THE DESIGN OF A SOURCE TO SIMULATE THE GAMMA-RAY SPECTRUM EMITTED BY A RADIOISOTOPE THERMOELECTRIC GENERATOR

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A simulated source was designed to duplicate the gamma spectrum of a uniform cylindrical 2200-watt PuO_2 RTG containing 81% Pu^{238} and 1.2 ppm Pu^{236}. Gamma rays from the decay of Pu^{238}, Am^{241}, Pu^{239}, and the $O^{18}(\alpha,n)Ne^{21}$ reaction were catalogued in broad energy groups. Pu^{236}, which decays ultimately to Th^{228}, was treated separately, since an exact duplicate can be made by using Th^{228}. The selection of sources involves a compromise between half life, cost, and gamma-ray energy. We have chosen $Ba^{133}(T_{1/2} = 7.2y)$, $Cs^{137}(T_{1/2} = 30y)$, and $Co^{60}(T_{1/2} = 5.2y)$ which provide gamma rays to cover the spectrum from about 350 kev to 1.3 Mev. Two 46 and one 22 mc Th^{228} sources provide simulation at various times in the life of the fuel capsule up to 18 years, which covers the time span of an outer planet mission. The emission from the Th^{228} represents the overwhelming contribution of the gamma spectrum after the first few years. Therefore, the small changes in the intensity of the rest of the spectrum represent a minor perturbation on the entire spectrum. The sources, in the form of 13-inch long rods are placed in a concentric hole in a cylinder of depleted uranium which provides shielding equivalent to the self shielding of the fuel capsule. The thickness of the U^{238} cylinder (0.55 cm) was determined by Monte Carlo calculations to insure that the spectrum emerging from the simulated source closely matched that of the fuel capsule.

INTRODUCTION

It is well established that RTG's fueled by $Pu^{238}O_2$ will be used to provide instrument power on space missions where solar energy is inadequate. An obvious one is the forthcoming Outer Planets Mission.

Although the absolute number of photons per disintegration of Pu^{238} is small ($\sim 50/10^8$ for $E > 160$ kev), the gamma intensity is not negligible as we are dealing with about seventy thousand curies of Pu^{238} per source. In addition, Pu^{236}, which appears as an impurity of about 1.2 ppm decays to Th^{228}, which becomes, after about 3 years, the major source of gamma radiation. This will be discussed in greater detail shortly.

Many of the instruments aboard a space vehicle may be sensitive to this source of gamma radiation. Long-term exposure may result in radiation damage to instrumentation and electronic packages. Also, the increase in background resulting from this spurious source of radiation on sensitive detectors must be measured. For these reasons the radiation field at various positions on a spacecraft has to be mapped. The use of a fueled Multi-Hundred Watt (MHW) generator for this purpose would be wasteful. Besides, the possession of such a source imposes numerous safety, handling, and accountability problems in a laboratory. In order to avoid these difficulties, we have designed a radioactive source which reproduces the major features of the spectrum emitted by an MHW within about 20% in the radial direction and 35% in the axial direction. Using this approach we are able to represent the gamma radiation spectrum from an RTG for a cost of under $6000 while eliminating the inherent problems cited above. More importantly, the simulated source enables experiments to be conducted with an aged radiation spectrum, thus duplicating the conditions that would exist at various ages in the life of a mission.

SOURCE DESIGN

The basic philosophy of the design was to reproduce the unattenuated spectrum and then calculate the proper amount of shielding to account for the self-shielding of the fuel and subsequent attenuation of the cladding and outer jackets.

The first part of the problem is essentially a bookkeeping procedure. The following sources of radiation were included:

1. Plutonium-238 decay.
2. Gamma rays from the excited states of Ne^{21} in the $O^{18}(\alpha,n)Ne^{21}$ reaction.
3. Americium-241 decay. (Am^{241} is derived from the decay of Pu^{241}).
4. Thorium-228 decay.

Item 4 is a special (and easier) problem and will be treated separately.

The selection of sources for Items 1-3 involves a compromise between energy, half life, and ease of production. We have chosen $Ba^{133}(T_{1/2} = 7.2y)$, $Cs^{137}(T_{1/2} = 30y)$ and $Co^{60}(T_{1/2} = 5.2y)$ to cover the spectrum from about 350 kev to 1.3 Mev.

Table 1 shows the latest available data on the absolute intensity of gamma rays from Pu^{238}. A cursory examination of this table reveals that beyond about 160 kev there is nothing substantial until the region of 700 kev is reached. Although there are intense low-energy lines, they are ignored in the source design because they are enormously attenuated. The decay intensities are added up and placed in broad energy groups. The same procedure is followed for the Am^{241} and the Ne^{21} decay. The latter two give rise to an additional group around 350 kev.

The simulation of the Pu^{236} decay is relatively simple and can be done very accurately. This can be seen by an examination of Figure 1 showing the decay chain of Pu^{236}, leading ultimately to Pb^{208}. No gamma rays worthy of consideration are emitted

TABLE 1

Pu^{238} Absolute Gamma-Ray Intensities

E (kev)[a]	Photons/disintegration x 10^8	
	Reier (Ref. 1)	Lederer et al (Ref. 2)
152.71 ± 0.05	seen	1270 ± 90
200.9 ± 0.2		5 ± 1
207.6	seen	
235.9 ± 0.3?		0.01 ± 0.005
258.3 ± 0.2		0.011 ± 0.02
299.2 ± 0.2		0.07 ± 0.02
706.1 ± 0.3		0.14 ± 0.02
708.42 ± 0.20		0.38 ± 0.04
742.77 ± 0.10	6.35 ± 0.21	7.6 ± 0.7
766.39 ± 0.10	26.7 ± 0.8	33 ± 3
786.30 ± 0.10	4.98 ± 0.16	4.8 ± 0.4
805.8 ± 0.3		0.18 ± 0.02
808.25 ± 0.15	0.999 ± 0.063	1.1 ± 0.1
851.70 ± 0.10	1.64 ± 0.06	1.9 ± 0.2
880.5 ± 0.3		0.23 ± 0.03
883.23 ± 0.10	1.270 ± 0.048	1.1 ± 0.1
904.37 ± 0.15	0.072 ± 0.021	0.10 ± 0.02
926.72 ± 0.15	0.71 ± 0.04	0.83 ± 0.08
941.9 ± 0.2	0.58 ± 0.02	0.67 ± 0.07
946.0 ± 0.3		0.13 ± 0.02
1001.03 ± 0.15	1.08 ± 0.04	1.4 ± 0.2
1041.8 ± 0.3	0.20 ± 0.02	0.28 ± 0.02
1085.4 ± 0.3		0.11 ± 0.02

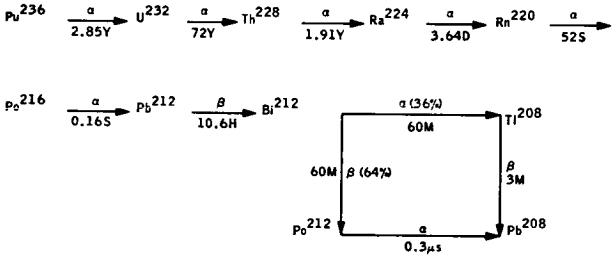

FIGURE 1. Plutonium-236 Decay Chain

until Th^{228} is reached. It then decays emitting gamma rays from Pb^{212}, Bi^{212}, and Tl^{208}, the latter producing the well-known 2.61 Mev gamma ray in 100% of the decays. Fortunately, Th^{228} is readily available and may be purchased in the desired encapsulated form. The buildup of Th^{228} is determined by solving the three linear differential equations starting with Pu^{236}. These are shown in Eq. 1-3. The activity of the Th^{228} is given by the solution, Eq. 4.

$$\frac{dN_1}{dt} = -\lambda_1 N_1 \tag{1}$$

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \tag{2}$$

$$\frac{dN_3}{dt} = \lambda_2 N_2 - \lambda_3 N_3 \tag{3}$$

$$\lambda_3 N_3 = \lambda_1\lambda_2\lambda_3 N_{10} \left[\frac{1}{\lambda_1 - \lambda_2} \cdot \frac{1}{\lambda_1 - \lambda_3} \cdot e^{-\lambda_1 t} + \frac{1}{\lambda_2 - \lambda_1} \cdot \frac{1}{\lambda_2 - \lambda_3} \cdot e^{-\lambda_2 t} + \frac{1}{\lambda_3 - \lambda_1} \cdot \frac{1}{\lambda_3 - \lambda_2} \cdot e^{-\lambda_3 t} \right]$$

N_{10} is the amount of Pu^{236} present at t = 0

Table II gives the amount of activity of each of the isotopes for a 2200 watt fuel source at different ages of the fuel starting with 1.2 ppm of Pu^{236}. The buildup of the Ba^{133} source with age is due to the increase of Am^{241} resulting from the decay of Pu^{241}. The Cs^{137} and Co^{60} are used mainly to simulate the decay of Pu^{238}. Their decrease with time reflects mainly the half life of Pu^{238} ($T_{1/2}$ = 86.4y). The barium, cesium, and cobalt will be packaged in a single capsule. In addition, we have ordered three separate capsules of Th^{228}, so that we will be able to reproduce the thorium activity at fuel ages of 0, 3, 5, 8, 18 years. The amount of Ba^{133}, Cs^{137}, and Co^{60} corresponds to t = 0 only. The error introduced by not using different quantities of these isotopes as the fuel ages is small since the Th^{228} activity overshadows the others within a few years.

TABLE 2

Quantity of Isotopes (Mc) For Simulated Source

Year	Ba^{133}	Cs^{137}	Co^{60}	Th^{228}
0	1.30	26.0	0.75	0
1	1.37	25.9	0.75	4.24
5	1.58	25.3	0.73	49.9
10	1.79	24.6	0.70	88.1
18	2.05	23.1	0.64	102

SHIELD DESIGN

Having selected the isotopes, the next step is to calculate a shield thickness such that the emitted spectrum is the same as that from the real source. The actual source is a 13 inch long cylinder of fuel pucks having a 2.731 cm radius, enclosed in an 0.051 cm tantalum shell, which in turn, is inserted concentrically in a graphite cylinder having a wall thickness of 3.175 cm. The fuel is a mixture of PuO_2, ThO_2, and M_O. The concentration of each element is shown in Table III. The density of the mixture is 9.17 g/cm^3.

TABLE 3

Concentration of Elements in the Fuel

Element	Weight %
Pu	68.8
Th	7.6
Mo	13.3
O	10.4

Since the real fuel is composed largely of high Z elements, depleted uranium was selected as the shield to reproduce the self-shielding of the source. The natural radioactivity of the depleted uranium and it's impurities add insignificantly to the simulated source and can be neglected. Figure 2 shows a sketch of the real and simulated source. Monte Carlo calculations were run comparing the spectrum in the radial, axial, and 45° directions of the real source with a 13 in. line source (the diameter of the capsules for the simulated source is 1/4 inch). The results in the radial direction and at 45° are very encouraging. Figure 3 shows a comparison between the real and simulated source in the radial direction. Except in the very low energy region, where the statistics are about 40%, the agreement is within about 20%. (The mismatch of the 600 to 700 kev peak from the Cs^{137} and the 700 to 800 kev peak in the real case is expected and is not considered a serious problem).

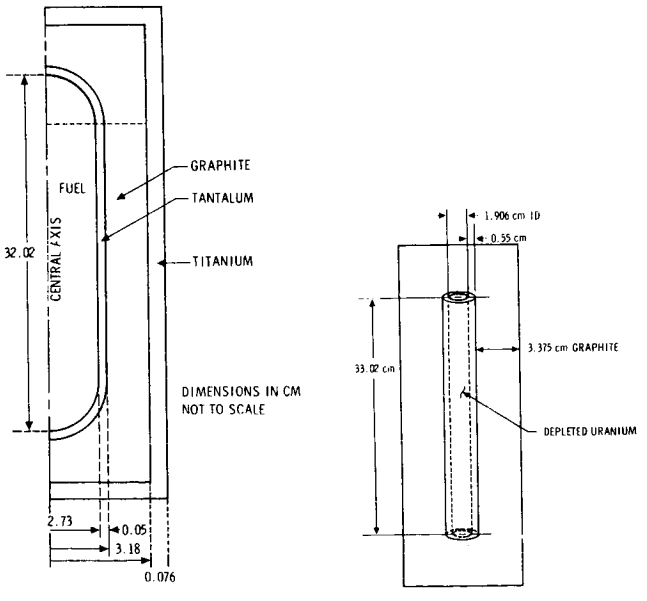

FIGURE 2. Simulated and Real Source

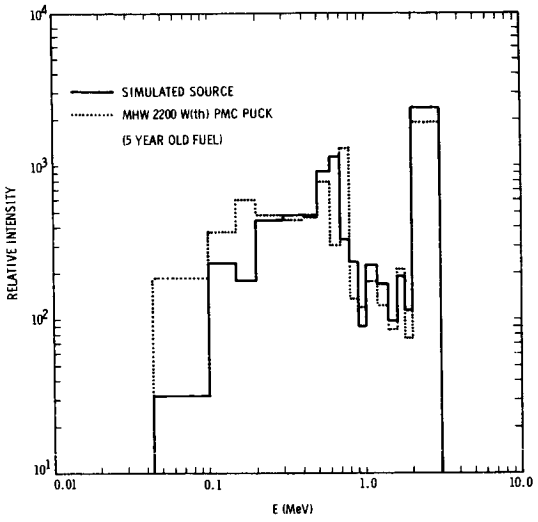

FIGURE 3. Comparison of Spectrum in the Radial Direction from the Simulated and Real Source

Because of the enormous self shielding, we were not able to simulate the radiation in the axial direction by using depleted uranium or a combination of depleted uranium and a lighter element. The best result we were able to obtain is shown in Figure 4. This uses seven cm of copper at the ends of the simulated source. A compromise had to be made between the high and low end of the spectrum. If a small medium energy source could be placed inside the end shield, the problem would be simplified and a much better match could be obtained.

It is a pleasure to acknowledge the assistance of Mr. Michael A. Dore in the computational analysis.

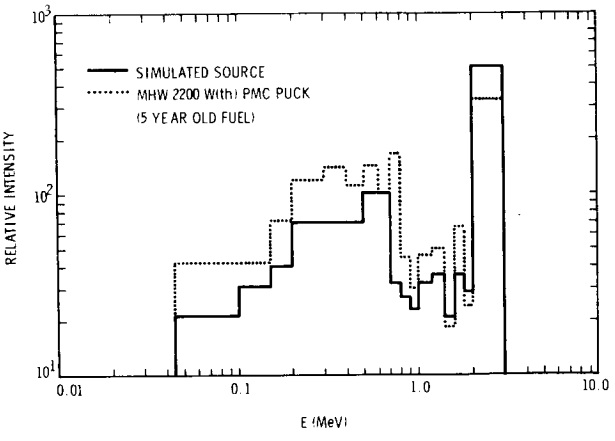

FIGURE 4. Comparison of Spectrum in the Axial Direction from the Simulated and Real Source.

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2. C. M. Lederer, F. Asaro, and I. Perlman. Nuclear Chemistry Annual Report (1968), UCRL-18667.