ANS NETS 2018 – Nuclear and Emerging Technologies for Space
Las Vegas, NV, February 26 – March 1, 2018, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2018)

RADIOISOTOPE POWER SYSTEM DOSE ESTIMATION TOOL

Michael B. R. Smith[1]

[1]*Oak Ridge National Laboratory, 1 Bethel Valley Road, P.O. Box 2008, Oak Ridge, TN, 37931*
(865) 314-9717, smithmb@ornl.gov

The Radioisotope Power System Dose Estimation Tool (RPS-DET) is used to create, perform, and analyze particle-transport simulations of radioisotope power systems (RPSs). RPS-DET consists of a Matlab graphical user interface (GUI) to generate and analyze Monte Carlo N-Particle 6 (MCNP6) input and output files. Simulation geometries are created using a library-based method of combining multiple RPS units and environmental scenarios, while source terms are produced from databases of time-dependent photon and neutron spectra generated by the software packages IsoChain and ORIGEN. Simulation results are saved in a three-dimensional format for neutron and photon flux and dose in tissue or silicon and may be interactively inspected via the GUI. RPS-DET allows flexibility in the simulation-space by providing the ability to mix and match RPS units with relevant environments. RPS-DET also captures the effects of fuel-aging for the particle-energy-spectra and intensity. This work has been benchmarked against measurements of existing RPS units and found to comparably predict neutron and gamma flux, absorbed dose, and dose equivalent in humans and electronics (silicon).

I. INTRODUCTION

Radioisotope power systems (RPSs) generate power from the decay heat of radioisotopes which is converted into electricity.[1] Typical fuels for US-developed RPS systems use PuO_2 fuels, which contain high-activity alpha (α) emitting isotopes.[1] These α-particles do not escape the surrounding fuel, and they convert most of their kinetic energy into thermal energy, which is ultimately converted into electricity. While α emissions generate heat for power and attenuate locally, secondary emissions and reaction channels produce gamma-rays (γ) and neutrons (η), which deposit little-to-no heat and which do escape the RPS system. These escaped particles adversely affect personnel and electronics near any RPS, creating a potential for significant occupational exposures and damage to electronics.[2] Since missions using RPSs are typically unmanned, occupational exposures for humans are currently limited to terrestrial fuel fabrication, RPS assembly, transport, and spacecraft integration, while electronic exposures last for the entire lifetime of the mission and can span decades. The ability to predict exposure from RPS units in varying environments while reflecting the effects of aging fuel is a concern for all agencies and planners associated with missions requiring nuclear fuels. A devoted simulation tool provides significant support in standardizing, comparing, and developing a prediction model for RPSs. This ability provides insight into identifying optimum locations for RPS electronics that are sensitive to radiation fields, and it also estimates occupational doses during anticipated human exposure timeframes.

II. RADIOISOTOPE POWER SYSTEM DOSE ESTIMATION TOOL (RPS-DET)

The Radioisotope Power System (RPS) Dose Estimation Tool (RPS-DET) is a simulation package used to predict the intrinsic radiation effects of an RPS as a function of RPS-type, surrounding environment, and fuel age. The entire RPS-DET application is written with Matlab[3] and can be divided into three sections; (1) generation of input files, (2) particle transport and results, and (3) post-processing and interaction with results.

II.A. Input File Generation

Monte Carlo N-Particle 6 (MCNP6) is a particle transport code developed at Los Alamos National Laboratory (LANL).[4] Every MCNP6 input file includes a geometry, source term, and particle tallies, at a minimum. A typical MCNP6 simulation requires a single custom input file describing a specific simulation scenario. RPS-DET analyzes the MCNP6 simulation structure by allowing sections of an input file to be mixed and matched according to the requirements of the analysis. This is accomplished by using prewritten text files, or libraries, of relevant geometries and source terms that can be identified, combined, and included in an input file.

II.A.1. Simulation Geometry

For example, a user creates a composite geometry using RPS-DET by selecting from a list of RPS units, referred to as *objects of interest* (OOIs) (TABLE I). Relevant RPS units and components found in the RPS-DET library are the general-purpose heat source (GPHS), the multi-mission radioisotope thermoelectric generator (MMRTG), the GPHS-radioisotope thermoelectric generator (GPHS-RTG), and the advanced Stirling radioisotope generator (ASRG).[1]

TABLE I. RPS-DET Objects of Interest (OOI)

OOI #	OOI brief description
1–4	1–4 iridium-clad PuO_2
5–22	1–18 stacked GPHS modules
23	1 MMRTG (8 GPHSs) *
24	1 GPHS-RTG (18 GPHSs) *
25	1 ASRG (2 GPHSs)
26–29	4 separate dynamic RPS models†

*GPHSs are vertically stacked.
† Models are not described in detail for proprietary reasons.

The user then places chosen OOI in one of the available environments of interest (EOIs) shown in TABLE II.

TABLE II. RPS-DET Environments of Interest (EOI)

EOI#	EOI Brief Description
1	Suspended in vacuum
2	Suspended in air
3	On steel table, in concrete room, in air
4	On concrete floor, in concrete room, in air
5	In hot-cell on concrete floor
6	In RPS shipping cask (#9904)
7	In unmanned aeroshell in air
8	In unmanned aeroshell in vacuum
9	In manned spacecraft in air
10	In manned spacecraft in vacuum
11	On lunar regolith in vacuum
12	Buried in lunar regolith
13	On Martian regolith in Martian atmosphere
14	Buried in Martian regolith
15	Submerged in freshwater
16	Submerged in saltwater
17	In atmosphere of Titan
18	On ice slab in vacuum

The user chooses the duration of a given OOI in an EOI, which dictates the age of the fuel and thus the specific source term for a given simulation. This combinatorial approach for geometries, along with 100 years of fuel age, increases the number of possible simulations (Fig. 1).

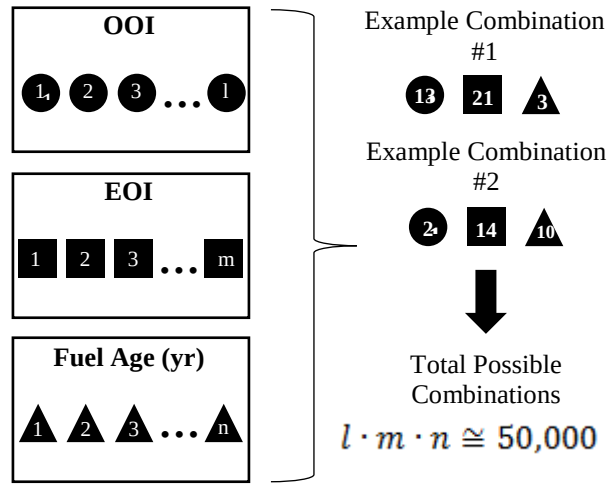

Fig. 1. Illustration of possible combinations of OOIs and EOIs evaluated at different fuel ages.

II.A.2. Simulation Source Terms

The ability to reflect the aging of PuO_2 fuel is important because the η and γ activities and their associated energy spectra change over time. Also, while the α-particle emission drives the heat generation of an RPS unit, the η and γ emissions are what drive external flux/dose concerns. For these reasons, RPS-DET only transports η and γ-particles.

RPS-DETs γ-ray spectra are generated using a combination of the National Nuclear Data Center (NNDC)[5] gamma ray spectra for radioisotopes, which are coupled to a transmutation software known as IsoChain,[6] which was developed at Oak Ridge National Laboratory (ORNL). IsoChain calculates the decay chains and isotopic abundances from a parent-isotope's initial mixture as a function of time. Annual time steps are solved over a 100-year timespan for the initial isotopic concentrations of PuO_2 shown in TABLE III. The isotopic concentrations shown in TABLE III reflect the average fuel mixtures for the three radioisotope thermoelectric generators (RTGs) used on the 1997 Cassini mission.[7]

TABLE III. RPS-DET Initial Fuel Assay

Element	*% Weight PuO_2*
Oxygen	11.8
Plutonium	88.2

Plutonium Isotope	*% Weight of Plutonium*
^{242}Pu	0.136
^{241}Pu	0.218
^{240}Pu	2.176
^{239}Pu	15.275
^{238}Pu	82.194
^{236}Pu	< 0.001

While the γ-intensities and energies for the plutonium isotopes do not cause significant external dose concerns, the transmutation and production of daughter isotopes such as thallium, bismuth, and lead do present concerns. RPS-DET includes all daughter isotopes of these plutonium decay chains, and it includes their respective γ-ray spectra given that the isotope contains γ-energies ≥ 30 keV and γ-intensities ≥ 0.1%. These criteria were established to minimize the simulation of particles that will likely attenuate in the surrounding RPS material and thus not contribute significantly to the external particle density. When a fuel age is chosen, RPS-DET accesses these values from its library and weights each respective γ-ray spectrum by its isotopes' relative activity and then compiles the composite γ-ray source term to be used in the specific simulation.

Neutron spectra (n-spectra) are generated with the ORIGEN[8] software package using an approach similar to that used for the γ-ray spectra based on isotopic abundances, although not all neutron populations from this fuel type come directly from decay processes. While spontaneous fissions from plutonium isotopes represent a portion of the n-spectra, the remaining larger portion of the spectra is the product of α-n reaction channels from ^{18}O atoms and other light elements like fluorine, boron, carbon, and magnesium.[9] An example of this relationship is demonstrated in research conducted at the California Institute of Technology's Jet Propulsion Laboratory (JPL), as shown in Fig. 2 (Ref. 10).

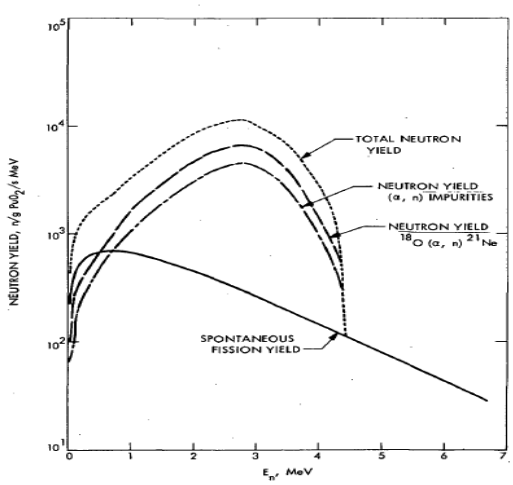

Fig. 2. PuO_2 neutron spectra based on spontaneous fission and α-*η* reactions.

ORIGEN calculates the isotopic concentrations of the fuel assay as a function of time and then it attributes combined neutron spectra based on spontaneous fission and α-*η* reactions. These values are generated in energy-dependent annual time steps and saved in the RPS-DET library to be used as a neutron source term when building input files.

II.B. MCNP6 Transport and Results

After RPS-DET has written the input file specified by the user, MCNP6 runs the simulation. Three dimensional volumetric tallies, or *mesh tallies*, are calculated and saved as text files for post processing. Each simulation calculates fluence (#/cm^2/s), absorbed dose in tissue (Gy, RAD), dose equivalent in tissue (Sv, REM), and absorbed dose in silicon (Gy, RAD).

II.C. Post Processing and Data Interaction

RPS-DET reads the MCNP6 output files and presents them in an interactive GUI. This format allows a user to interactively explore the simulation results in qualitative and quantitative capacities by showing three-dimensional radiation fields, along with specific analytical values of interest. A screenshot of the GUI used for RPS-DET post-processing can be seen in Fig. 3, with brief explanations of each feature described below.

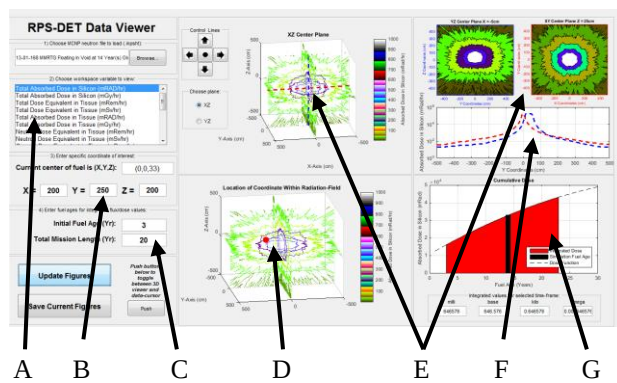

Fig. 3. RPS-DET post-processing GUI features.

TABLE IV. Explanation of features in RPS-DET GUI.

Feature	Brief Explanation
A	User selects data/units to be displayed: total, neutron or gamma, flux, dose equivalent in tissue, or absorbed dose in silicon or tissue
B	User enters XYZ coordinate of interest
C	User specifies initial fuel age and mission duration
D	3D display of flux/dose field with specific coordinate shown (in red)
E	Interactive 3D sliced planes (left arrow) and 2D contour maps (right arrow); 2D contour maps automatically update as 3D planes are manipulated
F	Centerline flux/dose profiles from interactive

	3D planes, which automatically update as 3D planes are manipulated
G	Estimated integrated flux/dose at user-specified coordinate (B) along with initial fuel age and mission length (C)

III. BENCHMARKING

RPS-DET has been benchmarked against measurements[11] of Mars Science Laboratory MMRTG and New Horizons GPHS-RTG and found to agree at most within a factor of 2 when using simulations of 5-year-old fuel for MMRTG and 10-year-old fuel for GPHS-RTG. These comparisons are shown in Fig. 4.

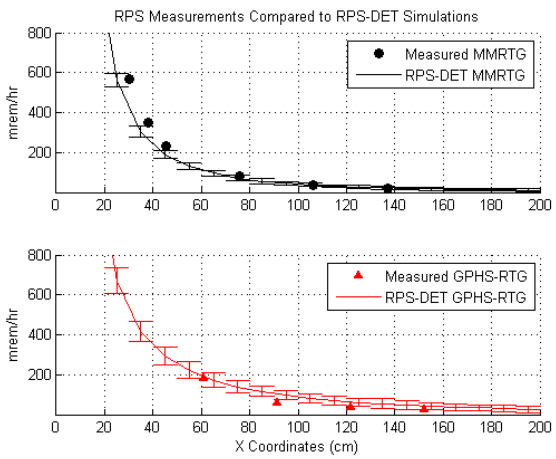

Fig. 4. Benchmarking data for RPS-DET.

IV. CONCLUSIONS

RPS-DET is a dose estimation tool used to predict the radiation implications of RPS units being evaluated by the US Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). This tool will aid in forecasting cumulative effects caused by intrinsic radiation fields emitted from current and/or future RPS designs. Estimations of this type will help optimize location-specific concerns for radiation-sensitive flight electronics and spacecraft materials, and it will also help determine biological exposures during RPS preparation, assembly, transportation, and integration of fuels and generators.

ACKNOWLEDGMENTS

This work was funded by the NASA RPS Program Office, and much appreciation is given to them and Glenn Research Center for their guidance and support, specifically June Zakrajsek and Paul Schmitz. Field measurements, fueling details, and detailed information regarding MMRTG and GPHS-RTG were provided by Dr. Steve Johnson and Kelly Lively at Idaho National Laboratory (INL). Information regarding the materials and dimensions of MMRTG were provided by Bill Otting of Aerojet Rocketdyne. This work was initiated while the author was attending the University of Tennessee, and many technical contributions were made by Dr. Lawrence Heilbronn from the Nuclear Engineering Department**.** Special thanks to Dr. Lou Qualls at ORNL for his mentorship and instruction during this project.

REFERENCES

1. Y. LEE and B. BAIRSTOW, *Radioisotope Power Systems Reference Book for Mission Designers*, JPL (2015).
2. ALTERA CORPORATION, *Introduction to Single-Event Upsets*, White Paper, 2013.
3. MATLAB and Statistics Toolbox R2013b, The MathWorks, Inc., Natick, Massachusetts (2013).
4. T. GOORLEY, M. JAMES, et al. "Features of MCNP6," *Annals of Nuclear Energy*, Vol. 87, Part 2, pp. 772–783 (Jan. 2016).
5. "National Nuclear Data Center" [Online]. Available: http://www.nndc.bnl.gov (Accessed 1/1/2017).
6. C. L. ALMANZA, H. A. LOVETT, F. SCHMITRROTH, M. A. GARLAND, and S. MIRZADEH, "Iso-Chain: A User Friendly Two-Group Nuclear Transmutation and Decay Code," *American Nuclear Society (ANS) Mid-Winter 6 Meeting and Technology Expo*, pp. 441–442 (Jan. 2016).
7. J. GRANDIDIER, J. B. GILBERT and G. A. CARR, "Cassini Power Subsytem," *Nuclear & Emerging Technologies for Space (NETS) 2017*, Orlando, Florida, Feb. 27–Mar. 2, ANS (2017).
8. W. WIESELQUIST, "Capabilities of ORIGEN in SCALE 6.2," Reactor and Nuclear Systems Division (RNSD) Summer Seminar, ORNL (Jul. 19, 2016).
9. G. M MATLACK and C. F. METZ, "Radiation Characteristics of ^{238}Pu," Los Alamos National Laboratory, Los Alamos, New Mexico, LA-3696 (1967).
10. M. TAHERZADEH, "Neutron Radiation Characteristics of Plutonium Dioxide Fuel", JPL, Pasadena, California, 32-1555 (1972).
11. Electronic communication (email) with Director of Space and Nuclear Power and Isotope Technology Division, INL (2017).