N71-38278

NASA TECHNICAL MEMORANDUM

NASA TM X-2414

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EFFECT ON SHIELD WEIGHT OF ADDING A FIXED-POSITION CONTAINMENT VESSEL IN THE UNIT SHIELD OF A 250-MEGAWATT MOBILE REACTOR

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1971

1. Report No. NASA TM X-2414	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

EFFECT ON SHIELD WEIGHT OF ADDING A FIXED-POSITION CONTAINMENT VESSEL IN THE UNIT SHIELD OF A 250-MEGAWATT MOBILE REACTOR

5. Report Date
November 1971

6. Performing Organization Code

7. Author(s)
Millard L. Wohl and David Spielberg

8. Performing Organization Report No.
E-6462

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
126-15

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The computer code UNAMIT was used to calculate optimized 4π-spherical, tungsten-water unit shield weights for three 250-megawatt reactors, a highly moderated, a lightly moderated, and a fast reactor. The effect on shield weight of the inclusion as part of the shield of a 1.39-meter (4.6-ft) inner radius refractory containment vessel of 5.08, 7.62, and 12.7 centimeter (2-, 3-, and 5-in.) thicknesses was calculated. The vessels were not optimally placed from a minimum shield weight point of view. The increases in shield weight due to inclusion of the vessels as part of the shields reflect the degree of nonoptimum placement of these thick layers of heavy material but were far less than the actual vessel weights. The vessels weighed 22 670, 34 900, and 59 800 kilograms (50 000, 77 000, and 132 000 lb). The total weight increase due to these vessels was 2 268, 5 890, and 15 420 kilograms (5 000, 13 000, and 34 000 lb), respectively.

17. Key Words (Suggested by Author(s))
Reactor shielding
Shield weight
Unit shield
Nuclear power
Mobile reactor
Containment vessel or reactor containment vessel

18. Distribution Statement
Unclassified - unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price* $3.00

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* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

One-dimensional, 4π-spherical, tungsten-water unit shield weight optimization calculations were performed to determine the effect on shield weight of including a fixed-thickness, fixed-location spherical containment shell as part of the shield. The vessels were not optimally placed from a minimum shield weight point of view. The increases in weight due to the inclusion of the vessels as part of the shields reflect the degree of nonoptimum placement of these thick layers of heavy material but were far less than the vessel weights.

All shield weight determinations were made for a dose rate constraint of 2.5 millirem per hour at 39.6 meters (130 ft) from the reactor center. The refractory metal containment vessel (T-222 (Ta-10W-2Re)) had a 4.6-foot inner radius. Shield materials used were tungsten and borated water.

Optimum-weight shields were generated for two thermal reactors and one fast reactor. The thermal reactor designs are similar except for a change in moderator fraction and, correspondingly, core size. The fast core has a higher fuel fraction than does the thermal core and a different reflector.

The thermal gas-cooled reactor design was based on AGN ML-1 technology. The fast gas-cooled reactor design was based on GE 710 technology. The detailed geometric and material compositions of these reactor cores are not used directly in the shield weight optimization calculations; they are used only to generate proper material atom densities for spherical homogeneous core models to be used in Monte Carlo and subsequent optimization calculations. The reactors were sphericized as described and optimum shield weights were generated using the computer code UNAMIT. The results of the shield optimization calculations are summarized.

The optimized reactor shield weight data show that including a fixed-thickness containment vessel as part of the shields for the three reactors increases the shield weight by a relatively small amount even for the thickest or 12.7-centimeter (5-in.) containment shell. The shield weight increases for the cases including a 12.7-centimeter (5-in.) thick, 59 000-kilogram (132 000-lb) containment vessel was about 13 percent; for the 7.62-centimeter (3-in.-thick), 35 100-kilogram (77 500-lb) vessel about 5 percent; and for the 5.08-centimeter (2-in.-thick), 22 700-kilogram (49 100-lb) vessel about 3 percent, which is the approximate uncertainty in the total optimum shield weight values.

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INTRODUCTION

Recent work on nuclear-propelled airplanes and air cushion vehicles includes requirements for minimum weight unit shields to provide on-board, omnidirectional, low dose rates. To this end, systematic shield weight optimization techniques have been developed.

Unit shield weight optimization studies that have been done in the past (ref. 1) considered the use of high-performance shield materials only. It will be necessary, in order to prevent fission product release to the environment due to high internal temperatures and pressures in the event of a reactor accident, to include as part of the shield a fixed-thickness containment vessel with an inner radius of 1.39 meters (4.6 ft). Such a vessel would be fabricated of a ductile, high-temperature material such as an alloy of iron, nickel, columbium, or tantalum.

The containment vessel thickness and position within the shield are dictated by postaccident temperature and pressure inside the vessel. Because the vessel does provide shielding but is not at an optimum location, the shield weights reported will include the vessel weight. The weight difference will reflect the degree of nonoptimum placement of this thick layer of material. The primary purpose of this study is to examine the effect on unit shield weights, for fast and thermal 250-megawatt gas-cooled reactors, of including a fixed-thickness, fixed-position containment vessel within the shield.

The shield layers are optimized about the containment vessel with the optimization code UNAMIT (ref. 2). The effect on shield weight will be determined for two thermal reactors and one fast reactor. The thermal reactor designs are similar except for a change in moderator fraction and, correspondingly, core size.

The thermal gas-cooled reactor design was based on AGN ML-1 technology (ref. 3 and appendix A). The fast gas-cooled reactor design was based on GE 710 technology (ref. 4 and appendix B). Each reactor is enclosed within a heavy-walled T-222 (Ta-10W-2Re) containment vessel; in the calculations, reduced-density tungsten was used to represent T-222. The detailed geometric and material compositions of these reactor cores are not used directly in the shield weight optimization calculations; they are used only to generate proper material atom densities for spherical homogeneous core models to be used in Monte Carlo and subsequent optimization calculations.

Shield weights have been computed for sphericized models of these reactors for a dose-rate constraint of 2.5 millirem per hour at a distance of 39.6 meters (130 ft) from the reactor center. Calculations have been performed for containment vessel thicknesses of 5.08, 7.62, and 12.7 centimeters (2, 3, and 5-in.) (containment vessel weights of 22 700, 35 100, and 59 900 kg (49 000, 77 000, and 132 000 lb)); for a highly moderated thermal reactor (moderator water fraction = 0.54); a less moderated thermal reactor (moderator water fraction = 0.37); and a fast reactor. Calculations have also been done without the containment vessel for the fast reactor and the highly moderated thermal reactor.

ANALYSIS

Spherical Reactor Calculational Models

In order to perform the one-dimensional spherical shield optimization analyses, the reference reactor cores had to be converted from their normal cylindrical geometric configurations to spherical configurations; a flat radial power distribution was used in the analysis.

A schematic of the highly moderated reactor is shown in appendix A. The reactor was sphericized by constructing a spherical core of equal volume and homogeneous composition using the materials designated in table I. The radius of the equivalent spherical reactor, including the beryllium reflector, is 68.6 centimeters. The lightly moderated reactor is shown in appendix A; it is similar to the highly moderated reactor except that the moderator fraction is reduced from 54 to 37 percent. The new equivalent spherical core radius, including reflector, is 63.0 centimeters.

For the fast reactor, a spherical core having the same cross-sectional area as a vertical section of the cylindrical core was selected. The spherical core radius was 42.9 centimeters. Had the core been sphericized on an equal volume basis, as were the thermal reactors, the spherical core radius would have been 43.5 centimeters. The thicknesses of the coolant passage, the Inconel thermal shield, and reflector regions surrounding the core were preserved as 2.3, 2.1, and 12.7 centimeters, respectively. A schematic of the fast reactor is shown in appendix B. Core material compositions are given in figure 3, and homogenized material densities are listed in table I.

In order to begin the shield optimization for the reactors, an initial shield configuration was analyzed by means of a Monte Carlo calculation. The computer code UNAMIT (ref. 2) was then used for all subsequent optimization calculations.

It should be emphasized that the UNAMIT code is not a radiation transport method, as is a Monte Carlo or S_n code. It may be regarded as a weight-minimizing shield perturbation method, which accepts an initial shield configuration and attenuation and production parameters for shield materials. It then uses coefficients in a weight reduction procedure to achieve minimum shield weight.

TABLE I. - MATERIAL DENSITIES

(a) Reactor core material homogenized densities

Element	Atom density, atoms/b-cm[a]		
	Highly moderated thermal reactor	Lightly moderated thermal reactor	Fast reactor
H	1.976×10^{-2}	9.88×10^{-3}	----------
O	1.184×10^{-2}	6.90×10^{-3}	1.33×10^{-2}
Al	5.12×10^{-3}	5.12×10^{-3}	----------
[b]Zr	1.744×10^{-2}	1.744×10^{-2}	2.02×10^{-3}
U^{235}	9.79×10^{-4}	9.79×10^{-4}	6.20×10^{-3}
Be^{9}	1.23×10^{-1}	1.23×10^{-1}	----------
W	----------	----------	1.526×10^{-2}
U^{238}	----------	----------	4.46×10^{-4}
Fe	----------	----------	6.371×10^{-3}
Cr	----------	----------	1.466×10^{-2}
Ni	----------	----------	6.753×10^{-2}

(b) Shield material atom densities

Element	Shield material or mix				
	Borated water	Pure tungsten	Tungsten water mix for $\rho = 7.96$ g/cm^3	Tungsten water mix for $\rho = 5.03$ g/cm^3	T-222
	Atom density, atoms/b-cm				
W	---------	6.31×10^{-2}	2.39×10^{-2}	1.42×10^{-2}	[c]5.58×10^{-2}
H	6.45×10^{-2}	---------	3.94×10^{-2}	4.97×10^{-2}	----------
B^{10}	1.73×10^{-4}	---------	1.03×10^{-4}	1.32×10^{-4}	----------
B^{11}	7.85×10^{-4}	---------	4.82×10^{-4}	6.07×10^{-4}	----------
O	3.37×10^{-2}	---------	2.06×10^{-2}	2.60×10^{-2}	----------

[a] Atoms/b-cm = (atoms/cm^3) (10^{-24} cm^2)/(b).

[b] Zr cross sections were used to represent Mo, since good Mo cross sections were not available.

[c] Reduced-density tungsten used to represent T-222.

Description of Optimization Calculations

The computer code UNAMIT (ref. 2) was used for all the optimized shield weight calculations. It has a general multicomponent dose-rate structure capability for handling the dose-rate contributions of both neutrons and gamma rays. Using the geometric description of the initial shield configuration and all the parameters listed (ref. 2), the code varies radii of successive spherical shells, except those which are fixed by the user, such as the bounding radii of the containment vessel in the present series of calculations. The code searches 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. It then prints out the shield layer radii in the minimum weight configuration, as well as the shield weight and specified dose-rate constraint.

The radiation attenuation and production model is described in reference 2. A neutron component and one secondary gamma-ray component were used in these calculations. Neutron dose-rate attenuation coefficients for the tungsten-water mixes in the shields considered here were computed on the basis of removal cross sections of 0.1118 square centimeter per gram for water and 0.01025 square centimeter per gram for tungsten (ref. 5). Attenuation coefficients for secondary-producing neutrons in regions radially outward from a thin inner borated water region initially assumed in a thermal reactor shield optimization were assigned values of 0.2, 0.16, 0.13, and 0.114, respectively. These attenuation coefficients were derived from slopes of dose rate against distance curves (ref. 2). The gamma-ray attenuation coefficients were derived from the slopes of dose rate against distance curves also as described in reference 2. UNAMIT eliminated the inner water region and produced the configuration shown in the first sketch of figure 6.

The core leakage dose rate, needed by UNAMIT, was obtained, for the highly moderated reactor and the fast reactor, from Monte Carlo calculations. The reactor core materials and configurations are specified in table I(a) and in appendix A. The shield material compositions are given in table I(b). T-222 was assumed to be tungsten of density 17 grams per cubic centimeter.

The leakage dose rate for the lightly moderated reactor is obtained by modification for the heavily moderated reactor. For sources that are uniformly distributed in the core and exponentially attenuated through many mean free paths, the integrated fractional leakage is inversely proportional to the core radius; this is the assumption used to determine the leakage dose rate for the lightly moderated reactor. The surface dose rates are shown in table II in millirems per hour.

TABLE II. - DOSE RATE AT SURFACE OF

EQUIVALENT SPHERICAL CORE

Reactor	Leakage dose rate, mrem/hr	
	Neutrons	Gamma rays
Highly moderated	1.4×10^{11}	3.26×10^{9}
Lightly moderated	1.29	4.74
Fast	7.84	1.44×10^{10}

DISCUSSION OF RESULTS

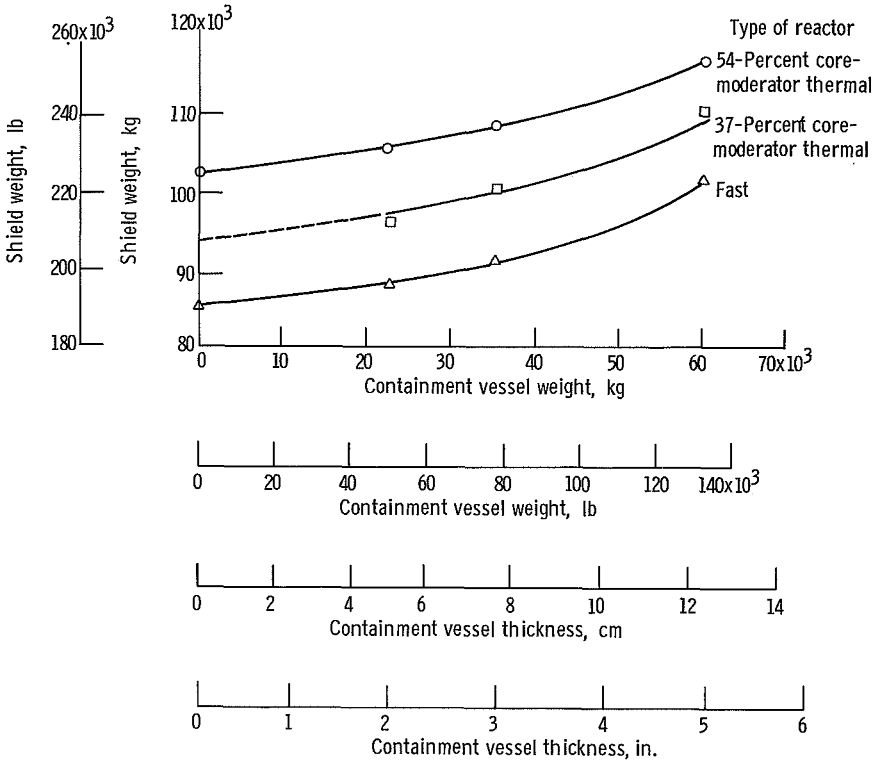
Optimum-weight shields were calculated for the two thermal reactors and one fast reactor described in the introduction and analysis sections. Optimized shield weights are shown in table III and are plotted in figure 1(a) as a function of containment vessel weight and thickness; the containment vessel weight is included in the shield weight.

The weight increase due to the presence of the containment vessel is shown in figure 1(b). The optimized configurations are shown schematically in figures 2 to 4. The shield layer composition, density, and dimensions are presented in table IV. The first shield configuration estimate and the final optimized shield for the heavily moderated reactor having 7.62-centimeter (3-in.) thick containment shell are compared in figure 5. Figure 6 shows the shield configuration for successive trial calculations in the search for the layer configuration which results in minimum shield weight.

TABLE III. - OPTIMIZED REACTOR SHIELD WEIGHTS

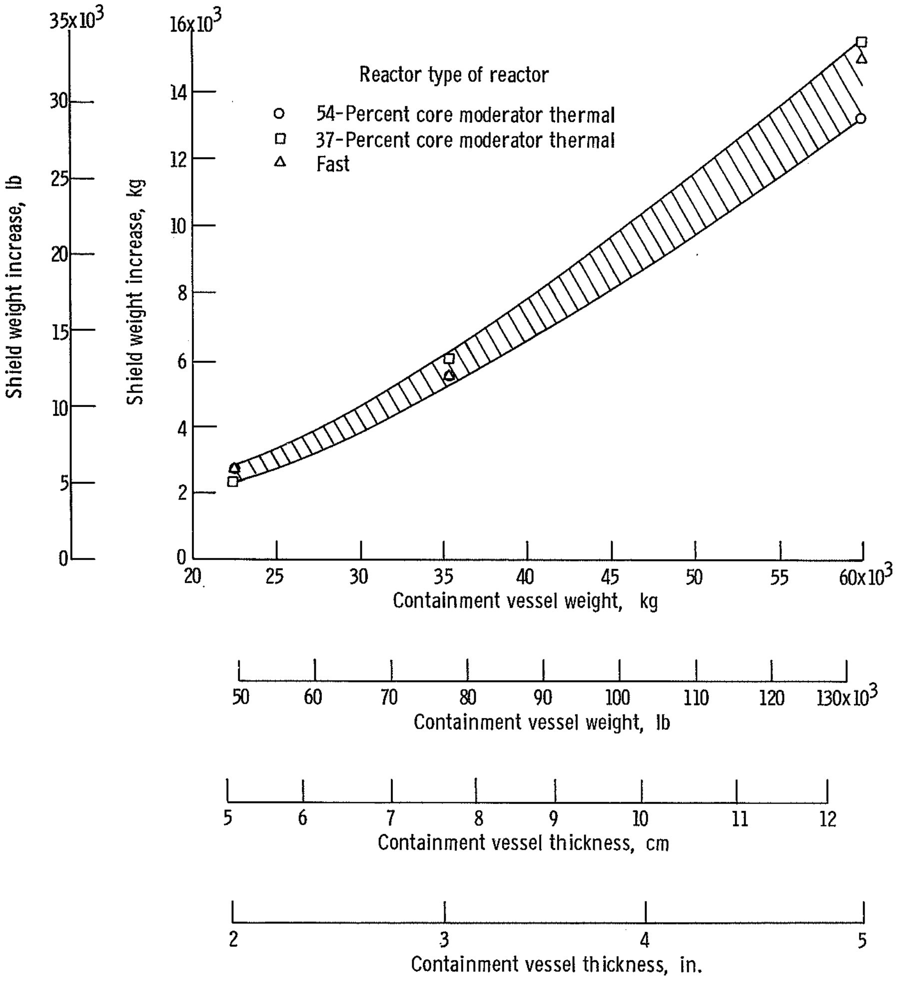
Containment shell weight		Containment shell thickness		Shield weight					
				Highly moderated reactor; 54-percent H_2O		Lightly moderated reactor; 37-percent H_2O		Fast reactor	
kg	lb	cm	in.	kg	lb	kg	lb	kg	lb
0	0	0	0	102×10^{3}	226×10^{3}	94.3×10^{3}	[a]208×10^{3}	86.6×10^{3}	191×10^{3}
22.7×10^{3}	49.1×10^{3}	5.08	2	105	232	96.6	213	89.3	197
35.1	77.5	7.62	3	108	238	100.0	221	92.2	203
59.9	132	12.7	5	116	255	109.7	242	102.4	224

[a]Extrapolated value.



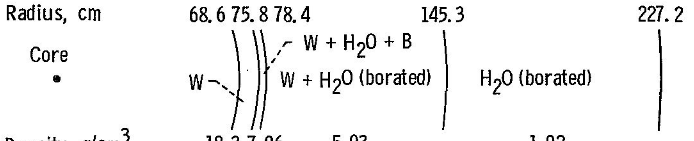
(a) Effect on shield weight of adding a containment vessel within the shield.

Figure 1. - Shield weight as function of containment vessel weight.

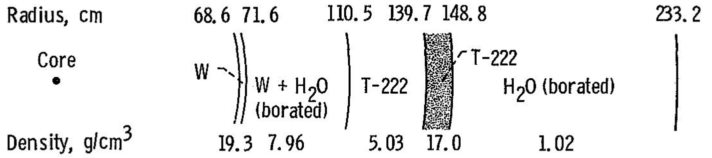


(b) Shield weight increase due to presence of containment vessel. Inside diameter, 2.8 meters (9.2 ft).

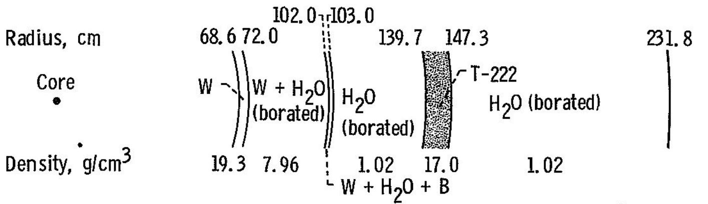
Figure 1. - Concluded.



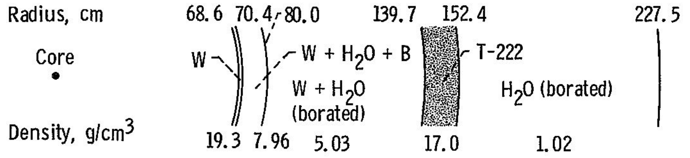
No containment shell; weight, 100 000 kilograms (221 000 lb).



5.08-Centimeter (2-in.) containment shell; weight, 105 000 kilograms (232 000 lb).

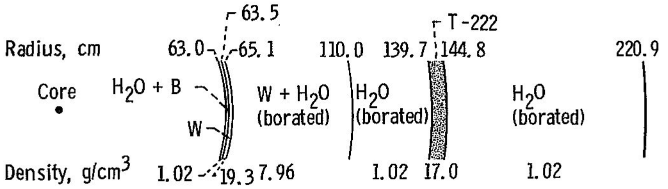


7.62-Centimeter (3-in.) containment shell; weight, 108 000 kilograms (238 000 lb).

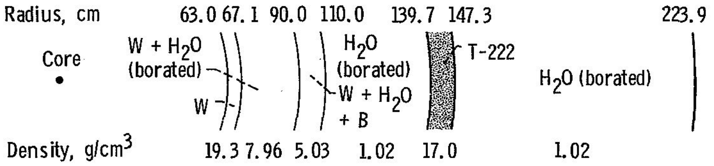


12.7-Centimeter (5-in.) containment shell; weight, 116 000 kilograms (255 000 lb).

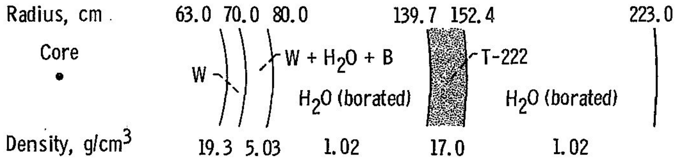
Figure 2. - Final optimized shield configurations and weight for highly moderated reactor.



5.08-Centimeter (2-in.) containment shell; weight, 96 700 kilograms (213 000 lb).

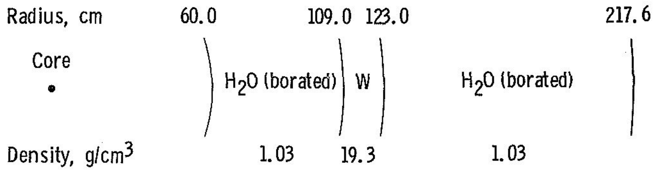


7.62 Centimeter (3-in.) containment shell; weight, 100 000 kilograms (221 000 lb).

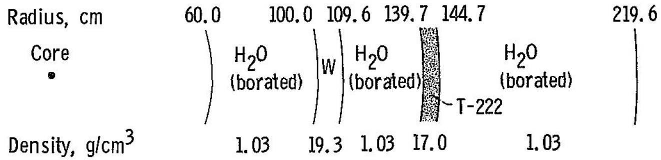


12.7-Centimeter (5-in.) containment shell; 109 000 kilograms (242 000 lb).

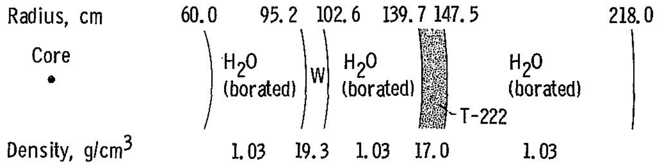
Figure 3. - Final optimized shield configurations and weights for lightly moderated reactor.



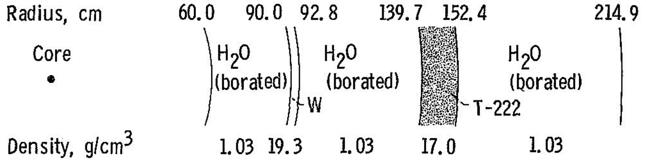
No containment shell; weight, 86 000 kilograms (191 000 lb).



5.08-Centimeter (2-in.) containment shell; weight, 89 000 kilograms (197 000 lb).

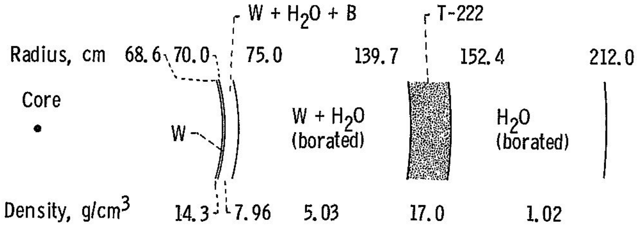


7.62 Centimeter (3-in.) containment shell; weight, 92 000 kilograms (203 000 lb).

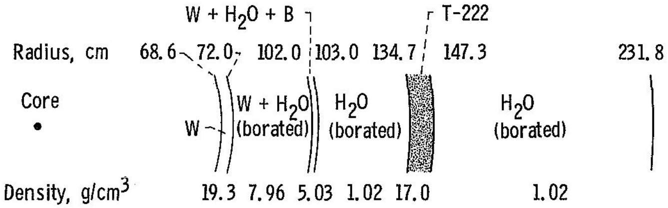


12.7-Centimeter (5-in.) containment shell; weight, 101 000 kilograms (224 000 lb).

Figure 4. - Final optimized shield configurations and weights for fast reactor.

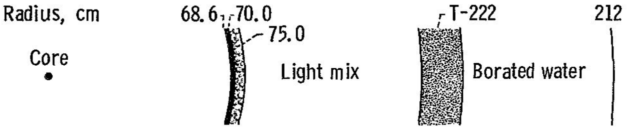


First estimate configuration; weight, 136 000 kilograms (300 000 lb).

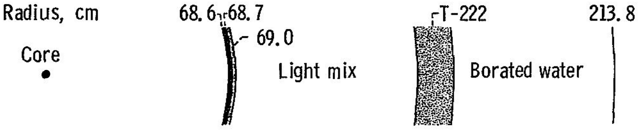


Optimized configuration; weight, 108 000 kilograms (238 000 lb).

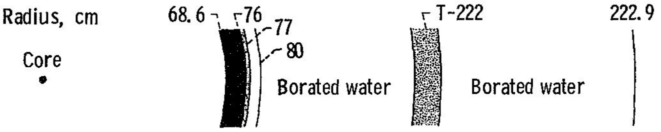
Figure 5. - First estimate and optimum shield configurations for highly moderated thermal reactor with 7.62-centimeter (3-in.) containment shell.



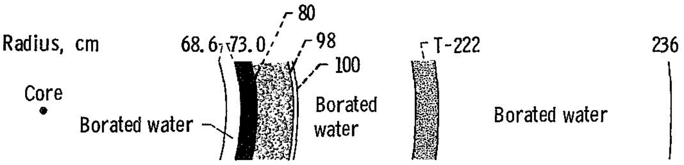
Trial A; shield weight, kilograms (300 400 lb)



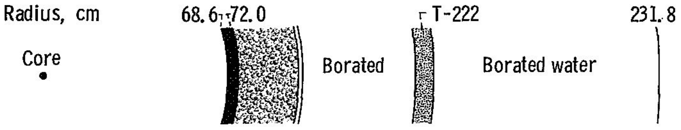
Trial B; shield-weight, 135 500 kilograms (298 300 lb).



Trial C; shield weight, 104 000 kilograms (244 000 lb).



Trial D; shield weight, 109 000 kilograms (242 000 lb).



Trial E; shield weight, 108 000 kilograms (238 000 lb).

▇ Tungsten

Heavy mix Tungsten-borated water mixture; density, 7.96 g/cm^3

Light mix Tungsten-borated water mixture; density, 5.03 g/cm^3

Figure 6. - Approach to a minimum-weight shield for highly-moderated reactor with 7.62-centimeter (3-in.) containment shell.

TABLE IV. - FINAL OPTIMIZED SHIELD CONFIGURATIONS

Type of reactor	Size of containment shell	Shield region number	Region outer radius, cm	Region composition	Density, g/cm^3
Highly moderated thermal	No containment shell	1	73.8	W	19.3
		2	78.4	W+H_2O+B	7.96
		3	145.3	W+H_2O+B	5.03
		4	227.2	H_2O+B	1.02
	5.08 cm (2 in.)	1	71.6	W	19.3
		2	110.5	W+H_2O+B	7.96
		3	139.7	W+H_2O+B	5.03
		4	144.8	T-222	17.0
		5	233.2	H_2O+B	1.02
	7.62 cm (3 in.)	1	72.0	W	19.3
		2	102.0	W+H_2O+B	7.96
		3	103.0	W+H_2O+B	5.03
		4	139.7	H_2O+B	1.02
		5	147.3	T-222	17.0
		6	231.8	H_2O+B	1.02
	12.7 cm (5 in.)	1	70.4	W	19.3
		2	80.0	W+H_2O+B	7.96
		3	139.7	W+H_2O+B	5.03
		4	152.4	T-222	17.0
		5	227.5	H_2O+B	1.02
Lightly moderated thermal	5.08 cm (2 in.)	1	63.5	H_2O+B	1.02
		2	65.1	W	19.3
		3	110.0	W+H_2O+B	7.96
		4	139.7	H_2O+B	1.02
		5	144.8	T-222	17.0
		6	220.9	H_2O+B	1.02
	7.62 cm (3 in.)	1	67.1	W	19.3
		2	90.0	W+H_2O+B	7.96
		3	100.0	W+H_2O+B	5.03
		4	139.7	H_2O+B	1.02
		5	147.3	T-222	17.0
		6	223.9	H_2O+B	1.02
	12.7 cm (5 in.)	1	70.0	W	19.3
		2	80.0	W+H_2O+B	5.03
		3	139.7	H_2O+B	1.02
		4	152.4	T-222	17.0
		5	223.0	H_2O+B	1.02
Fast	No containment shell	1	109.0	H_2O+B	1.02
		2	123.0	W	19.3
		3	217.6	H_2O+B	1.02
	5.08 cm (2 in.)	1	100.0	H_2O+B	1.02
		2	109.6	W	19.3
		3	139.7	H_2O+B	1.02
		4	144.7	T-222	17.0
		5	219.6	H_2O+B	1.02
	7.62 cm (3 in.)	1	95.2	H_2O+B	1.02
		2	102.6	W	19.3
		3	139.7	H_2O+B	1.02
		4	147.3	T-222	17.0
		5	218.0	H_2O+B	1.02
	12.7 cm (5 in.)	1	90.0	H_2O+B	1.02
		2	92.8	W	19.3
		3	139.7	H_2O+B	1.02
		4	152.4	T-222	17.0
		5	214.9	H_2O+B	1.02

Several observations can be made:

(1) Adding a containment vessel increases shield weight; this weight penalty increases with vessel thickness. The fractional weight penalty is greater for less moderated reactors. In the 54-percent moderator fraction reactor a 5.08-centimeter (2-in.) containment vessel thickness resulted in a 2.7-percent weight increase, or essentially no weight change within the accuracy of the calculation. A 12.7-centimeter (5-in.) thickness resulted in a 13-percent increase.

(2) Removing moderator from the core, thus reducing core size, reduces shield weight. Reducing the moderator fraction from 54 to 37 percent reduced shield weight by 9 percent.

In a fast reactor shield, a 12.7-centimeter (5-in.) thickness caused a 17-percent weight increase.

An examination of figures 2 to 4 shows that the optimized shields have certain general characteristics:

(1) As containment vessel thickness increases, less heavy shield material is required near the core.

(2) As containment vessel thickness increases, less water is required outside the shell, but more water is required inside the shell.

(3) Although the containment vessel has good gamma-ray attenuation characteristics, fixing the thickness and inner radius tends to increase the optimized shield weight; the fractional weight increase is, however, rather small.

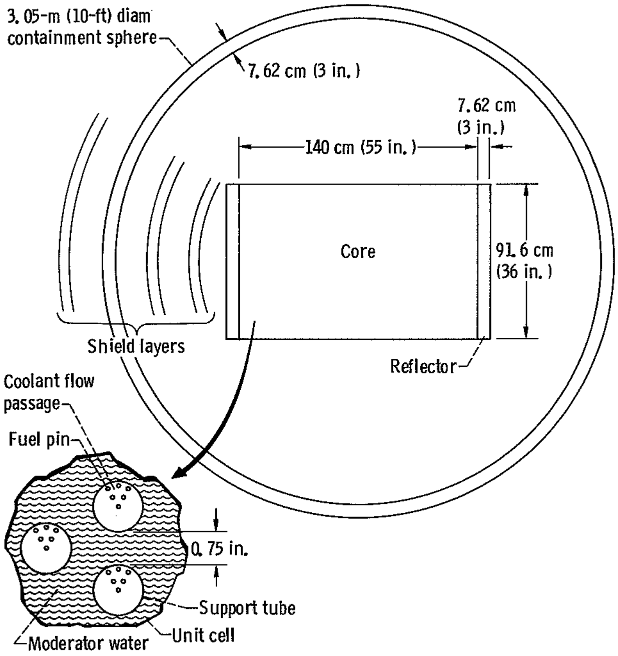
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 11, 1971,
126-15.

APPENDIX A

THERMAL REACTOR CONFIGURATIONS

The thermal gas-cooled reactor design, used to obtain the sphericized reactor configurations for the optimization analyses, was based on AGN ML-1 technology (ref. 3). It consists of a heterogeneous, partially enriched, uranium-dioxide-fueled, water-moderated, helium-cooled reactor located within a heavy-walled T-222 spherical containment vessel. The core contains 331 fuel-element bearing pressure tubes. Each fuel element is a pin-bundle assembly of 19 pins.

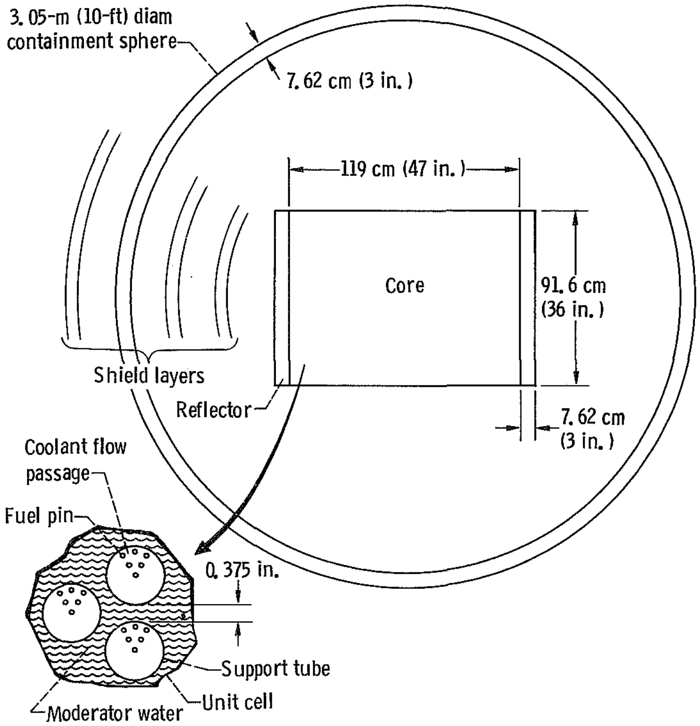
The schematic configurations, with material compositions, for the highly moderated and lightly moderated thermal reactors considered are shown in figures 7 and 8.



Region	Material	Volume fraction	Volume, m^3	ft^3	Weight, kg	(lb)
Core	Fuel	0.055	0.077	(2.72)	724	(1 600)
	Clad and matrix	.103	.144	(5.09)	1 350	(3 000)
	Structure	.088	.123	(4.35)	886	(1 960)
	Water	.535	.750	(26.40)	718	(1 590)
	Gas coolant	.120	.168	(5.94)	0	(0)
	Insulation	.092	.129	(4.55)	565	(1 250)
Reflector	Beryllium	1.000	-----	------	575	(1 270)
Structure	AM-355	-----	-----	------	~4 540	(10 000)
			Total		9 380	(20 670)
Containment shell[a]	T-222	-----	-----	------	35 200	(77 500)

[a] Thickness, 7.62 centimeters (3 in.).

Figure 7. - Highly moderated gas-cooled reactor.



Region	Material	Volume fraction	Volume, m^3 (ft^3)	Weight, kg (lb)
Core	Fuel	0.075	0.077 (2.72)	724 (1 600)
	Clad and matrix	.140	.144 (5.09)	1 350 (3 000)
	Structure	.120	.123 (4.35)	886 (1 960)
	Water	.365	.375 (13.20)	359 (795)
	Gas coolant	.164	.168 (5.94)	0 (0)
	Insulation	.126	.129 (4.55)	565 (1 250)
Reflector	Beryllium	1.000	----- ------	490 (1 080)
Structure	AM-355	-----	----- ------	~5 030 (10 000)
			Total	8 720 (19 685)
Containment shell[a]	T-222	-----	----- ------	35 200 (77 500)

[a] Thickness, 7.62 centimeters (3 in.).

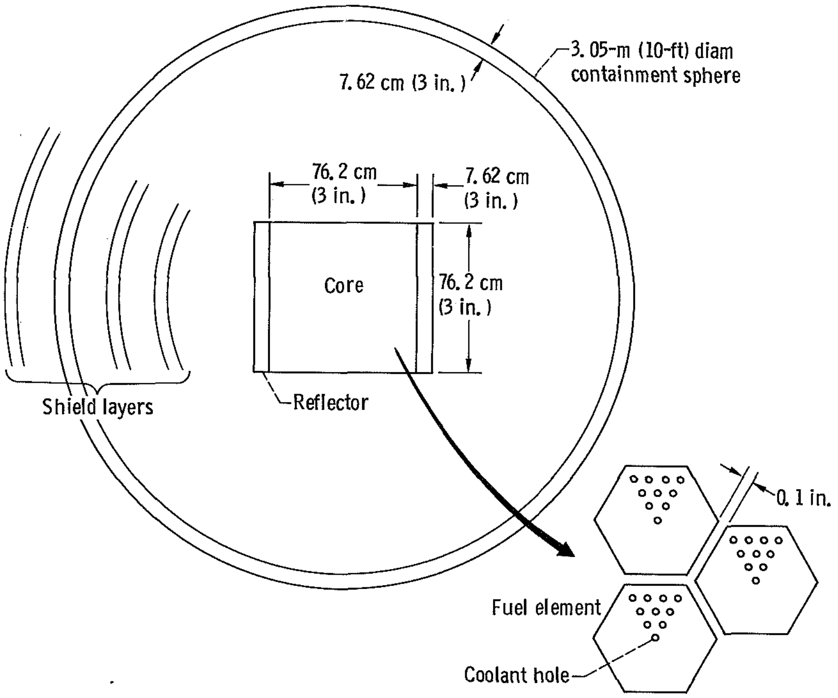
Figure 8. - Lightly moderated gas-cooled reactor.

APPENDIX B

FAST REACTOR CONFIGURATION

The fast gas-cooled reactor design was based on GE 710 technology (ref. 4). It consists of refractory-metal, hexagonal fuel elements with tubular coolant flow channels; radial reflector removel is used for reactivity control. The fuel material is enriched UO_2 with W-30 Re-30Mo cladding and lining for the coolant channels.

The schematic configuration for the fast reactor, along with material compositions, is shown in figure 9.



Region	Material	Volume fraction	Volume, m^3 (ft^3)	Weight, kg (lb)
Core	Fuel	0.24	0.084 (2.95)	837 (1 850)
	Matrix (W)	.26	.091 (3.20)	1 720 (3 800)
	Clad and structure	.103	.036 (1.27)	678 (1 500)
	Gas coolant	.38	.133 (4.67)	0 (0)
Reflector	Molybdenum	.90	----- -----	3 810 (8 200)
Structure	Inconel 625	----	----- -----	3 030 (6 700)
			Total	10 075 (22 050)
Containment shell[a]	T-222	----	----- -----	35 200 (77 500)

[a] Thickness, 7.62 centimeters (3 in.).

Figure 9. - Gas-cooled fast reactor.

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NASA-Langley, 1971 —— 22 E-6462

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