

Science Instrument Sensitivities to Radioisotope Power System Environment

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ABSTRACT

Radioisotope Power Systems (RPS) have been and will be enabling or significantly enhancing for many missions, including several concepts identified in the 2011 Planetary Science Decadal Survey. Some mission planners and science investigators might have concerns about possible impacts from RPS-induced conditions upon the scientific capabilities of their mission concepts. To alleviate these concerns, this paper looks at existing and potential future RPS designs, and examines their potential radiation, thermal, vibration, electromagnetic interference (EMI), and magnetic fields impacts on representative science instruments and science measurements.

Radiation impacts from RPS on science instruments are of potential concern for instruments with optical detectors and instruments with high-voltage electronics. The two main areas of concern are noise effects on the instrument measurements, and long-term effects of instrument damage. While RPS by their nature will contribute to total radiation dose, their addition for most missions should be relatively small. For example, the gamma dose rate from one Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) would be an order of magnitude lower than the environmental dose rate at Mars, and would have a correspondingly lower contribution to instrument noise and to any permanent damage to payload sensors. Increasing the number of General Purpose Heat Source (GPHS) modules used in an RPS would be expected to increase the generated radiation proportionally; however, the effect of more GPHS modules is mitigated from a strictly linear relationship by self-shielding effects. The radiation field of an RPS is anisotropic due to the deviation of the modules from a point-source-geometry. For particularly sensitive instruments the total radiation dose could be mitigated with separation or application of spot shielding.

Though a new, higher-power RPS could generate more heat per unit than current designs, thermal impact to the flight system could be mitigated with shading and pointing if required by the mission. Alternatively, excess heat could prove beneficial in providing needed heat to spacecraft components and instruments in some thermal environments.

Vibration for a new higher-power Stirling Radioisotope Generator (SRG) would be expected to be similar to the recent Advanced Stirling Radioisotope Generator (ASRG) design.

While vibration should be low, it must be considered and addressed during spacecraft and instrument design.

EMI and magnetic fields for new RPS concepts are expected to be low as for the current RPS, but must be considered and addressed if the mission includes sensitive instruments such as magnetometers.

The assessment conducted for this paper focused on orbiter instrument payloads for two representative mission concepts—a Titan Saturn System Mission (TSSM) and a Uranus Orbiter and Probe (UOP)—since both of these Decadal Survey concepts would include many diverse instruments on board. Quick-look design studies using notional new RPS concepts were carried out for these two mission concepts, and their specific instrument packages were analyzed for their interactions with new RPS designs. The original Decadal Survey TSSM and UOP concepts did not have complete instrument performance requirements so typical measurement requirements were used where needed. Then, the general RPS environments were evaluated for impacts to various types of instruments.

This paper describes how the potential impacts of the RPS on science instruments and measurements were assessed, which impacts were addressed, proposed mitigation strategies against those impacts, and provides an overview of future work.

1.0 INTRODUCTION

The purpose of this assessment was to understand potential RPS environmental impacts on science instruments, in terms of instrument survival and effects on measurements, and to identify potential mitigation strategies. The assessment focused on radiation, thermal, vibration, EMI, and magnetic fields.

The estimated induced environments and impacts on instruments are summarized in *Table 1*.

Table 1. Summary of Potential RPS Impacts on Orbiter Instruments

Power System Induced Environments	Min Level of Impact	Max 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 RPS	TBD for Potential Stirling (ASRG = 35 N maximum dynamic force)	Need to damp vibration for sensitive imagers.	Separation, damping
EMI	Low for TE RPS	Potential Stirling EMI in 20 dB uV/m range	Detector and magnetometer noise	Separation
Magnetic	< 0.1 nT	< 0.1 nT	Magnetometer noise.	Separation

Quick-look design studies using notional new RPS concepts were carried out for TSSM and UOP. In this report, the original studies are referred to as the Decadal Survey TSSM Study and the Decadal Survey UOP Study, while the new studies are referred to as the 2014 TSSM Study and the 2014 UOP Study. The specific instrument packages from the TSSM and UOP mission concepts were analyzed in greater depth for their interactions with new RPS designs. The original Decadal Survey TSSM and UOP concepts did not have complete instrument performance requirements so typical measurement requirements were used where needed. Then, the general RPS environments were evaluated for impacts to various types of instruments.

RPS utilize ²³⁸Pu in the form of plutonium dioxide, which is principally an alpha emitter and relatively easy to shield. The possible effects of the radiation on payload include damage to electronics and sensitive surfaces, increased noise on the sensors, and complicating measurement of the pristine *in situ* environment due to the addition of RPS-generated energetic electrons, ions, and neutrons. RPS may use either thermoelectrics (TE) or a Stirling engine to generate electrical power. Radioisotope thermoelectric generators (RTGs) use thermocouples, and have no moving parts, hence no vibration. Stirling Radioisotope Generators (SRGs) would have moving parts in their Stirling engines, but would likely use these engines in opposed pairs with electronic controllers to cancel out the majority of the vibration. The design specification for the ASRG stated an Electromagnetic Compatibility (EMC) design performance equal or superior to the thermocouple implementation [1 - ICD]. There are several possible mitigation strategies to ameliorate the effects of RPS on instruments. Separation is a very effective strategy, although spacecraft design becomes challenging when separation distances exceed a few meters. Spot shielding around soft components can be very effective for energetic particles (Galileo used kilograms of tantalum for this purpose); however, it would not be very effective for gamma rays, which are best shielded with high-Z material (though the gamma shielding generates secondary electrons that are also problematic for instrumentation). The shielding requirements would also reduce the effective specific power density.

2.0 ANALYZED POWER SYSTEM DESCRIPTIONS

For the purpose of this assessment it was assumed that the RPS used 250 W_{th} GPHS modules. The only currently available RPS is the MMRTG; a potential enhanced MMRTG (eMMRTG) is currently under development. The two notional RPS designs considered in this assessment were a 6-GPHS SRG and a 16-GPHS Advanced Radioisotope Thermoelectric Generator (ARTG). The 6-GPHS SRG would produce 300 W_e end of mission (EOM) and 1,500 W_{th} beginning of life (BOL), and the 16-GPHS ARTG would produce 350 W_e EOM and 4,000 W_{th} BOL. Both systems would be designed to deliver at least 300 W_e after 14 years of flight. See Table 2 for additional RPS parameters.

Table 2. Existing and Notional RPS Parameters

Notional RPS	MMRTG	eMMRTG	6-GPHS SRG	16-GPHS ARTG	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%	

3.0 IMPACT OF RPS IMPLEMENTATIONS ON 2014 TSSM AND UOP PAYLOADS

The total estimated radiation dosage experienced by the instruments is the sum of the RPS and the environmental component (which varies by mission). Instrument parts are typically designed with a Radiation Design Factor (RDF) of 2, so if the radiation dose from the RPS is 2 krad, and the radiation dose from the environment is 25 krad, then instruments would need to be designed for $(2+25) * 2 = 54$ krad tolerance.

Assessment showed that the instruments investigated require little or no changes to accommodate either new RPS design, the ARTG or the SRG. Payloads have been integrated with 18-GPHS RTGs on, for instance, Galileo, Ulysses, Cassini, and Pluto New Horizons. Radiation levels from the Galileo GPHS RTGs (~300 W_e , 4.4 kW_{th} , 18 GPHS, 7.8 kg Pu) were slightly higher than the 16-GPHS ARTG implementation studied here. Note that some of these missions accommodated the RTGs on a boom, and utilized heat shields to protect the payload from directly viewing the hot power source. Additionally, no significant changes in instrument impacts would be anticipated with the SRG and ARTG relative to current ASRG and MMRTG designs. As

larger units, they would produce more radiation and heat per unit, and would be expected to produce more vibration and EMI, but at a given power level, the total impact should be similar. As system designs mature, more investigation may be warranted.

3.1 Decadal Survey TSSM Study

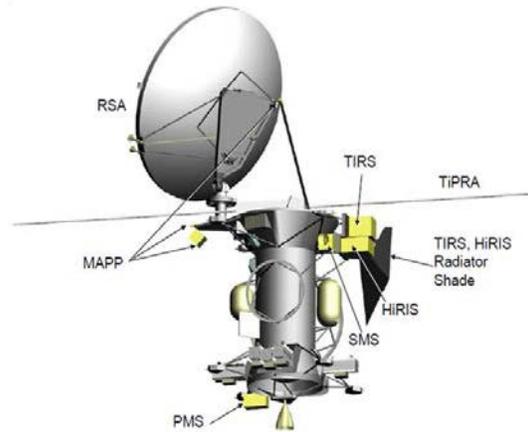


Figure 1. Decadal Survey TSSM Study notional RPS Spacecraft Layout shows the 5 MMRTG cluster with a thermal shield to protect instrument radiators from viewing the generators. PMS is located close to the MMRTGs, which poses a risk in the form of instrument noise. The Ion and Neutral Mass Spectrometer (INMS) is located ~3 m from the RTGs on Cassini and has operated successfully.[2 - TSSM Final Report]

In the Decadal Survey TSSM study (Figure 1), radiation from the MMRTGs to the payload was estimated to be on the order of 2 krad for payloads using the higher radiation 5-MMRTG version using a total of 40 GPHS modules. This level would be acceptable for the nominal payload but may be too high for utilization of some Commercial Off The Shelf (COTS) parts.

The thermal design could successfully incorporate the SRG or the ARTG. The High-Resolution Imager and Spectrometer and Thermal Infrared Spectrometer would be thermally isolated and utilize existing thermal shades.

The Decadal Survey TSSM study determined that at 35N of maximum induced mechanical disturbance (the design specification of the ASRG as defined in the ASRG Interface Control Document (ICD) [1 - ICD]) the spacecraft would likely need some vibration damping. The ASRG observed values were slightly lower: 22 N measured on the Engineering Unit. Larger SRG designs with more engines or larger engines could have slightly higher disturbance forces than the ASRG ICD values (even if each engine is

dual opposed, the vibration error would be expected to increase with the square root of number or size of units); this would need to be verified when the design is more mature.

The Decadal Survey TSSM study assessed the ASRG EMI values to be of no concern for all payload measurements. The 6-GPHS SRG is a notional system but should be at similar EMI levels as ASRGs; this would need to be verified when the design is more mature.

3.2 Decadal Survey UOP Study

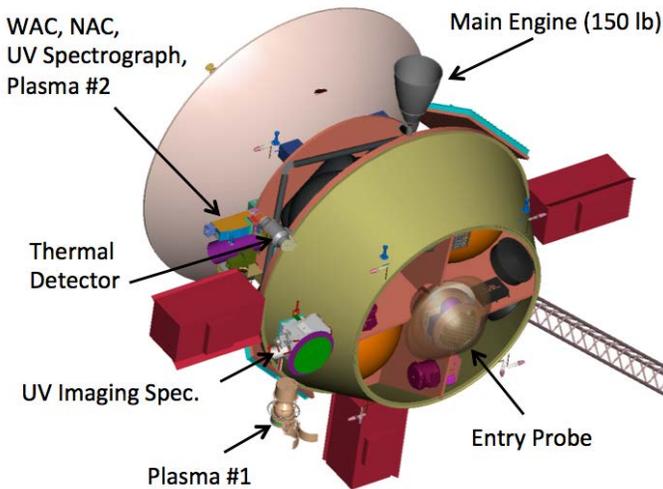


Figure 2. Decadal Survey UOP Study notional RPS Spacecraft Layout. The ASRGs are represented by the 3 brown boxes. For scale, the antenna is 2.5 meters. The UV instruments and the cameras are located a bit closer than usual to the radioisotope sources, so radiation noise (SEU) may present a problem in this configuration. This is mitigated by the small number of GPHS that were required for an ASRG.

The close proximity (<0.5 meter) of instruments to the RPS in the notional spacecraft layout (Figure 2) would result in higher noise levels but would not exceed typical radiation dose constraints for instruments (at that distance the instruments would experience ~2.5 krad/year from Galileo style RTGs). The noise from radiation could be readily ameliorated by relocation of the payload or the power sources.

Replacing the ASRGs with ARTGs would increase thermal output by a factor of 4. This has been addressed historically with addition of heat shields around the power system, though this would be complicated by the compact spacecraft design.

The considered UOP configuration could make microphonics and jitter a potential issue because of proximity of instruments to RPS. The SRG disturbance forces would likely be slightly higher than ASRG observed values; this would need to be verified when the design is more mature. This could require addition of dampers and/or relocation of the payload.

UOP would carry instruments sensitive to EMI but is designed to operate with ASRGs. The new RPS designs are expected to be at similar EMI levels as ASRGs; this would need to be verified when the design is more mature.

4.0 ENVIRONMENTAL IMPACT OF RPS IMPLEMENTATIONS ON PAYLOADS AND MITIGATION STRATEGIES

4.1 Radiation

By their nature, RPS can be significant sources of radiation, and payloads and their measurements could be impacted by this radiation. RPS emits alpha particles, which are easily shielded, but they also can be a source of gamma rays and some neutrons.

GALILEO RADIOISOTOPE THERMOELECTRIC GENERATOR ISODOSE-ISOFUX CONTOURS

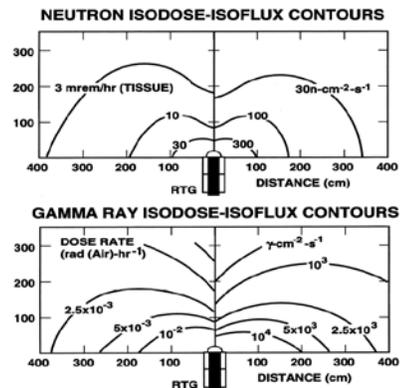


Figure 3. Galileo RTG measured dose and flux contours. [3 - Garrett]: RPS are a significant source of neutrons and gamma rays. The flux from the Galileo GPHS RTG (which contained 18 GPHS modules) would provide about 300 n-cm⁻²s⁻¹ of neutrons to the payload with 1-meter separation distance. The gamma ray dose for 8 years is 0.7 krad (in air, and less behind the normal 100 mil of aluminum). Note that in this figure the dose rate for neutrons is in REMs (tissue) while the dose rate for gammas are in Rad (silicon).

The potential effects of this radiation on payload would include damage to electronics and sensitive surfaces (from total ionizing dose [TID] and direct displacement damage

[DDD]), increased noise on the sensors, and confused measurement of the pristine *in situ* environment by adding energetic electrons, ions, and neutrons.

The contribution to TID from an 18-GPHS RTG (Figure 3 [3 - Garrett]) would be on the order of 0.7 krad over 8 years with 1-meter separation, much lower than environmental radiation. If configuration issues force < 0.5 meter separation between the RPS and sensitive components, the contribution could be 2.5 krad/year; the TID would be ~25 krad over 10 years, which could be approximately equal to the environmental dose for a typical mission of that duration. If so, the total dose would be 50 krad. Using a RDF of 2, the payload must be designed to withstand 100 krad. This is a large number for some parts – typically operational amplifiers (op amps), analog to digital converters (ADC), and memory, which are normally soft at about the 25 krad level. These parts would need to be made more robust or be more heavily shielded, otherwise the gain parameters in the op amps could change, and the ADCs and memory could have single event upsets (SEUs), latch up, and permanent failures. This is not a hard limit; the Galileo instruments were (mostly successfully) designed to withstand 150 krad. COTS parts can be as soft as 1 krad, and may be impractical for use with RPS.

Radiation would also cause increased noise in detectors, especially band gap materials such as Charge-Coupled Devices (CCDs), HgCdTe and InSb. Most bolometer arrays are insensitive to radiation effects. Devices that use cascade amplifiers (e.g. Photomultiplier Tubes [PMT] and microchannel plates [MCP]) multiply the effects of SEUs, which can reduce the sensitivity of the (limited life) detector surfaces behind them. Detectors that are designed to be sensitive to the radiation (such as a Gamma Ray Spectrometer [GRS] – an instrument not included in the study payloads) could saturate, or require an unreasonably large dynamic range to measure small effects in the presence of a large signal arising from the radioisotopes. Most instruments in the notional TSSM have detectors that would experience increased noise from RPS. The imaging instruments (High Resolution Imager and Spectrometer [HiRIS] and Thermal Infrared Spectrometer [TIRS]) could also display long-term effects from displacement damage. Similarly, the UOP instruments would be sensitive in the same way, with the two cameras and near-IR spectrometer being at risk for long term effects. These instruments would need to undergo radiation testing to characterize their behavior, which would determine if they need spot shielding. The instruments on the probe itself (assuming the probe is powered by batteries during operation) would have no noise issues – but the electronics would be at risk as mentioned above and the laser in the nephelometer may also be particularly sensitive to displacement damage.

RPS are not likely to significantly disturb the pristine *in situ* environment. Neither gamma rays nor neutrons become

trapped and concentrated in spacecraft or planetary fields. They can interact with *in situ* neutral and charged species, but the cross sections (and local densities) are so low that the changes to the environment are difficult to detect. Additionally, spacecraft charging effects have not been significant on past missions [4 - Ferguson].

Gamma Rays - Gamma rays dissipate their energy in the payload through the photoelectric effect, Compton scattering, or pair production, depending on the energy of the gamma ray (Figure 4). The net result is generation of electrons (and lower-energy gamma rays that may emit in different directions). Damage to instrument electronics and detectors could arise principally from formation of electron hole pairs, shifting threshold voltages, increasing leakage currents, and buildup of charges that could lead to electrostatic discharge (ESD) damage, an example of which is shown in Figure 5.

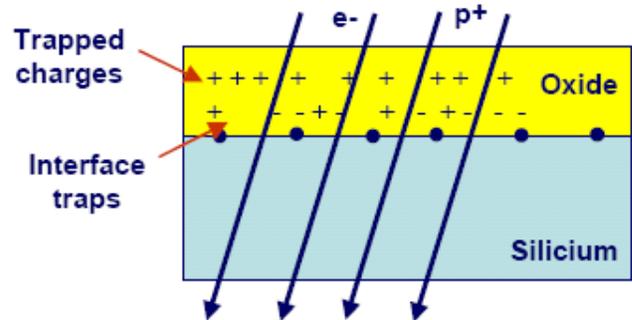


Figure 4. Interaction of electrons (and protons) with silicon oxide [5 - De Donder]. The sources of electrons are gamma rays, electrons, low energy protons, and momentum exchange between neutrons and nuclei.

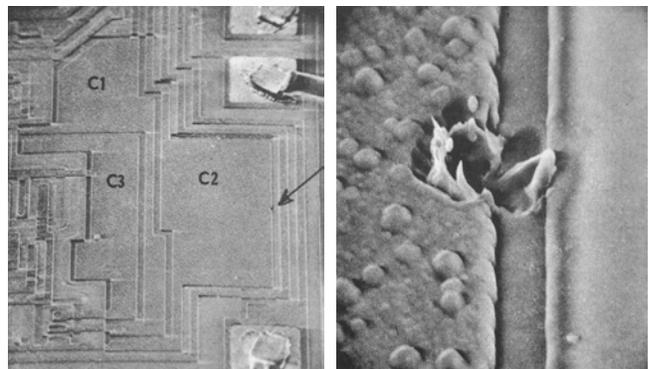


Figure 5. ESD damage in a MOS capacitor [5 - De Donder]. Buildup of charge in a device can lead to catastrophic failure due to ESD.

Electronics parts that are particularly sensitive include memory, ADCs and circuits utilizing operational amplifiers. Charge sensitive amplifiers, used in pulse height and width measurement (particularly for *in situ* instrumentation), are

also affected – though at much higher doses than are relevant for this study (see *Figure 6*).

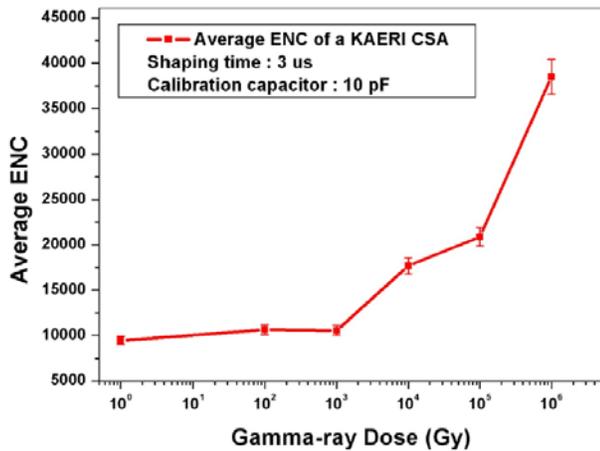


Figure 6. [6 - Kim] Change in performance of a charge sensitive amplifier (CSA) with dose. ENC is “Equivalent Noise charge” and provides a measure of circuit performance. The effect on measurements is that the perceived pulse width broadens and the perceived pulse height decreases with increasing ENC. The circuit under test included two JFETs and a PNP NPN complementary transistor pair. 10 Gray (Gy) = 1 krad. CSAs are typically used in mass spectrometers and particle and electron detectors.

The electrons also create an increase in noise in most detectors. For band gap detectors such as CCDs, InSb, GaAs, and HgCdTe the interactions (SEUs) could lead to spikes (and anti-spikes, depending on the biasing) over a wide range of amplitudes. The obvious spikes can be removed readily, but more subtle changes in amplitude are often difficult to detect. Creation of electron hole pairs could lead to more persistent defects – changing the flat field calibration of the detectors.

Detectors using cascade amplifiers, such as photomultiplier tubes (PMT) and micro-channel plates (MCP), could amplify radiation-induced electrons by factors in the range of 10⁸. The amplifiers themselves would not be affected but the dynode material behind the amplifier can be eroded (and the work function can decrease) so that high electron fluxes can damage instrument performance. These devices are typically used in electron and particle detectors, mass spectrometers and UV spectrometers. The damage would be significant only when the amplifiers are powered on, and could be mitigated by limiting use of the amplifiers or through shielding.

Gallium arsenide devices, typically used in radar and microwave devices, are less sensitive to radiation effects than silicon devices, as shown in *Figure 7*.

STOPPING POWERS IN SILICON

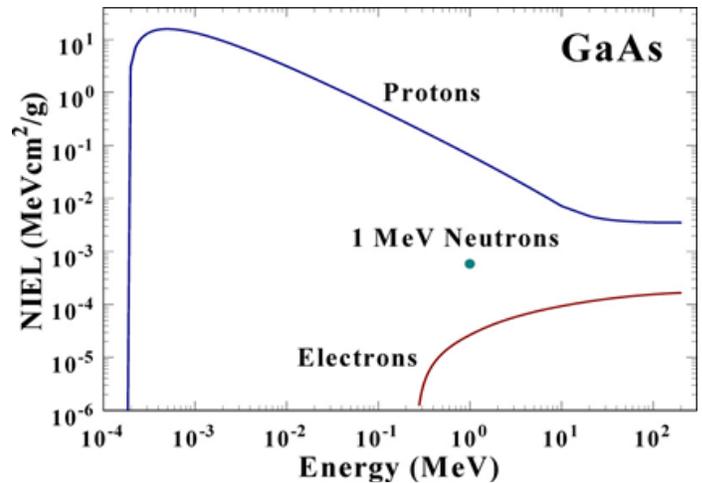
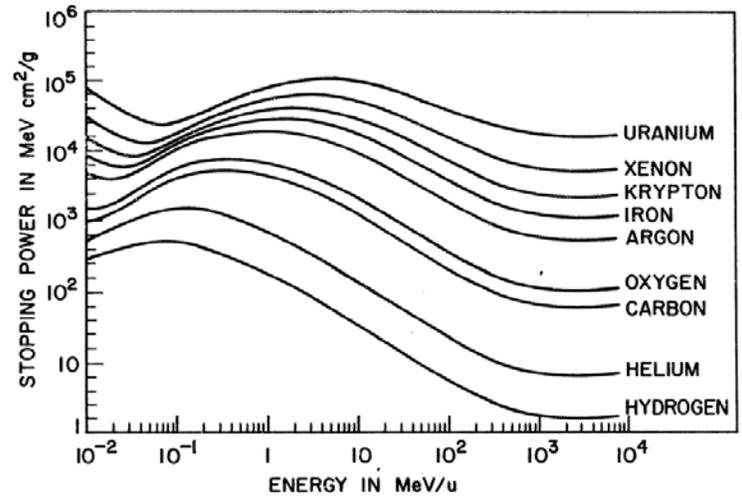


Figure 7. Stopping power in Silicon and GaAs [5 - De Donder]. Note change in scales. GaAs devices are much less affected by a given fluence of protons.

The flux of gamma rays for an 18-GPHS RPS unit at 1 meter separation is about $2.5 \cdot 10^3 \gamma \text{ cm}^{-2} \text{ sec}^{-1}$. For a 1k x 1k focal plane with 10 micron pixels, 100 ms exposure (and a gamma ray cross section of 1), each pixel would receive $2.5 \cdot 10^{-5}$ hits/exposure or 25 pixels would exhibit spikes for each exposure. In reality, the cross section is smaller and the actual number of spikes induced by the RPS in each exposure would be less than 10, or 0.001%, which is better than effects from natural radiation, secondary emissions, and high solar activity.

Note that even for RPS at close proximity a gamma dose rate of 25 krad over 10 years is similar to the dose seen for Mars missions. The noise from gamma rays is proportional to dose rate, and thus the noise from the RPS should be similar to the noise seen on solar-powered Mars missions.

Neutrons - Neutrons dissipate their energy by collision with or absorption by nuclei. Though neutrons carry no charge, they are considered to be ionizing radiation due to the electrons ejected during momentum transfer to the target nuclei. The cross sections for neutron impact are smaller than those for protons. The mass of neutrons and protons leads to lattice defects upon impact (*Figure 8*).

Lattice defects lead to long-term damage due to Frenkel pairs (vacancies and interstitial) [5 - De Donder]. This can lead to change in performance of optical devices, creation of color centers in glass, surface erosion, and dimensional changes.

An RPS neutron flux of 300 n/cm²-s at 1 meter separation represents a dosage rate in Si of $\sim 9 \times 10^{-8}$ krad/hr [7 - FNI]. Over 15 years of operation this would correspond to a total dose in Si of $\sim 1 \times 10^{-2}$ krad from neutrons, suggesting that displacement damage from neutrons would pose a negligible risk to the payload.

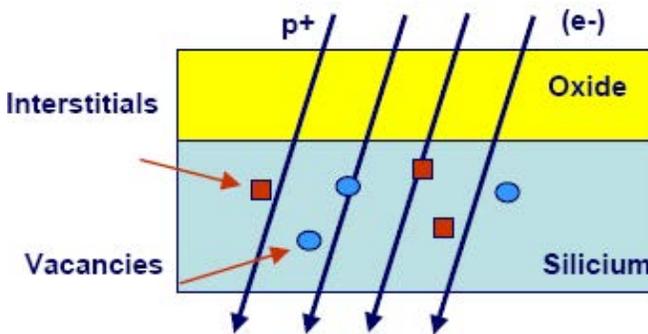


Figure 8. Impacts of neutrons, protons in the 1-10 MEV range and electrons in the 150keV range [5 - De Donder] can generate vacancies and interstitials leading to changes in device performance.

Additionally, neutron interactions can cause single event failures [8 - Becker][5 - De Donder] such as errors and burnout in memory devices.

Radiation effects on the study payloads - Radiation damage from RPS would only be significant for instruments that need to be located < 0.5 meter from the RPS. This would not be an issue for the TSSM concept: the contribution from RPS at ~ 2 krad would be less than the environmental contribution. The UOP concept could have a radiation contribution from RPS on the order of the environmental contribution, if the instruments cannot be relocated.

The sample payloads for the notional TSSM and UOP missions, Table 3 would all be subject to radiation damage as discussed above. The various particle detectors and the mass spectrometer would use CSAs rather than ADCs and would be less sensitive to the total radiation dose. None of the instruments would require a large memory. The Fourier Transform Infrared (FTIR) spectrometer (TIRS) may be

sensitive to gain changes in the Michaelson motor circuits and the lasers in nephelometer and FTIR may be affected by high doses of radiation.

Table 3. Mission payloads. Most of the payload utilizes electronic elements that would need additional shielding to survive doses above 50 krad. This may limit the lifetime of the MCP detectors. Most of the instruments have high-radiation equivalents in either the Galileo payload (150 krad) or the Juno payload (80 krad). Most of the detectors would experience increased noise due to radiation effects. The Galileo CCD survived a total dose of over 300 krad and the Galileo nephelometer survived 75 krad.

Notional Mission	Instrument	Exemplar	Detector	Electronics	Potential Impact
UOP	WAC	New Horizons LORRI	CCD	ADC	Radiation, Vibration
	NAC	Messenger MDIS	CCD	ADC	Radiation, Vibration
	VNIR	New Horizons RALPH	HgCdTe	ADC	EMI
	Thermal	MRO DIVINER	Thermopile	ADC	Thermal
	UV Spectrometer	New Horizons Alice	MCP, dynode	ADC	None
	SWAP Plasma Instrument 1	New Horizons SMP	MCP, Dynode	CSA	Noise from gammas
	JEDI Plasma Instrument 2	Juno JEDI	MCP, Dynode	CSA	Noise from gammas
	Magnetometer	Cassini, Ulysses	Helium or Fluxgate Sensor	ADC, FPGA	EMI – potential impact from SRG
	USO	New Horizons USO	Oscillator	Logic, heater cks	
	UOP – probe	Mass spectrometer	Galileo	MCP	CSSA
Atmospheric structure		Galileo	Strain gauge	ADC	None
Nephelometer		Galileo	CCD	Laser, CSA	Radiation
USO		New Horizons USO	Oscillator	Logic, heater cks	
TSSM	Imager/spectrometer (HIRIS)	LORRI, HIRISE, CRISM, M3	CCD, HgCdTe	ADC	Thermal
	Penetrating radar/altimeter (TIPRA)	SHARAD, MARSIS	Antenna	GaAs amps, CSA	
	Mass Spectrometer (PMS)	ROSINA	Magetof (cascade amp)	Dynode surface	Radiation
	Sub Millimeter Spectrometer	MRO, ODIN, MLS	Antenna	GaAs, CSA	Vibration (microphonic)

Notional Mission	Instrument	Exemplar	Detector	Electronics	Potential Impact
	Thermal IR spectrometer	CIRS	HgCdTe, bolometer	ADC, Laser, amp	
	Magnetometer	Cassini, Ulysses	Helium or Fluxgate Sensor	ADC, FPGA	EMI – potential impact from SRG
	Energetic particle detector	PEPSSI, JEDI	MCP, dynode surface	CAS	Noise from gammas
	Langmuir Probe	Cassini	Antenna	ADC	None
	Plasma	PEPE	MCP	CAS	Noise from gammas
	Accelerometer	Cassini, Juno		Amplifiers	

Laser components that might be used in a Nephelometer would become a concern at 100 krad and likely become problematic at 300 krad.

Detectors are particularly sensitive to radiation. At 25 krad, charge-coupled devices (CCDs) experience degradation of charge transfer efficiency and increases in dark current, leading to reduction of the imager’s signal to noise ratio. At 100 krad, CCDs are not likely to be viable without significant spot shielding or special process enhancements; for example the Galileo CCD survived a dose of over 300 krad using tantalum shielding.

CMOS detectors are less sensitive to radiation effects, and the ability to directly address pixels improves readout strategies and opens additional approaches to spike detection and removal. At 300 krad, custom radiation-hardened designs for CMOS image sensors and CMOS readout integrated circuits (ROICs) for infrared focal planes are required.

The PMS instrument could have issues depending on design, as a microchannel plate is an amplifier that can avalanche electrons and damage the detector.

At 25 krad, all types of instruments would experience minor issues with radiation tolerance of signal chain components that limits the ability to reuse existing designs. At 50 krad, all types of instruments would experience significant issues with component radiation hardness, resulting in performance compromises and increased cost.

Figure 9 shows a summary of the specific effects of TID, DDD, and transients/background noise on several types of instruments. The red boxes mark significant impacts, while the green boxes mark minimal impacts.

Radiation Source	CCD	CMOS	APD	IR	Thermal	Photo cathode	MCP	Laser Components
TID	Id ↑ Δ Id ↑ "hot" pixels	Id ↑ Δ Id ↑ "hot" pixels	Id ↑	Id ↑, R _s ↓ Δ Id ↑ "hot" pixels	Δ → ↓	Min Effect	Min Effect	Min Effect
DDD	CTE ↓ Id ↑ Δ Id ↑ "hot" pixels QE ↓ Δ QE ↑	Id ↑ Δ Id ↑ "hot" pixels QE ↓ Δ QE ↑	Id ↑ Δ QE ↑	Id ↑ Δ Id ↑ "hot" pixels QE ↓ Δ QE ↑	Min Effect	Min Effect	Min Effect	Min Effect
Transients	False Signals	False Signals	False Signals	6x False Signals	No Effect	False Signals	False Signals	No Effect

CCD	Charge Coupled Device	I _d ↑	Dark Current Increase
CMOS	Complementary Metal Oxide Semiconductor	Δ I _d ↑	Dark Current Non-uniformity Increase
APD	Avalanche Photodiode	CTE ↓	Charge Transfer Efficiency Decrease
MWIR	Mid-Wavelength Infrared	QE ↓	Quantum Efficiency Decrease
MCP	Micro Channel Plate	Δ QE ↑	Quantum Efficiency Non-uniformity Increase

Figure 9. Radiation Effects Summary [9 - Blazejewski]

Radiation Mitigation - Several mitigation strategies could ameliorate the effects of RPS radiation on instruments. Separation would be a very effective strategy as radiation decreases as r², but designs can become challenging when separation distances exceed a few meters.

SEU-type events could be mitigated with error correction codes, and, for detectors, with spike detection and removal. Spike detection could be challenging, since there is a continuous distribution of the amplitude of the spikes. In general, spike removal techniques utilize higher sampling rates and/or larger data volumes and greater acquisition times.

Displacement damage in detectors could be corrected with thermal annealing [10 - Hopkinson]. Many instruments have flown annealing heaters, but they are rarely used - both because of risk to the detectors (such as damage to solder joints or bump bonds) and because of changes in “flat field” calibration.

MCPs amplify noise events with electron cascades, which can reduce the lifetime of the detectors. Faraday cone detectors are less sensitive to radiation effects.

The Juno mission (launched in 2011) had to deal with designing for the high-radiation Jupiter environment, and can serve as a practical example of radiation accommodations. The mission employed a 180 kg radiation vault to reduce the mission dose to the electronics to no greater than 25 krad (attenuated from ~300 krad at 100 mil Aluminum). With a RDF of 2, this allowed the mission to use 50 krad capable components. The team used radiation characterization and lot acceptance tests to verify the parts met the performance requirements. If the parts were not capable to 50 krad, the team attenuated the dose by applying shielding at the box level, using favorable box placement within the radiation vault, and in some cases by employing shielding at the circuit board level.

In addition to end of mission dose shielding, the Juno team also used shielding to suppress radiation induced noise for several of the detectors on the spacecraft: CCDs in the Star Tracker optical heads, CCDs in the advanced stellar compass optical heads, CCD in the Juno camera, MCPs in the JADE and UVS instruments, and IR detector in the JIRAM instrument. Extensive radiation testing was performed for many of the detectors to characterize their behavior in the Jovian radiation environment. [11 - McAlpine]

4.2 Thermal

The thermal outputs of the notional nuclear power systems considered are listed in Table 4. Both styles of power system would generate a significant amount of waste heat. Shielding the payload from the radiated thermal energy was relatively straightforward for missions such as Galileo and Cassini; however, it could be more difficult if the mission implementation could not accommodate booms and radiator shields. Instrument radiators would need to be shielded from view of the power system radiators. Optics may require blanketing or shielding to avoid distortion arising from differential heating. The radiated power would also add to complexity of the launch configuration.

Table 4. Thermal waste heat from the existing and notional radioisotope power systems considered [total heat/waste heat]

MMRTG	eMMRTG	6-GPHS SRG	16-GPHS ARTG
[2.0/1.9] kW _{th}	[2.0/1.85] kW _{th}	[1.5/1.15] kW _{th}	[4.0/3.55] kW _{th}

Waste heat from a 16-GPHS ARTG would be twice the ~2 kW_{th} 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.

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. Given that the heat from the power source is all coming from a known direction it should be possible to find clear fields of view for the radiators.

There are off-nominal thermal cases that should be considered. For example, if a 6-GPHS SRG ceases functioning, the waste heat to be rejected directly from the reactor radiators increases from 1.15 W_t to 1.5 W_t.

In general, thermal issues can be accommodated: separating sensitive instruments from the RPS, pointing radiators and

thermal imagers away from the RPS, and using heat shades to protect sensitive instruments.

4.3 Vibration

Stirling convertor tests and the interface specifications for ASRGs show vibration levels that are well within typical spacecraft environmental specifications and thus should not be an issue for heritage instruments. As shown in Figure 10, the frequency of the vibration is 102.2 Hz, and the ASRG ICD gives a value of 35 N for the maximum dynamic force while subsequent testing demonstrated levels of 22 N [1 - ASRG ICD][12 - EU ASRG Test Report].

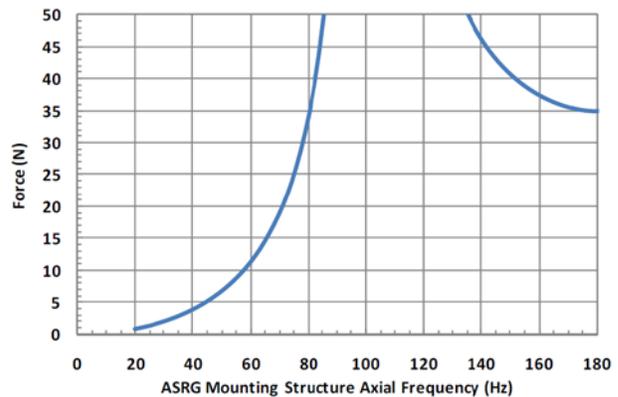


Figure 10. ASRG Nominal Vibration Spectrum [1 - ASRG ICD]

Operation of an SRG after failure of one engine would result in an unbalanced mode and higher vibrations. This level of vibration could have a significant impact on spacecraft measurements. The matching opposed Stirling engine can also be shut off to avoid this vibration issue, if the spacecraft can continue to operate at the lower power level. The vibration spectrum for an unbalanced ASRG is shown in Figure 11, with a value of 500 N for the dynamic force [1 - ASRG ICD][12 - EU ASRG Test Report].

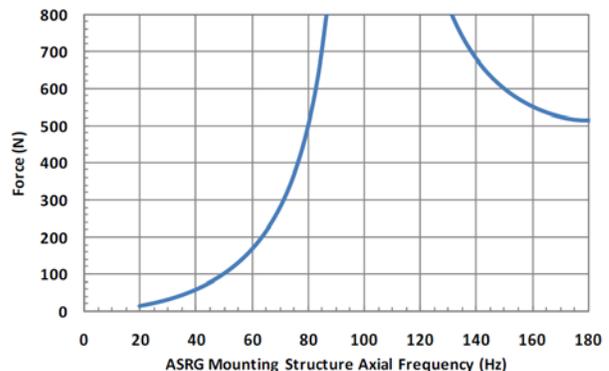


Figure 5.2-2. Disturbance Force to the SV During Single-ASC Operation.

Figure 11. ASRG Vibration Spectrum with one operating engine. [1 - ASRG ICD]

Cameras could be affected by vibration/jitter without proper damping. Finite Element Models (FEM) of MSL and Cassini were analyzed with ASRG disturbances in 2012 [13 – Thelander]. For MSL, the most sensitive constraint was the ChemCam, with an acceleration limit of 3.0 g and a maximum angular displacement amplitude limit of 80 microrad – the results were well within constraints due to MSL’s primary frequency mode being far removed from the 102 Hz ASRG frequency. For Cassini, the most sensitive constraint was the CIRS spectrometer with a base acceleration limit of 0.01 g and a maximum angular displacement amplitude limit of 5 microrad. The Cassini results showed peak acceleration criteria up to 0.04 g for some instruments (though not for the CIRS) when assuming a worst-case scenario (all three ASRG vibrations summed and no damping adapters); there were no violations of the angular displacement constraint. The MSL and Cassini FEM study recommended that missions carry out standard vibration analysis including RPS forcing functions and if there is a concern, either isolate instruments individually, modify the RPS-to-spacecraft interface or instrument pallet structure, or mount the RPS in a different configuration. [13 – Thelander]

Based on the FEM analysis, the RPS Program concluded that the “ASRG produces a jitter source that is typical as compared to other spacecraft components that are being used for sensitive flight missions” and that vibration isolation adapters could be designed to specific missions to meet jitter requirements [14 - RPS-REF-0099].

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.

There are residual concerns about possible higher vibration levels in higher power Stirling engines. Further design maturation and analysis is needed to quantify these vibration levels.

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.

In general, vibration issues could be mitigated by separating sensitive instruments from Stirling engines and damping vibration, if necessary. Missions using Stirling devices need to have a contingency plan for a single engine failure – whether that plan is to include accommodations for the increased vibration, or to cease operation of the matched pair engine.

4.4 Electromagnetic Interference (EMI)

No EMI issues have been identified for RPS that lie beyond normal environmental specifications although there is still concern about fields that may be generated by Stirling engines, particularly operating in an unbalanced mode. The projected electric fields radiation emissions limits from the ASRG ICD [1 – ICD] are shown in Figure 12; these were design limits and have not been tested. There were concerns about the Electra limits, but otherwise there were not expected to be issues meeting the EMI requirements.

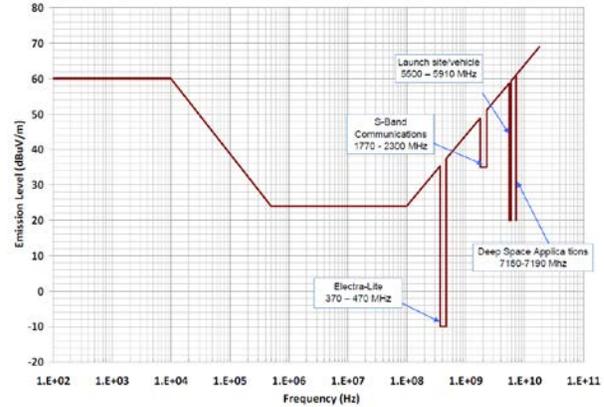


Figure 12. ASRG Electric Fields Radiated Emissions Limits

Flight experience from past missions shows that use of RTGs do not lead to large charge imbalances.

As with vibration, there are residual concerns about possible higher EMI levels in notional higher power Stirling engines. Further design maturation and analysis is needed to quantify these EMI levels.

EMI varies with distance as $1/r^2$ so separation is an effective strategy.

4.5 Magnetic Fields

The RTG on Galileo created a local magnetic field of less than 1 nT at the payload. The current trend for payload magnetic requirements is an order of magnitude more stringent, 0.1 nT at the magnetometer. ASRGs, operating in balanced mode, were rated to meet this requirement. However, magnetic cleanliness for unbalanced operation or with notional larger Stirling engines remains to be verified.

5.0 FORWARD WORK

During the course of this assessment effort, several topics were uncovered that would benefit from further assessment.

The instrument impacts assessment focused on two representative spacecraft concepts: TSSM and UOP. Assessment of additional spacecraft and instrument suites may provide further insights, particularly as these are both orbiter missions.

In-situ space environment issues could use further study. The literature does not suggest major impacts on the local environment from waste heat or ionization, but this is not a heavily studied topic and could use additional review for larger RPS. Also, note that the analyses described in this white paper focused on orbiter instruments as opposed to landed payloads, which operate in significantly different environments and may have different thermal issues. Seismometry experiments may be especially sensitive to vibration.

Mission designers could benefit from further identification of mitigation strategies and from representative trade studies on shield mass versus separation distance (potentially using a deployable boom) versus improved instrument radiation hardening versus spot shielding.

Vibration appears to be a minor impact, but there are concerns about new Stirling RPS designs and about possible unbalanced operation of Stirling engines (resulting from a failure of one engine of an opposed pair) that could use additional analysis and testing. Likewise, EMI appears to be a minor impact, but requires analysis and testing of EMI fields from Stirling engines operating in an unbalanced mode. Magnetic cleanliness for new RPS concepts needs to be quantified.

6.0 CONTRIBUTORS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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