Monte Carlo Radiation Analysis of a Spacecraft Radioisotope Power System

Matthew T. Wallace
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Ave
Pasadena, California 91109

Summary

Of the five outer planets - Jupiter, Saturn, Uranus, Neptune, and Pluto - Jupiter is nearest to the sun at 483 million miles, while Pluto orbits at a solar distance of over three billion miles. None of these bodies are close enough to the sun to be explored by solar powered spacecraft. To date, and into the near future, spacecraft sent to study and photograph these planets will require Radioisotope Thermoelectric Generators (RTGs) to convert heat into electrical power.

The Cassini Mission to Saturn is scheduled to fly three of the General Purpose Heat Source (GPHS) RTGs shown in Figure 1. The radioisotope fuel is encased in a stack of 18 GPHS graphite modules, each of which holds 4 of the iridium-clad PuO_2 fuel pellets. The modules are surrounded by multi-foil insulation, which in turn is enclosed in a finned aluminum shell. The shell supports 572 SiGe thermoelectric uncouples that penetrate through the insulation. The temperature differential across the unicouple creates an electrical potential, that in conjunction with the other uncouples generates several hundred watts of power.

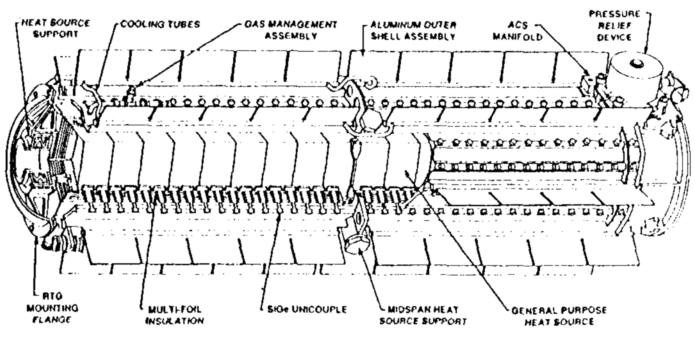

Figure 1
GPHS-RTG

While the static conversion and long fuel life of RTGs make them dependable space power sources, the neutron and photon radiation from the fuel can create equipment and personnel hazards. Ionizing dose from high energy gamma, and neutron displacement damage threaten spacecraft electronics, while low energy radiation can degrade science instrument return. In addition, personnel exposure risks complicate integration and launch operations near RTGs.

Various empirical, deterministic, statistical, and hybrid techniques have been used in an effort to closely characterize the radiation from RTGs. Most recently, the GPHS-RTG design was modelled using the Los Alamos Monte Carlo code MCNP4 (reference 1) on both a CRAY Y-MP and an IBM 486 PC.

Beginning from a user defined source, MCNP4 statistically simulates transport of a series of individual particles (neutron, photon, or electron) through a computer modelled geometry. The contributions from the particles are tallied at a point, over a surface, or in a cell until a representative value is attained. Particle energy, direction, event cross-sections, and other continuous and discrete distributions are stochastically sampled using Monte Carlo techniques. Numerous non-analog variance reduction and modelling options are available.

Most of the GPHS-RTG was modelled in detail, making extensive use of the MCNP4 repeated structure features. In the interest of simplicity and reduced run-time however, the 130 layers of insulation and 572 thermoelectric uncouples were lumped into two cells of homogeneously distributed representative elements. The validity of this simplification was demonstrated through independent runs that confirmed the relatively small importance of these components over the full neutron and photon spectrum.

The fuel source spectrum was initially

based on previous analyses of the PuO_2 fuel. That work was then updated to account for differences in fuel age, Pu-236 concentrations, monatomic Oxygen-18 content, and light element impurity levels all of which significantly impact either photon or neutron source levels.

A determined effort was made to ensure that the problem phase space was well sampled. Of particular concern, due to the sensitive science instruments, was the low energy photon spectrum. Photon transport was done using a "Detailed Physics Treatment" that included pair production, photo-electric fluorescent emissions, Compton and Thomson scattering down to 0.001 Mev. X-ray generation in the thick shielding for the spacecraft camera CCDS required bremsstrahlung approximations as well. No thermal neutron transport was modelled, however fast neutron fission in the fuel was included.

Several variance reduction features were used during the analysis to minimize run-time and improve the accuracy of the mode 1. They included source biasing, implicit capture, energy splitting, and forced collision. However, weight windows, energy cut-off, and statistical roulette games were purposely avoided where practical to help preclude data loss in the tail of the energy spectrum.

The statistical precision of the final RTG model was good. Most energy bins converged to a relative error of R=0.05 within 100,000 histories, where:

$$R = \frac{S_{\bar{x}}}{\bar{x}}, \qquad S_{\bar{x}} = std\ dev, \quad \bar{x} = mean$$

All tallies were well behaved with little fluctuation in detector statistics. Results compared well with empirical measurements, and the model has been used extensively to produce 3-D analyses of spacecraft, instrument, and personnel radiation patterns (Figure 2).

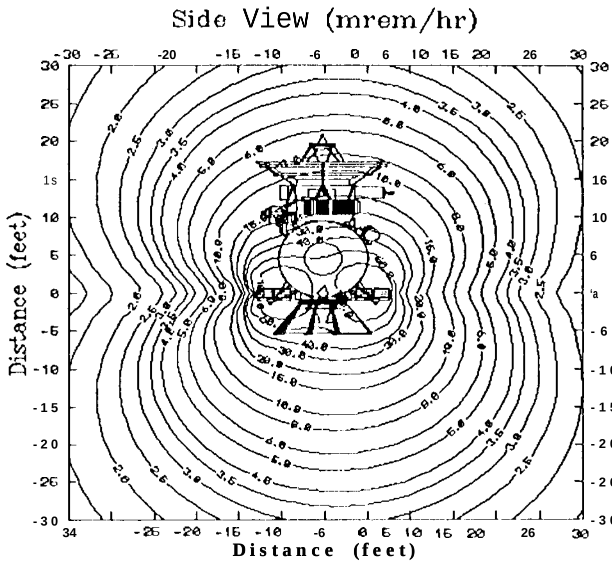

Figure 2
Cassini Spacecraft Radiation

References:

1. Los Alamos Document LA-7396-M, "MCNP - A General Monte Carlo Code for Neutron and Photon Transport," Version 4, 6/26/1990