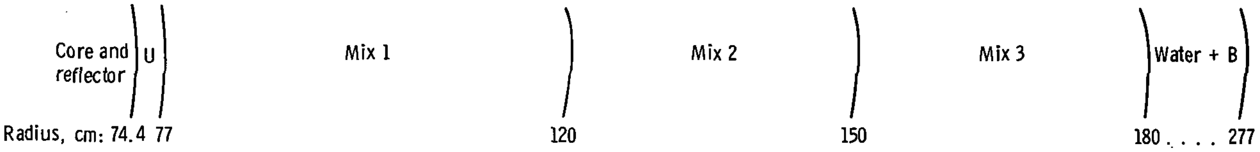
(1) An optimization calculation where the limiting values of inner and outer shield layer radii are such that the optimized shield contains respective amounts of the uranium-water mixtures not far different from those dictated by the Monte Carlo configuration specified in table I: The shield configuration determined here is called the "standard shield" in the following discussion.



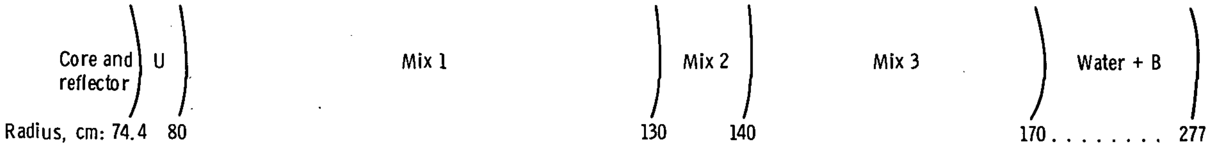
(a) Standard shield. Reactor radius, 90 centimeters; shield weight, 208 000 kilograms (459 000 lb).

(b) Optimum shield. Reactor radius, 90 centimeters; shield weight, 202 000 kilograms (445 000 lb).

Figure 1. - Shield design for reactor with power level of 375 megawatts.

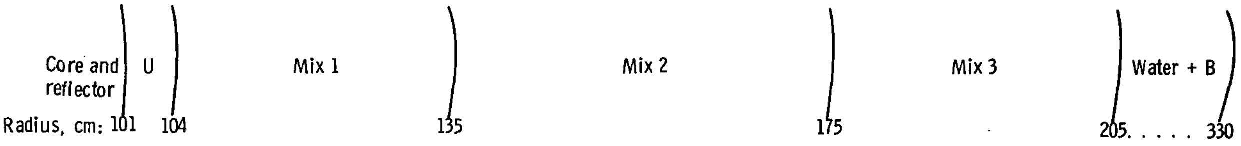


(a) Standard shield. Reactor radius, 74.4 centimeters; shield weight, 163 000 kilograms (360 000 lb).

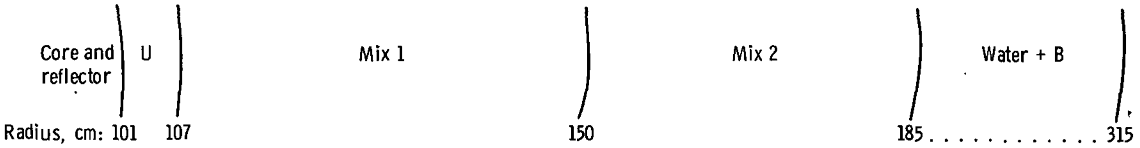


(b) Optimum shield. Reactor radius, 74.4 centimeters; shield weight, 159 000 kilograms (350 000 lb).

Figure 2. - Shield design for reactor with power level of 200 megawatts.



(a) Standard shield. Reactor radius, 101 centimeters; shield weight, 252 000 kilograms (557 000 lb).



(b) Optimum shield. Reactor radius, 101 centimeters; shield weight, 237 000 kilograms (521 000 lb).

Figure 3. - Shield design for reactor with power level of 550 megawatts.

(2) An optimization calculation where there are essentially no constraints on any layer thicknesses: This allows UNAMIT to make greater adjustments in shield layer configuration so that the optimized configuration need not bear as close a resemblance to the Monte Carlo configuration as in case 1 above. The final configuration arrived at here is called the "optimum shield", and it is the optimum shield weights that are considered to be minimum shield weights.

The initial UNAMIT run was performed for a five-layer shield similar to the stepwise-homogenized Monte Carlo shield configuration specified in table I. This standard shield is shown schematically in figure 1(a). The dose rate constraint in this and all the configurations presented in figures 1 to 3 is 0.25 mrem per hour at 9.14 meters (30 ft) from the reactor center.

The weight of the standard shield (fig. 1(a)) for a 375-megawatt power level is 208 000 kilograms (459 000 lb). The optimum shield displayed schematically in figure 1(b) has a weight of 202 000 kilograms (445 000 lb), or 3 percent less than that of the standard shield (fig. 1(a)).

The standard shield shown in figure 2(a) for a reactor power level of 200 megawatts has a weight of 163 000 kilograms (360 000lb). The optimum shield for the 200-megawatt reactor power level, shown in figure 2(b), has a weight of 159 000 kilograms (350 000 lb), or essentially the same as that of the standard shield.

The 550-megawatt standard shield, shown in figure 3(a), has a weight of 252 000 kilograms (557 000 lb). The optimum shield for the 550-megawatt power level has a weight of 237 000 kilograms (521 000 lb), or 7 percent less than that of the standard shield.

The minimum shield weights determined by UNAMIT for the nine reactor-core-parameter configurations analyzed are represented by the points in figure 4. Curves are plotted as a function of reactor outer radius for both constant power level and constant power density. The solid curves connect constant power level points. The dashed curves connect constant power density points.

DISCUSSION OF RESULTS

As can be seen from figure 4, the optimum shield weights vary from 140 000 kilograms (309 000 lb) for the small-core, high-power-density, 200-megawatt reactor to 325 000 kilograms (718 000 lb) for the large-core, low-power-density, 550-megawatt reactor. These weights, again, are for an external dose rate constraint of 0.25 mrem per hour at 9.14 meters (30 ft) from the reactor center, which represents a factor of about 250 more attenuation than was required in earlier parametric minimum shield weight studies.

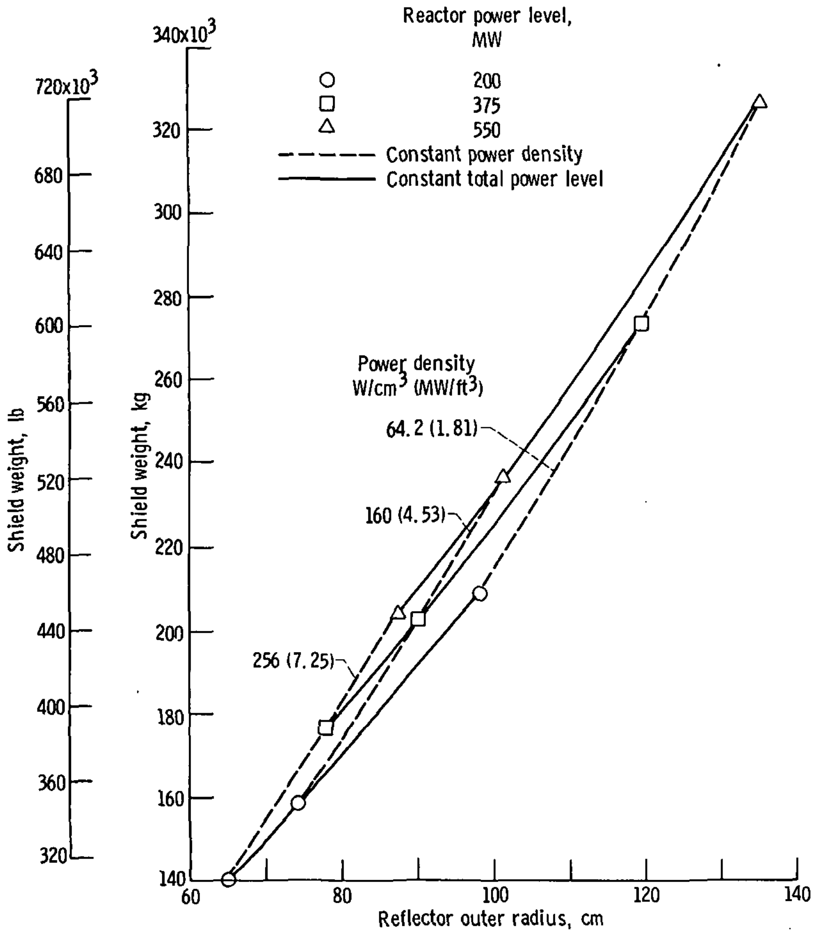


Figure 4. - Uranium-water shield weights. Dose rate, 0.25 mrem per hour at 9.14 meters (30 ft) from reactor center.

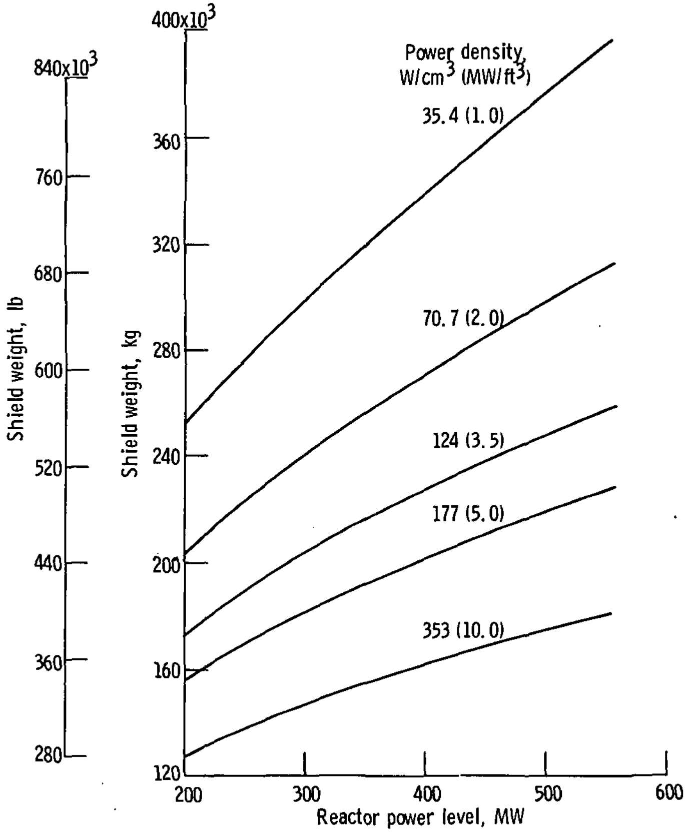


Figure 5. - Uranium-water shield weights as function of reactor power level and power density.

A curve fit of the shield weight data generated, performed with the computer program RAPIER (ref. 5), yielded the following analytic relation between shield weight, reactor power level, and power density:

$$W_s = 44100P^{(0.473-0.0539 \ln \rho_P)}$$

where W_s is the shield weight in pounds, P the reactor power level in megawatts, and ρ_P the core power density in megawatts per cubic foot. This expression is valid, of course, only in the 200- to 550-megawatt power range and the 64.2- to 256-watt-per-cubic-centimeter (1.810 to 7.25-MW/ft^3) power density range covered in the optimization calculations because these are the ranges over which calculations were made.

Several curves plotted from this equation for power densities of 35.4, 70.7, 124, 177, and 353 watts per cubic centimeter (1, 2, 3.5, 5, and 10 MW/ft^3) are shown in figure 5; and, as expected, shields for the highest power density cores (smallest core radius for a given power level) weigh the least.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 18, 1971,
132-15.

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