# Nuclear Radiation Environment Analysis for Thermoelectric Outer Planet Spacecraft

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The radioisotope thermoelectric generator (RTG) nuclear radiation environment analysis of a recent design of the Thermoelectric Outer Planet Spacecraft (TOPS) is presented. The neutron and gamma-ray transport calculations were performed using Monte Carlo methods and a three-dimensional geometric model of the spacecraft. The results are compared with similar calculations performed for an earlier design.

## I. INTRODUCTION

Due to the great distance between the sun and the four outer planets, a spacecraft designed to conduct outer planet missions will require a solar-independent source of electrical power. At the Jet Propulsion Laboratory, the spacecraft currently being designed for such missions is equipped with radioisotope thermoelectric generators (RTG's) and is appropriately named the Thermoelectric Outer Planet Spacecraft (TOPS).

Important inputs to the TOPS design are the RTG radiation intensities and energy spectra at radiation-sensitive scientific instrument locations. This information can be used to confirm that the radiation levels to which the instruments will be exposed are below established interference and/or damage thresholds (ref. 1). The information can also be used to estimate the effects of spacecraft configuration changes on shielding and scattering.

## II. ANALYSIS

The gamma and neutron radiation transport analysis was performed using the RAMPART Monte Carlo computer code (ref. 2), a revised and expanded version of the FASTER code (ref. 3). The code treats the entire spectrum of particle energies simultaneously and makes considerable use of importance sampling.

The spacecraft design for which the radiation environment was calculated is configuration 12k. Although there are some structural differences, this newer configuration differs from the previous one, configuration 12j (ref. 4), primarily in the arrangement of the RTG's. The RTG's are mounted four in tandem in the earlier design, while pairs of RTG's are mounted side-by-side in the new design. The new configuration is the preferred one from a safety and operations point of view.

A structurally simplified form of the spacecraft which preserves the essential features of its shape and mass formed the basic input. The three-dimensional geometric model consisted of 66 plane or quadratic surfaces bounding 70 material regions of homogeneous density. The model contained the 4.3-m-diameter antenna dish, subdish, feedhorn, and hub, the electronics compartment, the propulsion bay (including the hydrazine fuel and fuel tank), and the four RTG's. The material compositions, weights, and densities for the regions defining the spacecraft, obtained from preliminary design information, are presented in table 1. The antenna dish is a homogeneous mixture of the Chromel-R mesh and the 48 aluminum ribs. For the electronics compartment, the following homogeneous composition was assumed, weight-%: plastics, 40; copper, 34; aluminum, 23; silicon dioxide, 3. The propulsion bay was approximated with a 50/50 mixture by weight of aluminum and iron.

Prior to the Monte Carlo transport analysis, the pairs of RTG's were each doubly rotated. The rotation angles orient the pairs of RTG's such that the direction of maximum RTG self-shielding (axial direction) is toward the region occupied by the science payload.

Table 1. -Material compositions for TOPS configuration 12k geometric model.

| REGION DESCRIPTION | COMPOSITION | WEIGHT, kg | TOTAL WEIGHT, kg | DENSITY, g/cm$^3$ |
|---|---|---|---|---|
| ANTENNA SECTION DISH | Cr<br>Ni<br>Al<br>Fe | 0.19<br>0.68<br>7.30<br>0.03 | 8.20 | 0.0413 |
| HUB | Al | 9.55 | 9.55 | 0.0179 |
| FEED HORN | Al | 5.45 | 5.45 | 0.0875 |
| SUB-DISH | Al | 9.10 | 9.10 | 2.7 |
| SPACECRAFT BUS ELECTRONICS CHASSIS | Al | 25.9 | 25.9 | 2.7 |
| ELECTRONICS COMPARTMENT | H<br>C<br>O<br>Si<br>Cu<br>Al | 5.68<br>75.5<br>3.27<br>2.85<br>68.7<br>46.4 | 202.4 | 0.446 |
| FUEL TANK | Ti | 10.5 | 10.5 | 4.5 |
| FUEL (FULL TANK) | $N_2H_4$ | 56.4 | 56.4 | 1.0 |
| PROPULSION BAY (OTHER THAN FUEL TANK AND CONTENTS) | Al<br>Fe | 33.4<br>33.4 | 66.8 | 0.132 |

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## III. RTG RADIATION

The heat source used in the calculations consisted of solid solution cermet fuel disks stacked in a cylindrical, refractory metal capsule for a total loading of 1000 W(th). The fuel was assumed to be five-year-old commercial grade $PuO_2$ with 1.2 ppm $^{236}Pu$. Two of these heat sources in-line comprise one multihundred-watt (MHW) RTG (ref. 5). The 2000-W(th) MHW-RTG is shown schematically in fig. 1. The spacecraft carries a complement of four RTG's (eight heat sources) on board; i.e., 8000 W(th). Finally, a converter jacket was simulated in order to include the shielding effect of the thermoelectric materials.

The plane between the two pairs of RTG's perpendicular to the plane in which they lie constitutes a plane of symmetry for the calculation. Using this symmetry, only half of the heat sources emitted radiation (but with double intensity) during the calculation. The remaining four heat sources were passive and served merely to absorb or scatter neutrons and gammas. This scheme makes the sampling process more efficient for point detectors located in the plane of symmetry.

The gamma source spectrum (ref. 6) was described using 21 energy groups with the Lawrence Radiation Laboratory gamma cross sections, including the photoelectric and pair production processes. Compton scattering is treated explicitly by the code. The neutron source spectrum (ref. 7) was described using 23 energy group $P_0$ cross sections with a transport correction for elastic scattering. Elastic scattering for the hydrogen component in the hydrazine fuel is handled explicitly in the program. The neutron spectrum was multiplied by a factor of 1.3 to simulate subcritical multiplication.

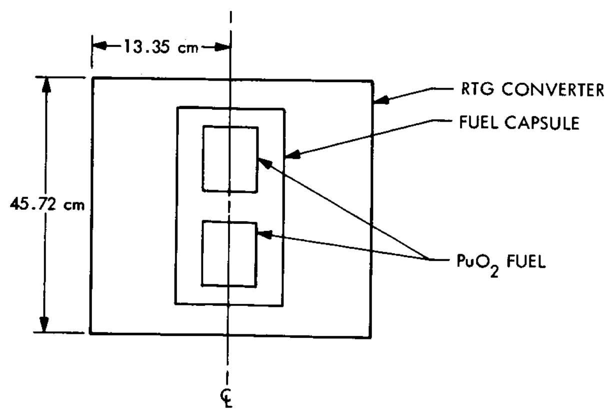


Figure 1. –Schematic diagram of 2000-W(th) MWH-RTG.

The MHW-RTG neutron and gamma leakage fluxes were calculated with the RAMPART code, using 28 point detectors at 15-deg intervals placed 50, 100, 200, and 400 cm from the RTG geometric center. Due to cylindrical symmetry, it was necessary to calculate the fluxes over only one quadrant. Figure 2 is a polar plot of the calculated "bare" MHW-RTG neutron and gamma-ray isoflux contours. Note the interesting result that the neutron and gamma-ray isoflux curves are similar in shape.

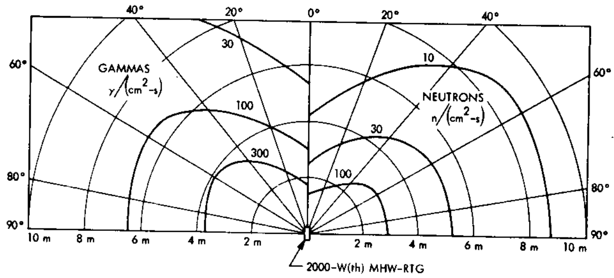


Figure 2. –Neutron and gamma-ray isoflux contours for the "bare" MWH-RTG (coordinate system origin at RTG geometric center).

## IV. RESULTS AND DISCUSSION

For the spacecraft radiation analysis, a total of 38 point detectors located in the bus and in the science area were used. All but four of these detectors were placed in the plane of symmetry. The results are based on 200 history packets for both neutrons and gamma rays. The gamma and neutron intensities near the science payload were normalized to a single point, run for 800 histories, at the science payload. As in the case of the "bare" RTG, the gamma-ray and neutron isoflux contours are similar in shape. Therefore, for clarity, single lines were used in fig. 3 to map the neutron and gamma-ray isoflux contours. Note that the science payload is not located in a region of minimum RTG radiation. This condition is explained by the presence of the full tank of hydrazine fuel in the propulsion bay and by the scattering contribution from the antenna section. Nevertheless, comparison of these dose rates with those due to the "bare" RTG shows a reduction in intensity of about an order of magnitude due to the spacecraft structure. An increase in intensity of a factor of 2 to 5 for gammas and 1.5 to 2.5 for neutrons was observed for detectors lying directly behind the fuel tank when the tank was empty.

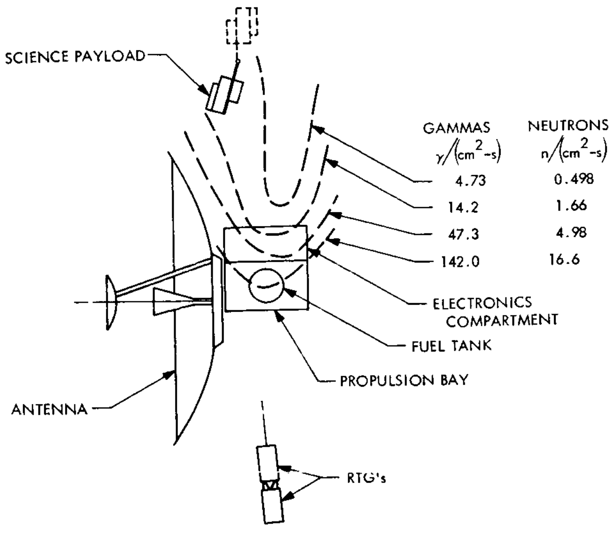


Figure 3. –Neutron and gamma-ray isoflux contours for TOPS configuration 12k.

Gamma-ray dose rates along traverses in the plane of symmetry and perpendicular to the plane of symmetry through the science payload are shown in figs. 4a and 4b. In the figures, the gamma dose rates of configuration 12k are compared with those from configuration 12j. The gamma dose rates are higher for the new TOPS configuration by about a factor of seven. Note in fig. 4b how much more quickly the "bare" RTG values are assumed in configuration 12k. This condition is due to the fact that the shielding cone of the spacecraft bus is much smaller in this RTG arrangement. The overall increase in the radiation levels throughout the spacecraft is not unexpected, since configuration 12j was optimized to provide maximum RTG self-shielding.

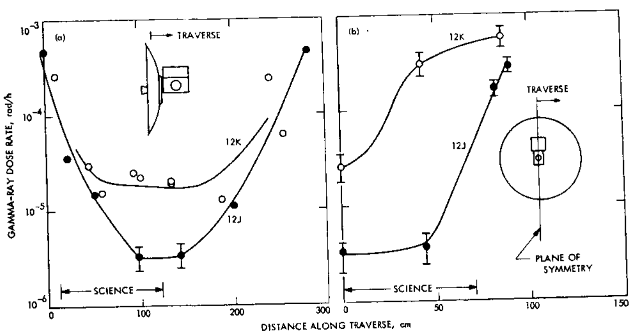


Figure 4. –Gamma-ray dose rate: (a) along a traverse in plane of symmetry at science payload; (b) perpendicular to plane of symmetry through science payload.

Figure 5 compares the differential neutron flux at the science payload with the axial RTG differential neutron leakage flux. Figure 6 makes a similar comparison for gamma radiation.

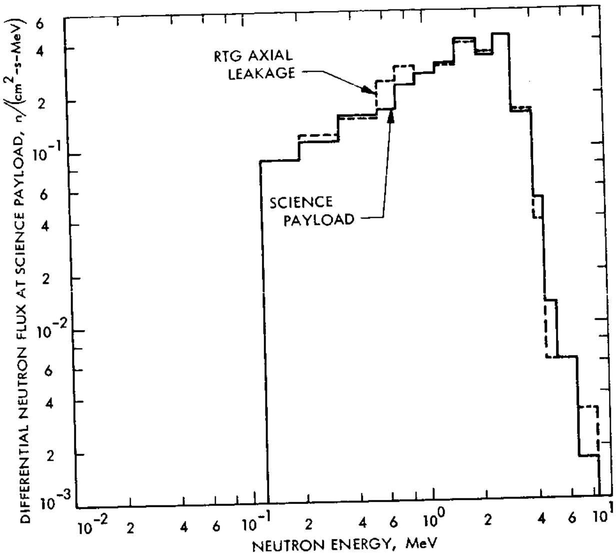


Figure 5. –Differential neutron flux vs neutron energy (data normalized at 2.6 MeV).

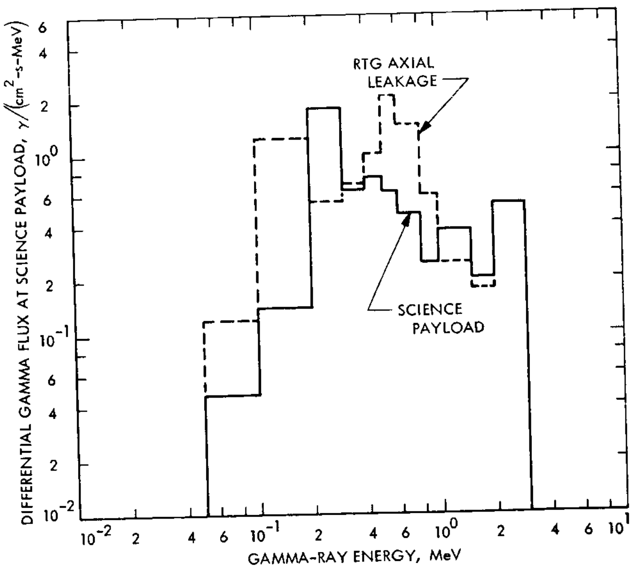


Figure 6. –Differential gamma-ray flux vs gamma-ray energy (data normalized at 2.6 MeV).

Ratios of configuration 12k scattering data to configuration 12j scattering data at the science payload are given in table 2. Standard errors are from 20 to 50% for gammas and 10 to 30% for neutrons. The table shows that higher orders of scatter are more important in the new configuration and that the effective buildup factors are twice as large. The scattering contribution from the antenna dish is lower for the new configuration mainly because the mass of the Chromel-R mesh was reduced to 0.9 kg from 3.15 kg. On the other hand, the scattering contribution from the antenna hub is larger due to the increase in solid angle as seen from the RTG's. The scattering contribution from the entire antenna section is about 30% of the total.

A TOPS radiation test model (RTM) is presently under construction at the Jet Propulsion Laboratory. The RTM construction will conform to the analytical model as closely as possible. When completed, the RTM will be used to verify experimentally the analytical results reported in this paper and to provide detailed data on the radiation environment of the science instruments.

Table 2. –Ratios of configuration 12k scattering data to configuration 12j scattering data at science payload.

| | EFFECTIVE BUILDUP FACTOR | ANTENNA DISH SCATTER | ORDER OF SCATTER | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 1 | 2 | 3 | 4 |
| GAMMAS | 2.0 | 0.4 | 1.0 | 0.7 | 1.5 | 1.0 | 4.0 |
| NEUTRONS | 2.0 | 0.6 | 0.4 | 0.7 | 0.8 | 7.0 | 2.3 |

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