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A Sensitivity Study on Radiation Dose of 500W RTPV having Different Source Shapes

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1. Introduction

Radioisotope Thermoelectric Generators (RTG) has been considered as a power supply system for long-lived operation in space. RTG is an essentially nuclear battery that converts the heat resulted from the radioactive decay into electricity. RTG has the advantage of high energy density and long life operation because of the very long half-life of the radioisotopes. However, RTG systems have relatively low thermoelectric energy conversion efficiency of 3-7%. On the other hand, Radioisotope Thermo-Photo-Voltaic (RTPV) system has typically much higher energy conversion efficiency of 15~30% than RTG system [1].

The objective of this work is to perform radiation dose and safety analysis of the RTPV system for 500W. In particular, comparative shielding analysis using two different types of RTPV (the cubic homogeneous source type and the cylindrical heterogeneous source type) were performed to show their relative performances. In addition, we analyzed the effects of the relative positions of the cylindrical sources on the total radiation dose.

2. Radiation safety analysis

This section shows the description and simulation results of RTPV system for radiation safety analysis.

2.1 Radiation Shielding Analysis Procedure

Pu-238 have higher energy and power densities than the other radioisotopes. Moreover, $^{238}PuO_2$ has a lower specific power of 480W/kg but higher volumetric power of 5.52 W/cm^3. So, $^{238}PuO_2$ is selected as the radio-compound for the RTPV system [2]. The radiation safety analysis consists of two steps. First, the ORIGEN-S code was used to evaluate the intensities and spectra of neutrons and gamma rays emitted from the $^{238}PuO_2$ [3]. And the neutron and gamma doses are calculated using Monte Carlo transport calculation code. In particular, we used MONACO/MAVRIC that is the Monte Carlo code to perform the neutron and gamma transport calculations [4].

2.2 The Simulation Codes for Radiation Shielding Analysis

We evaluated the intensities and spectra of neutrons and gamma rays from the $^{238}PuO_2$ sources with ORIGEN-S. ORIGEN-S which is a part of SCALE6.1 is a computer code for evaluating the radioactive decay of radionuclide and the amount of radionuclide after the neutron irradiation and cooling. The alpha decay of ^{238}Pu accompanies 5.5MeV energy. Also additional neutrons are released as the results of the reactions (i.e., (α,n) reactions) of ^{17}O and ^{18}O with the alpha particles and the spontaneous fission. In addition, gamma rays are released as the radioactive decay of ^{238}Pu while the spontaneous fission of ^{238}Pu and (α,n) reactions generate additional gammas rays. We estimated these neutron and gamma source intensities and spectra by using the ORIGEN-S code [3].

We performed radiation safety analysis by using MONACO/MAVRIC codes with the specified intensities and spectra of the radiation source from using ORIGEN-S. MONACO is a new 3-D Monte Carlo code being developed within SCALE for shielding calculations. It is a multi-group Monte Carlo transport code with fixed sources for shielding applications. The MAVRIC sequence is completely automated for shielding analysis [4].

2.3 Description of RTPV System Using Homogeneous Cubic Source and Cylindrical Sources

In our previous work, a homogeneous cubic source sequentially surrounded by a tungsten material region and a thin emitter region of tantalum was considered for RTPV device [5]. In this work, the effects of the packing factor which is the ratio of heat source region (i.e., $^{238}PuO_2$ region) volume to the total region enclosed by the emitter on the radiation dose are analyzed. Also, the radiation dose for the different source shapes. In particular, a cladding is considered to enclose the source region in order to prevent releasing of $^{238}PuO_2$ under accident.

The size of the source is fixed because the release of heat source is fixed to 500W. The total region enclosed by emitter consists of a 4.4910cm x 4.4910cm x 4.4910cm central cubic source region and its three surrounding regions. The central source region is first surrounded by iridium (Ir) cladding region. The second surrounding region is tungsten (W) radiation shielding region that is followed by a 0.5cm thick tantalum (Ta) outer emitter region. The thickness of the shielding material is determined by the packing factor. Fig. 2 shows the configuration of the cubic heat source region for RTPV device.

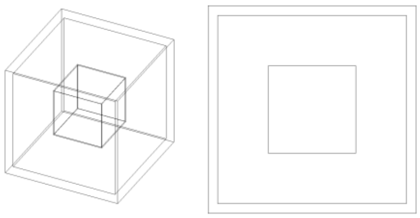


Fig. 2. Geometric model for the source of a cubic design.

The radiation dose is estimated in a 10cm thick spherical water shell which is located at 100cm distance from the center of the source. The region between RTPV device and the water spherical shell is assumed to be filled with air. Fig. 3 shows MONACO/MAVRIC in SCALE6.1 geometric modelling for radiation safety analysis. The radiation dose was converted from the radiation fluxes using the ICRU-57 dose conversion factors provided with SCALE6.1 [6].

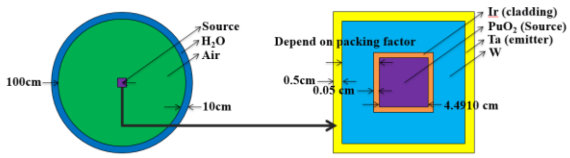


Fig. 3. Geometric model for the RTPV device.

In this work, we also considered RTPV device where four separate cylindrical source zones having iridium cladding are symmetrically located. And the dose values in a 10cm thick spherical water shell which is located at 100cm distance from the center of the source are estimated with MONACO/MAVRIC. In particular, the dose values for this RTPV device having cylindrical sources are compared with those for the one having cubic source. As with the previous design using single cubic source, the total volume of the source is fixed because the release of heat source volume is fixed to 500W. Fig. 4 and 5 show geometric modeling of the RTPV device having separated cylindrical source. A cylinder source whose radius and height are 1.217cm and 4.867cm, respectively, releases one fourth of the total 500W heat. The distances between cylindrical sources are adjusted to keep the same distance between the outer surface of the source cladding and the inner surface of the shielding.

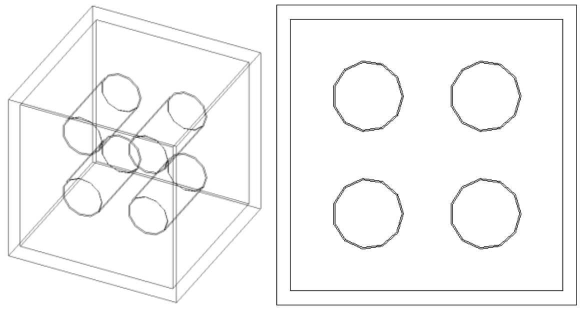


Fig. 4. Geometric model for the source of the cylindrical design.

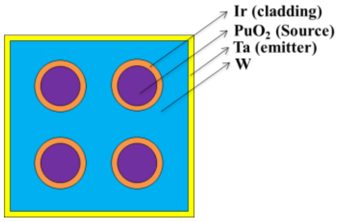


Fig. 5. Geometric model for the source of the cylindrical design.

2.4 Comparison of the total doses for different RTPV designs

In this section, the radiation doses are comparatively estimated for the RTPV devices using a single cubic source and separated cylindrical sources described above. Table I compares the total doses values in a 10cm thick measurement water shell. Table I shows that the dose values for the separated cylindrical sources are smaller than that for the single cubic sources for all the packing factors. For example, the RTPV having cylindrical sources gives lower total radiation dose by 11%than the one having a cubic source. As expected, these differences in the dose values decrease as the packing factor increase. Fig. 6 compares these dose values graphically.

Table I: Total doses in the measurement sell between two source designs (mSv/hr)

	Dose in the water shell (mSv/hr)		
	Total dose value		
packing factor (%)	Cylinder	Cubic	
10	1.08E-01	1.20E-01	(10.9 [a])
30	1.30E-01	1.41E-01	(8.3)
50	1.41E-01	1.49E-01	(6.1)
55	1.43E-01	1.51E-01	(5.6)

[a] Relative discrepancies (%) in total dose

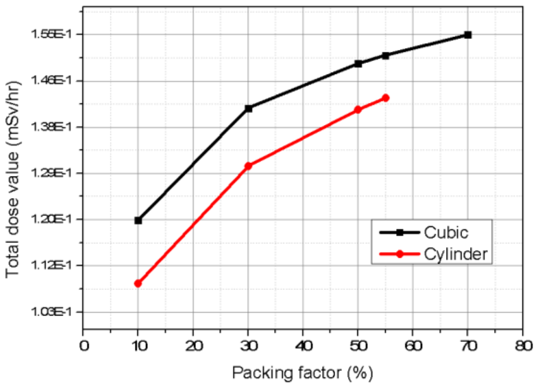
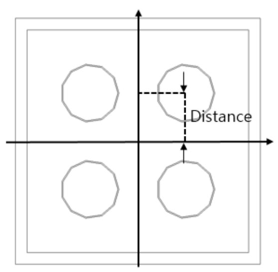


Fig. 6. Comparison of the total doses between two source types.

2.5 The Effect of The Source Position on The Total Dose

Figures 2 and 4 show that the distance between the emitter and the outer surface of source for cylindrical sources are smaller than that for a cubic source. While the source strength for each source is small for the cylindrical sources than the cubic source. The total source volume is fixed because the packing factor (10%) is fixed to estimate the effect of the source position on the total dose. Fig. 7 shows the distances between center of RTPV and the center of a source for the different cases. And Fig. 8 shows the geometric models for the different cases. The total radiation doses are compared in Table II. Table II shows that the total dose value for Case A is smaller than the others. While the tightly packed sources (i.e., case D) give the largest total radiation dose. Fig. 9 compares these dose values graphically. As shown in Table II, the neutron dose is much more dominant than the gamma dose.



Case	Distance (cm)
A	2.09
B	1.58
C	1.40
D	1.37

Fig. 7. Geometric model for estimating effect of source positions.

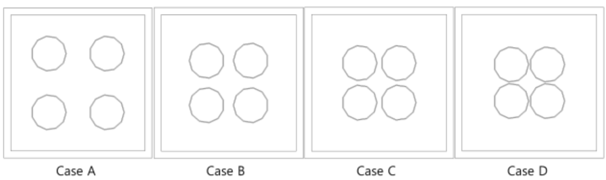


Fig. 8. Geometric model for different positions of sources.

Table II: Doses in the measurement sell each cases (mSv/hr)

CASE	Neutron source		Photon source	Total dose value
	Neutron dose	Photon dose	Photon dose	
A	1.04E-01	4.29E-03	1.49E-04	1.08E-01
B	1.06E-01	4.49E-03	6.80E-05	1.10E-01
C	1.08E-01	4.59E-03	5.86E-05	1.12E-01
D	1.09E-01	4.68E-03	4.59E-05	1.14E-01
CUBIC	1.15E-01	4.92E-03	6.55E-05	1.20E-01

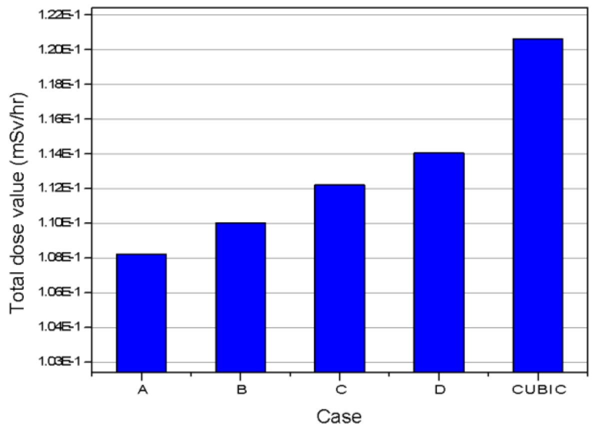
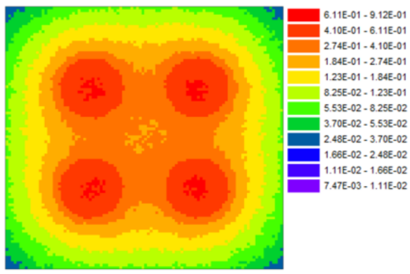
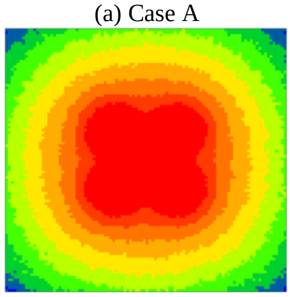


Fig. 9. Comparison of the total doses between each cases.

Figures 10(a) and 10(b) compare the neutron dose distributions at the central planes for the RTPV devices. As expected, it is shown that the neutron dose distribution for the loosely packed sources is much more flat and the dose for this case at the boundaries is lower than those for the tightly packed sources.



(a) Case A



(b) Case D

Fig. 10. Comparison of the neutron dose distributions at the central planes (with same scale in dose, Sv/hr)

3. Conclusions

In this work, a sensitivity study on the total radiation dose was performed for 500W RTPVs having different source configurations. In particular, comparative shielding analysis using two different types of source design (a cubic source type and cylindrical sources type) were performed to show their relative performances. The results show that the RTPV device using the cylindrical sources type has lower dose values by 6~11% depending on the packing factor at the measurement cell than the RTPV device using the cubic source type. Also, we investigated the effect of the compactness of four cylindrical sources on the radiation dose. The results showed that the loosely packed sources give lower total radiation dose than the closely packed sources. In particular, it shows that the loosely packed cylindrical sources can reduce total radiation dose by 10% than the single cubic source.

Acknowledgement

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