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# Designing Spacecraft Power Systems to Solve Planetary Protection Challenges

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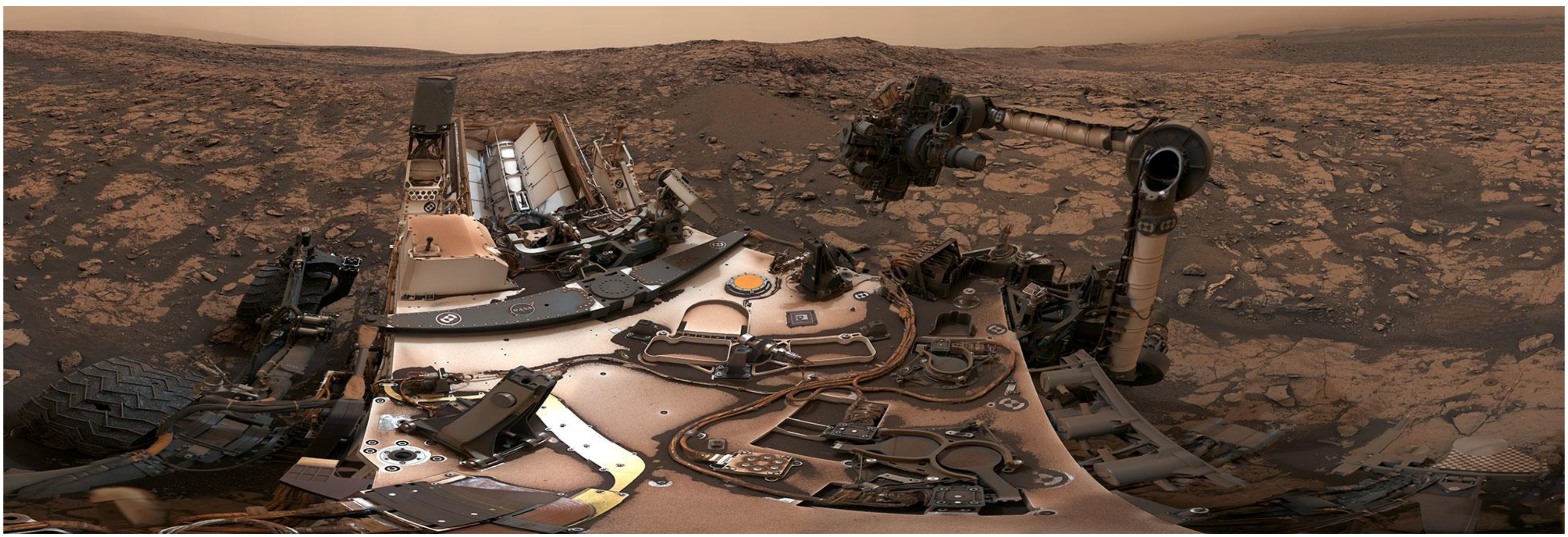


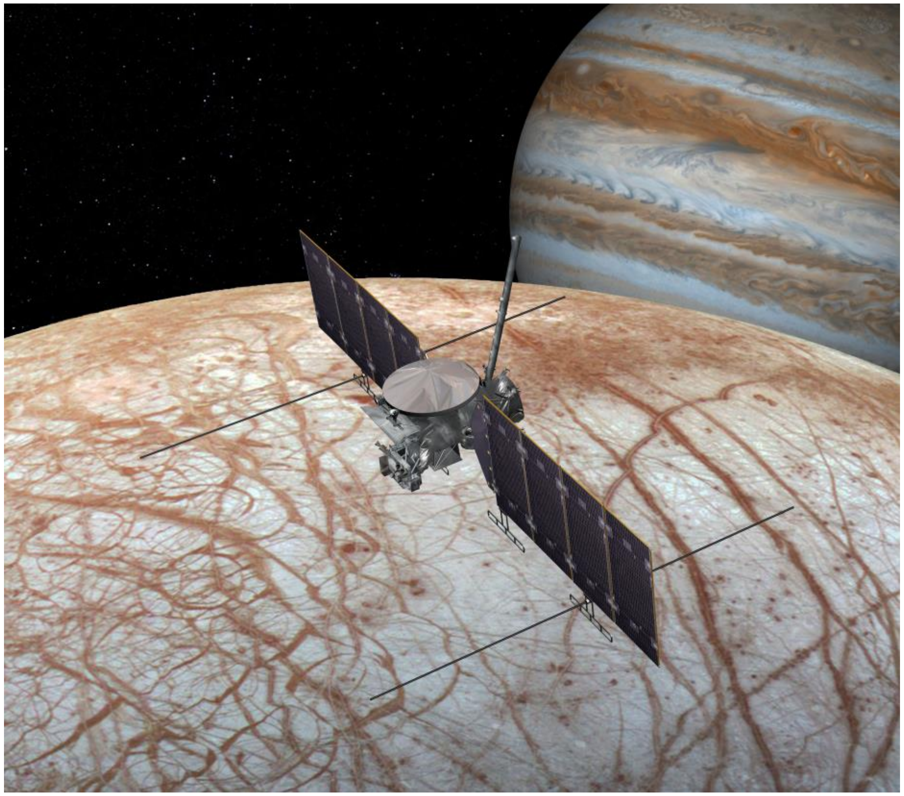
*August 9, 2018 NASA's Curiosity rover on Mars, a 360-degree panorama of its current location on Vera Rubin Ridge*

# Planetary protection requirements ensure *valid* and *safe* scientific exploration for extraterrestrial life

NASA Objectives during robotic missions beyond Earth:

•(*valid*) Avoid forward contamination of other worlds by terrestrial organisms carried on spacecraft.

•(*safe)* Prevent backward contamination of Earth by extraterrestrial life or bioactive molecules in samples returned for scientific study.



*Artist vision of the Clipper spacecraft orbiting Europa which is an icy moon of Jupiter.*

# Enduring Authority of the Outer Space Treaty

**The Outer Space Treaty of 1967:**

- Proposed to the UN in 1966
- Signed at Washington, London, Moscow on January 27, 1967
- Entered into force October 10, 1967

- **Article IX.** States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.

- **Article VI.** States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty.

https://www.state.gov/t/isn/5181.htm

# Relationship to COSPAR

NASA recognizes that only the 1967 Outer Space Treaty (OST) sets forth legal planetary protection requirements.  It is however NASA policy to follow the Committee on Space Research (COSPAR) Planetary Protection Policy of 2017 ("COSPAR Planetary Protection Policy"), as amended. In carrying out this policy, NASA is guided by advice and recommendations by the National Academies of Sciences, Engineering, and Medicine as well as other independent advisory panels.

*Expanding the knowledge frontier of space*
*for the benefit of humankind*

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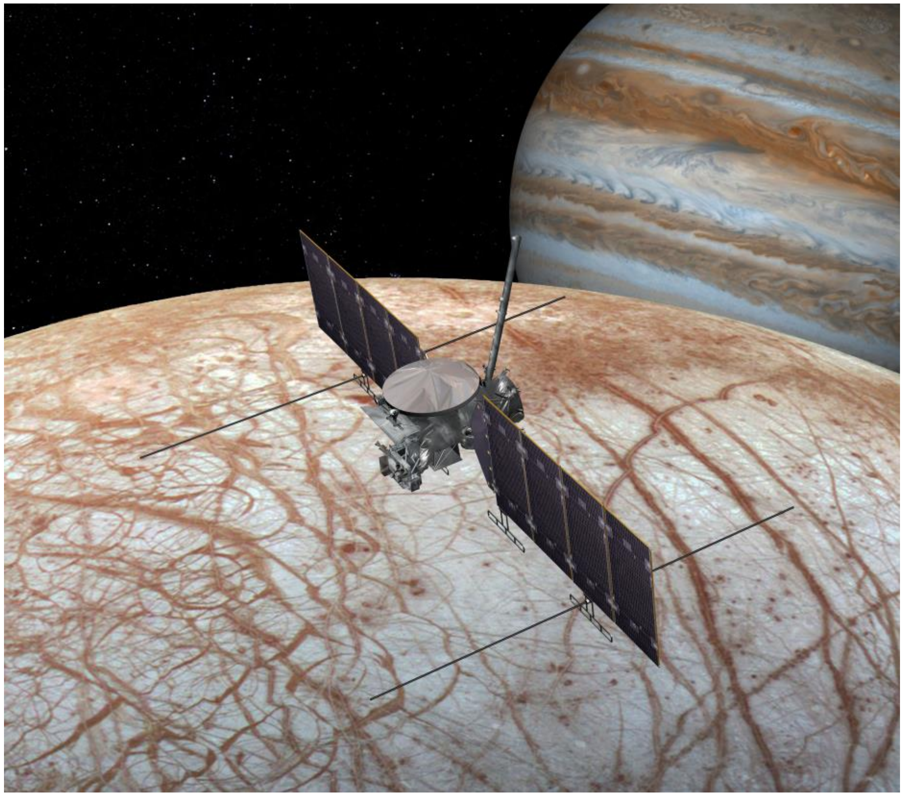

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# Planetary Protection Mission Categories (NASA/ESA/COSPAR Policy)

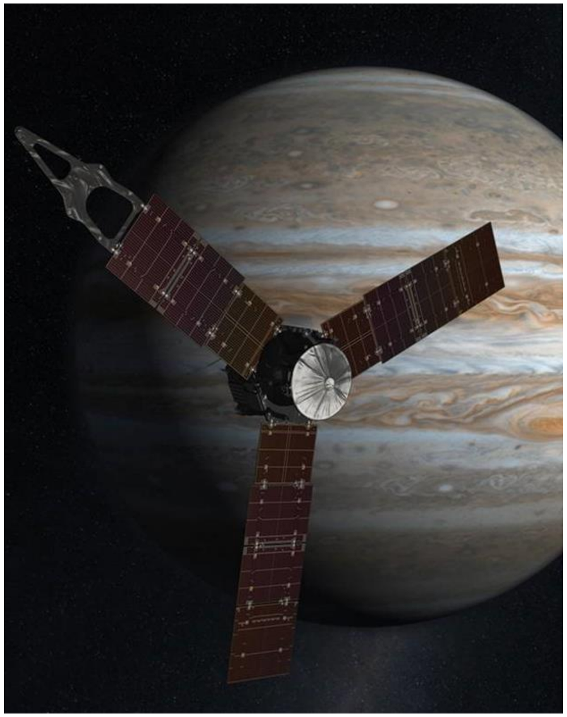
| Types of Planetary Bodies | Mission Type | Misson Category |
|---|---|---|
| Not of direct interest for understanding the process of chemical evolution. No protection of such planets is warranted. | Any | I |
| Of significant interest relative to the process of chemical evolution, but only a remote chance that contamination by spacecraft could jeopardize future exploration. Documentation is required. | Any | II |
| Of significant interest relative to the process of chemical evolution, and/or the origin of life or for which scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment. Substantial documentation and mitigation is required. | Flyby, Orbiter *Mars, Europa, Enceladus* | III |
| Same as Cat III | Lander, Probe *Mars, Europa, Enceladus* | IV *IVa, IVb, Ivc Mars* |
| Any solar system body. Unrestricted applies only to bodies deemed by scientific opinion to have no indigenous life forms. | Earth Return *Restricted or Unrestricted* | V |

# Categorization for Current New Frontiers Missions

## New Horizons
Pluto-Kuiper Belt
**Category II**

*January 2006 Launch*
*Flyby Pluto July 2015*
*Kuiper image August 2018*

## JUNO
Jupiter Polar Orbiter
**Category III**



*August 2011 Launch*
*Arrival Jupiter July 2016*
*13th flyby July 2018*

## OSIRIS-REx
Asteroid Sample Return
**Category V Unrestricted**

*September 2016 Launch*
*Final approach Bennu 2018*

# Planetary Protection Provisions for Robotic Extraterrestrial Missions

NPR 8020.12D
Effective Date: April 20, 2011
Expiration Date: December 20, 2018

| 5.1 | | Numerical Implementation Limits for Forward Contamination Calculations not Otherwise Specified |
|---|---|---|
| | 5.1.1 | To the degree that numerical limits are required to support the overall policy objectives of this document, and except where numerical requirements are otherwise specified, the limit to be used is that the probability that a planetary body will be contaminated during the period of biological exploration shall be no more than 1x10-3. No specific format for probability of contamination calculations is specified. |
| | 5.1.2 | The period of biological exploration shall extend at least 50 years after a PP Category III or IV mission arrives at its protected target and no longer than the time point after which no organisms remain viable on the spacecraft. |
| | 5.1.3 | For all launch vehicle elements leaving Earth's orbit, the probability of impacting Mars shall be less than 1x10-4 for a period of 50 years. The probability of impact assessment should be provided in the Planetary Protection Plan. |
| | 5.1.4 | For all spacecraft crossing Mars orbit en route to other targets, the probability of impacting Mars shall be less than 1x10-2 for a period of 50 years. The probability of impact assessment should be provided in the Planetary Protection Plan. |
| | 5.1.5 | In the context of missions to icy satellites, "contamination" is defined as the introduction of a single viable terrestrial microorganism into a liquid-water environment. |

NPR 8020.12D
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# Planetary Protection Provisions for Robotic Extraterrestrial Missions

| | | | |
|---|---|---|---|
| **5.3** | | | **PP Category-specific Requirements for Mars** |
| 5.3.2 | | | PP Category IV for Mars is subdivided into IVa, IVb, and IVc. Missions shall comply with requirements appropriate to the subcategory they have been assigned. Requirements for missions carrying life detection instruments that access special regions will include a combination of those listed under IVb and IVc, as determined on a mission-by-mission basis. |
| | 5.3.2.1 | | PP Category IVa. Lander systems not carrying instruments for the investigations of extant Martian life shall: |
| | | a | Be restricted to a surface biological burden level of 3 x 10+5 spores in total and an average of 300 spores per square meter of exposed external and internal spacecraft surfaces. |
| | | b | Provide an assessment of Entry, Descent, and Landing (EDL) expected performance against environmental and other design cases, identifying included and excluded factors, and, to the extent available, quantitative assessments of confidence levels. |
| | 5.3.2.2 | | PP Category IVb. Lander systems designed to investigate extant Martian life shall comply with all of the requirements of PP Category IVa and also with one of the following requirements: |
| | either | a | The entire landed system is restricted to a surface biological burden level of 30 spores (see 5.3.2.4) or to levels of biological burden reduction driven by the nature and sensitivity of the particular life-detection experiments, whichever are more stringent, and protected from recontamination. |
| | or | b | The entire landed system is restricted to a surface biological burden level of 30 spores (see 5.3.2.4) or to levels of biological burden reduction driven by the nature and sensitivity of the particular life-detection experiments, whichever are more stringent, and protected from recontamination. |

# Cleanroom Garments and Sample Acquisition

## Garment Zones

*Booties, hairnet and mask followed by hood, bunny, suit, boots, gloves and wrist tape.*

## Polyester Wipes


*Spacecraft hardware and transfer surfaces are sampled by wiping or swabbing.*

## Extraction of Microbes

*Polyester wipe inserted into sterile glass bottle with deionized water for extraction.*

# NASA Standard Spore Assay

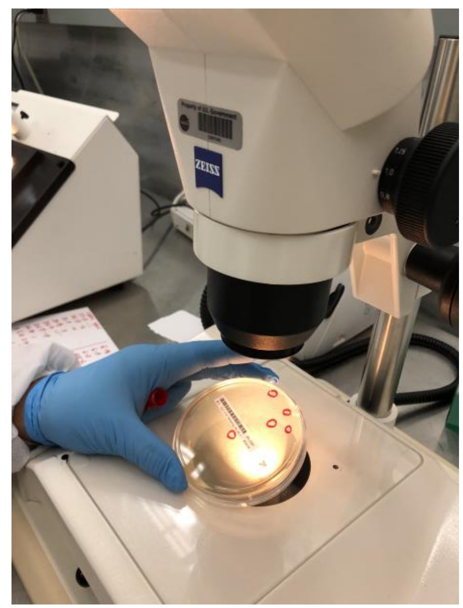
Sterilization of glassware and growth media in autoclave

*Heat shock of the extracted samples at 80°C for 15 minutes*

*Quenching shocked samples in ice bath*

*Quantitative aliquots plated on Trypticase Soy Agar*

*Visual enumeration of colony forming units after incubation at 32˚C for 24, 48, and 72 hours*



*Bar coding enables reliable tracking of bioburden data*

# Lethality is determined by treatment and growth of ordinary terrestrial organisms found on spacecraft

**Table 1. Experimental D-values of *Bacillus atrophaeus* spores under controlled and ambient humidity**

| Bacillus Atrophaeus | | | | | | |
|---|---|---|---|---|---|---|
| | Ambient humidity | | | Controlled humidity | | |
| Temp. (C) | D-value (min.) | St. Dev. (min.) | 3 sigma D-value (min) | D-value (min.) | St. Dev. (min.) | 3 sigma D-value (min) |
| 115 | 92.6 | 5.6 | 115 | 27.2 | 0.64 | 29.65 |
| 125 | 33.9 | 0.8 | 37 | 19.7 | 0.56 | 21.9 |
| 135 | 9.56 | 0.30 | 10.8 | 9.09 | 0.42 | 10.74 |
| 150 | 1.37 | 0.068 | 1.65 | 1.66 | 0.057 | 1.89 |
| 170 | 0.35 | 0.02 | 0.41 | 0.40 | 0.031 | 0.531 |

D-value refers to a decadal (factor of 10) decrease in viable spores

Spry et al. 2010, JPL Publication D-3458revA1

# Lethality is determined by treatment and growth of very heat resistant terrestrial organisms

**Table 3. Experimental D-values of *Bacillus* ATCC 29669 spores**

| Bacillus ATCC 29669 Spores | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ambient Humidity | | | Controlled Humidity | | |
| **Temp.( °C)** | **Units** | **D-value** | **St. dev.** | **3 sigma D-value** | **D-value** | **St. dev.** | **3 sigma D-value** |
| **115[a]** | Days | 3.35 | NA | NA | 1.92 | NA | NA |
| **125** | hr. | 18.8 | 3.79 | 22.6 | 10.10 | 0.26 | 11.0 |
| **150** | Min | 66.4 | 3.96 | 80.8 | 40.0 | 1.14 | 44.1 |
| **170** | Min | 9.76 | 0.423 | 11.3 | 4.90 | 4.90 | 5.39 |
| **200** | Sec | 20.5 | 0.660 | 22.9 | 17.8 | 0.46 | 19.5 |

Spry et al. 2010, JPL Publication D-3458revA1

# Dryness and Lethality

At 125$^{o}$C, the ambient humidity and controlled humidity lethality rate constants are statistically different at the 99.00% confidence limit:

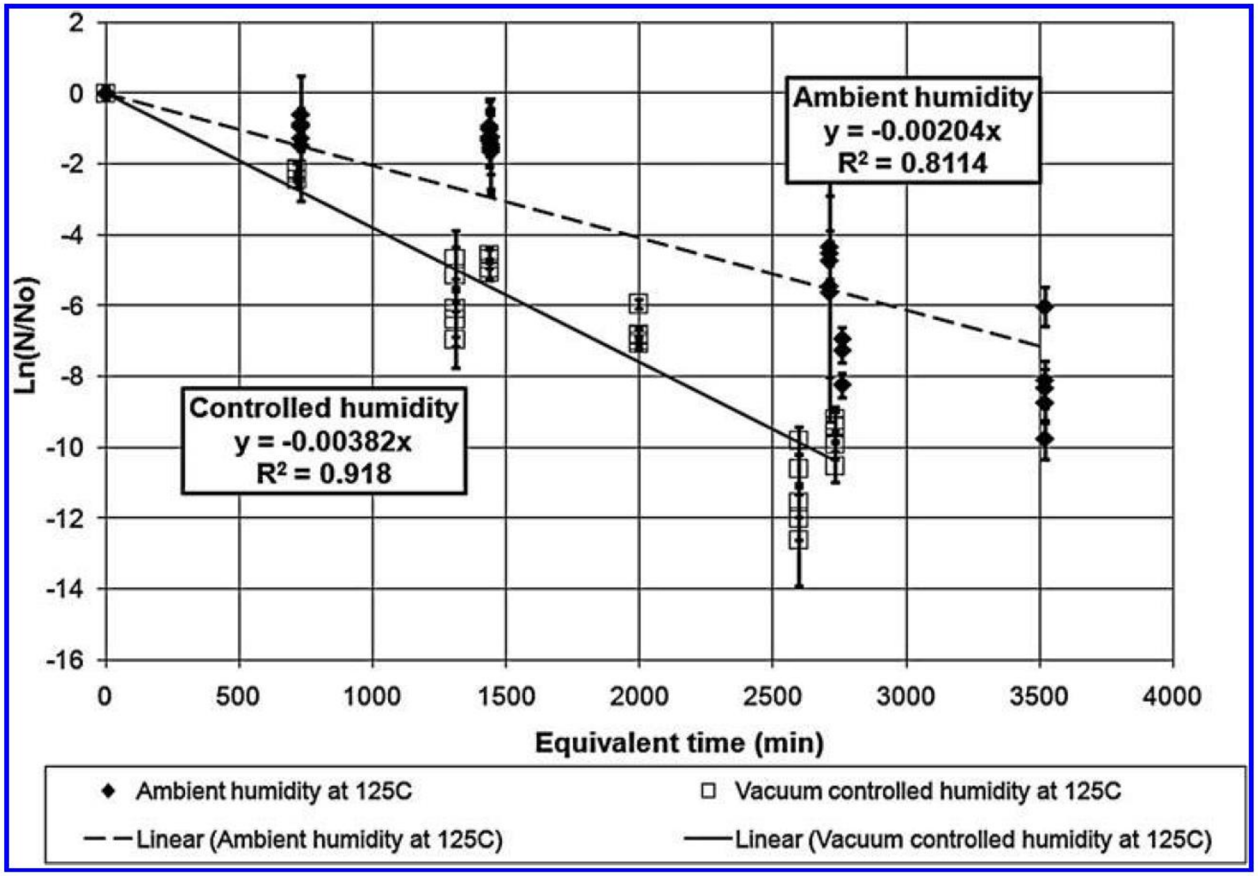
***Dryness increases lethality of exposure to heat at 125$^{o}$C or below***

At 135$^{o}$C, 150$^{o}$C and 170$^{o}$C, the ambient humidity and controlled humidity lethality rate constants are statistically the same at the 95% confidence limit:

***Dryness does not increase lethality at or about 130$^{o}$C***

Spry et al. 2010. JPL Publication D-3458revA1

# Graphic representation of lethality data for a very dry-heat resistant organism




No = number of visible colonies growing on agar before heat treatment

N = number of visible colonies growing on agar after heat treatment

Schubert and Beaudet, 2011, Astrobiology

**ECSS-Q-ST-70-57C**
30 August 2013

# Dry Heat Bioburden Reduction for Flight Hardware

## exposed, mated and encapsulated surfaces are distinct cases

This standard defines procedures for the reduction of microbiological contamination of flight hardware using heat.

The procedures described in this standard cover:

- Reduction of microbiological contamination on exposed surfaces, mated surfaces and encapsulated in materials.
- Reduction of microbiological contamination in dry, ambient and uncontrolled humidity environments.

This standard also sets requirements for the conditioning of the flight hardware, bioburden reduction cycle development, and equipment to be used for applying a bioburden reduction procedure.

**ECSS-Q-ST-70-57C**
30 August 2013

Temperature dependent D-values in minutes for 2 to 3 order of magnitude surface bioburden reduction under dry humidity conditions shall be calculated using equation [5-1] for temperatures ≤ 140 °C and equation [5-2] for temperatures > 140 °C, with the temperature (T) in °C:

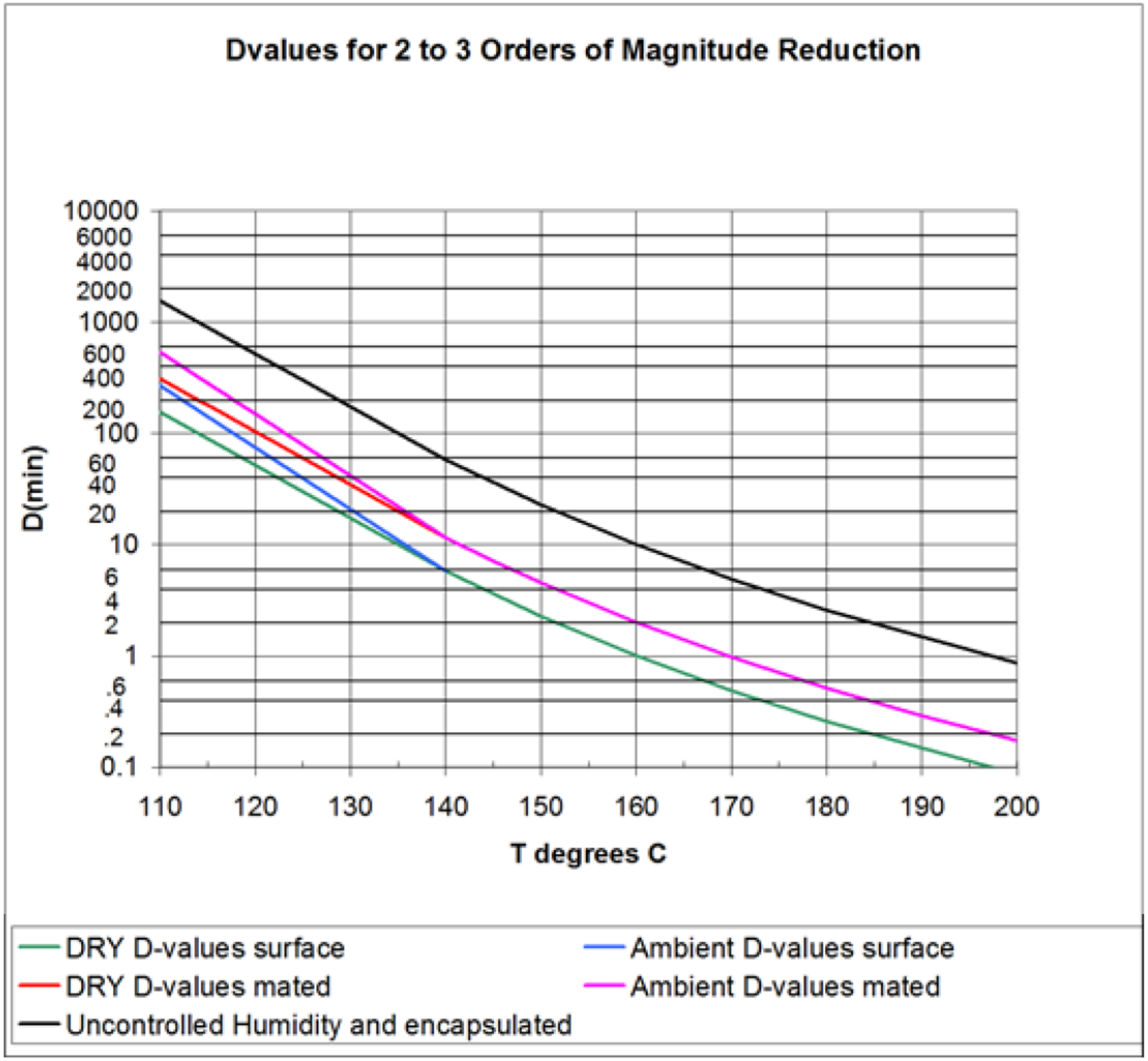
$$D(\min) = 30 \times 10^{\frac{(125-T)}{21}}$$

$$D(\min) = 5{,}79 \times 10^{\frac{(140-T)}{(23 \times T)/140}}$$

NOTE 1 A 2 or 3 order of magnitude reduction is achieved by multiplying the respective D-values in equations [5-1], [5-2], and [5-3] by a factor of 2 or 3, respectively.

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

**ECSS-Q-ST-70-57C**
30 August 2013



# So Why Talk About Nuclear Power Sources?

- Heat
  - Radioisotope Thermal Generators convert heat from decaying $^{238}$Pu with an efficiency of ~6%
  - Space nuclear reactor concepts vary:

$$6\% < \epsilon < 35\%$$

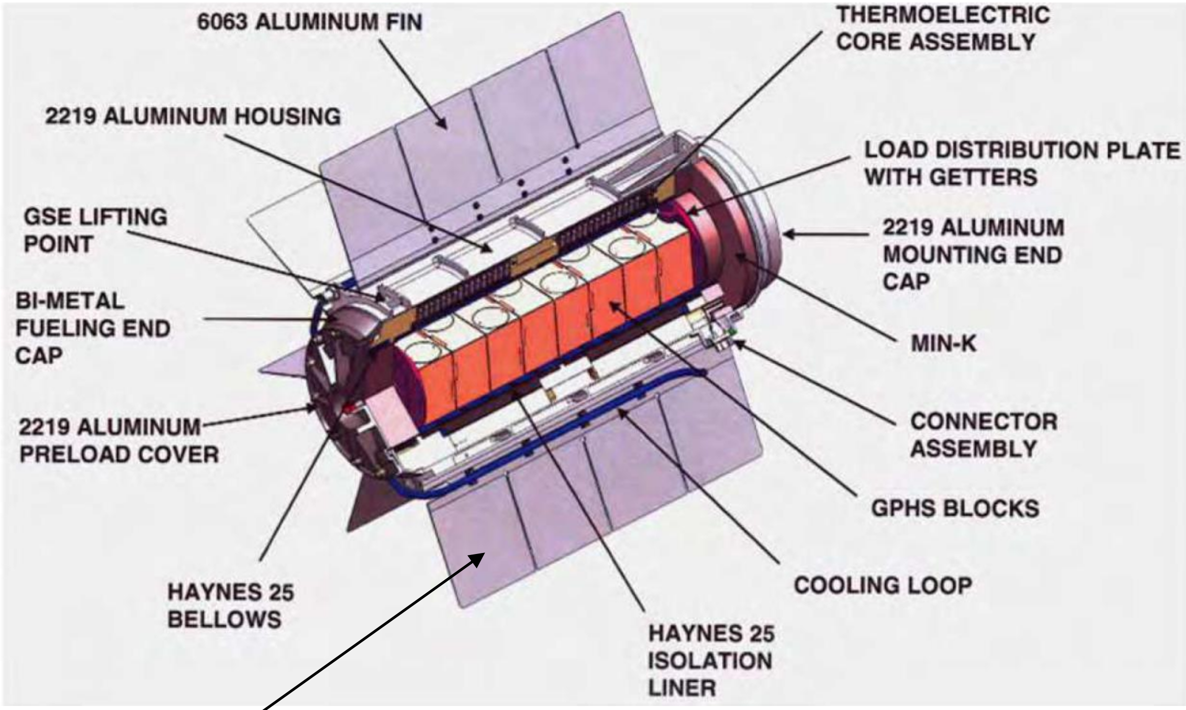
- Radiation
  - RTGs: Fairly benign
  - Reactors: How much do you need?

"One man's trash is another man's treasure"

Olde English Proverb

# MMRTG Overview

- The MMRTG generator is about 25 inches (64 centimeters) in diameter (fin-tip to fin-tip) by 26 inches (66 centimeters) tall and weighs about 94 pounds (45 kilograms)
- 10.6 pounds (4.8 kilograms) of plutonium dioxide (including Pu-238) that
- Initially provides approximately 2,000 watts of thermal power and 110 watts of electrical power when exposed to deep space environments.




Nominal 200° C Surface Temp, Radiative Flux 2000 W/m$^2$

Hammel, T. E., Bennett, R., Otting W. & Finale, S. (2009) Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and Performance Prediction Model. AIAA, 2009-4576, *7th International Energy Conversion Engineering Conference,* Denver, Colorado, 2009

# Getting the heat where you need it

- Use electric power for Ohmic heating ➔ wasteful…
- Smarter ways to do it
  - Forced Fluid Loops
    - Flexible means of transferring heat from a hot surface to heat another colder surface.  Still needs power to drive pumps
  - Louvers and Insulation
    - Typically spacecraft elements are protected from radiant heat
    - Variable emissivity insulation layers can be used to create hot spots in areas for long term heating
    - Louvers with bimetallic actuators could act as “windows” to a radiator to hold an area in a desired temperature range
  - Heat Pipes
    - Multiple technology options: constant conductance, variable conductance, loop, and diode heat pipes
    - Attachment of heat pipes between hot and cold surfaces is accomplished by use of thermally conductive adhesive, press fit, or clamping

Where you go matters:  Moon, planets with atmospheres, deep space all have special considerations

Patano, et al, Utilizing Radioisotope Power System Waste Heat for Spacecraft Thermal Management, NASA/TM-2005-213990

# Radiation Sterilization

- Industrial Standard: ISO 11137-2:2013 *Sterilization of health care products -- Radiation -- Part 2: Establishing the sterilization dose*
  - Specifies methods for determining the minimum dose needed to achieve a specified requirement for sterility and methods to substantiate the use of **25 kGy or 15 kGy as the sterilization dose to achieve a sterility assurance level, SAL, of $10^{-6}$**.
  - ISO 11137-2:2013 also specifies methods of sterilization dose audit used to demonstrate the continued effectiveness of the sterilization dose.

1 gray = 1 joule/kilogram
2.5 kGy = 2.5 Mrad ➔ For gamma rays this equates to 2.5Mrem

# Nuclear Power System Source Terms

RPS

- Primary
  - Alpha decay of $^{238}Pu$
  - Associated gamma yield

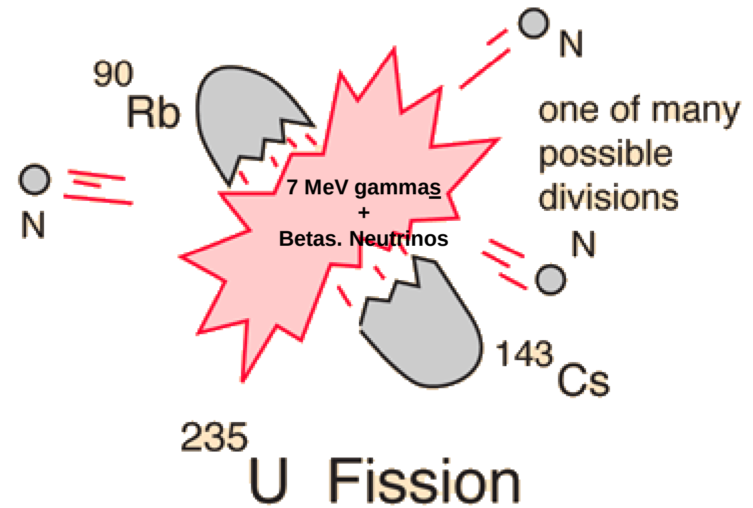
Gamma Radiation From Plutonium-238 Product

| Isotope | Energy, Mev. | Photons/gram-sec. |
|---|---|---|
| $^{238}Pu$ | 0.017 (L x-ray) | $6.7 \times 10^{10}$ |
| | 0.043 | $2.0 \times 10^{8}$ |
| | 0.099 | $4.6 \times 10^{7}$ |
| | 0.150 | $5.2 \times 10^{6}$ |
| | 0.203 | $2.0 \times 10^{4}$ |
| | 0.760 | $2.6 \times 10^{5}$ |
| $^{239}Pu$ | 0.017 (L x-ray) | $3.4 \times 10^{7}$ |
| | 0.052 | $2.4 \times 10^{4}$ |
| $^{240}Pu$ | Less abundant than $^{239}Pu$ | |
| $^{241}Pu$ | 0.145 | $\leq 4 \times 10^{4}$ |
| $^{236}Pu$ | 0.048 | $\leq 7 \times 10^{7}$ |

- Secondary
  - Neutrons and prompt gammas from spontaneous fission of $^{238}Pu$
  - Depends of $^{18}O$ "enrichment"
  - 11,300 n/sec ➔ 113 n/sec

Nuclear Reactor

- Primary
  - – Neutron induced fission of $^{235}U$
  - – ~200 MeV/fission




- Secondary
  - – Radioactive decay of fission products
  - – Depends on burnup (i.e., how long the reactor has operated at power

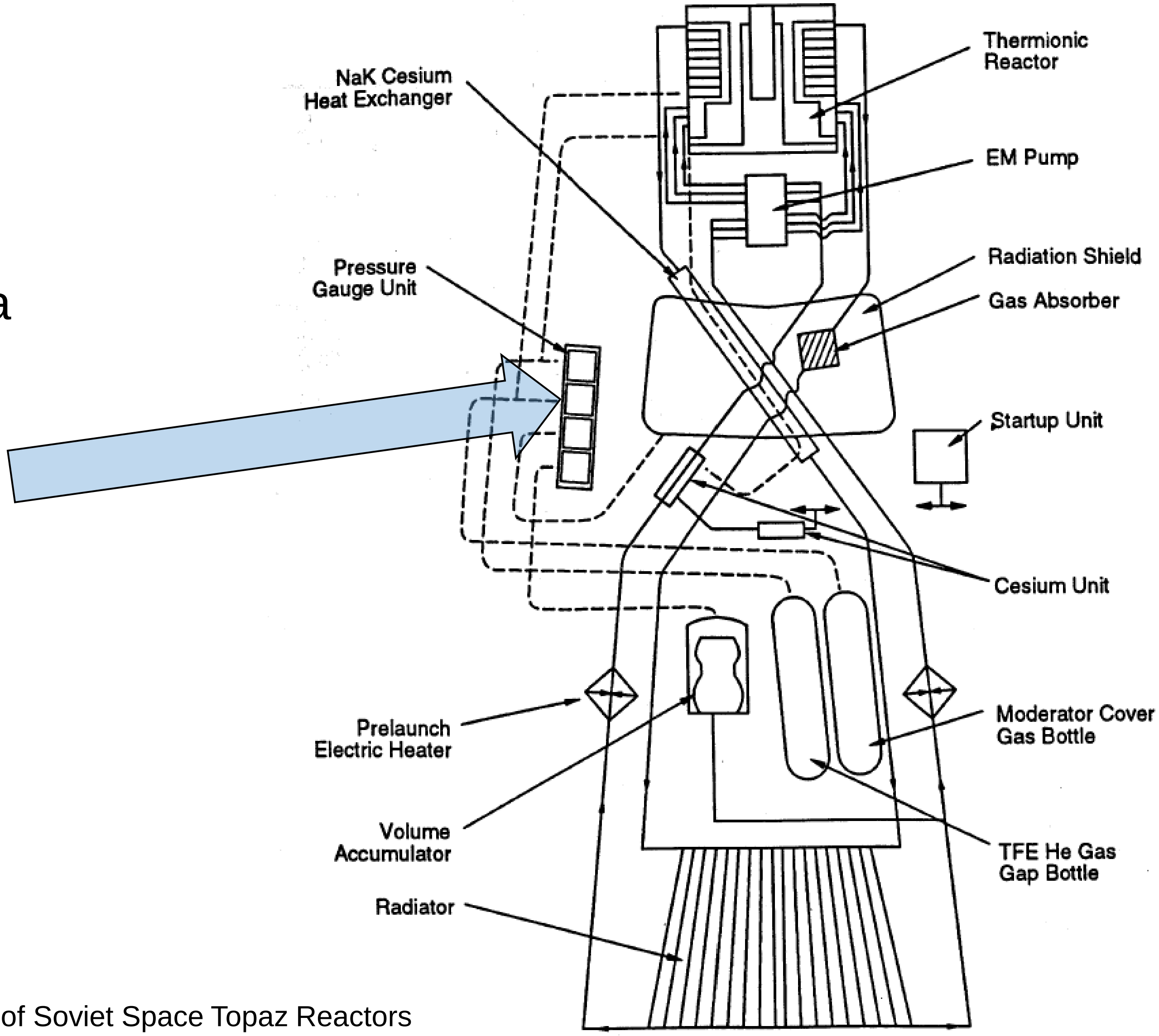
RPS radiation source diminishes over time, Nuclear Reactor scales with power and duration of operation

LA-3696 UC-41, HEALTH AND SAFETY TID-4500, *Radiation Characteristics of Plutonium-238*

# Schematic Reactor with Shield

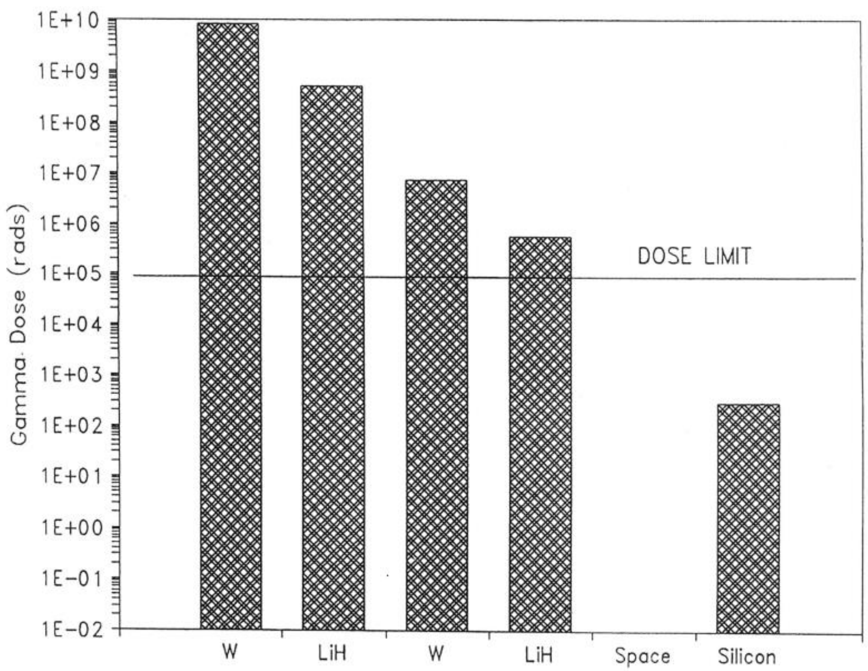
Radiation shield is a composite structure

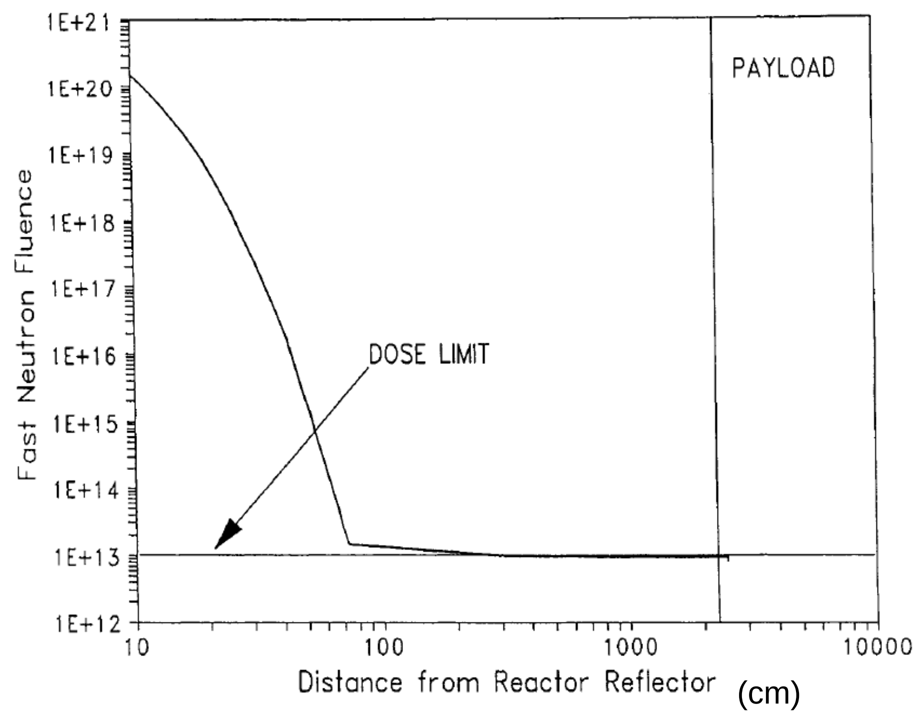
- High Z materials shield intense gamma flux
- Low Z materials shield neutrons




Lecture Notes on History of Soviet Space Topaz Reactors

# Representative Radiation Doses from 10 Years at Nominal 500 kW



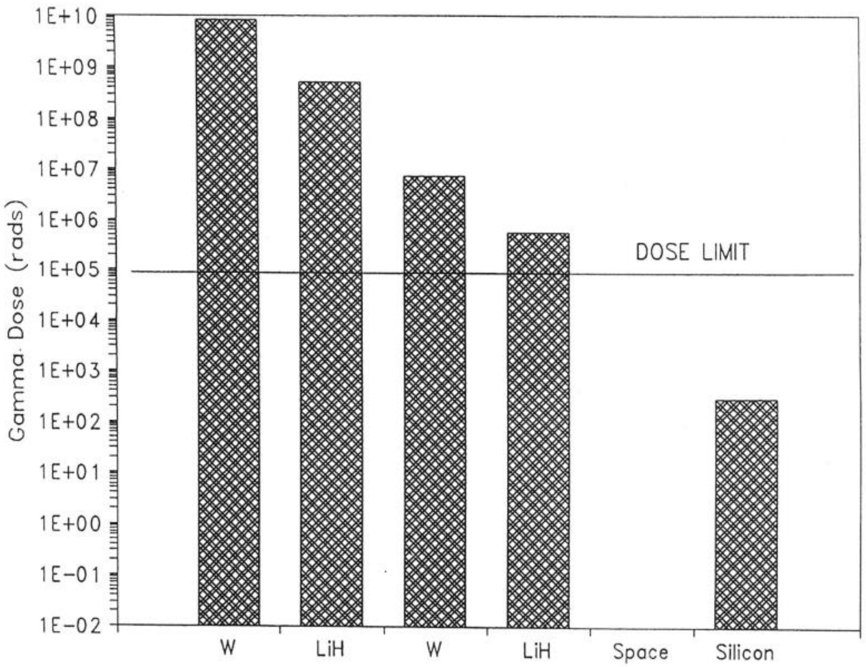

**System Modeling and Reactor Design Studies of the Advanced Thermionic Initiative Space Nuclear Reactor**

**Hsing H. Lee, Shahab Abdul-Hamid & Andrew C. Klein**

**To cite this article:** Hsing H. Lee, Shahab Abdul-Hamid & Andrew C. Klein (1996) System Modeling and Reactor Design Studies of the Advanced Thermionic Initiative Space Nuclear Reactor, Nuclear Technology, 115:1, 1-21, DOI: 10.13182/NT96-A35271

# Design Considerations

- 1 Mrad/year dose environment in front of second tungsten shield @ 500 kW thermal power – scales linearly with time and power
- Fast neutron dose in this region will increase the dose; however, neutron activation of the sterilized article will be to be taken into account




Key takeaways

1. Reactors can provide ample amounts of heat, ohmic or passive methods of heat transfer are equally viable
2. Using radiation sterilization methods will require complex engineering of radiation shields, but may be worth the effort depending on planetary protection objectives and goals

# Conclusions

- Heat and radiation from RTG's and reactors are potentially useful to increase lethality for terrestrial organisms during multi-year cruises to bioburden-protected destinations in the outer solar system.
- Research is needed on lethality in the temperate range of 80º to 120º C for time periods of years.
- Research is needed on lethality for specific types of ionizing radiation and for secondary products (chemical cascade) from radiolysis of water molecules such as peroxides and radicals.