Radioisotope Power System Effects on Science Instruments and Measurements

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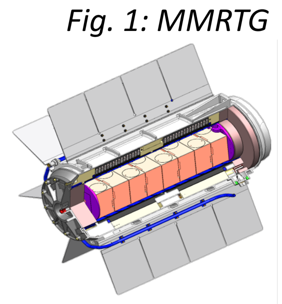
INTRODUCTION

For more than five decades, Radioisotope Power Systems (RPS) have played a critical role in the exploration of space, enabling missions of scientific discovery to destinations across the solar system by providing electrical power to explore remote and challenging environments - some of the hardest to reach, darkest, and coldest locations in the solar system.

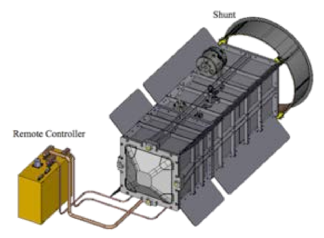
Fig. 1: MMRTG



RPS use the decay of a radioisotope (Pu-238) as a heat source, and convert the heat to electrical power via various methods.

- Radioisotope Thermoelectric Generators (RTGs) use Thermoelectrics (TE), which create a voltage via the Seebeck effect.
- Stirling Radioisotope Generators (SRGs) use Stirling engines, which use the heat to drive pistons and then convert the motion into electricity.

Fig. 2: Notional Advanced SRG (ASRG)



RPS INDUCED ENVIRONMENTS

RPS could induce environments that impact science instruments and measurements. To address these concerns, this poster describes existing and potential future RPS designs and their potential radiation, thermal, vibration, electro-magnetic interference (EMI), and magnetic-fields effects on representative science instruments and science measurements.

These potential impacts to science instruments must be understood (and mitigated where necessary) to ensure mission success.

Power System Induced Environments	Minimum Level of Impact	Maximum Level of Impact	Environment Impacts on Orbiter Instruments	Mitigation Strategies
Gamma Radiation	< 1 krad over 15 years at 1 meter for 2-GPHS RPS	1.5 krad over 15 years at 1 meter for 18-GPHS RPS	Damage to sensitive components (memory, ADCs, operational amplifiers). Increase in noise in most detectors.	Shielding, separation, error correction codes, use of less sensitive components
Neutron Radiation	~3 n/cm^2-s at 0.5 meters for 2-GPHS ASRG	300 n/cm^2-s at 1 meter for 18-GPHS RPS	Single event failures. Detector noise from displacement damage.	Shielding, separation, error correction codes, spike detection and removal, thermal annealing, use of less sensitive components
Thermal	0.5 kW_t for 2-GPHS RPS	4.5 kW_t for 18-GPHS RPS	Need to isolate RPS from radiators, thermal imagers.	Separation, pointing instruments away from RPS, heat shades
Vibration	0 for TE	TBD for Potential Stirling (ASRG = 35 N maximum dynamic force)	Need to damp vibration for sensitive imagers.	Separation, damping
EMI	Low for TE	Potential Stirling EMI in 20 dB uV/m range	Detector and magnetometer noise	Separation
Magnetic	< 0.1 nT	< 0.1 nT	Magnetometer noise.	Separation

REFERENCE POWER SYSTEMS

This assessment focused on four RPS:

- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG): 8-GPHS system currently powering Mars Science Laboratory
- Enhanced MMRTG (eMMRTG): Upgraded MMRTG currently under development.
- 6-GPHS SRG: Notional future higher-power system.
- 16-GPHS Segmented Modular Radioisotope Thermoelectric Generator (SMRTG) : Notional future higher-power system.

Notional RPS	MMRTG	eMMRTG	6-GPHS SRG	16-GPHS SMRTG	Unit
BOL Power (4 K)	125	157	370	456	W_e
BOM Power (4 K, BOL + 3 years)	108	146	357	434	W_e
EOM Power (4 K, BOL + 17 years)	55	103	297	347	W_e
BOL Power (270 K)	124	154	331	454	W_e
BOM Power (270 K, BOL + 3 years)	107	143	319	432	W_e
EOM Power (270 K, BOL + 17 years)	55	101	266	346	W_e
Degradation Rate	4.8%	2.5%	1.16%	1.6%	
Diameter	20.3	20.3	33	20.3	cm
Radiator Tip-to-tip Diameter	65	65	N/A	53.7	cm
Length	68	68	65	106.8	cm
GPHS Heat Load (BOL)	2,000	2,000	1,500	4,000	W_{th}
GPHS Heat Load (EOM)	1,784	1,784	1,312	3,567	W_{th}
BOL Waste Heat	1,875	1,843	1,089	3,544	W_{th}
Disturbance Force (@ 100 Hz)	N/A	N/A	16.9	N/A	N
BOL Specific Power	2.9	3.6	7.9	8.4	$W_{e/}$ kg
System Mass	43.6	43.6	46.8	54.2	kg
BOL Efficiency	6.3%	7.9%	24.7%	11.4%	
EOM Efficiency	3.1%	5.8%	22.6%	9.9%	

Reference: Bairstow et al., Science Instrument Sensitivities to Radioisotope Power System Environment, 36th IEEE Aerospace Conference, Big Sky, Mt (2016)

RADIATION IMPACTS

RPS are significant sources of radiation. RPS primarily emit alpha particles, which are easily shielded, but also produce gamma rays and neutrons. The potential effects on payload include:

- Damage to electronics and sensitive surfaces
  - Total Ionizing Dose (TID)
  - Direct Displacement Damage (DDD)
- Increased noise on the sensors
- Complicating measurement of the pristine in situ environment by adding energetic electrons, ions, and neutrons.

Induced radiation is a function of the number of GPHS modules, and distance between the RPS and the payload.

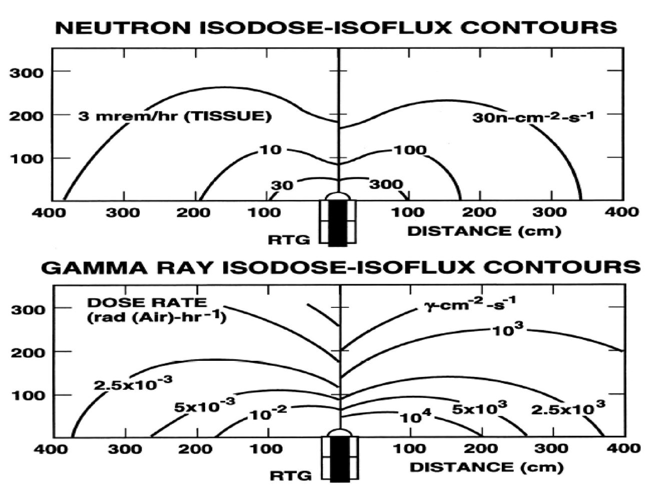
- The relationship with number of GPHS modules is not strictly linear, due to self-shielding effects.
- The relationship with separation distance is roughly $1/r^2$.

The TID from a Galileo style 18-GPHS RTG at 1 meter separation is ~1 krad over 10 years.

- This is an order of magnitude lower than the environmental dose rate at Mars, and would have a correspondingly lower contribution to instrument noise and to permanent damage to payload sensors.
- Missions with multiple units would see higher TID.
- RPS with fewer GPHS would induce lower TID.
- COTS parts can be as soft as 1 krad, and may be impractical for use with RPS.

- If configuration issues force < 0.5 meter separation between the RPS and the payload, the TID could be significantly higher.
- Some parts (operational amplifiers, analog to digital converters, and memory) are normally soft at about the 25 krad level, though it is possible to shield them or make them more robust.

Fig. 3: Galileo RTG Isodose-Isoflux Contours



Radiation Impact Mitigation

- Separation is a very effective strategy as radiation decreases as r^2, but the design would become challenging when separation distances exceed a few meters. Sensitive components could be shielded in a radiation vault or with spot shielding.
  - E.g. Juno used a 180 kg radiation vault to reduce the Jupiter dose to the electronics from ~300 krad to 25 krad. With a RDF of 2, this allowed the mission to use 50 krad capable components.
- SEU-type events could be mitigated with error correction codes, and, for detectors, with spike detection and removal.
- DDD in detectors could be corrected with thermal annealing.
- Instruments could be designed to be more robust, though this can be costly.
  - E.g. Components on Galileo were designed to 150 krad to survive the Jupiter environment.

THERMAL IMPACTS

RPS BOM Thermal Output [Total Heat / Waste Heat]

MMRTG	eMMRTG	6-GPHS SRG	16-GPHS SMRTG
[2.0/1.9] kW_t	[2.0/1.85] kW_t	[1.5/1.15] kW_t	[4.0/3.55] kW_t

Heating from the 16-GPHS SMRTG would be twice the ~2 kW_t of current existing RPS (i.e., MMRTG).

- We have found no reports in the literature of this level of radiated waste heat having a measurable effect on orbital in situ measurements.

Thermal Impact Mitigation

The thermal output from the RPS could impact instruments, but these effects could be mitigated.

- Certain sensitive instruments (e.g. IR spectrometers, thermal spectrometer, and other instruments requiring cooling) would need to be pointed away from the RPS end of the spacecraft and shaded.
- Instrument radiators would need to be shielded from view of the power system radiators.
- Optics might require blanketing or shielding to avoid distortion arising from differential heating.
- The radiated power would also add to complexity of the launch configuration.

VIBRATION IMPACTS

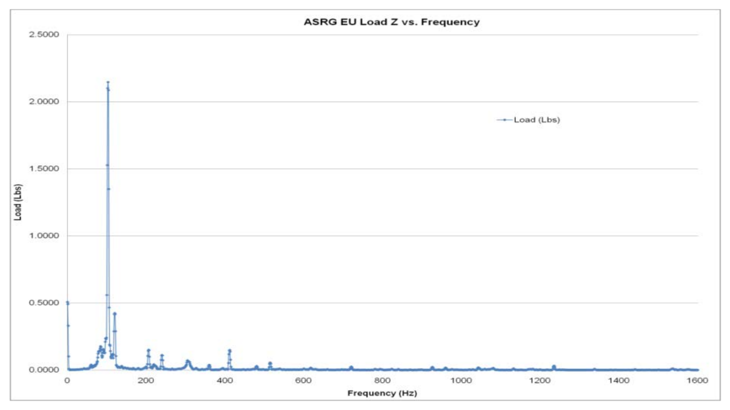
SRGs would use Stirling engines with moving parts to produce power. Though opposed pairs balance out most of the vibration, there are still residual effects.

- Vibration levels for the ASRG have been tested, with the conclusion that SRGs would produce jitter within the bounds of sensitive flight missions (see below).
- Higher power Stirling engines might have higher vibration levels; further design maturation and analysis is needed.
- TE devices do not produce vibration.

Certain instruments are sensitive to vibration/jitter:

- Cameras have acceleration and maximum angular displacement amplitude limits to avoid line-of-sight jitter.
- Some instruments (e.g. submillimeter spectrometer) are sensitive to microphonics
- Seismometers could be very sensitive to vibration if they are looking at the same vibration spectrum; these and other in-situ instruments would require additional study.

Fig. 4: ASRG Engineering Unit Test Data, ~10 N Load at 102 Hz



Vibration Impact Mitigation

- Separation of RPS and the payload would reduce the effect of vibration.
  - The magnitude of vibration impact is a strong function of the separation distance between the vibration source and the sensitive area, with a less than perfectly stiff structure soaking up much of the vibration.
- Vibration could be damped using isolation adapters or adjusting the spacecraft structure or design.
- Missions using Stirling devices would need to have a contingency plan for a single engine failure – whether that plan is to include accommodations for the increased vibration issues, or to cease operation of the matched pair engine.

EMI AND MAGNETIC FIELDS

No EMI issues have been identified for RPS that lie beyond normal environmental specifications.

- The electric fields radiation emissions limits from the ASRG ICD are ~20 dBuV/m for sensitive frequencies.
- EMI from TE RPS is low.

The current trend for payload magnetic requirements is 0.1 nT at the magnetometer.

- ASRGs, operating in balanced mode, are rated to meet this requirement.
- Magnetic fields from TE RPS is low.

Larger Stirling engines, or SRGs in unbalanced operation might generate more EMI or magnetic fields. Further design maturation and analysis would be needed to quantify these levels.

Separation is an effective mitigation strategy, as EMI varies with distance as $1/r^2$ and magnetic fields vary with distance as $1/r^3$.

CONCLUSIONS

RPS can induce radiation, thermal, vibration, EMI, and magnetic field environments that must be understood to avoid impacting spacecraft payloads and science measurements.

- Given a 1 meter separation distance, radiation from RPS would be lower than the contribution from most space environments, and the same mitigation approaches apply.
- Though a new, higher power RPS could generate more heat per unit than the ASRG and the MMRTG, thermal impact could be mitigated with shading and pointing, if required, by the mission. Alternatively, excess heat could provide benefits in some thermal environments.
- Vibration for new SRGs would be expected to be similar to the ASRG test data, and while this would be expected to be low, it would need to be considered and addressed during spacecraft and instrument design.
- EMI and magnetic fields for new RPS would be expected to be low as for the current RPS, but would need to be considered and addressed if there are sensitive instruments.