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Preface

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Acknowledgment

Extreme gratitude and appreciation must be given to the people who helped to direct this study to a useful result. In particular, special thanks must be given to Mr. E. Anderson of Mound Research, who gave much time in the critical evaluation of the data and resulting calculations. Also appreciated were the suggestions contributed by Dr. Albenesius, and Dr. Peterson of Savannah River Laboratory, Mr. P. Brown of General Electric Company and Mr. H. Bermanis of United Engineers & Constructors, Inc.

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Abstract

An extensive investigation was performed to characterize the net gamma ray source intensity and spectrum for PuO_2 fuel. All major sources were considered, including the gamma radiation from the various polutonium isotopes and their decay, and the decay of fission products, as well as gammas due to spontaneous fission and (α, n) reactions with ^{18}O and other light element purities. Particular attention was paid to ^{236}Pu and its daughter products. These sources are tabulated for 20 energy groups, which range from 1 KeV to 7 MeV. For each of the age-dependent composite source spectra so determined, gamma ray fluxes were calculated for three different thicknesses of fuel in a typical PuO_2 fueled capsule. These gamma fluxes were determined at the capsule surface, as well as at several exterior points.

Gamma Radiation Characteristics of Plutonium Dioxide Fuel

I. Introduction

In the exploration of space to the planet Jupiter and beyond, one of the non- solar-dependent sources of primary electrical power under serious study is the Radioisotope Thermoelectric Generator (RTG), which uses plutonium dioxide fuel. The plutonium isotopes have very long half-lives and can be considered usable for scientific missions in space up to 12 yr in duration. However, the nuclear radiation produced by the radioactive isotopes may interfere with the successful operation of the spacecraft electronics as well as with the sensitive particle and flux detectors that constitute the space science experiments. These interferences may cause spurious count rates, unwanted signal noises, or changes in material properties. Thus, the nuclear radiations emitted by the radioisotopes provide significant neutron and photon radiation exposure which must be determined and studied.

This study was undertaken to determine the sources of neutron and gamma radiation and their emitted spectrum. Such information must be known before it is possible to determine the extent of the nuclear detector instrument response to the radiation produced by the isotopes. During this investigation, the following were performed:

(1) The nuclear properties of plutonium dioxide fuel components were obtained from the literature.

(2) Sources of gamma radiation produced by the primary plutonium isotope decays, and by the fuel contaminants (which may change with fuel processing methods), were identified and their intensities determined.

(3) For each of the gamma source intensities identified in (2), the gamma fluxes were calculated for three different thicknesses of fuel in a typical RTG capsule. The gamma fluxes were determined at the capsule surface as well as at positions exterior to the capsule. The results of this study will be useful for assessing the effects of plutonium isotopes, of fuel contamination, and of fuel thickness (self-shielding) for periods of time beginning with the *fresh* (immediately after chemical separation) fuel and extending up to 18-yr-old fuel.

II. Description

A. Isotopic Composition and Nuclear Characteristics

The production grade of plutonium 238 product fuel consists of a mixture of plutonium isotopes having the nominal weight distribution as follows (Ref. 1):

Isotope	Abundance (wt %)
^{238}Pu	81.0
^{239}Pu	15.0
^{240}Pu	2.9
^{241}Pu	0.8
^{242}Pu	0.1
^{236}Pu	1.2×10^{-4}

For other variations in the isotope abundances in plutonium dioxide, one may review Refs. 2 and 3. Each of the isotopes listed will have nuclear characteristics which relate to the properties of natural radioactivity and neutron fission. These properties are given in Table 1 (Refs. 4–9).

B. Gamma Radiation

Gamma rays emitted by the plutonium dioxide fuel are derived from three prominent sources:

(1) *Gamma radiation from plutonium isotopes and their decay products exclusive of* ^{236}Pu. The gamma photons produced by the plutonium isotopes will be due to natural radioactivity, prompt gammas from fission, and decay of fission products.

(2) *Gamma radiation from radioactive decay of* ^{236}Pu *and daughter nuclides.* In this study, ^{236}Pu was considered as a fuel contaminant which varied from 1.2 parts/10^6, weight fraction (g ^{236}Pu/g PuO_2), in the current commercial, or production, grade of plutonium dioxide fuel, down to the 0.1 part/10^6 desirable in the biomedical grade.

(3) *Gamma radiation from alpha particle interaction with the isotope* ^{18}O. The interaction $^{18}O(\alpha, n)\,^{21}Ne$ produces ^{21}Ne in excited states as well as the ground states. These states above the ground state are 0.35, 1.38, 1.90, 2.40, and 2.70 MeV. The excited states of ^{21}Ne decay immediately, accompanied by the gamma rays with energies equal to the difference between the excited states and the ground state energies.

The gamma radiation resulting from the $^{17}O(\alpha, n)\,^{20}Ne$ reaction was neglected since it has been suggested (Ref. 10) that the abundance of ^{17}O is one-tenth the abundance of ^{18}O, and the nuclear cross section is one-tenth of ^{18}O. This interaction has not been fully investigated and cannot be treated adequately here. Bremsstrahlung is negligible, and the inelastic gammas are a function of spacecraft geometry and materials. These also are not considered here.

The corresponding gamma spectra derived from each source are listed in Tables 2 to 5. All calculative techniques and appropriate numbers used in the study are given in Appendixes A to E. The term *plutonium product fuel* refers to the mixture of plutonium isotopes listed at the beginning of this section.

Table 1. Neutron activity of isotopes

Isotope	Activity of pure isotope (disintegration per g)	Spontaneous fission half-life, yr	Neutrons/fission of pure isotope	Radioactive half-life of pure isotope, yr
^{238}Pu	6.21×10^{11} 6.36×10^{11} 6.44×10^{11}	4.9×10^{10} (Refs. 1, 4, 5)	2.33 ± 0.08, spontaneous (Ref. 1) 2.75 ± 0.01[a] 2.93 (Ref. 6)	89.6 (Ref. 1) 87.4[b] 86.4 (Ref. 7)
^{239}Pu	$2.27 \pm 0.04 \times 10^9$	5.5×10^{15} (Refs. 1, 7)	2.90 ± 0.04 induced (Refs. 1, 7, 8)	$2.44 \pm 0.05 \times 10^4$ (Refs. 1, 7)
^{240}Pu	$8.36 \pm 0.13 \times 10^9$ 8.38×10^9	1.2×10^{11} (Refs. 1, 9) 1.45×10^{11} (Ref. 7)	2.257 ± 0.046 (Refs. 1, 9) Spontaneous	$6.6 \pm 0.1 \times 10^3$ (Ref. 1) 6.58×10^3 (Ref. 7)
^{241}Pu	$4.24 \pm 0.10 \times 10^{12}$ 3.92×10^{12} 4.16×10^{12}	— — —	— — —	12.95 ± 0.28 (Ref. 1) 14.0[b] 13.2 (Ref. 7)
^{242}Pu	$1.47 \pm 0.02 \times 10^8$	8.5×10^{10} (Ref. 1)	2.18 ± 0.09, spontaneous (Ref. 1)	$3.73 \pm 0.05 \times 10^5$ (Ref. 1)
^{236}Pu	1.97×10^{13}	3.5×10^9 (Refs. 1, 7)	2.30 ± 1.9 (Ref. 1)	2.85 ± 0.01 (Refs. 1, 7)

[a]Dunford, C. Private communication.
[b]Anderson, E. Private communication.

Table 2. Gamma rays from decay of plutonium isotopes and their decay products

Isotope	Gamma ray energy, KeV	Abundance, % of isotopic decay		
		Ref. 7	Ref. 1	Ref. 11
^{238}Pu	17.0	13.0 (Ref. 3)	—	—
	43.6	3.8×10^{-2}	3.8×10^{-2}	
	99.6	8.0×10^{-3}	8.0×10^{-3}	7.4×10^{-3}
	152.5	10^{-3}	1.1×10^{-3}	6.8×10^{-4}
	207.8	4.0×10^{-6}	4.0×10^{-6}	1.2×10^{-5}
	742.4	9.0×10^{-6}	—	4.5×10^{-6}
	765.8	3.5×10^{-5}	5.0×10^{-5}	2.0×10^{-5}
	785.8	6.0×10^{-6}	—	2.8×10^{-6}
	807.6	6.0×10^{-5}	Very small	6.0×10^{-7}
	851.3	—	—	1.2×10^{-6}
	875.0	—	2.0×10^{-5}	—
	882.9	—	—	7.4×10^{-7}
	926.5	—	—	5.0×10^{-7}
	941.8	—	—	6.0×10^{-7}
	1001.1	—	—	8.5×10^{-7}
	1041.8	—	—	2.0×10^{-7}
	1085.1	0.81×10^{-6}	—	1.0×10^{-7}
^{239}Pu	17.0	—	—	9.9×10^{-2} (Ref. 3)
	38.6	7.0×10^{-2}	2.0×10^{-3}	—
	51.6	2.0×10^{-2}	7.0×10^{-3}	7.0×10^{-3}
	129.0 (Ref. 7) 121.0 (Ref. 1)	5.0×10^{-3}	1.5×10^{-3}	—
	207.0	—	4.4×10^{-4}	—
	340.0	—	6.6×10^{-4}	—
	375.0	1.2×10^{-3}	1.3×10^{-3}	—
	414.0	1.2×10^{-2}	8.8×10^{-4}	—
	650.0	8.0×10^{-5}	—	—
	770.0	2.0×10^{-5}	—	—
^{240}Pu	17.0	—	—	—
	45.3	—	—	—
	650.0	2×10^{-5}		—
^{241}Pu	100.0	—	10^{-3}	—
	145.0	1.6×10^{-4}	2.0×10^{-4}	1.21×10^{-4} (Ref. 3)
^{241}Am	60.0	36.0	—	—
	101.0	4×10^{-2}		—
	208.0	6×10^{-4}	—	—
	335.0	8×10^{-4}	—	—
	370.0	4×10^{-4}	—	—
	663.0	5×10^{-4}	—	—
	772.0	3×10^{-4}	—	—
^{237}Np	30.0	14.0	—	—
	86.0	14.0	—	—
	145.0	1.0	—	—
^{237}U	14.0	41.0	—	—
	33.2	16.0	—	—
	60.0	36.0	—	—
	208.0	23.0	—	—

Table 3. Gamma rays emitted by equilibrium fission product gammas and prompt fission gammas

Gamma ray energy interval, Mev	Equilibrium fission product gammas		
	Number of photons per fission (Ref. 12)	Expression for $N(E)$, photons/fission	Calculated number of photons per fission
0.1–0.4	1.61	The photon yield per	1.61
0.4–0.9	4.84	fission was calculated with	4.86
0.9–1.35	0.50	analytic functions fitted to	0.50
1.35–1.80	0.60	the tabulated values of	0.61
1.80–2.20	0.31	photon yield per fission	0.28
2.20–2.60	0.12	from Ref. (12).	0.11
2.60–3.00	0.01		0.04
0.1–0.4		$21.5E$	
0.4–0.65		$5.77e^{E}$	
0.65–0.9		$22.60e^{-1.1E}$	
0.9–0.965		$-121.5E + 117.75$	
0.965–1.35		$0.38e^{0.30E}$	
1.35–1.60		$0.00045e^{5.3E}$	
1.60–1.80		$586.8e^{-3.5E}$	
1.80–3.0		$67.8e^{-2.3E}$	

Prompt fission gammas

The gamma rays emitted by prompt fission were assumed to have the spectral shape provided by the spontaneous fission of ^{235}U (Ref. 16). Within the interval 0.30–1.0 MeV, the relation used was

$$N(E) = 26.8e^{-2.30E} \text{ photons/fission.}$$

From 1.0 to 7.0 MeV the relation became

$$N(E) = 8.0e^{-1.10E} \text{ photons/fission.}$$

These expressions were integrated numerically within each energy interval required for the subsequent RTG study. The calculations for the prompt fission gamma and the equilibrium fission product gammas are given in Appendix E.

C. Radioisotope Thermoelectric Generator Gamma Flux

The gamma sources generated in the study are tabulated for 20 gamma energy intervals with the lowest gamma energy boundary corresponding to 1 KeV and the highest corresponding to 7 MeV. The capsule power output of 1575 W(th) was extended to include 3468 and 5679 W(th) in order to provide the effect of fuel self-shielding on radiated gamma fluxes. (Additional data used in the photon radiation analysis are given in Table 12.)

The gamma ray cross sections were calculated with a corrected version of the computer program GAMLEG (Ref. 13), which averaged the cross sections in each of the given energy intervals with the gamma flux spectrum given in Ref. (1) for plutonium dioxide product fuel. GAMLEG is a computer code that numerically integrates the absorption, scattering, and total cross sections, and provides average values of the cross sections for an arbitrary selection of gamma energy intervals. In addition,

Table 4. Gamma rays from ^{236}Pu and daughter nuclides

Isotope	Gamma ray energy, KeV	Abundance, % of isotope decay	
		Ref. 1	Ref. 7
^{236}Pu	46.0 48.0 (Ref. 1) (Ref. 11)	4.7×10^{-2}	3.1×10^{-2}
	110.0	1.2×10^{-2}	1.2×10^{-2}
	165.0	6.6×10^{-4}	6.6×10^{-4}
	520.0	–	1.7×10^{-4}
	570.0	–	1.0×10^{-4}
	645.0	–	2.4×10^{-4}
^{212}Pb	115.1	–	0.7
	176.7	–	0.2
	238.6	82.0 (Ref. 3)	47.0
	300.1	–	3.2
	415.2	–	0.16
^{212}Bi	Due to β decay (64% yield)		
	40.0	–	2.0
	288.0	–	0.5
	460.0	–	0.8
	727.0	7.3	7.1
	785.0	–	1.1
	893.0	6.6	0.42
	953.0	0.2	0.10
	1074.0 1079.0	0.66	0.60
	1513.0	0.86	0.31
	1620.0	–	1.8
	1800.0 1809.0	Small	0.11
^{212}Bi	Due to α decay (36% yield)		
	288.2	–	0.28
	328.0	–	0.110
	434.0 453.0 473.0 493.0	–	0.42
^{208}Tl	280.0	10.0	–
	511.0	25.0	23.0
	583.0	80.0	86.0
	860.0	15.0	12.0
	2614.0	100.0	100.0

Table 5. Gamma rays from $^{18}O(\alpha, n)^{21}Ne$ reaction

Gamma ray energy, MeV	Calculated activity, photons/g-s PuO_2 (see Appendix D)
0.35	4×10^3
1.38	8.9×10^2
1.90	1.8×10^2
2.40	1.8×10^2
2.70	1.8×10^2

calculations can be made on the averages of the Klein-Nishina differential scattering cross section which correspond to the group-to-group scattering cross section tables. In each of the corresponding gamma energy intervals, the sources of prominent gammas emitted by the plutonium dioxide fuel are tabulated for time periods beginning with the fresh fuel and extending to 18 years of fuel aging. Tables 6 to 10 list the gamma source intensities from each contributing isotope source. The emitted gamma spectra given in Tables 6 to 10 are written in terms of three basic sources of photons which are due to the contaminants ^{236}Pu, ^{18}O, and the decay of the primary isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu.

The gamma activity for each source of radiation was applied to a plutonium 238 fueled capsule with the conceptual design given in Fig. 1. Figure 2 shows the specific geometric model of the capsule chosen for calculating the surface gamma flux (photons/s-cm^2) and gamma flux at detector positions in a radial midplane extending from the capsule. The dimensions for each capsule and corresponding thermal power output are given in Table 11, and material properties were assumed as shown in Table 12.

Surface gamma fluxes were calculated with the computer program ANISN (Ref. 14) in which each of the primary gamma sources were included up to 18 yr in elapsed time periods for the 1575 W(th), 3468 W(th), and 5679 W(th) RTG designs. ANISN is a computer program which solves the one dimensional multigroup Boltzmann transport equation with anisotropic neutron or gamma scattering.

The calculated flux of the plutonium isotopes (exclusive of ^{236}Pu and $^{18}O(\alpha, n)^{21}Ne$ sources) and their decay products at the surface of the fuel capsule varied slightly up to 18 years, but was assumed to remain constant with time. The radiated gamma fluxes produced by the $^{18}O(\alpha, n)^{21}Ne$ reaction at time periods other than fresh are calculated by multiplying the values corresponding to the fresh $^{18}O(\alpha, n)^{21}Ne$ gamma yield by the time decay factors available in Appendix D.

The results of these calculations, indexed in Table 13 and given in Table 14, will provide the gamma flux radiated by a typical RTG for the following variations:

(1) Fuel impurities such as ^{236}Pu and ^{18}O.

(2) Fuel region thickness.

(3) Elapsed time periods varying up to 18 yr from initial chemical separation.

Table 6. Gamma activity, $T = 0$ yr (photons/s–g PuO_2)

Energy interval, MeV	Decay of isotopes and daughter nuclides							
	^{238}Pu (81%)	^{239}Pu (15%)	^{240}Pu (2.9%)	^{241}Pu (0.8%)	^{241}Am	^{237}U	Isotopes	^{236}Pu (1.2 10^6)
6.0–7.0							5	
5.0–6.0							14	
4.0–5.0							45	
3.0–4.0							147	
2.0–3.0							580	
1.8–2.0							264	
1.6–1.8							400	
1.4–1.6							408	
1.2–1.4							356	
1.0–1.2	1.36×10^3						1.78×10^3	
0.9–1.0	8.12×10^3						8.56×10^3	
0.8–0.9	1.25×10^4						1.34×10^4	
0.7–0.8	1.24×10^5						1.24×10^5	
0.6–0.7		300	43.0				1.54×10^3	50.0
0.5–0.6							1.25×10^3	56.2
0.4–0.5		2.65×10^3					3.97×10^3	
0.3–0.4		5.92×10^3					7.31×10^3	
0.2–0.3	5.45×10^4	1.33×10^3					5.62×10^4	
0.044–0.2	2.17×10^8	3.63×10^4		4.42×10^4			2.17×10^8	9100
0.001–0.044	5.91×10^{10}	3.06×10^5					5.91×10^{10}	

Table 6 (contd)

Energy interval, MeV	Decay of isotopes and daughter nuclides (contd)				Fission[a]	$^{18}O(\alpha, n)^{21}Ne$	Total
	^{212}Pb	^{212}Bi	^{208}Tl	^{236}Pu + daughters (1.2 10^6)			
6.0–7.0					5.0		5.0
5.0–6.0					14.0		14.0
4.0–5.0					45		45
3.0–4.0					147.0		147
2.0–3.0					580	360	940
1.8–2.0					264	180	444
1.6–1.8					400		400
1.4–1.6					408		408
1.2–1.4					356	890	1.25×10^3
1.0–1.2					412		1.78×10^3
0.9–1.0					433		8.56×10^3
0.8–0.9					900		1.34×10^4
0.7–0.8					1.004×10^5		1.24×10^5
0.6–0.7				50.0	1.192×10^3		1.59×10^3
0.5–0.6				56.2	1.248×10^3		1.30×10^3
0.4–0.5					1.32×10^3		3.97×10^3
0.3–0.4					1.39×10^2	4.0×10^3	1.13×10^4
0.2–0.3					3.82×10^2		5.62×10^4
0.044–0.2				9100	2.30×10^2		2.17×10^8
0.001–0.044					0.0		5.91×10^{10}

[a]Includes prompt gammas and those from fission products.

Table 7. Gamma activity, $T = 1$ yr (photons/s–g PuO_2)

Energy interval, MeV	Decay of isotopes and daughter nuclides							
	^{238}Pu (81%)	^{239}Pu (15%)	^{240}Pu (2.9%)	^{241}Pu (0.8%)	^{241}Am	^{237}U	Isotopes	^{236}Pu (1.2 10^6)
6.0–7.0							5	
5.0–6.0							14	
4.0–5.0							45	
3.0–4.0							146	
2.0–3.0							576	
1.8–2.0							262	
1.6–1.8							397	
1.4–1.6							405	
1.2–1.4							354	
1.0–1.2	1.35×10^3						1762	
0.9–1.0	8.06×10^3						8490	
0.8–0.9	1.23×10^4						1.32×10^4	
0.7–0.8	1.23×10^5				129.0		1.24×10^5	
0.6–0.7		300.0	43.0		214.0		1741	39.2
0.5–0.6							1239	44.1
0.4–0.5		2.65×10^3					3961	
0.3–0.4		5.92×10^3			514.0		7812	
0.2–0.3	5.41×10^4	1.33×10^3			257.0	1.39×10^5	1.95×10^5	
0.044–0.2	2.15×10^8	3.63×10^4		4.21×10^4	1.54×10^7	2.18×10^5	2.30×10^8	7133
0.001–0.044	5.86×10^{10}	3.06×10^5				3.45×10^5	5.86×10^{10}	

Table 7 (contd)

Energy interval, MeV	Decay of isotopes and daughter nuclides (contd)				Fission[a]	^{18}O (α, n) ^{21}Ne	Total
	^{212}Pb	^{212}Bi	^{208}Tl	^{236}Pu + daughters (1.2 10^6)			
6.0–7.0					5.0		5
5.0–6.0					14.0		14
4.0–5.0					45.0		45
3.0–4.0					146.0		146
2.0–3.0			9797.1	9800	576.0	357	1.07×10^4
1.8–2.0					262.0	179	441
1.6–1.8					397.0		397
1.4–1.6					405.1		405
1.2–1.4					354.0	883	1237
1.0–1.2		536.4		536.4	412		2.30×10^3
0.9–1.0		19.0		19	430		8.49×10^3
0.8–0.9		80.0	1175.7	1255.7	894		1.44×10^4
0.7–0.8		1560		1560	997		1.26×10^5
0.6–0.7				39.2	1184		1.78×10^3
0.5–0.6			1.07×10^4	1.07×10^4	1239		1.20×10^4
0.4–0.5	46.1	193.3		239.4	1311		4.20×10^3
0.3–0.4		10.8		10.8	1378	3970	1.18×10^4
0.2–0.3	1.45×10^4	122.5	979.7	1.56×10^4	379		2.11×10^5
0.044–0.2	259.3			7392.3	228		2.30×10^8
0.001–0.044		380.4		380.4	0.0		5.86×10^{10}

[a] Includes prompt gammas and those from fission products.

Table 8. Gamma activity, $T = 5$ yr (photons/s–g PuO_2)

Energy interval, MeV	Decay of isotopes and daughter nuclides							
	^{238}Pu (81%)	^{239}Pu (15%)	^{240}Pu (2.9%)	^{241}Pu (0.8%)	^{241}Am	^{237}U	Isotopes	^{236}Pu (1.2 10^6)
6.0–7.0							5	
5.0–6.0							14	
4.0–5.0							44	
3.0–4.0							142	
2.0–3.0							561	
1.8–2.0							255	
1.6–1.8							387	
1.4–1.6							395	
1.2–1.4							344	
1.0–1.2	1.31×10^3						1.71×10^3	
0.9–1.0	7.81×10^3						8.23×10^3	
0.8–0.9	1.20×10^4						1.29×10^4	
0.7–0.8	1.19×10^5				581.0		1.21×10^5	
0.6–0.7		300.0	43.0		969.0		2.47×10^3	14.8
0.5–0.6							1.20×10^3	16.7
0.4–0.5		2.65×10^3					3.93×10^3	
0.3–0.4		5.92×10^3			2325.0		9.59×10^3	
0.2–0.3	5.24×10^4	1.33×10^3			1163.0	1.14×10^5	1.69×10^5	
0.044–0.2	2.09×10^8	3.63×10^4		3.45×10^4	6.98×10^7	1.79×10^5	2.79×10^8	2693
0.001–0.044	5.69×10^{10}	3.06×10^5				2.83×10^5	5.69×10^{10}	

Table 8 (contd)

Energy interval, MeV	Decay of isotopes and daughter nuclides (contd)				Fission[a]	$^{18}O(\alpha, n)^{21}Ne$	Total
	^{212}Pb	^{212}Bi	^{208}Tl	^{236}Pu + daughters (1.2 10^6)			
6.0–7.0					5.0		5.0
5.0–6.0					14.0		14
4.0–5.0					44.0		44.0
3.0–4.0					142		142
2.0–3.0			1.15×10^5	1.15×10^5	561	346	1.16×10^5
1.8–2.0					255	173	428
1.6–1.8					387		387
1.4–1.6					395		395
1.2–1.4					344	856	1.20×10^3
1.0–1.2		6.3×10^3		6.30×10^3	401		8.01×10^3
0.9–1.0		223		223	419		8.45×10^3
0.8–0.9		938	1.38×10^4	1.48×10^4	870		2.77×10^4
0.7–0.8		1.83×10^4		1.83×10^4	971		1.39×10^5
0.6–0.7				14.8	1.15×10^3		2.48×10^3
0.5–0.6			1.24×10^5	1.25×10^5	1.21×10^3		1.26×10^5
0.4–0.5	541.0	2.27×10^3		2.81×10^3	1.28×10^3		6.74×10^3
0.3–0.4		127		127	1.34×10^3	3850	1.36×10^4
0.2–0.3	1.70×10^5	1.44×10^3	1.15×10^4	1.83×10^5	369		3.52×10^5
0.044–0.2	3045.0			5.73×10^3	222		2.79×10^8
0.001–0.044		4.47×10^3		443	0.0		5.69×10^{10}

[a]Includes prompt gammas and those from fission products.

Table 9. Gamma activity, T = 10 yr (photons/s–g PuO_2)

Energy interval, MeV	Decay of isotopes and daughter nuclides							
	^{238}Pu (81%)	^{239}Pu (15%)	^{240}Pu (2.9%)	^{241}Pu (0.8%)	^{241}Am	^{237}U	Isotopes	^{236}Pu (1.2 10^6)
6.0–7.0							5	
5.0–6.0							13	
4.0–5.0							44	
3.0–4.0							138	
2.0–3.0							543	
1.8–2.0							247	
1.6–1.8							375	
1.4–1.6							382	
1.2–1.4							334	
1.0–1.2	1.26×10^3						1.65×10^3	
0.9–1.0	7.52×10^3						7.93×10^3	
0.8–0.9	1.15×10^4						1.24×10^4	
0.7–0.8	1.15×10^5				1039		1.17×10^5	
0.6–0.7		3.0×10^2	43.0		1732		3.20×10^3	4.4
0.5–0.6							1.17×10^3	4.9
0.4–0.5		2.65×10^3					3.89×10^3	
0.3–0.4		5.92×10^3			4158.0		1.14×10^4	
0.2–0.3	5.05×10^4	1.33×10^3			2079.0	0.89×10^5	1.43×10^5	
0.044–0.2	2.01×10^8	3.63×10^4		2.70×10^4	1.25×10^8	1.40×10^5	3.26×10^8	792
0.001–0.044	5.47×10^{10}	3.06×10^5				2.21×10^5	5.47×10^{10}	

Table 9 (contd)

Energy interval, MeV	Decay of isotopes and daughter nuclides (contd)				Fission[a]	^{18}O (α, n) ^{21}Ne	Total
	^{212}Pb	^{212}Bi	^{208}Tl	^{236}Pu + daughters (1.2 10^6)			
6.0–7.0					5		5
5.0–6.0					13		13
4.0–5.0					44		44
3.0–4.0					138		138
2.0–3.0			2.04×10^5	2.04×10^5	543	333	2.05×10^5
1.8–2.0					247	167	414
1.6–1.8					375		375
1.4–1.6					382		382
1.2–1.4					334	824	1.16×10^3
1.0–1.2		1.11×10^4		1.113×10^4	389		1.28×10^4
0.9–1.0		400		400	406		8.33×10^3
0.8–0.9		1.66×10^3	2.44×10^4	2.61×10^4	843		3.85×10^4
0.7–0.8		3.24×10^4		3.24×10^4	941		1.50×10^5
0.6–0.7				4.4	1117.0		3.20×10^3
0.5–0.6			2.22×10^5	2.22×10^5	1170.0		2.23×10^5
0.4–0.5	957.0	4.01×10^3		4.97×10^3	1237		8.86×10^3
0.3–0.4		224		224	1301	3.7×10^3	1.53×10^4
0.2–0.3	3.0×10^5	2.57×10^3	2.04×10^4	3.23×10^5	358		4.66×10^5
0.044–0.2	5387.0			6.18×10^3	216		3.26×10^8
0.001–0.044		7.9×10^3		7.90×10^3	0.0		5.47×10^{10}

[a]Includes prompt gammas and those from fission products.

Table 10. Gamma activity, T = 18 yr (photons/s–g PuO_2)

Energy interval, MeV	Decay of isotopes and daughter nuclides							
	^{238}Pu (81%)	^{239}Pu (15%)	^{240}Pu (2.9%)	^{241}Pu (0.8%)	^{241}Am	^{237}U	Isotopes	^{236}Pu (1.2 10^6)
6.0–7.0							5	
5.0–6.0							13	
4.0–5.0							40	
3.0–4.0							131	
2.0–3.0							519	
1.8–2.0							236	
1.6–1.8							358	
1.4–1.6							365	
1.2–1.4							318	
1.0–1.2	1.19×10^3						1.56×10^3	
0.9–1.0	7.07×10^3						7.46×10^3	
0.8–0.9	1.08×10^4						1.16×10^4	
0.7–0.8	1.08×10^5				1558.0		1.10×10^5	
0.6–0.7		300	43		2546.0		3.96×10^3	1.0
0.5–0.6							1.12×10^3	1.0
0.4–0.5		2.65×10^3					3.83×10^3	
0.3–0.4		5.92×10^3			6231.0		1.34×10^4	
0.2–0.3	4.74×10^4	1.33×10^3			3116.0	0.60×10^5	1.12×10^5	
0.044–0.2	1.89×10^8	3.63×10^4		1.81×10^4	1.87×10^8	0.94×10^5	3.76×10^8	118.3
0.001–0.044	5.14×10^{10}	3.06×10^5				1.49×10^5	5.14×10^{10}	

Table 10 (contd)

Energy interval, MeV	Decay of isotopes and daughter nuclides (contd)				Fission[a]	^{18}O (α, n) ^{21}Ne	Total
	^{212}Pb	^{212}Bi	^{208}Tl	^{236}Pu + daughters (1.2 10^6)			
6.0–7.0					5		5
5.0–6.0					13		13
4.0–5.0					40		40
3.0–4.0					131		131
2.0–3.0			2.34×10^5	2.34×10^5	519	272	2.35×10^5
1.8–2.0					236	157	393
1.6–1.8					358		358
1.4–1.6					365		365
1.2–1.4					318	774	1.09×10^3
1.0–1.2		1.29×10^4		1.28×10^4	371		1.45×10^4
0.9–1.0		455		455	387		7.91×10^3
0.8–0.9		1910	2.81×10^4	3.00×10^4	805		4.16×10^4
0.7–0.8		3.73×10^4		3.73×10^4	898		1.48×10^5
0.6–0.7				1.0	1066		3.96×10^3
0.5–0.6			2.56×10^5	2.56×10^5	1116		2.57×10^5
0.4–0.5	1103.0	4623		5.73×10^3	1180		9.56×10^3
0.3–0.4		258		258	1241	3480	1.71×10^4
0.2–0.3	3.46×10^5	2930.0	2.34×10^4	3.72×10^5	342		4.84×10^5
0.044–0.2	6202.0			6.32×10^3	206		3.76×10^8
0.001–0.044		9096.0		9.1×10^3	0.0		5.14×10^{10}

[a]Includes prompt gammas and those from fission products.

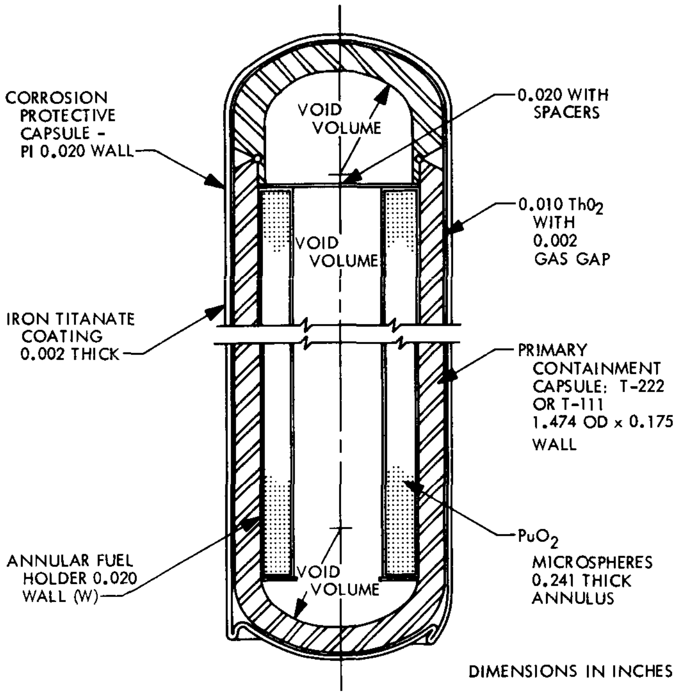

Fig. 1. Conceptual design of the ^{238}Pu fueled capsule

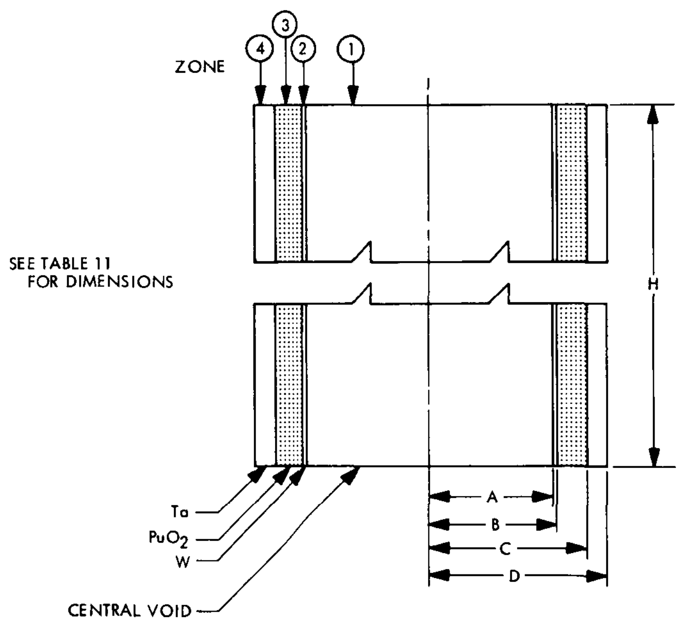

Fig. 2. Fuel capsule geometry for gamma flux analysis

To determine the radiated gamma surface fluxes, one can do as follows for a given fuel thickness: (1) select the gamma source and its time of consideration, and read the corresponding radiated gamma fluxes given in Table 14; and (2) numerically sum all gamma sources to obtain the correct total radiated gamma flux. The radiated gamma flux due to the ^{236}Pu isotope corresponds to a concentration of 1.2 parts/10^6 of ^{236}Pu and can be corrected for the proper concentration of ^{236}Pu. For example, if ^{236}Pu concentration is 0.1 part/10^6 in the 1575 W(th) capsule, simply multiply the radiated flux corresponding to this capsule at the given age, as shown in Table 14, by the factor 0.1/1.2. The product will be the gamma flux emitted by ^{236}Pu plus daughter nuclides present in the 0.1 part/10^6 concentration.

Table 11. Assumed capsule dimensions

Dimension, cm	Capsule power output, W(th)		
	1575	3468	5679
A	3.234	3.234	3.234
B	3.285	3.285	3.285
C	4.023	4.7610	5.4990
D	4.519	5.2570	5.9950
H	32.188	32.188	32.188

Table 12. Assumed material properties

Zone	Material	Density, g/cm^3	Atomic density,[a] atoms/cm^3	Modified[b] atomic density
1	Void	0.0	0.0	
2	Tungsten (W)	19.3	0.06319	4.67628
3	Plutonium dioxide fuel (PuO_2)[c]	7.308[d]	0.016320	1.79520
	Plutonium (Pu)	—	0.016320	1.53408
	Oxygen (O)	—	0.03264	0.26112
4	Tantalum (Ta)	16.6	0.05526	4.0338
5	Tungsten (W)	19.3	0.06319	4.6763

[a]This density corresponds to the P_0 Legendre expansion term in the Klein–Nishina cross sections.

[b]This density corresponds to the P_1–P_5 Legendre expansion terms in the Klein–Nishina cross sections. The P_1–P_5 Legendre terms of hydrogen were used and corrected by the atomic number Z of the isotope used in the analysis.

[c]A thermal power density of 2.888 W(th)/cm^3 results, assuming 0.396 W(th)/g-PuO_2.

[d]The plutonium dioxide fuel density 10.7 g/cm^3 was multiplied by the volume fraction 0.683.

The computer code QAD B was used to calculate the gamma exposure rates at receptor or detector positions extending radially and axially from each RTG. In QAD B (Refs. 15 and 16), each source of gamma energy is computed as a point kernel, which is attenuated by the distance between the source and detector position as well as the material composition along the source–detector line. The computed attenuated flux is the uncollided gamma flux due to single scattering events multiplied by a suitable

Table 13. Index for Tables 14 and 15

Source number	Gamma source	Time, yr	Capsule power, W(th)
1	^{238}Pu + isotopes + decay products	Fresh	1575
2	$^{18}O\ (\alpha, n)\ ^{21}Ne$	Fresh	
3	^{236}Pu decay + daughter nuclides	Fresh	
4	^{236}Pu decay + daughter nuclides	1	
5	^{236}Pu decay + daughter nuclides	5	
6	^{236}Pu decay + daughter nuclides	10	
7	^{236}Pu decay + daughter nuclides	18	
8	^{238}Pu + isotopes + decay products	Fresh	3468
9	$^{18}O\ (\alpha, n)\ ^{21}Ne$	Fresh	
10	^{236}Pu decay + daughter nuclides	Fresh	
11	^{236}Pu decay + daughter nuclides	1	
12	^{236}Pu decay + daughter nuclides	5	
13	^{236}Pu decay + daughter nuclides	10	
14	^{236}Pu decay + daughter nuclides	18	
15	^{238}Pu + isotopes + decay products	Fresh	5679
16	$^{18}O\ (\alpha, n)\ ^{21}Ne$	Fresh	
17	^{236}Pu decay + daughter nuclides	Fresh	
18	^{236}Pu decay + daughter nuclides	1	
19	^{236}Pu decay + daughter nuclides	5	
20	^{236}Pu decay + daughter nuclides	10	
21	^{236}Pu decay + daughter nuclides	18	

Note: ^{236}Pu concentration (fresh) of 1.2 parts/10^6 assumed in all relevant cases.

buildup factor to determine the collided gamma flux, or the attenuation, which includes multiple scattering events between the source and detector positions.

The gamma flux rates presented in Table 15 are computed for different detector positions extending from each of the three capsule designs and for each of the various gamma source intensities given in Tables 6 to 10. The gamma flux rates have been summed for each of the flux rates corresponding to the isotope composition of the production grade of PuO_2 (Refs. 7 and 17) and are plotted in Figs. 3 through 8. For any variation in the isotopes ^{18}O and ^{236}Pu found in the commercial grade of PuO_2, one can select the gamma flux rates given in Table 15 and multiply the gamma flux produced by ^{18}O or ^{236}Pu by the ratio of the new concentration to the concentration used in this study (0.2% ^{18}O in natural oxygen and 1.2 parts/10^6 ^{236}Pu in product fuel).

The emitted gamma spectrum will be assumed to remain unchanged from the capsule surface (radial midplane only) to various detector positions in the same radial midplane. For this reason, only total gamma flux rates have been tabulated for the exterior detector positions.

Table 14. Plutonium dioxide: gamma photon surface fluxes at midplane

Gamma source 1: ^{238}Pu + isotopes and decay products[a] Time 0 yr Capsule power 1575 W(th)		Gamma source 2: $^{18}O\ (\alpha, n)\ ^{21}Ne$ Time 0 yr Capsule power 1575 W(th)		Gamma source 3: ^{236}Pu decay and daughter nuclides Time 0 yr Capsule power 1575 W(th)	
Energy interval, MeV	Flux, photons/s–cm^2	Energy interval, MeV	Flux, photons/s–cm^2	Energy interval, MeV	Flux, photons/s–cm^2
6.0–7.0	1.09274×10^1	6.0–7.0	0.0	6.0–7.0	0.0
5.0–6.0	3.19061×10^1	5.0–6.0	0.0	5.0–6.0	0.0
4.0–5.0	1.06562×10^2	4.0–5.0	0.0	4.0–5.0	0.0
3.0–4.0	3.59364×10^2	3.0–4.0	0.0	3.0–4.0	0.0
2.0–3.0	1.38919×10^3	2.0–3.0	8.24061×10^2	2.0–3.0	0.0
1.8–2.0	6.23476×10^2	1.8–2.0	4.12197×10^2	1.8–2.0	0.0
1.6–1.8	9.09526×10^2	1.6–1.8	7.61248×10^2	1.6–1.8	0.0
1.4–1.6	9.56260×10^2	1.4–1.6	7.68004×10^1	1.4–1.6	0.0
1.2–1.4	8.99081×10^2	1.2–1.4	1.56016×10^3	1.2–1.4	0.0
1.0–1.2	2.92849×10^3	1.0–1.2	3.06084×10^2	1.0–1.2	0.0
0.9–1.0	1.03959×10^4	0.9–1.0	1.50432×10^2	0.9–1.0	0.0
0.8–0.9	1.49095×10^4	0.8–0.9	1.45684×10^2	0.8–0.9	0.0
0.7–0.8	1.02619×10^5	0.7–0.8	1.40533×10^2	0.7–0.8	0.0
0.6–0.7	2.04398×10^4	0.6–0.7	1.28879×10^2	0.6–0.7	2.81568×10^1
0.5–0.6	1.65722×10^4	0.5–0.6	1.15888×10^2	0.5–0.6	2.53716×10^1
0.4–0.5	1.24608×10^4	0.4–0.5	9.64589×10^1	0.4–0.5	7.83508
0.3–0.4	7.37900×10^3	0.3–0.4	2.31330×10^2	0.3–0.4	4.09562
0.2–0.3	2.57823×10^3	0.2–0.3	3.88954×10^1	0.2–0.3	1.29844
0.044–0.2	7.84181×10^1	0.044–0.2	1.04096	0.044–0.2	4.30893×10^{-2}
0.001–0.044	8.24486×10^{-3}	0.001–0.044	9.05290×10^{-5}	0.001–0.044	3.67550×10^{-6}
Total	1.95648×10^5	Total	4.30457×10^3	Total	6.68006×10^1

Table 14 (contd)

Gamma source 4:
^{236}Pu decay and daughter nuclides
Time 1 yr
Capsule power 1575 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	2.24345×10^{4}
1.8–2.0	1.23577×10^{3}
1.6–1.8	1.24820×10^{3}
1.4–1.6	1.26904×10^{3}
1.2–1.4	1.30055×10^{3}
1.0–1.2	2.09323×10^{3}
0.9–1.0	7.86781×10^{2}
0.8–0.9	2.00102×10^{3}
0.7–0.8	2.19842×10^{3}
0.6–0.7	1.11686×10^{3}
0.5–0.6	4.77593×10^{2}
0.4–0.5	1.61373×10^{3}
0.3–0.4	9.36795×10^{2}
0.2–0.3	3.21746×10^{2}
0.044–0.2	8.82168
0.001–0.044	5.39828×10^{-4}
Total	4.33414×10^{4}

Gamma source 5:
^{236}Pu decay and daughter nuclides
Time 5 yr
Capsule power 1575 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	2.63198×10^{5}
1.8–2.0	1.44979×10^{4}
1.6–1.8	1.46437×10^{4}
1.4–1.6	1.48882×10^{4}
1.2–1.4	1.52578×10^{4}
1.0–1.2	2.45596×10^{4}
0.9–1.0	9.23051×10^{3}
0.8–0.9	2.35164×10^{4}
0.7–0.8	2.58259×10^{4}
0.6–0.7	1.28622×10^{4}
0.5–0.6	5.58239×10^{4}
0.4–0.5	1.88721×10^{4}
0.3–0.4	1.09120×10^{4}
0.2–0.3	3.76080×10^{3}
0.044–0.2	8.25528×10^{1}
0.001–0.044	8.40405×10^{-3}
Total	5.07932×10^{5}

Gamma source 6:
^{236}Pu decay and daughter nuclides
Time 10 yr
Capsule power 1575 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	4.66864×10^{5}
1.8–2.0	2.57164×10^{4}
1.6–1.8	2.59752×10^{4}
1.4–1.6	2.64089×10^{4}
1.2–1.4	2.70645×10^{4}
1.0–1.2	4.35066×10^{4}
0.9–1.0	1.63718×10^{4}
0.8–0.9	4.16319×10^{4}
0.7–0.8	4.57185×10^{4}
0.6–0.7	2.27761×10^{4}
0.5–0.6	9.89354×10^{4}
0.4–0.5	3.34397×10^{4}
0.3–0.4	1.93378×10^{4}
0.2–0.3	6.66218×10^{3}
0.044–0.2	1.89959×10^{2}
0.001–0.044	5.18950×10^{-3}
Total	9.00599×10^{5}

Gamma source 7:
^{236}Pu decay and daughter nuclides
Time 18 yr
Capsule power 1575 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	5.35797×10^{5}
1.8–2.0	2.95135×10^{4}
1.6–1.8	2.98104×10^{4}
1.4–1.6	3.03082×10^{4}
1.2–1.4	3.10606×10^{4}
1.0–1.2	5.00270×10^{4}
0.9–1.0	1.87957×10^{4}
0.8–0.9	4.78951×10^{4}
0.7–0.8	5.27127×10^{4}
0.6–0.7	2.61946×10^{4}
0.5–0.6	1.14114×10^{5}
0.4–0.5	3.85234×10^{4}
0.3–0.4	2.22684×10^{4}
0.2–0.3	7.67152×10^{3}
0.044–0.2	2.19250×10^{2}
0.001–0.044	5.73176×10^{-3}
Total	1.03491×10^{6}

Gamma source 8:
^{238}Pu + isotopes + decay products[a]
Time 0 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	3.11766×10^{1}
5.0–6.0	9.15588×10^{1}
4.0–5.0	3.05956×10^{2}
3.0–4.0	1.03326×10^{3}
2.0–3.0	3.96415×10^{3}
1.8–2.0	1.77177×10^{3}
1.6–1.8	2.57036×10^{3}
1.4–1.6	2.70777×10^{3}
1.2–1.4	2.55789×10^{3}
1.0–1.2	5.34024×10^{3}
0.9–1.0	1.44950×10^{4}
0.8–0.9	2.06496×10^{4}
0.7–0.8	1.28623×10^{5}
0.6–0.7	2.80276×10^{4}
0.5–0.6	2.30238×10^{4}
0.4–0.5	1.67140×10^{4}
0.3–0.4	9.72466×10^{3}
0.2–0.3	3.33692×10^{3}
0.044–0.2	9.68699×10^{1}
0.001–0.044	1.28631×10^{-2}
Total	2.65066×10^{5}

Gamma source 9:
$^{18}O(\alpha, n)^{21}Ne$
Time 0 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s–cm²
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	1.16819×10^{3}
1.8–2.0	5.82781×10^{2}
1.6–1.8	1.20013×10^{2}
1.4–1.6	1.21695×10^{2}
1.2–1.4	2.12704×10^{3}
1.0–1.2	4.62504×10^{2}
0.9–1.0	2.27767×10^{2}
0.8–0.9	2.20093×10^{2}
0.7–0.8	2.11329×10^{2}
0.6–0.7	1.91692×10^{2}
0.5–0.6	1.69937×10^{2}
0.4–0.5	1.38817×10^{2}
0.3–0.4	2.64971×10^{2}
0.2–0.3	4.86122×10^{1}
0.044–0.2	1.31854
0.001–0.044	2.93580×10^{-6}
Total	6.05676×10^{3}

[a]Includes spontaneous fission gammas and fission product gammas ($k_{effective} = 0.40$)

Table 14 (contd)

Gamma source 10:
^{236}Pu decay and daughter nuclides
Time 0 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	0.0
1.8–2.0	0.0
1.6–1.8	0.0
1.4–1.6	0.0
1.2–1.4	0.0
1.0–1.2	0.0
0.9–1.0	0.0
0.8–0.9	0.0
0.7–0.8	0.0
0.6–0.7	3.31110×10^1
0.5–0.6	2.90787×10^1
0.4–0.5	9.14273
0.3–0.4	4.73201
0.2–0.3	1.49087
0.044–0.2	4.81974×10^{-2}
0.001–0.044	5.84410×10^{-6}
Total	7.76035×10^1

Gamma source 11:
^{236}Pu decay and daughter nuclides
Time 1 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	3.18032×10^4
1.8–2.0	1.95593×10^3
1.6–1.8	1.98543×10^3
1.4–1.6	2.02939×10^3
1.2–1.4	2.08968×10^3
1.0–1.2	3.14682×10^3
0.9–1.0	1.24267×10^3
0.8–0.9	2.76248×10^3
0.7–0.8	2.97406×10^3
0.6–0.7	1.62855×10^3
0.5–0.6	5.70391×10^3
0.4–0.5	2.07093×10^3
0.3–0.4	1.20675×10^3
0.2–0.3	4.09212×10^2
0.044–0.2	1.13384×10^1
0.001–0.044	5.83672×10^{-4}
Total	6.10203×10^4

Gamma source 12:
^{236}Pu decay and daughter nuclides
Time 5 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	3.73110×10^5
1.8–2.0	2.29467×10^4
1.6–1.8	2.32928×10^4
1.4–1.6	2.38085×10^4
1.2–1.4	2.45158×10^4
1.0–1.2	3.69208×10^4
0.9–1.0	1.45790×10^4
0.8–0.9	3.24601×10^4
0.7–0.8	3.49340×10^4
0.6–0.7	1.88242×10^4
0.5–0.6	6.66815×10^4
0.4–0.5	2.42265×10^4
0.3–0.4	1.40727×10^4
0.2–0.3	4.78542×10^3
0.044–0.2	1.12511×10^2
0.001–0.044	1.31744×10^{-2}
Total	7.15271×10^5

Gamma source 13:
^{236}Pu decay and daughter nuclides
Time 10 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	6.61826×10^5
1.8–2.0	4.07030×10^4
1.6–1.8	4.13170×10^4
1.4–1.6	4.22317×10^4
1.2–1.4	4.34864×10^4
1.0–1.2	6.54145×10^4
0.9–1.0	2.58578×10^4
0.8–0.9	5.74746×10^4
0.7–0.8	6.18518×10^4
0.6–0.7	3.33408×10^4
0.5–0.6	1.18180×10^5
0.4–0.5	4.29301×10^4
0.3–0.4	2.49406×10^4
0.2–0.3	8.47843×10^3
0.044–0.2	2.41751×10^2
0.001–0.044	7.12230×10^{-3}
Total	1.26827×10^6

Gamma source 14:
^{236}Pu decay and daughter nuclides
Time 18 yr
Capsule power 3468 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	7.59546×10^5
1.8–2.0	4.67129×10^4
1.6–1.8	4.74175×10^4
1.4–1.6	4.84673×10^4
1.2–1.4	4.99072×10^4
1.0–1.2	7.52007×10^4
0.9–1.0	2.96856×10^4
0.8–0.9	6.61082×10^4
0.7–0.8	7.12859×10^4
0.6–0.7	3.83366×10^4
0.5–0.6	1.36282×10^5
0.4–0.5	4.94402×10^4
0.3–0.4	2.87108×10^4
0.2–0.3	9.75978×10^3
0.044–0.2	2.78765×10^2
0.001–0.044	8.05833×10^{-3}
Total	1.45714×10^6

Gamma source 15:
^{238}Pu + isotopes + decay products[a]
Time 0 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	5.41158×10^1
5.0–6.0	1.58637×10^2
4.0–5.0	5.31846×10^2
3.0–4.0	1.79496×10^3
2.0–3.0	6.85509×10^3
1.8–2.0	3.05964×10^3
1.6–1.8	4.41956×10^3
1.4–1.6	4.65961×10^3
1.2–1.4	4.41351×10^3
1.0–1.2	7.61123×10^3
0.9–1.0	1.69881×10^4
0.8–0.9	2.39657×10^4
0.7–0.8	1.38142×10^5
0.6–0.7	3.19004×10^4
0.5–0.6	2.60728×10^4
0.4–0.5	1.88376×10^4
0.3–0.4	1.09003×10^4
0.2–0.3	3.71790×10^3
0.044–0.2	1.07720×10^2
0.001–0.044	1.35308×10^{-2}
Total	3.04190×10^5

[a]Includes spontaneous fission gammas and fission product decay gammas ($k_{effective} = 0.30$).

Table 14 (contd)

Gamma source 16:
^{18}O (α, n) ^{21}Ne
Time 0 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	1.34323×10^{3}
1.8–2.0	6.68884×10^{2}
1.6–1.8	1.46759×10^{2}
1.4–1.6	1.49139×10^{2}
1.2–1.4	2.38528×10^{3}
1.0–1.2	5.48482×10^{2}
0.9–1.0	2.69940×10^{2}
0.8–0.9	2.60130×10^{2}
0.7–0.8	2.48878×10^{2}
0.6–0.7	2.24385×10^{2}
0.5–0.6	1.97630×10^{2}
0.4–0.5	1.60224×10^{2}
0.3–0.4	2.80338×10^{2}
0.2–0.3	5.33532×10^{1}
0.044–0.2	1.45190
0.001–0.044	2.55817×10^{-5}
Total	6.93810×10^{3}

Gamma source 17:
^{236}Pu decay and daughter nuclides
Time 0 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	0.0
1.8–2.0	0.0
1.6–1.8	0.0
1.4–1.6	0.0
1.2–1.4	0.0
1.0–1.2	0.0
0.9–1.0	0.0
0.8–0.9	0.0
0.7–0.8	0.0
0.6–0.7	3.45107×10^{1}
0.5–0.6	3.00675×10^{1}
0.4–0.5	9.50602
0.3–0.4	4.90504
0.2–0.3	1.54553
0.044–0.2	4.94647×10^{-2}
0.001–0.044	6.01187×10^{-6}
Total	8.05843×10^{1}

Gamma source 18:
^{236}Pu decay and daughter nuclides
Time 1 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	3.65697×10^{4}
1.8–2.0	2.40009×10^{3}
1.6–1.8	2.44198×10^{3}
1.4–1.6	2.50122×10^{3}
1.2–1.4	2.57899×10^{3}
1.0–1.2	3.74472×10^{3}
0.9–1.0	1.51489×10^{3}
0.8–0.9	3.13671×10^{3}
0.7–0.8	3.34224×10^{3}
0.6–0.7	1.89773×10^{3}
0.5–0.6	6.05706×10^{3}
0.4–0.5	2.27950×10^{3}
0.3–0.4	1.33273×10^{3}
0.2–0.3	4.51040×10^{2}
0.044–0.2	1.25653×10^{1}
0.001–0.044	4.62359×10^{-4}
Total	7.02611×10^{4}

Gamma source 19:
^{236}Pu decay and daughter nuclides
Time 5 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	4.29030×10^{5}
1.8–2.0	2.81575×10^{4}
1.6–1.8	2.86489×10^{4}
1.4–1.6	2.93439×10^{4}
1.2–1.4	3.02563×10^{4}
1.0–1.2	4.39356×10^{4}
0.9–1.0	1.77726×10^{4}
0.8–0.9	3.68542×10^{4}
0.7–0.8	3.92563×10^{4}
0.6–0.7	2.19725×10^{4}
0.5–0.6	7.08171×10^{4}
0.4–0.5	2.66709×10^{4}
0.3–0.4	1.55490×10^{4}
0.2–0.3	5.27576×10^{3}
0.044–0.2	1.27751×10^{2}
0.001–0.044	1.44309×10^{-2}
Total	8.23668×10^{5}

Gamma source 20:
^{236}Pu decay and daughter nuclides
Time 10 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	7.61017×10^{5}
1.8–2.0	4.99460×10^{4}
1.6–1.8	5.08178×10^{4}
1.4–1.6	5.20505×10^{4}
1.2–1.4	5.36689×10^{4}
1.0–1.2	7.78499×10^{4}
0.9–1.0	3.15220×10^{4}
0.8–0.9	6.52609×10^{4}
0.7–0.8	6.95109×10^{4}
0.6–0.7	3.89216×10^{4}
0.5–0.6	1.25511×10^{5}
0.4–0.5	4.72637×10^{4}
0.3–0.4	2.75580×10^{4}
0.2–0.3	9.34777×10^{3}
0.044–0.2	2.65905×10^{2}
0.001–0.044	8.64492×10^{-3}
Total	1.46051×10^{6}

Gamma source 21:
^{236}Pu decay and daughter nuclides
Time 18 yr
Capsule power 5679 W(th)

Energy interval, MeV	Flux, photons/s—cm^2
6.0–7.0	0.0
5.0–6.0	0.0
4.0–5.0	0.0
3.0–4.0	0.0
2.0–3.0	8.73382×10^{5}
1.8–2.0	5.73205×10^{4}
1.6–1.8	5.83211×10^{4}
1.4–1.6	5.97359×10^{4}
1.2–1.4	6.15932×10^{4}
1.0–1.2	8.94849×10^{4}
0.9–1.0	3.61877×10^{4}
0.8–0.9	7.50557×10^{4}
0.7–0.8	8.00953×10^{4}
0.6–0.7	4.47480×10^{4}
0.5–0.6	1.44717×10^{5}
0.4–0.5	5.44210×10^{4}
0.3–0.4	3.17184×10^{4}
0.2–0.3	1.07587×10^{4}
0.044–0.2	3.06467×10^{2}
0.001–0.044	9.85794×10^{-3}
Total	1.67785×10^{6}

Table 15. Plutonium dioxide: gamma photon fluxes vs detector position

Gamma source 1:
^{238}Pu + isotopes + decay products
Time 0 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519 cm, 0, 0 (midplane)	1.95648 × 10^5
5.257, 0, 0	2.140 × 10^5
5.995, 0, 0	1.950 × 10^5
40.0, 0, 0	1.184 × 10^4
100.0, 0, 0	2.00 × 10^3
0, 0, 17.7	1.870 × 10^5
0, 0, 22.7	6.040 × 10^4
0, 0, 37.7	7.670 × 10^3
0, 0, 40.0	6.132 × 10^3
0, 0, 100.0	3.424 × 10^2

Gamma source 2:
^{18}O (α, n) ^{21}Ne
Time 0 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	4.30457 × 10^3
5.257, 0, 0	4.705 × 10^3
5.995, 0, 0	4.288 × 10^3
40.0, 0, 0	2.604 × 10^2
100.0, 0, 0	4.39 × 10^1
0, 0, 17.7	4.113 × 10^3
0, 0, 22.7	1.328 × 10^3
0, 0, 37.7	1.688 × 10^2
0, 0, 40.0	1.349 × 10^2
0, 0, 100.0	7.533

Gamma source 3:
^{236}Pu decay and daughter nuclides
Time 0 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	6.68006 × 10^1
5.257, 0, 0	7.301 × 10^1
5.995, 0, 0	6.653 × 10^1
40.0, 0, 0	4.040
100.0, 0, 0	0.681
0, 0, 17.7	6.384 × 10^1
0, 0, 22.7	2.061 × 10^1
0, 0, 37.7	2.619
0, 0, 40.0	2.094
0, 0, 100.0	0.1170

Gamma source 4:
^{236}Pu decay and daughter nuclides
Time 1 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	4.33414 × 10^4
5.257, 0, 0	4.737 × 10^4
5.995, 0, 0	4.317 × 10^4
40.0, 0, 0	2.622 × 10^3
100.0, 0, 0	4.421 × 10^2
0, 0, 17.7	4.142 × 10^4
0, 0, 22.7	1.338 × 10^4
0, 0, 37.7	1.700 × 10^3
0, 0, 40.0	1.358 × 10^3
0, 0, 100.0	75.850

Gamma source 5:
^{236}Pu decay and daughter nuclides
Time 5 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	5.07932 × 10^5
5.257, 0, 0	5.552 × 10^5
5.995, 0, 0	5.059 × 10^5
40.0, 0, 0	3.073 × 10^4
100.0, 0, 0	5.181 × 10^3
0, 0, 17.7	4.8538 × 10^5
0, 0, 22.7	1.568 × 10^5
0, 0, 37.7	1.991 × 10^4
0, 0, 40.0	1.592 × 10^4
0, 0, 100.0	8.89 × 10^2

Gamma source 6:
^{236}Pu decay and daughter nuclides
Time 10 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	9.00599 × 10^5
5.257, 0, 0	9.844 × 10^5
5.995, 0, 0	8.970 × 10^5
40.0, 0, 0	5.449 × 10^4
100.0, 0, 0	9.186 × 10^3
0, 0, 17.7	8.606 × 10^5
0, 0, 22.7	2.779 × 10^5
0, 0, 37.7	3.531 × 10^4
0, 0, 40.0	2.823 × 10^4
0, 0, 100.0	1.576 × 10^3

Gamma source 7:
^{236}Pu decay and daughter nuclides
Time 18 yr
Capsule power 1575 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
4.519, 0, 0 (midplane)	1.03491 × 10^6
5.257, 0, 0	1.131 × 10^6
5.995, 0, 0	1.0308 × 10^6
40.0, 0, 0	6.261 × 10^4
100.0, 0, 0	1.056 × 10^4
0, 0, 17.7	9.890 × 10^5
0, 0, 22.7	3.194 × 10^5
0, 0, 37.7	4.057 × 10^4
0, 0, 40.0	3.244 × 10^4
0, 0, 100.0	1.811 × 10^3

Gamma source 8:
^{238}Pu + isotopes + decay products
Time 0 yr
Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	2.65066 × 10^5
5.995, 0, 0	2.823 × 10^5
6.733, 0, 0	2.594 × 10^5
40.0, 0, 0	1.856 × 10^4
100.0, 0, 0	3.088 × 10^3
0, 0, 17.7	2.693 × 10^5
0, 0, 22.7	8.562 × 10^4
0, 0, 37.7	1.113 × 10^4
0, 0, 40.0	9.092 × 10^3
0, 0, 100.0	6.55 × 10^2

Gamma source 9:
^{18}O (α, n) ^{21}Ne
Time 0 yr
Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	6.05676 × 10^3
5.995, 0, 0	6.450 × 10^3
6.733, 0, 0	5.927 × 10^3
40.0, 0, 0	4.24 × 10^2
100.0, 0, 0	7.056 × 10^1
0, 0, 17.7	6.154 × 10^3
0, 0, 22.7	1.956 × 10^3
0, 0, 37.7	2.544 × 10^2
0, 0, 40.0	2.078 × 10^2
0, 0, 100.0	1.500 × 10^1

[a]Origin of coordinate placed at center of capsule.

Table 15 (contd)

Gamma source 10: ^{236}Pu decay and daughter nuclides; Time 0 yr; Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	7.76035×10^{1}
5.995, 0, 0	8.265×10^{1}
6.733, 0, 0	7.595×10^{1}
40.0, 0, 0	5.432
100.0, 0, 0	0.904
0, 0, 17.7	7.885×10^{1}
0, 0, 22.7	2.507×10^{1}
0, 0, 37.7	3.260
0, 0, 40.0	2.662
0, 0, 100.0	0.192

Gamma source 11: ^{236}Pu decay and daughter nuclides; Time 1 yr; Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	6.10203×10^{4}
5.995, 0, 0	6.500×10^{4}
6.733, 0, 0	5.972×10^{4}
40.0, 0, 0	4.272×10^{3}
100.0, 0, 0	7.109×10^{2}
0, 0, 17.7	6.200×10^{4}
0, 0, 22.7	1.971×10^{4}
0, 0, 37.7	2.563×10^{3}
0, 0, 40.0	2.093×10^{3}
0, 0, 100.0	1.508×10^{2}

Gamma source 12: ^{236}Pu decay and daughter nuclides; Time 5 yr; Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	7.15271×10^{5}
5.995, 0, 0	7.618×10^{5}
6.733, 0, 0	7.000×10^{5}
40.0, 0, 0	5.007×10^{4}
100.0, 0, 0	8.333×10^{3}
0, 0, 17.7	7.267×10^{5}
0, 0, 22.7	2.310×10^{5}
0, 0, 37.7	3.004×10^{4}
0, 0, 40.0	2.454×10^{4}
0, 0, 100.0	1.767×10^{3}

Gamma source 13: ^{236}Pu decay and daughter nuclides; Time 10 yr; Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	1.26827×10^{6}
5.995, 0, 0	1.351×10^{6}
6.733, 0, 0	1.241×10^{6}
40.0, 0, 0	8.878×10^{4}
100.0, 0, 0	1.478×10^{4}
0, 0, 17.7	1.289×10^{6}
0, 0, 22.7	4.097×10^{5}
0, 0, 37.7	5.327×10^{4}
0, 0, 40.0	4.350×10^{4}
0, 0, 100.0	3.133×10^{3}

Gamma source 14: ^{236}Pu decay and daughter nuclides; Time 18 yr; Capsule power 3468 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.257, 0, 0 (midplane)	1.45714×10^{6}
5.995, 0, 0	1.552×10^{6}
6.733, 0, 0	1.426×10^{6}
40.0, 0, 0	1.020×10^{5}
100.0, 0, 0	1.698×10^{4}
0, 0, 17.7	1.481×10^{6}
0, 0, 22.7	4.707×10^{5}
0, 0, 37.7	6.120×10^{4}
0, 0, 40.0	5.000×10^{4}
0, 0, 100.0	3.600×10^{3}

Gamma source 15: ^{238}Pu + isotopes + decay products; Time 0 yr; Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm²
5.995, 0, 0 (midplane)	3.04190×10^{5}
6.733, 0, 0	3.228×10^{5}
7.471, 0, 0	2.982×10^{5}
40.0, 0, 0	2.434×10^{4}
100.0, 0, 0	4.046×10^{3}
0, 0, 17.7	3.240×10^{5}
0, 0, 22.7	1.106×10^{5}
0, 0, 37.7	1.552×10^{4}
0, 0, 40.0	1.275×10^{4}
0, 0, 100.0	1.065×10^{3}

Table 15 (contd)

Gamma source 16:
$^{18}O(\alpha, n)^{21}Ne$
Time 0 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	6.93810×10^3
6.733, 0, 0	7.361×10^3
7.471, 0, 0	6.800×10^3
40.0, 0, 0	5.550×10^2
100.0, 0, 0	9.228×10^1
0, 0, 17.7	7.389×10^3
0, 0, 22.7	2.521×10^3
0, 0, 37.7	3.539×10^2
0, 0, 40.0	2.907×10^2
0, 0, 100.0	2.428×10^1

Gamma source 17:
^{236}Pu decay and daughter nuclides
Time 0 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	8.05843×10^1
6.733, 0, 0	8.550×10^1
7.471, 0, 0	7.900×10^1
40.0, 0, 0	6.4471
100.0, 0, 0	1.072
0, 0, 17.7	8.582×10^1
0, 0, 22.7	2.929×10^1
0, 0, 37.7	4.110
0, 0, 40.0	3.377
0, 0, 100.0	0.282

Gamma source 18:
^{236}Pu decay and daughter nuclides
Time 1 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	7.02611×10^4
6.733, 0, 0	7.455×10^4
7.471, 0, 0	6.886×10^4
40.0, 0, 0	5.621×10^3
100.0, 0, 0	9.345×10^2
0, 0, 17.7	7.483×10^4
0, 0, 22.7	2.554×10^4
0, 0, 37.7	3.583×10^3
0, 0, 40.0	2.944×10^3
0, 0, 100.0	2.459×10^2

Gamma source 19:
^{236}Pu decay and daughter nuclides
Time 5 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	8.23668×10^5
6.733, 0, 0	8.739×10^5
7.471, 0, 0	8.073×10^5
40.0, 0, 0	6.590×10^4
100.0, 0, 0	1.096×10^4
0, 0, 17.7	8.772×10^5
0, 0, 22.7	2.993×10^5
0, 0, 37.7	4.201×10^4
0, 0, 40.0	3.451×10^4
0, 0, 100.0	2.883×10^3

Gamma source 20:
^{236}Pu decay and daughter nuclides
Time 10 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	1.46051×10^6
6.733, 0, 0	1.550×10^6
7.471, 0, 0	1.432×10^6
40.0, 0, 0	1.169×10^5
100.0, 0, 0	1.943×10^4
0, 0, 17.7	1.556×10^6
0, 0, 22.7	5.308×10^5
0, 0, 37.7	7.449×10^4
0, 0, 40.0	6.120×10^4
0, 0, 100.0	5.112×10^3

Gamma source 21:
^{236}Pu decay and daughter nuclides
Time 18 yr
Capsule power 5679 W(th)

Detector position[a] (r, θ, z)	Flux, photons/s–cm^2
5.995, 0, 0 (midplane)	1.67785×10^6
6.733, 0, 0	1.780×10^6
7.471, 0, 0	1.645×10^6
40.0, 0, 0	1.343×10^5
100.0, 0, 0	2.232×10^4
0, 0, 17.7	1.787×10^6
0, 0, 22.7	6.097×10^5
0, 0, 37.7	8.557×10^4
0, 0, 40.0	7.030×10^4
0, 0, 100.0	5.872×10^3

One can determine the spectrum at some arbitrary (radial midplane only) detector position by multiplying the emitted spectrum values at the capsule surface by the ratio of the total flux at that detector position to the total flux at the capsule surface.

D. Summary

For this study, all calculations were completed with the following assumptions or conditions:

(1) The radioactive half-life of ^{238}Pu is 87.4 yr with a fission yield of 2.75 ± 0.01 neutrons/fission.

(2) The radioactive half-life of ^{241}Pu is 14 yr.

(3) In Table 2, the gamma ray abundances of each isotopic decay correspond to the values given in Ref. 7. Additional resonant gammas not given in Ref. 7 were taken from Refs. 11 and 1.

(4) The gamma rays emitted by prompt fission and equilibrium fission products were integrated in the given energy interval $\int N(E)\,dE$ to yield the total number of gammas produced per neutron fission.

(5) In Table 4, the gamma ray abundances were taken from Ref. 7. The methods of analysis for the direct yield of ^{236}Pu are given in Appendixes B and C.

(6) Although Refs. 18 and 19 suggest the 1.75 and 2.87 MeV photons obtained from the $^{18}O(\alpha, n)^{21}Ne$ reaction, it is felt that, because a NaI crystal was used in their experiment, the 1.90, 2.40, and 2.70 MeV photons given in Ref. 1 were contained as unresolved resonances in experiments of Refs. 18 and 19.

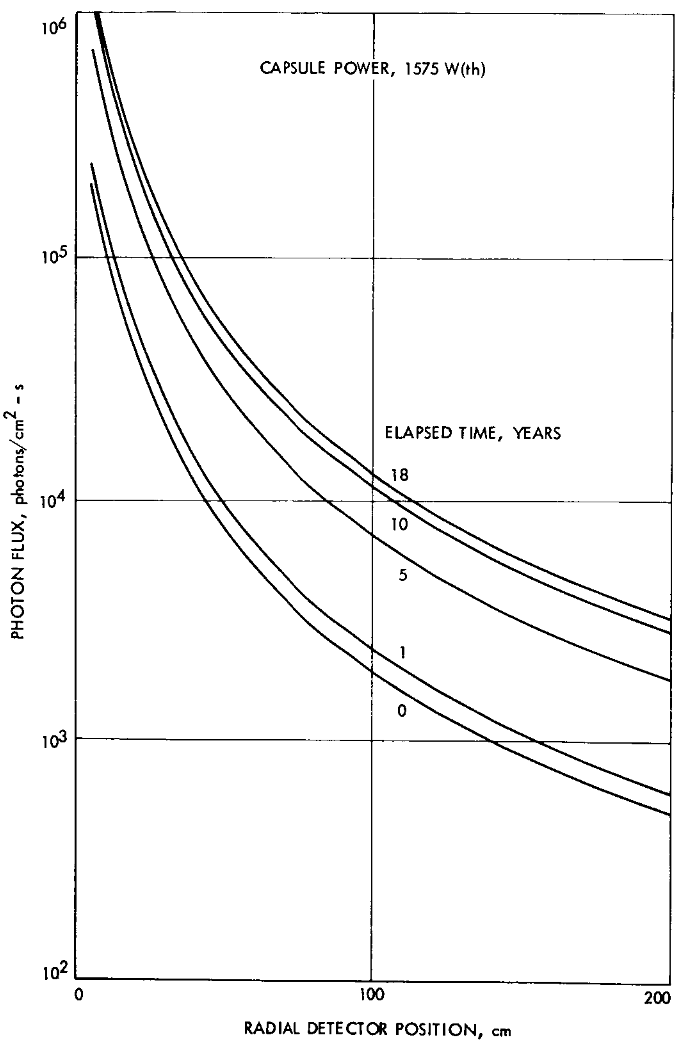

Fig. 3. Photon flux vs radial detector position, capsule power 1575 W(th)

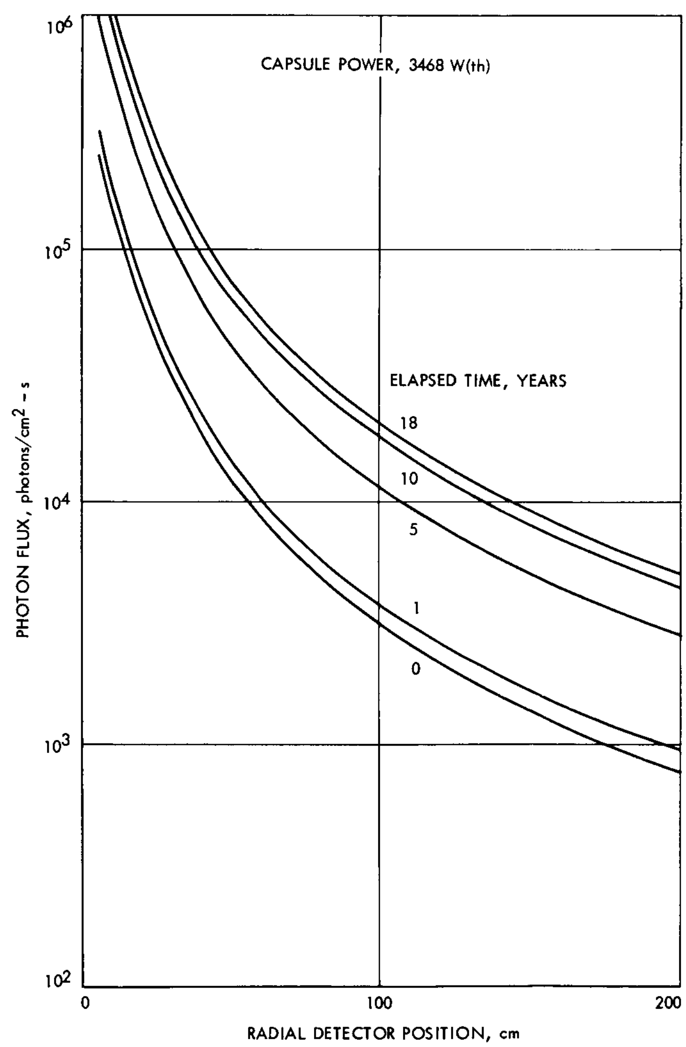

Fig. 4. Photon flux vs radial detector position, capsule power 3468 W(th)

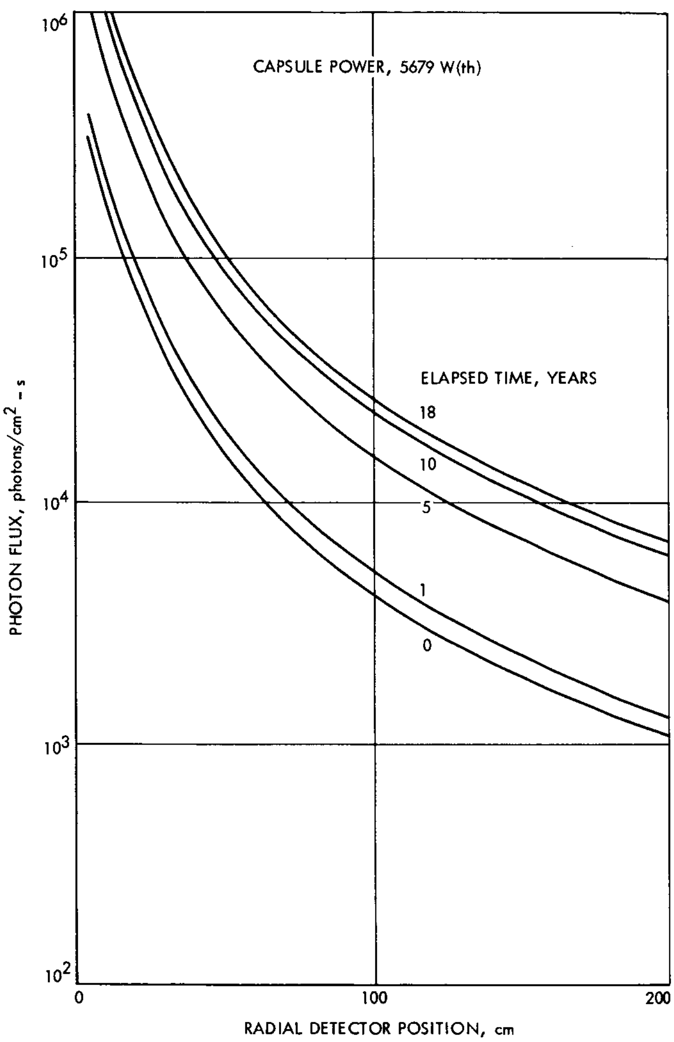

Fig. 5. Photon flux vs radial detector position, capsule power 5679 W(th)

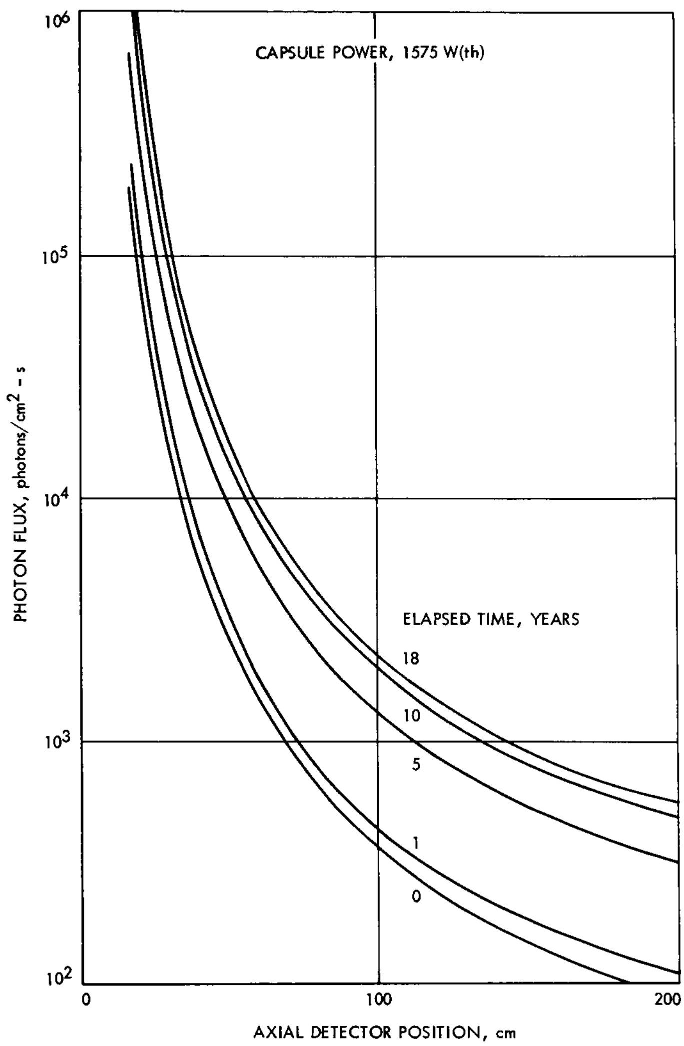

Fig. 6. Photon flux vs axial detector position, capsule power 1575 W(th)

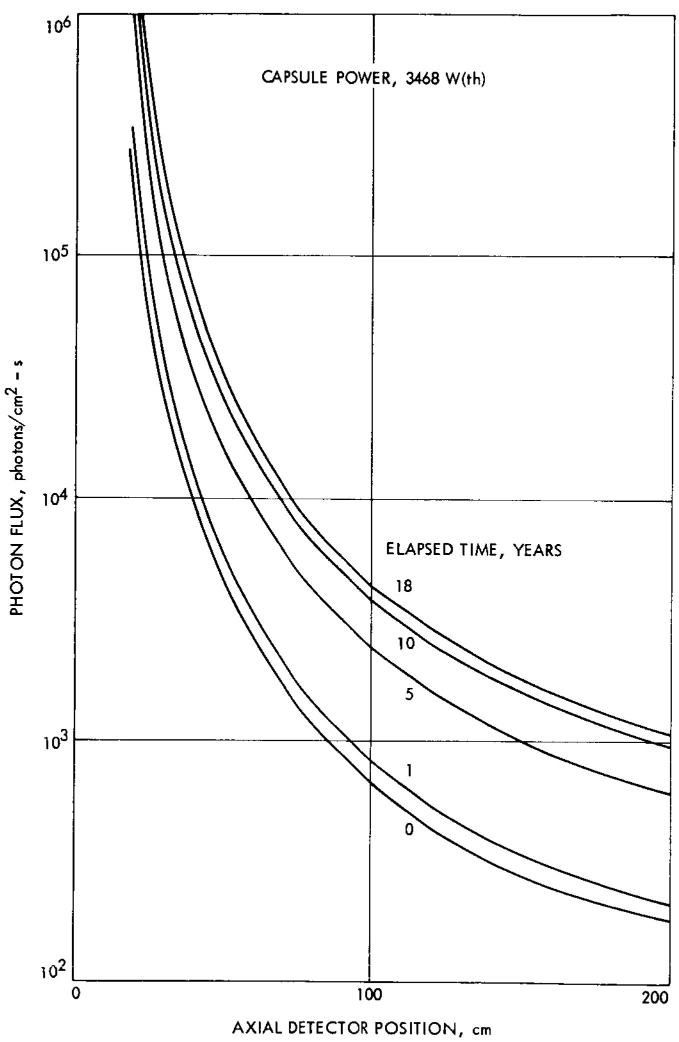

Fig. 7. Photon flux vs axial detector position, capsule power 3468 W(th)

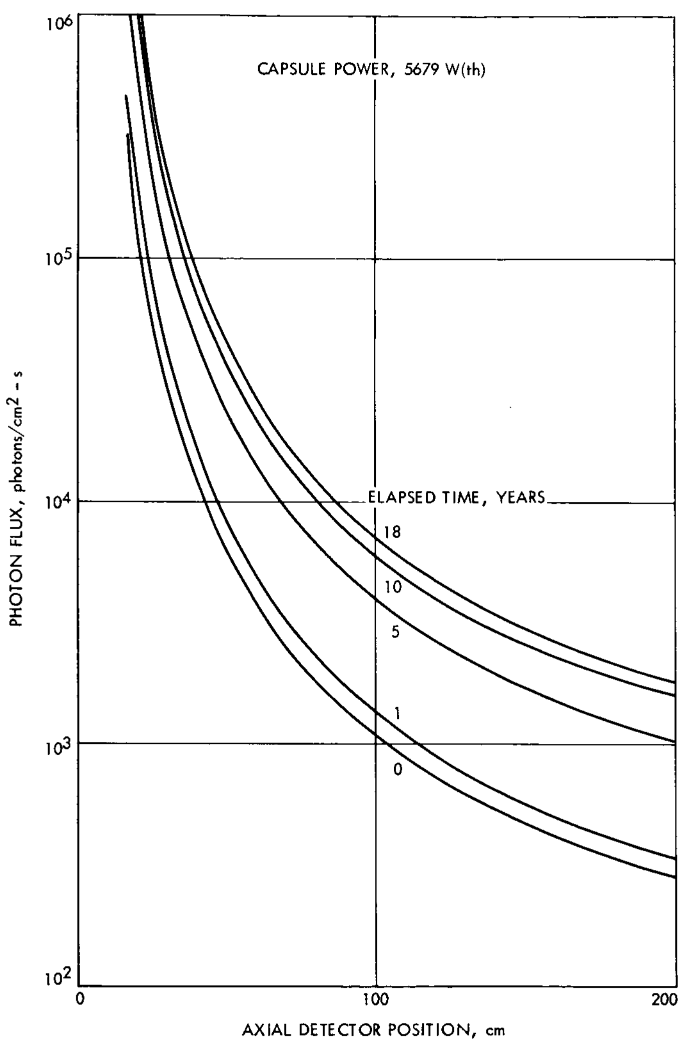

Fig. 8. Photon flux vs axial detector position, capsule power 5679 W(th)

Appendix A

Gamma Activity From Direct Decay of ^{241}Pu and Daughter Nuclides

The following demonstrates how the photon yield per gram of PuO_2 was determined for the case of the 145 KeV resonant gamma line. Other lines were done in a similar manner.

Photons/s–g PuO_2 =

activity of pure isotope × 0.008 × 0.881 × abundance,

where abundance is given in Table 2, the activity of pure isotope = 3.92×10^{12} dis*/s–g ^{241}Pu (Table 1),

$$0.008 \text{ is the fraction } \left(\frac{\text{g } ^{241}\text{Pu}}{\text{g Pu}}\right),$$

and

$$0.881 \text{ is the fraction } \left(\frac{\text{g Pu}}{\text{g PuO}_2}\right).$$

Thus the number of 145 KeV photons/s–g PuO_2 =

$$3.92 \times 10^{12} \frac{\text{dis}}{\text{s–g } ^{241}\text{Pu}} \times 0.008 \times 0.881 \times (1.6 \times 10^{-6}) = 4.42 \times 10^{4} \text{ photons/s–g PuO}_2.$$

The gamma emission from the decay products of ^{241}Pu was determined as follows:

$$^{241}\text{Pu} \xrightarrow[14\text{ yr}]{\beta} {}^{241}\text{Am} \xrightarrow[432\text{ yr}]{\alpha} {}^{237}\text{Np} \xrightarrow[2.14 \times 10^{6}\text{ yr}]{\beta}$$

decay chain 1
(approximately 100% yield),

and

$$^{241}\text{Pu} \xrightarrow[14\text{ yr}]{\alpha} {}^{237}\text{U} \xrightarrow[6.75\text{ day}]{\beta} {}^{237}\text{Np} \xrightarrow[2.14 \times 10^{6}\text{ yr}]{}$$

decay chain 2
(2.3×10^{-3}% yield).

*Disintegration.

The decay of the daughter nuclide ^{241}Am will produce a gamma spectrum which is calculated from the following abundances (see Table 2):

Gamma energy, KeV	Abundance, % of isotope decay
60	36.0
101	4×10^{-2}
208	6×10^{-4}
335	8×10^{-4}
370	4×10^{-4}
663	5×10^{-4}
772	3×10^{-4}

The net gamma activity of ^{241}Am was calculated with the Bateman equation where the decay chain is represented as

$$N_A \xrightarrow[\lambda_A]{} N_B \xrightarrow[\lambda_B]{} N_C \xrightarrow[\lambda_C]{},$$

where N_A is the number of parent atoms with decay constant λ_A, N_B is the number of atoms of the first daughter nuclide with decay constant λ_B, and N_C is the number of atoms of the second daughter nuclide with decay constant λ_C.

The activity (dis/s) of ^{241}Am represented by $N_B\lambda_B$ is written as

$$N_B\lambda_B = \frac{\lambda_A\lambda_B}{\lambda_B - \lambda_A}\{e^{-\lambda_A t} - e^{-\lambda_B t}\} N_{A0},$$

where N_{A0} is the initial supply of the parent atoms N_A and is equal to (g $^{241}Pu \times N_0)/A$. The symbol N_0 is the Avogadro number, and A is the gram atomic mass of the nuclide N_A. If activity (dis/s–g ^{241}Pu) is desired, then $N_{A0} = N_0/A$ is used.

The decay constants λ_A, λ_B corresponding to the parent and daughter nuclides were calculated as

$$\lambda_A\,(^{241}\mathrm{Pu}) = \frac{0.693}{\text{half-life (Table 1)}} = \frac{0.693}{14\,\mathrm{yr}},$$
$$= 0.0495\,\mathrm{yr}^{-1},$$
$$= 1.567 \times 10^{-9}\,\mathrm{s}^{-1},$$
$$\lambda_B\,(^{241}\mathrm{Am}) = 0.001604\,\mathrm{yr}^{-1}.$$

The activity of the gamma emitted by the decay of ^{241}Am is

$$\frac{\text{dis (number of photons)}}{\text{s–g PuO}_2} =$$
$$\left(\frac{\mathrm{g}\,^{241}\mathrm{Pu}}{\mathrm{g\,PuO_2}}\right) \times \left(\frac{N_0}{A}\right)(e^{-\lambda_A t} - e^{\lambda_B t}) \times \text{abundance.}$$

The photons emitted from the decay of ^{237}Np in each decay chain were neglected because of the long half-life and low photon abundances.

The photon activity of ^{237}U is defined as

$$\text{photons/s–g PuO}_2 =$$
$$\frac{\lambda_A N_0}{A}\, e^{-\lambda_A t} \left(\frac{\mathrm{g}\,^{241}\mathrm{Pu}}{\mathrm{g\,PuO_2}}\right) \times \text{abundance} \times \text{yield.}$$

All symbols have been previously defined.

The photon energy and abundances of ^{237}U were taken from Table 2;

Gamma energy, KeV	Abundance, % of isotope decay
14.0	41.0
32.2	16.0
60.0	36.0
208.0	23.0

and the decay factor $e^{-\lambda_A t}$ is

Time, yr	Decay factor $e^{-\lambda_A t}$
0	1.0
1	0.952
5	0.781
10	0.610
18	0.410

The resultant activities for ^{241}Pu and daughter nuclides are presented in Table 6.

Appendix B

Gamma Activity From ^{236}Pu Decay

With the contamination of ^{236}Pu assumed as 1.2 parts/10^6, the gamma emission rate of the ^{236}Pu primary decay gammas becomes (from Table 4)

Gamma energy, KeV	Abundance, % of isotope decay	Photons/ s–g ^{236}Pu	Photons/ s–g PuO_2
48	3.1×10^{-2}	6.107×10^{9}	6.46×10^{3}
110	1.2×10^{-2}	2.364×10^{9}	2.50×10^{3}
165	6.6×10^{-4}	13.0×10^{7}	13.75
520	1.7×10^{-4}	3.35×10^{7}	3.54
570	1.0×10^{-4}	1.97×10^{7}	2.08
645	2.4×10^{-4}	4.728×10^{7}	5.00

where

$$\text{activity}\left(\frac{\text{dis}}{\text{s–g }^{236}\text{Pu}}\right) = \text{activity of pure isotope} \times e^{-\lambda t} \times \text{abundance}$$

$$= 1.97 \times 10^{13}\,\frac{\text{dis}}{\text{s–g}} \times e^{-\lambda t} \times \text{abundance},$$

and

$$\text{activity}\left(\frac{\text{dis}}{\text{s–g PuO}_2}\right) =$$

$$\text{activity}\left(\frac{\text{dis}}{\text{s–g }^{236}\text{Pu}}\right) \times \left(\frac{\text{g }^{236}\text{Pu}}{\text{g PuO}_2}\right) = \text{activity} \times 1.2 \times 10^{-6}.$$

The decay factor $e^{-\lambda t}$ was taken to be the following:

Time	Decay factor $e^{-\lambda t}$
0	1.0
1	0.784
5	0.296
10	0.087
18	0.013

where

$$\lambda = \frac{0.693}{\text{half-life }^{236}\text{Pu}} = \frac{0.693}{2.85}.$$

Appendix C
Gamma Activity From Decay of ^{236}Pu Daughter Nuclides

Radioactive ^{236}Pu will decay into a large number of radioactive daughter nuclides which decay and emit photons. The only daughter nuclides considered in this study were ^{212}Pb, ^{212}Bi, and ^{208}Tl. Study of all other intermediate daughter nuclide activity was neglected because of the low photon abundance accompanying their decay.

The decay of the parent atom, ^{236}Pu, into its daughter nuclides was calculated from the Bateman equation and the following sequence of decay:

$$^{236}\mathrm{Pu} \xrightarrow[2.85\ \mathrm{yr}]{\alpha} {}^{232}\mathrm{U} \xrightarrow[72\ \mathrm{yr}]{\alpha} {}^{228}\mathrm{Th} \xrightarrow[1.91\ \mathrm{yr}]{\alpha}$$

$$^{224}\mathrm{Ra} \xrightarrow[3.64\ \mathrm{day}]{\alpha} {}^{220}\mathrm{Rn} \xrightarrow[52\ \mathrm{s}]{\alpha} {}^{216}\mathrm{Po} \xrightarrow[0.16\ \mathrm{s}]{\alpha}$$

$$\begin{array}{ccccc} ^{212}\mathrm{Pb} & \xrightarrow[10.6\ \mathrm{hr}]{\beta} & ^{212}\mathrm{Bi} & \xrightarrow[60\ \mathrm{min}]{\alpha\ (36\%)} & ^{208}\mathrm{Tl} \\ & 60\ \mathrm{min} & \downarrow\ \beta\ (64\%)\ 3\ \mathrm{min} & & \downarrow\ \beta \\ & & ^{212}\mathrm{Po} & \xrightarrow[0.3\ \mu\mathrm{s}]{\alpha} & ^{208}\mathrm{Pb}\,. \end{array}$$

The photon activity of ^{208}Tl is the photon activity of ^{212}Bi multiplied by the 36% yield factor. The photon activity of ^{212}Bi is the same as ^{212}Pb which, in turn, has the same activity of ^{228}Th. It becomes evident that the photon activity accompanying the radioactive decay of ^{212}Pb, ^{212}Bi, and ^{208}Tl is controlled by the growth of ^{228}Th, which has a half-life of 1.91 yr.

The decay chain relevant to this study, which corresponds to the growth of ^{228}Th, is due to

$$^{236}\mathrm{Pu} \xrightarrow[2.85\ \mathrm{yr}]{\alpha} {}^{232}\mathrm{U} \xrightarrow[72\ \mathrm{yr}]{\alpha} {}^{228}\mathrm{Th} \xrightarrow[1.91\ \mathrm{yr}]{\alpha},$$

and is represented as

$$N_A \xrightarrow[\lambda_A]{} N_B \xrightarrow[\lambda_B]{} N_C \xrightarrow[\lambda_C]{}\,,$$

where N_A is the number of parent atoms with decay constant λ_A, N_B is the number of the daughter nuclides with decay constant λ_B, and N_C is the number of daughter nuclides with decay constant λ_C.

The number of photons emitted by the daughter nuclide N_C (^{212}Bi, ^{212}Pb, or ^{208}Tl) is written as

photons/s–g ^{236}Pu =

$$\lambda_C N_{A0} \left\{ \frac{\lambda_A \lambda_B e^{-\lambda_A t}}{(\lambda_B - \lambda_A)(\lambda_C - \lambda_A)} + \frac{\lambda_A \lambda_B e^{-\lambda_B t}}{(\lambda_A - \lambda_B)(\lambda_C - \lambda_B)} + \frac{\lambda_A \lambda_B e^{-\lambda_C t}}{(\lambda_A - \lambda_C)(\lambda_B - \lambda_C)} \right\} \times \text{yield} \times \text{abundance},$$

where N_{A0} is the initial supply of ^{236}Pu atoms written here as N_0/A with N_0 being an Avogadro number and A the gram-atomic mass of ^{236}Pu. The photon abundances and yield factors were taken from Table 4. The photon activity per gram of PuO_2 was determined as

$$\text{photons/s–g PuO}_2 = \text{photons/s–g }^{236}\text{Pu} \times \text{concentration of }^{236}\text{Pu in PuO}_2.$$

The decay constants were calculated to be (see Table 1)

$$\lambda_A\ ^{236}\mathrm{Pu} = \frac{0.693}{\text{half-life}} = \frac{0.693}{2.85\ \mathrm{yr}} = 0.24316\ \mathrm{yr}^{-1},$$

$$\lambda_B\ ^{232}\mathrm{U} = 0.009365\ \mathrm{yr}^{-1},$$

and

$$\lambda_C\ {}^{228}Th = 0.36474\ yr^{-1}.$$

The activity of ^{228}Th for the various elapsed time periods were obtained as follows:

Time, yr	dis/s–g ^{236}Pu
1	2.742×10^{10}
5	3.222×10^{11}
10	5.696×10^{11}
18	6.560×10^{11}

When applied to PuO_2 fuel in which the concentration of ^{236}Pu may vary, the activity of the ^{228}Th per gm of PuO_2 becomes

Concentration/ time, part/10^6	1 yr	5 yr	10 yr	18 yr
1.2	2.8815×10^4	3.383×10^5	5.981×10^5	6.891×10^5
0.8	1.921×10^4	2.256×10^5	3.987×10^5	4.594×10^5
0.6	1.441×10^4	1.692×10^5	2.990×10^5	3.445×10^5
0.1	0.240×10^4	2.819×10^4	4.984×10^4	5.742×10^4

Appendix D
Gamma Activity Accompanying $^{18}O(\alpha, n)^{21}Ne$ Reaction

Alpha particles incident upon the isotope ^{18}O will produce ^{21}Ne in various excited states as well as in the ground state. The immediate decay of the ^{21}Ne excited states will produce photons with energy equal to the difference in energy between the excited state and the ground state.

It was assumed that alpha particles (72% at 5.49 MeV and 28% at 5.45 MeV) in the PuO_2 product fuel were derived from the decay of ^{238}Pu, which has a total neutron emission rate (Ref. 19) of

$$1.90 \times 10^4 \text{ n/s–g } ^{238}\text{Pu},$$

where 1.24×10^4 n/s–g ^{238}Pu is from the $^{18}O(\alpha, n)^{21}Ne$ reaction, 0.265×10^4 n/s–g ^{238}Pu is from spontaneous neutron fission, and 0.40×10^4 n/s–g ^{238}Pu is from the (α, n) reaction with impurities (Ref. 19).

The number of photons emitted per second–gram of PuO_2 was calculated as 1.24×10^4 n/s–g $^{238}Pu \times (0.714) \times$ photons emitted/neutron emission.

$$\text{The value } 0.714 = \left(\frac{\text{g } ^{238}\text{Pu}}{\text{g PuO}_2}\right),$$

and the photon emission rate per neutron emitted is taken from the above table. Each of the photon emission rates must be corrected for the decrease in ^{238}Pu activity by the factor $e^{-0.007929t}$. The rates then become the following:

Time, yr	Decay factor $e^{-\lambda t}$
0	1.000
1	0.992
5	0.961
10	0.924
18	0.867

The photon emission rate produced by the $^{18}O(\alpha, n)^{21}Ne$ reaction became as follows:

Gamma ray energy, MeV	Photons emitted/ neutron emission (Ref. 1)	Photons emitted/ s–g PuO_2
0.35	0.45	0.4×10^4
1.38	0.10	0.089×10^4
1.90	0.02	0.018×10^4
2.40	0.02	0.018×10^4
2.70	0.02	0.018×10^4

Appendix E
Activity From Fission Gammas

The emission per energy interval of prompt fission gammas and equilibrium fission product gammas are tabulated below. These values were determined from the data given on the following page.

Gamma ray energy interval, MeV	Total fission gamma spectrum $N(E)\,\Delta E$ per fission	Photons/s–g PuO_2		
		1575 W(th)[a]	3468 W(th)[b]	5769 W(th)[c]
6.0–7.0	0.007	5.0	10.0	15.1
5.0–6.0	0.020	14.0	28.2	43.0
4.0–5.0	0.063	45.0	88.8	1.355×10^2
3.0–4.0	0.207	147.0	291.9	4.451×10^2
2.0–3.0	0.815	5.787×10^2	11.492×10^2	1.752×10^3
1.8–2.0	0.371	2.634×10^2	5.231×10^2	7.977×10^2
1.6–1.8	0.559	3.969×10^2	7.882×10^2	1.202×10^3
1.4–1.6	0.575	4.083×10^2	8.108×10^2	1.236×10^3
1.2–1.4	0.501	3.557×10^2	7.064×10^2	1.077×10^3
1.0–1.2	0.584	4.147×10^2	8.234×10^2	1.256×10^3
0.9–1.0	0.609	4.324×10^2	8.587×10^2	1.309×10^3
0.8–0.9	1.268	9.003×10^2	17.879×10^2	2.726×10^3
0.7–0.8	1.470	10.044×10^2	20.727×10^2	3.161×10^3
0.6–0.7	1.679	11.921×10^2	23.674×10^2	3.610×10^3
0.5–0.6	1.758	12.482×10^2	24.788×10^2	3.780×10^3
0.4–0.5	1.859	13.200×10^2	26.212×10^2	3.997×10^3
0.3–0.4	1.954	13.874×10^2	27.552×10^2	4.202×10^3
0.2–0.3	0.538	3.820×10^2	7.586×10^2	1.157×10^3
0.044–0.2	0.323	2.294×10^2	4.554×10^2	0.695×10^3
0.001–0.044	0.0	0.0	0.0	0.0

For the 1575 W(th) capsule, the calculated fission rate was 0.71×10^3 n/s–g PuO_2; the fission rate used for the 3468 W(th) was 1.41×10^3 n/s–g PuO_2; and for the 5769 W(th) the fission rate became 2.15×10^3 n/s–g PuO_2.

The total fission gamma spectrum was determined from the following data, and is based on the data of Table 3.

Gamma ray energy interval, MeV	Prompt fission gamma spectrum $N(E)\Delta E$ per fission	Equilibrium fission product gamma spectrum $N(E)\Delta E$ per fission	Total fission gamma spectrum $N(E)\Delta E$ per fission
6.0–7.0	0.007	0.0	0.007
5.0–6.0	0.020	0.0	0.020
4.0–5.0	0.060	0.003	0.063
3.0–4.0	0.179	0.027	0.207
2.0–3.0	0.538	0.267	0.815
1.8–2.0	0.198	0.173	0.371
1.6–1.8	0.247	0.312	0.559
1.4–1.6	0.308	0.267	0.575
1.2–1.4	0.384	0.117	0.501
1.0–1.2	0.478	0.106	0.584
0.9–1.0	0.302	0.307	0.609
0.8–0.9	0.380	0.888	1.268
0.7–0.8	0.479	0.9910	1.470
0.6–0.7	0.602	1.077	1.679
0.5–0.6	0.758	1.000	1.758
0.4–0.5	0.954	0.905	1.859
0.3–0.4	1.201	0.753	1.954
0.2–0.3	0.0	0.538	0.538
0.044–0.2	0.0	0.323	0.323
0.001–0.044	0.0	0.0	0.0

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