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The F1 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG): A Power Subsystem Enabler for the Mars Science Laboratory (MSL) Mission

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Abstract. The Mars Science Laboratory (MSL) spacecraft carrying the Curiosity rover launched from Cape Canaveral Air Force Station (CCAFS) on November 26, 2011. Following an 8.5-month cruise and after a successful Entry, Descent and Landing (EDL) phase, the Curiosity rover arrived at the surface of Mars on August 6, 2012 UTC. At the core of the Curiosity rover power subsystem is the F1 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) supplied by the Department of Energy. Integration of the F1 MMRTG into the MSL spacecraft has provided the first opportunity to architect a power subsystem that also included a Solar Array (during the cruise phase of the mission and up to the initial stage of the EDL phase) and secondary Li-ion batteries for operation during the planned one Martian year surface phase of the mission. This paper describes the F1 MMRTG functional features as an enabler of the MSL mission and as a novel component of the MSL power subsystem architecture.

Keywords: Mars rover, MSL, RTG, Power System, Curiosity rover.

INTRODUCTION

The Mars Science Laboratory (MSL) spacecraft carrying the Curiosity rover successfully landed on the surface of Mars on August 6, 2012 UTC. The F1 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) supplied by the Department of Energy is its sole power source for the entire surface phase of the mission. This paper will discuss how MSL chose to integrate the MMRTG into the power system architecture. Furthermore, it will discuss accommodations made to use an RTG and secondary battery on the same power bus and how the F1 MMRTG will enable Curiosity to rove the surface of Mars and perform in-situ science for one Martian year and most likely longer.

MSL POWER SYSTEM ARCHITECTURE OVERVIEW

The MSL spacecraft is made up of three main mechanical and electrical stages: Cruise, Descent and Rover. Elements of the MSL power system are located in each of these stages, which allow extending the main power bus from the Rover up to the Cruise stage. Figure 1 shows a block diagram of the main components of the MSL power system and their location across all three stages. As seen in Figure 1, the MSL power system is primarily comprised of power sources, energy storage and power regulation and distribution elements. A unique feature of the MSL power system is the integration, for the first time in an interplanetary mission, of a solar array, secondary Li-ion batteries and an RTG as the power sources and energy storage components. The following is a description of the main elements of the MSL power system architecture according to their location across the spacecraft.

Cruise Stage

The main elements of the power system located in the Cruise stage include the solar array, Cruise Shunt Radiator (CSR), Cruise Power Assembly (CPA) and redundant Cruise Power and Analog Modules (CPAM-A/B). The MSL solar array uses triple junction solar cells and consists of 6 body-mounted substrate panels. The solar array is about 12.8 m^2 and uses parallel strings to produce 1200 W at Mars (assuming 30 degree Sun angle at 1.61 AU). On the front side, each substrate panel contains two solar array electrical segments, each consisting of an array of cell strings. In total, 12 electrical segments make up the MSL solar array. On the back side, each substrate panel has patch heater resistors that make up the CSR. The MSL CSR consists of 10 electrical stages, each mounted on the substrate side opposite a solar array segment. The numbering of solar array segments in Figure 1 (i.e., 1 through 12) indicates the sequence in which each segment is turned off (e.g., segment #12 is the last one off). The numbering of CSR stages in Figure 1 (i.e., 1 through 10) indicates the sequence in which each CSR stage is turned on (e.g., CSR stage #10 is the last one on).

Switching of the solar array segments and CSR stages is performed in the CPA. The CPA contains four electronic boards: two solar array interface slices (AIS-1/2) and two shunt driver slices (SDS-1/2). Switching of the solar array segments is performed in a full-on/full-off manner. The SDS provide linear control of the CSR stages, which is exercised as required to regulate the power bus voltage to the desired setpoint. As also seen in Figure 1, control signals (error voltage) are generated on the Rover (where power bus voltage sensing is done) and routed up to the Cruise stage into each AIS and SDS. The MSL power bus controller operates by regulating the power bus at the rover to the commanded voltage setpoint. During the cruise phase of the mission, power bus voltage regulation is performed by automatically switching solar array and CSR segments on and off, as determined by the controller logic. Prior to entry to the Mars atmosphere, the Cruise stage is separated from the rest of the MSL spacecraft as this is no longer required.

From a power system perspective, the CPAMs primary functions include power distribution to Cruise stage loads and measurement of power system voltage and current.

Descent Stage

The main elements of the power system located in the Descent stage include the Descent Power Assembly (DPA), power thermal batteries (PWTB-1/2), and redundant Descent Power and Analog Modules (DPAM-A/B). As in the Cruise stage, on the Descent stage the DPAMs primary functions are also power distribution to Descent stage loads and measurement of power system voltage and current. The DPA constitutes the central power bus node between the Rover and Cruise stage. As shown in Figure 1, the DPA provides relay-switched interfaces in the Descent Power Junction (DPJ) board for the power bus extending from the Rover and up to the Cruise stage. During Entry, Descent and Landing (EDL) the power bus is reconfigured to allow for electrical isolation between stages and to perform mechanical separation of all three stages, as required. The DPJ also provides isolated interfaces for the PWTBs, which are activated just before the Cruise stage is jettisoned and continue to power up the Descent stage all the way through Rover landing and flyaway. Each PWTB is designed for an operating life of 23 minutes. The Descent Pyro Firing (DPF) slices and the pyro thermal batteries (PYTB-A/B) make up the pyro subsystem on the Descent stage. Each DPF slice is fully redundant as are the PYTBs. The DPA also includes a power interface with the Descent Motor Control Assembly (DMCA). During EDL the DMCA is responsible for controlling the eight Mars Landing Engines used for powered descent.

Rover [Stage]

The main elements of the power system in the Rover [stage] include the Rover Power Assembly (RPA), Rover shunt radiator (RSR), Rover battery assembly unit (RBAU), redundant Rover Power and Analog Modules (RPAM-A/B) and the MSL MMRTG. As in the Cruise and Descent stages, on the Rover the RPAMs primary functions are also power distribution to Rover loads and analog-to-digital conversion of power system parameters (voltage and current). The RPA contains 4 electronic boards: 2 battery control boards (BCB-1/2), one power bus control (PBC) board and one Rover shunt driver slice (SDS-3). The PBC provides a relay-switched interface to extend the power bus from the Rover up to the Descent stage. As mentioned above, during EDL the power bus is reconfigured to allow for electrical isolation between stages and leaves the relays in the PBC in an open state. Furthermore, the PBC also contains circuitry to generate the control signals required to perform power bus regulation, and a set of relays that provide Arm and Enable functions for the Rover pyro system.

As in the Cruise stage, the SDS-3 provides linear control of the 5 RSR stages. Each BCB provides a dedicated interface with each of the two Rover batteries, which are mechanically contained in a single housing named the RBAU. The BCBs perform battery control and protection functions, while also including telemetry capabilities. Each of the Rover Li-ion secondary batteries is rated at 43Ah nameplate capacity for a total of 86 Ah of energy storage. The MMRTG is the only power source on the Rover during the Surface phase of the mission. During the Cruise phase, the MMRTG operates interconnected with the solar array and both sources provide all the power required on the three stages of the MSL spacecraft. The power output expected from the MSL MMRTG at the beginning of surface operations is 114 W.

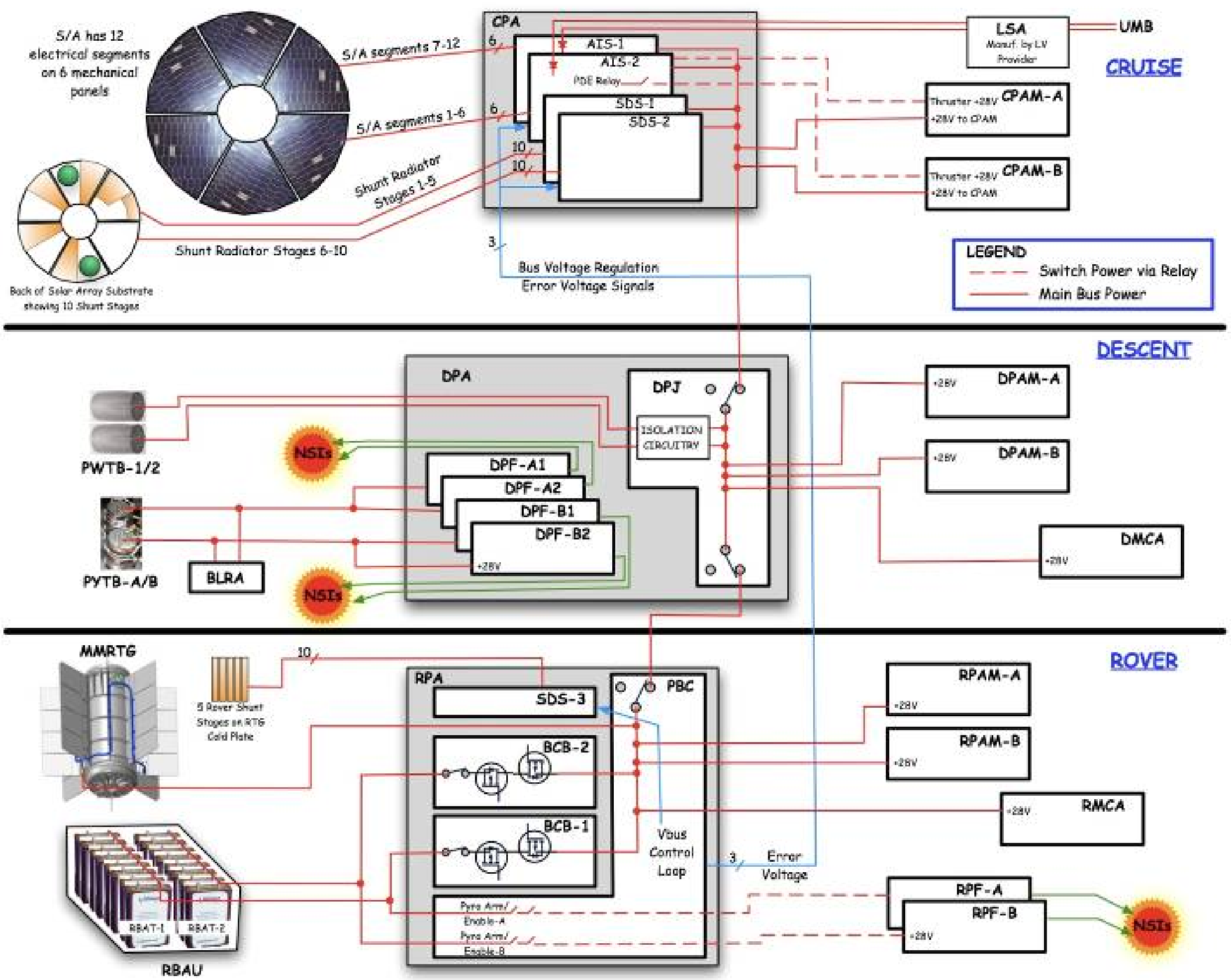

FIGURE 1. Block diagram of the main components of the MSL power system.

MMRTG DIRECT CONNECTION TO POWER BUS

As has been indicated previously, MSL has provided the first experience with integrated operation of an RTG power source, a solar array and rechargeable Li-ion batteries on an interplanetary mission. In defining the electrical interconnection of the F1 MMRTG with the MSL power system, very early designs took a rather conservative approach from a fault containment point of view. Such approaches considered isolated electrical interconnection of the F1 MMRTG with the rest of the MSL power bus, assuming F1 MMRTG failure modes like internal shorts from the thermocouple stack to the spacecraft chassis. At the time that these implementation approaches were being evaluated, the level of certainty in assessing the likelihood of occurrence of these and similar fault scenarios was also in the maturing process. Therefore, in considering possible fault containment designs for the MMRTG power interface cases like internal shorting between either power rail (high-side or low-side) to chassis needed to be addressed.

Likewise, redundancy in the fault containment approach needed to be included to ensure that under a single fault the F1 MMRTG would continue to remain available to the spacecraft power system. One additional important consideration was the goal to minimize power losses between the F1 MMRTG terminals and its connection with the MSL power bus. Examples of redundant fault containment approaches included spacecraft controller switches (solid-state and relays) and diode isolation. From several trades, it was immediately realized that implementation of a power interface with the F1 MMRTG that included fault containment or isolation would result in a non-negligible impact to flight system resources. As the design of the F1 MMRTG matured and some fault protection measures were incorporated into the F1 MMRTG design and test data became available for evaluation, the need for externally provided fault containment elements was re-considered. Based on an assessment of the likelihood of occurrence of specific fault scenarios, MMRTG test data, and foreseeable interactions with the rest of the flight system, it was decided that the F1 MMRTG interface with the power bus would be a direct connection. The most significant benefit of direct connection was the near-zero source power loss. Every watt of power used by the core avionics hardware for operation of the rover takes away almost 25Wh per sol of energy for science activities.

SURFACE ENERGY FROM MMRTG VS. SOLAR ARRAY

The very successful Mars Exploration Rovers used 1.3 square meter solar arrays mounted on the top deck of the rovers as their only power source combined with a Li-ion secondary battery for energy storage. Early in the surface mission the MER solar array produced an average of 700Wh each sol. This value was dependent on landing site latitude, seasons, dust in the air obscuring the sun and the amount of dust covering the panels. Over one Martian year the energy generated by the solar array ranged from 450Wh to 700Wh per sol.

MSL Curiosity rover was designed with a larger robotic arm and more advanced science payload that required a larger rover as well as more power to operate. Add in the possibility of landing sites at 60°N to 60°S latitude and a solar powered rover was not feasible. During the design phase of MSL, the F1 MMRTG was predicted to produce 95W—110W, depending on fin root temperature which is affected by surface temperatures. This power output variation is small when compared to a solar array design at high latitudes and affected by dust obscuration.

MSL landed at Gale Crater (4.5°S latitude) in the Martian spring. The F1 MMRTG will produce on average 114W continuously at the beginning of the surface mission. That is 2800Wh per Martian day (a Martian day is known as a sol) for engineering operations and science activities. The output power of the F1 MMRTG will slowly degrade over the Martian year ending in a predicted average value of 104W; or 2550Wh per sol. The consistency of the power source makes planning activities for single or multiple sols more straight forward, with less required energy margin as compared with MER power operations planning. Less energy margin translates into more planned science activities per sol.

Figure 2 shows the aft of Curiosity on sol 2 at Gale Crater. The F1 MMRTG is in the center of the photo with heat exchanger panels on each side of it and a fabric windbreaker across the ends of the heat exchangers.

FIGURE 2. The F1 MMRTG in Gale Crater on the surface of Mars. Navcam photo taken on sol 2 (Aug. 8, 2012).

SURFACE OPERATIONS BUS VOLTAGE DRIVEN BY BATTERY DISCHARGE

Rover activities and operational modes on Mars are highly variable and are typically planned on a tactical, day-by-day basis. During the first ninety sols, rover planners generate sequences of commands during the Martian night and upload command sequences to the rover around 10am local time. As a result, the actual power configuration of the vehicle is not known until several hours before actual execution. In addition, the rover has a wide variety of loads including motors and actuators which can change power states from several times per day to several times per second.

In contrast to most spacecraft utilizing RTGs, MSL experiences changes in the operating voltage of its power source at frequencies ranging from 10^{-5} Hz (for diurnal effects, such as battery discharge) up to 10^{5} Hz (for motor PWM control). There was some concern that this effect could manifest itself as a drop in usable output energy as this is not a typical use case for an RTG. As a result, JPL in conjunction with Teledyne Energy Systems, Idaho National Laboratories, and the US Department of Energy conducted a Variable Load Test at JPL.

Variable Load Test

The test consisted of running two voltage profiles on the Qualification Unit (QU) MMRTG. The QU MMRTG used resistive heater elements in place of actual fuel but was otherwise identical to the flight unit. The voltage profiles were chosen to represent a typical sol activity plan on Mars. For this test, a sol with a long drive sequence was simulated. This drive profile simulated the effects of short wheel motor movements followed by imaging activities that would be used by the rover for navigation and obstacle avoidance. In addition the profile included simulated communication passes at representative times in the sol.

Both profiles were identical in terms of total energy consumption. The first profile was a "stepped" profile, shown in figure 3, which simulated the actual rover loads with roughly one second granularity. Figure 4 provides a zoomed in view of the stepped profile. The second profile was a "smoothed" profile which used the average power from the "stepped" profile with roughly ten minute granularity. The goal of the test was to observe any differences in actual usable energy by the QU MMRTG due to thermal transients or any other effects on the MMRTG thermoelectrics from the highly variable load. An electronic load was used to place the MMRTG at the expected operating voltage.

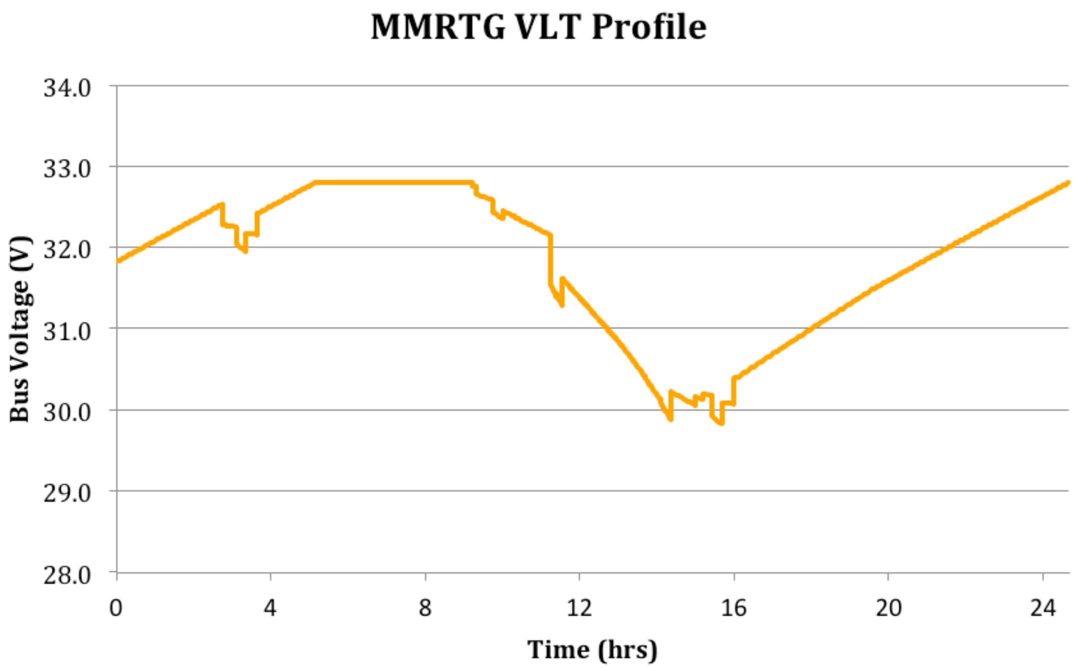

FIGURE 3. - MMRTG Variable Load Test (VLT) profile for a typical drive sol.

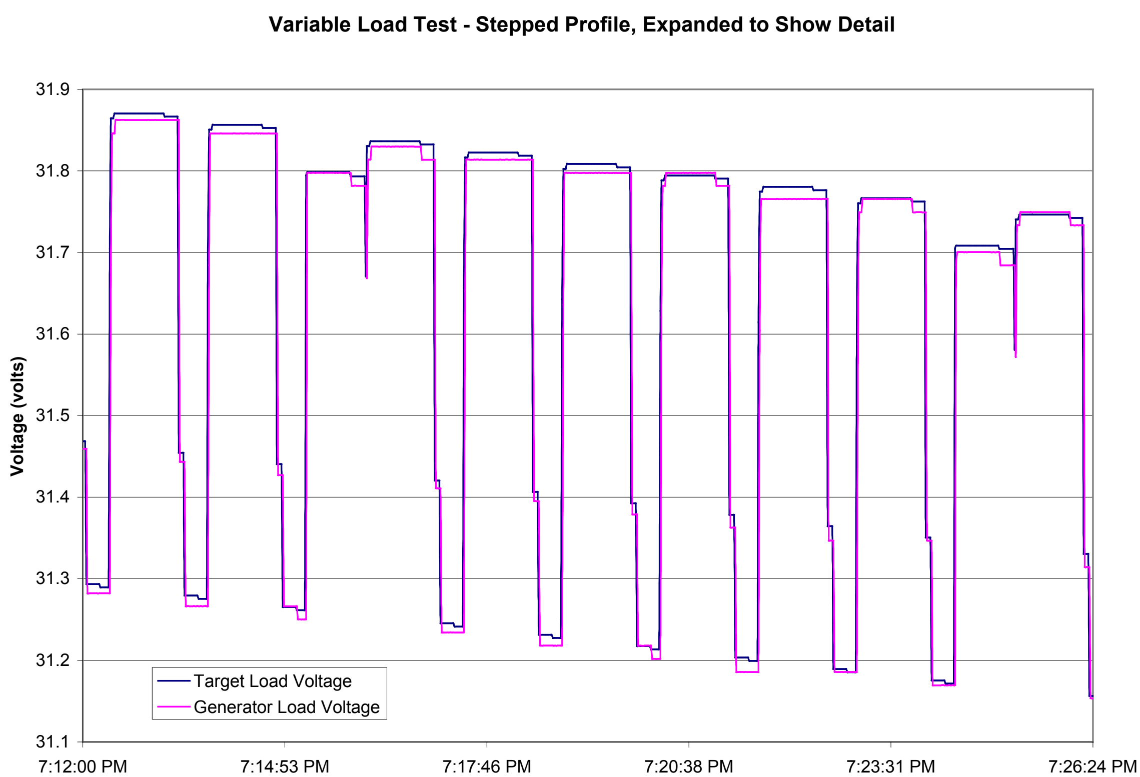

FIGURE 4. Stepped profile VLT results – portion expanded to show detail.

Results

The measured output energy for the stepped profile was 270.8Whr. The measured output for the smoothed profile was 271.3Whr. As there was no noticeable difference in MMRTG performance from the high-frequency load changes, it was concluded that this would not have an impact on surface power modeling. The roughly 0.18% difference in output energy is attributable to some of the differences in test setup, including small differences in the initial thermal and power source states for the two test runs.

CONCLUSION

The Mars Science Laboratory Curiosity rover power system with the F1 MMRTG and rechargeable Li-ion batteries has combined the stable, long-life power source of an RTG and the dependable, large capacity energy storage of 86Ah Li-ion batteries. As such, Curiosity is poised to discover new facets of Mars and its history over a greater distance and longer life than any previous mission to Mars.

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