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Multi-Mission Radioisotope Thermoelectric Generator Experience on Mars

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Abstract. The Mars Science Laboratory (MSL) Curiosity rover has been operating on Mars using the F1 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for over one and one-half Mars years (over three Earth years). During this extended period, Curiosity has provided a wealth of information about operating with a MMRTG in the Mars surface environment. This paper discusses MMRTG performance over the life of the mission as affected not only by expected radioisotope degradation, but also by the thermal environment, including seasonal, wind, and time-of-sol effects. Additionally, issues related to MMRTG internal shorts will be discussed including detection, impacts on operations, and clearing the shorts.

Keywords: RTG, MMRTG, Mars, Surface, Operations, MMRTG internal short.

INTRODUCTION

The Curiosity Mars rover is the first space application of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). Curiosity has been operating on the Martian surface for over 1230 sols which is 1.8 Martian years (equivalent to 3.4 Earth years). The MMRTG has provided consistent and predictable power, simplifying mission planning in a way that solar-powered missions cannot; however, degradation over time beyond initial expectations has occurred. Furthermore, some internal shorting has also been detected but has little impact on output power.

In this paper a brief description of the design of the MMRTG is provided, as well as some description of the integration of the MMRTG with the Curiosity rover. A brief outline of the modeling of the MMRTG is given, including discussion of the degradation rate. Finally, there is a description of the internal shorting and its impact on operations.

MMRTG DESIGN

The MMRTG design is similar to other RTGs, incorporating a radioisotope heat source that provides a heat flow through an array of thermoelectric (TE) couples. Electrical current is generated in the couples due to the Seebeck effect. The radioisotope heat source consists of eight General Purpose Heat Source (GPHS) blocks, each containing Pu^{238} in the form of plutonium dioxide. See **FIGURE 1** for an overview of the MMRTG construction.

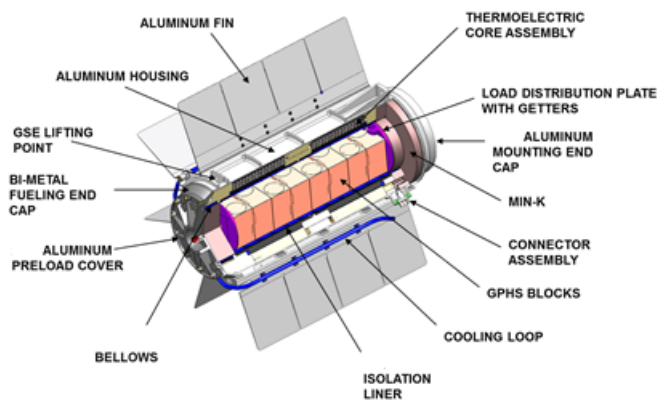

FIGURE 1. MMRTG Cutaway View

The heat from the GPHS blocks radiates onto the Thermoelectric Core Assembly (TCA). See **FIGURE 2** for an exploded view of the TCA. In the TCA, heat first enters the Heat Distribution Block (HDB), where it is conducted to the thermoelectric module and thence to the hot-side of the couples. The couples sit in recesses in the module bar where they are spring loaded to press against the HDB. Heat exits the couples on the cold side into the module bar and is then conducted to the case, where it is rejected by the fins.

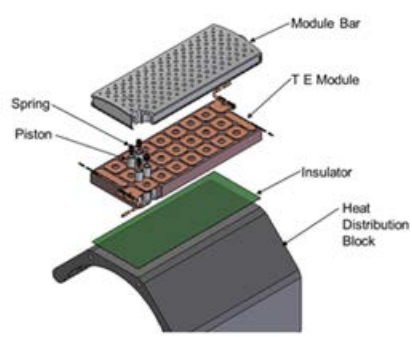

FIGURE 2. Thermoelectric Core Exploded View

Thermoelectric Couple Design

Each TE couple, see **FIGURE 3**, consists of two legs. The N-type leg generates current in the same direction as the heat flow and the P-type leg generates current in the opposite direction. The P-type leg is

divided into two segments, each optimized for a particular temperature range. The legs of each couple are electrically connected in series at the hot side, and connected in series at the cold side with other couples in a string. There are two strings in the MMRTG with cross strapping between couples for redundancy.

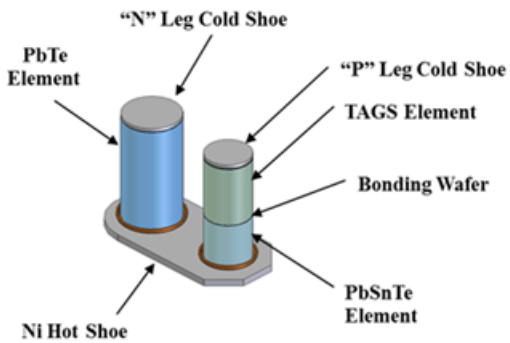

FIGURE 3. MMRTG Couple Construction

MMRTG INTEGRATION INTO MSL ROVER

Mechanical and Thermal Integration

The MSL MMRTG is mechanically attached to the rear of the rover at an angle as shown in **FIGURE 4**. The MMRTG's angle with respect to the vehicle is a product of desired dust mitigation, rover arm ballast, and the ideal configuration for integrating the MMRTG through the back shell of the spacecraft at the launch pad, after spacecraft integration.

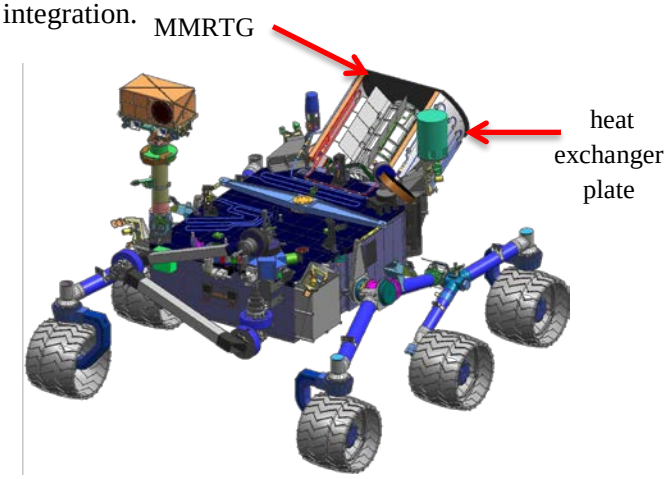

FIGURE 4. MMRTG Integrated with MSL Rover

Rover electronics are kept warm using the waste heat from the MMRTG, which is captured by heat exchanger plates. A thermal fluid loop is routed across the heat exchanger plates and into the rover electronics mounting plate in the rover body. The affects of wind on the temperature of the MMRTG were reduced through the addition of a fabric baffle on the back of the MMRTG.

Electrical Integration

Electrically, the MMRTG is connected to the floating power bus, with the MMRTG case connected to the rover chassis. This floating power bus is created by isolating it from the 24 to 32.8 volt primary bus high side and low side through 5 kΩ resistors as shown in **FIGURE 5**. The power bus measurement with respect to the primary power bus low side is what the engineering operations team calls the "bus balance voltage" and is used to detect any MMRTG chassis shorts. Five shunt stages, mounted on the heat exchanger plates, facilitate power bus voltage regulation by shunting away excess MMRTG power.

In addition to the circuity shown, there is also the capability to command a "Battle Short," which effectively connects the chassis (SPG in the diagram) to the primary bus return. This is useful in clearing MMRTG internal shorts, as will be discussed later.

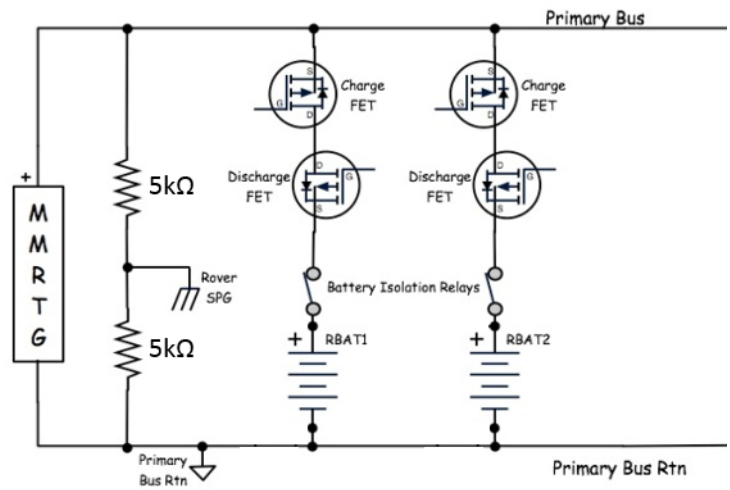

FIGURE 5. Floating Power Bus design

MMRTG MODELING

JPL uses an in-house tool, the Lifetime Performance Prediction Model (LPPM), to model MMRTG performance. LPPM is a FORTRAN-based, parametrically-driven general RTG simulation. LPPM supports a configurable steady-state thermal model. It computes generator performance by aggregating up from a model of a single average TE couple. It is designed to simulate performance over the lifetime of any cylindrical RTG. In addition, to assist in the design of new RTGs, it can calculate overall RTG dimensions and mass. In this case, the LPPM parameters have been configured to describe the Flight Unit 1 (F1) MMRTG in use by MSL.

TE Performance Modeling

TE couple performance is computed by dividing each TE segment into 26 sub segments. The temperature of each sub segment is computed and the applicable Seebeck coefficient, thermal conductivity and electrical resistivity are obtained from TE property tables specific to each TE material, based on temperature and generator heated hours (lifetime). The tables are developed from lifetime testing of TE material samples.

Degradation Modeling

LPPM supports modeling of several generator degradation mechanisms: radioisotope decay, TE material property changes over time at temperature, sublimation of TE materials and degradation of surrounding insulation due to deposition of sublimed materials. Radioisotope decay modeling simply uses the initial heat and the half-life of the radioisotope source to compute the heat generated at a given time in the future. TE material changes are incorporated into the TE property tables mentioned above. Sublimation at the sub segment level can be simulated as a cross-section area loss as a function of time at temperature. Property changes of surrounding insulation is computed as a function of couple weight loss due to sublimation; however, due to lack of test data and the small impact that sublimation has on generator performance, the sublimation mechanism was not incorporated into the MMRTG configuration of the LPPM.

The MMRTG output power has degraded at a higher rate than was originally expected. Analysis of results from the engineering unit (EU) have shown this to be due to increased internal electrical resistance and, to a lesser extent, increased thermal resistance. The EU is a highly instrumented, electrically-heated version of the MMRTG that is undergoing life testing. The current hypothesis is that this is occurring at the hot end of the couples. To handle this, an additional time-based straight-line empirical degradation was added to the model by adding additional (extraneous) electrical resistance at the hot end of the TE couples. The magnitude of this degradation is computed by fitting an exponential decay curve to actual output power and also to the modeled output power. The two exponentials are compared and adjustments are made to the beginning and ending values of the extraneous resistance until the decay curves are identical, see **FIGURE 6**.

To deal with this issue, a proposed enhanced MMRTG (eMMRTG) is being developed for future missions that would address the hot side electrical resistance degradation issue, as well as providing improved efficiency and significantly greater end-of-mission power through the use of more advanced TE materials.

Degradation Rate

As of this writing, the exponential degradation rate (r) for the generator is 4.62%, using an epoch time of MSL Sol 0 T 00:00:00 and a P_0 value (initial power) of 113.87 W.

Equation (1) can be used to estimate the power at some future date.

$$P(t) = P_0 e^{-rt} \quad (1)$$

Equation (2) can be used to compute time in Earth years given a Mars sol number.

$$t = Sol * 1.02749 / 365.25 \quad (2)$$

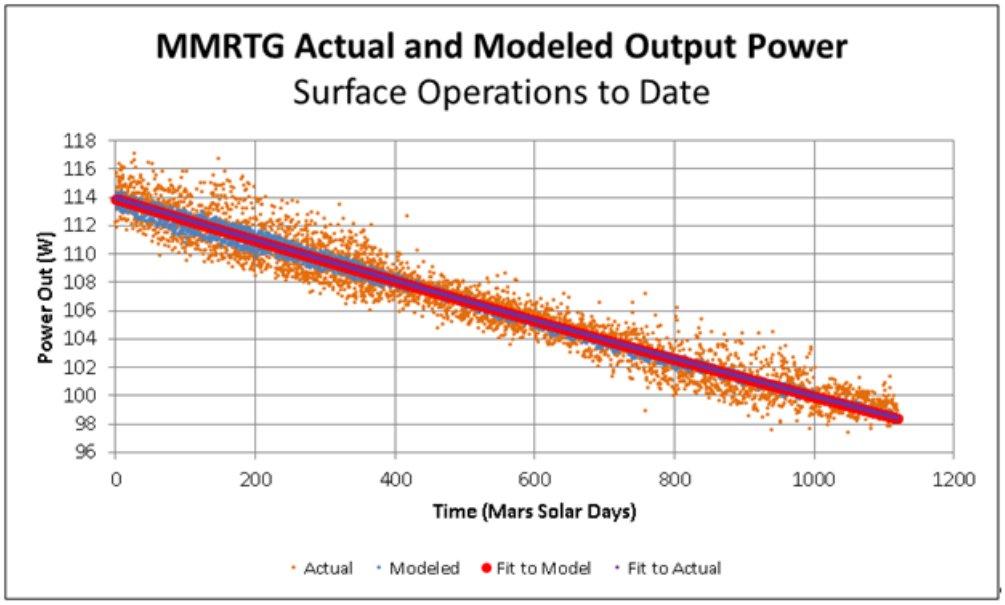

FIGURE 6. MMRTG Actual and Modeled Output Power

Drawback of Steady-State Thermal Model

LPPM uses a steady-state thermal model. This has the benefit of simplifying the parameters needed to create a configuration. Its downside is that the model does not respond to environmental temperature changes in a way similar to the actual generator. This has been evident during surface operations when the wind picks up. The actual generator gets a temporary performance boost when the wind cools the generator's fins, creating a larger temperature drop across the couples that can persist for some minutes. As the cooler temperature permeates the generator, reducing the temperature differential, the performance boost slowly disappears. A similar, but opposite process occurs when the wind subsides. By contrast, since the model is steady-state, the suddenly cooler or warmer fin temperature is assumed to instantly permeate the generator, producing little if any change in performance. In looking at **FIGURE 6**, one can see that the scattering of the actual output power is much broader than the modeled output power. This is due to the steady-state nature of the model. However, the average power output of the model matches the actuals quite well.

MMRTG INTERNAL SHORTING

The MSL Fault Protection (FP) software tracks telemetry and responds when telemetry is outside expected operational ranges. Bus balance voltage telemetry is used to detect electrical shorts from chassis to power bus or power bus return on the rover. If the bus balance voltage is out of range, then the FP software raises a fault and ceases scheduled mobility activities. Understanding and crafting effective operational policies for handling bus balance voltage anomalies is crucial for the mission.

On mission sol 456, MSL engineering operations staff observed an unexpected shift in bus balance voltage telemetry: the balance voltage shifted from its nominal ~11 volts to ~4 volts. Further review of telemetry indicated that balance voltage had intermittently shifted from nominal to ~4 volts several times over the previous sol, before "settling" into a continuous value of ~4V. Note: only by having the balance voltage sense circuitry/telemetry can MSL sense this internal short. Responding to the anomaly, the power engineering operations team immediately investigated potential operational causes of the short, as well as brought in RTG domain experts with particular knowledge of the behaviors of the RTGs used on NASA's Cassini Saturn orbiter.

The investigation team considered two classes of shorts to determine the root cause of the balance voltage shift: a "soft" short to chassis of about 1 kΩ between power bus return and chassis, and a hard short to chassis of a 0 to 4 V source, consisting of 0 to 1 kΩ. Based on the operations plan at the time of the observed balance voltage shift, the team conducted diagnostic activities to ferret out potential causes related to these two classes of shorts, ultimately observing that telemetry revealed a measurable drop in MMRTG current at the exact time the bus balance voltage shift occurred.

The working hypothesis is that an internal low impedance short on the MMRTG is the only credible root cause of the anomaly. MSL has determined that there is no impact to nominal operations with the short in place, as all electronics and instruments were designed and tested to work with any chassis voltage from the bus return to power bus voltage, with one exception. That exception is using the drill percussion mechanism with the battle short enabled. The sol 456 MMRTG short spontaneously cleared on sol 461 when the rover was asleep.

Over the sols since the first MMRTG short, MSL engineering operations has learned to evaluate telemetry to quickly and accurately identify an internal MMRTG short and explicitly clear a persistent soft short. Over this same period, the frequency of shifts in bus balance voltage has increased, but the balance voltage shift itself has remained fairly consistent.

Key observations:

- It is important to develop a procedure and supporting tool to assist
- Bus balance voltage shifts from its nominal value of ~11 volts to ~4 volts
- MMRTG current drop while the short is cleared is always very small
- Some MMRTG shorts events clear spontaneously, but most are cleared explicitly by using the battle short
- Having the ability to sense and clear an internal MMRTG short has proven invaluable in evaluating MMRTG behaviors and allow for even rudimentary investigations thereof.

Since the sol 456 MMRTG short, MSL has observed that the bus balance voltage shift is associated with an MMRTG short on the sol ranges listed below (see also **FIGURE 7**). For many of these, the short may have been intermittent. Usually the MMRTG short is observed for a few sols before it is cleared by battle short.

- 456 to 461 spontaneously cleared
- 816 to 836 explicitly cleared using the battle short checkout sequence
- 1084 to 1085 spontaneously cleared
- 1089 to 1092 spontaneously cleared
- 1158 to 1167 explicitly cleared using the battle short checkout sequence
- 1173 to 1182 explicitly cleared using the battle short checkout sequence
- 1186 to 1192 explicitly cleared using the battle short checkout sequence
- 1204 to 1223 explicitly cleared using the battle short checkout sequence
- 1233 to 1239 explicitly cleared using the battle short checkout sequence

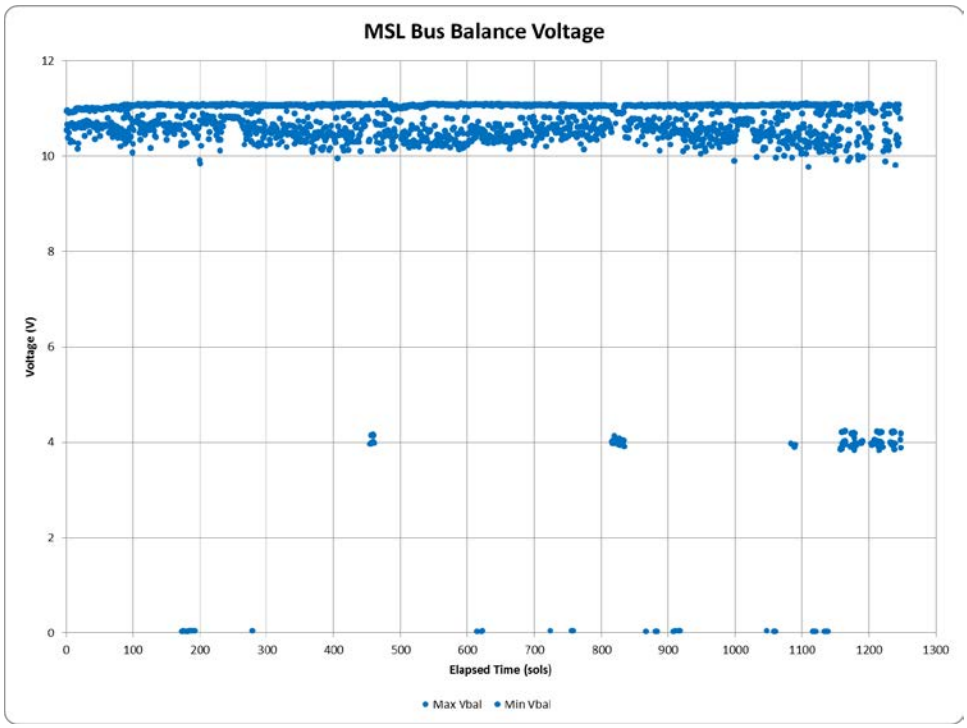

FIGURE 7. MSL Bus Balance Voltages

Possible Causes of Internal Shorts

The definitive cause of the internal MMRTG short has not been determined. The leading theory is that conductive material is sublimated and circulates within the MMRTG until it reaches a location within the stack where conditions are right for condensation, causing a leak path to the generator case, which is connected to the rover chassis. This condensation appears to occur at essentially the same location, as evidenced by the balance voltage shift *to* ~4 volts for each event. When the short does clear, it doesn't completely dissipate all condensation buildup; hence, relatively little additional condensation can cause a short to reform at the same location. One likely location for the short is from a TE couple to the module bar.

Clearing the MMRTG Short

MSL has a dedicated switch that is invoked to connect the power bus low side to the rover chassis. In MSL parlance, "invoking a battle short" closes this switch prior to using the percussive drill to minimize noise in the power bus. MSL has exploited this "battle short" activity to drive current through the MMRTG soft short and clear it.

Impact on Operations

Initially, the impact of the first MMRTG internal short on mission operations was significant; the project placed science operations on hold while the unexpected shift in bus balance voltage was under investigation. A week later, the project decided to attempt to clear the MMRTG short with the battle short activity, but the MMRTG short cleared spontaneously before the battle short could be used. Four hundred sols later, when the MMRTG short appeared again, the project had a better understanding of the issue and was able to eventually clear the MMRTG short with the battle short.

To date, there have been over nine instances of the MMRTG short. The MMRTG shorts have become more familiar to the power subsystem operations team - it is now standard procedure for the power operations team to monitor the MMRTG short for a few sols and then request the battle short.

CONCLUSION

The overall use of a MMRTG for surface operations on Mars has been a great success, notwithstanding the elevated degradation rate. To date, power availability has generally not been a limiting factor in operational planning. Internal shorting has not had a significant impact on operations and is expected to continue as it has on other RTG-powered missions.

NOMENCLATURE

$P(t)$	=	MMRTG output power at time t
P_0	=	MMRTG output power at the epoch time
Sol	=	Martian solar day number based on mission landing day (sol 0)
r	=	Exponential degradation rate.
t	=	Time in Earth years

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