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ANOTHER UPDATE ON THE MULTI-MISSION RADIOISOTOPE THERMOELECTRIC GENERATOR POWERING THE CURIOSITY ROVER

The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the Mars Science Laboratory (MSL) mission was developed by the United States Department of Energy (DOE) for the National Aeronautics and Space Administration (NASA) and fueled on October 28, 2008 in preparation for a late 2009 launch. Once launched, the MSL spacecraft provided a hi-fidelity telemetry stream measuring the generator's electrical and thermal performance. These data were used to update predictive models and a new prediction of the performance of the MMRTG on the surface of Mars was run just before Entry, Descent, and Landing (EDL) at Mars. Once landed the MMRTG powering Curiosity was found to be working extremely well, providing power above predictions and operating within its flight allowable temperature limits. The generator was producing approximately 114 W at the beginning of the surface mission, a mission of nearly two Earth years or one Mars year. This paper will elaborate on the MMRTG's performance throughout the primary mission and the initial months of the first extended mission as well as discuss related events and phenomena that affected the MMRTG's performance.

Key words: radioisotope thermoelectric generator, power output, energy lifetime.

Introduction

The United States Department Of Energy (DOE) developed the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the National Aeronautics and Space Administration (NASA) [1], and the generator was conceived as a multi-mission power source supporting missions going to such diverse destinations in the Solar System as Europa, Titan, the Moon, and others. It is a highly reliable, long-lived, rugged radioisotope power system (RPS). The MMRTG can be landed on other bodies, works in either vacuum or atmospheres, provides quiet power, and can be flown on NASA's certified launch vehicles.

The Mars Science Laboratory (MSL) was chosen as the first mission to use the MMRTG. The generator is now at the base of Gale Crater on Mars powering and heating the Curiosity rover. See Fig. 1. for a depiction of the rover. The MMRTG provides power to charge the rover's batteries and when the scientists have selected experiments, the rover draws on the batteries to run science instruments, drive the vehicle, and do other activities that draw high current. Simultaneously, infrared heat from the MMRTG is captured by two heat exchangers surrounding the MMRTG. The heat is then circulated to the rover electronics box to keep the electronics well within their operating limits.

Key mission dates include landing: Aug. 6, 2012 [2]; first drive: Aug. 22, 2012 [3]; end of primary mission: June 24, 2014 [4].

A close-up view of the Multi-Mission Radioisotope Thermoelectric Generator can be seen in Fig. 2.

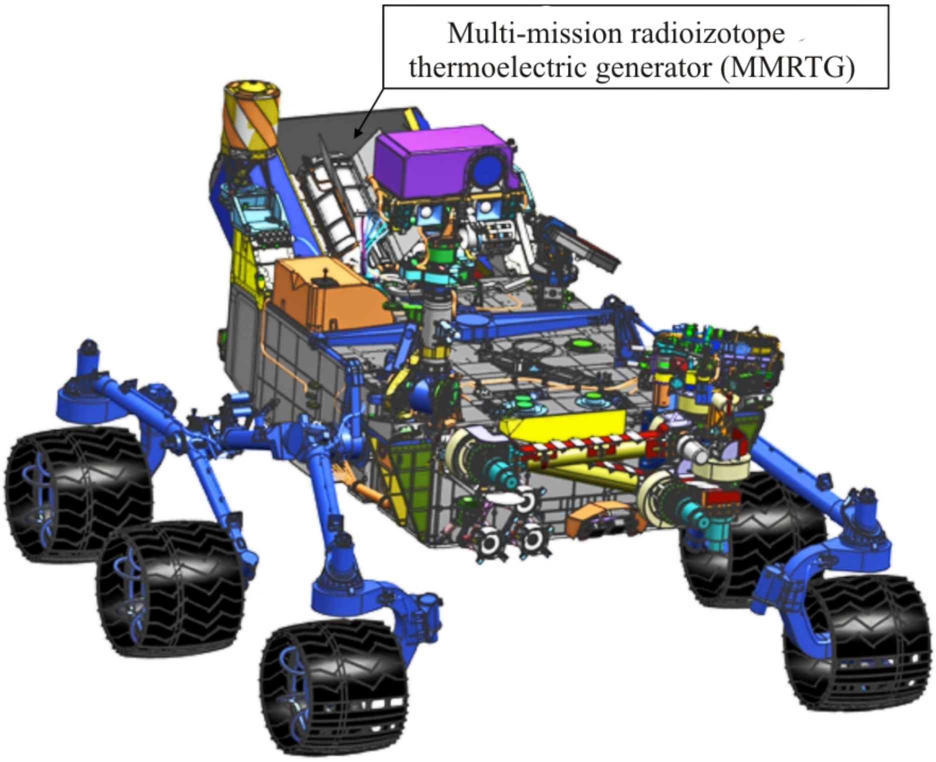

Fig. 1. Landed Rover Configuration. The Curiosity rover with MMRTG installed on the aft-end of the rover.

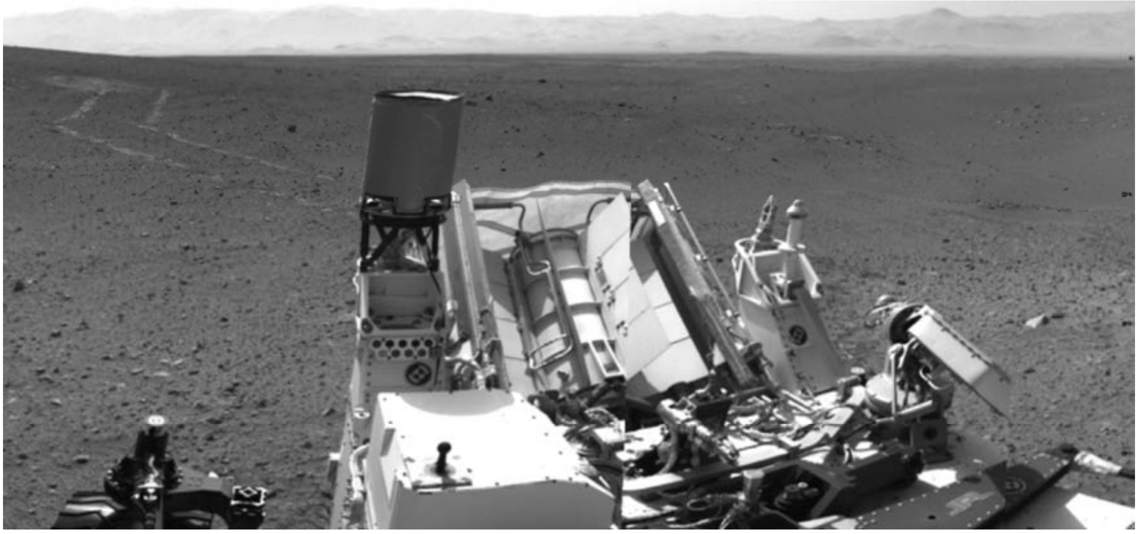

Fig. 2. MMRTG on Mars. This image was taken on sol 24.

This paper describes the MMRTG’s performance and predictions of its performance from pre-launch through the start of the first extended mission along with discussion of several events and phenomena that affected its performance.

Pre-launch predictions

A set of power predictions using conservative assumptions for aging and degradation were prepared before launch, in June 2011, just months before launch. There were three predictions from three unique models that were plotted together, and uncertainty was assigned (see Fig. 3.) [5]. The MSL Project was briefed on those predictions, and the inherent uncertainties in the predictions. The MSL Project managers chose to re-plan the surface mission using the revised predictions plus uncertainty. The power predictions plus uncertainty meant the battery would be charged slightly more slowly; and hence, some science activities would take longer to achieve and some eliminated. The re-planned mission would still meet the NASA requirements.

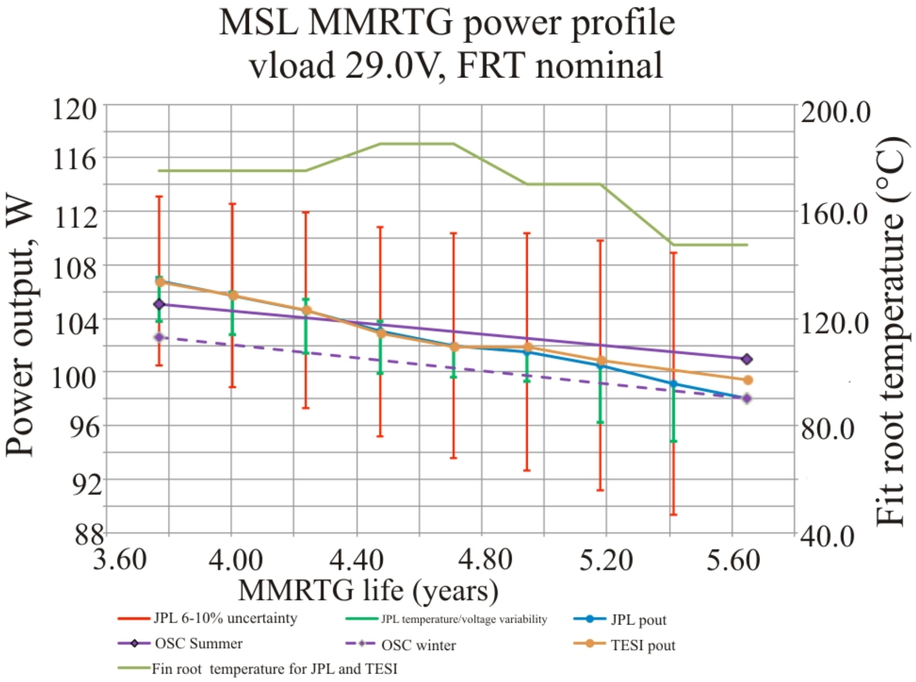

Fig. 3. Pre-Launch Power Predictions. MMRTG power prediction (power out, Pout) by the Jet Propulsion Laboratory (JPL) throughout the MSL surface mission including uncertainty, 6% at beginning of surface mission growing to 10% at end of mission. Orbital Sciences Corporation (OSC)/Analytix and Teledyne Energy Systems Inc. (TESI) data are also shown.

Landing

The temperature of the MMRTG rose rapidly from shortly before atmospheric entry until near landing as predicted. Venting the MMRTG cooling fluid caused this. The fluid was being circulated to the cruise stage where heat from the fluid was radiated over-board. To fly the entry vehicle in the Martian atmosphere, the cruise stage had to be jettisoned and the fluid vented to space. At approximately the same time as fluid venting, the segment of the power bus connecting the entry vehicle to the cruise stage was opened or dead-faced so that when the explosive bolt cutter severed the power bus wires, shorts would not affect the entry vehicle's performance. Fig. 4. depicts the primary sections of the Mars Science Laboratory spacecraft before atmospheric entry at Mars.

The power bus voltage dropped to ~31 V following power bus dead-facing [5]. This voltage change also shifted the MMRTG power operating curve to a new level, but downward power output trending remained at a steady rate except for a few minor transients. That is, the forced cooling of the

MMRTG had stopped, and it was still protected from direct interaction with the atmosphere inside the entry vehicle and so its fin root temperatures were rising rapidly.

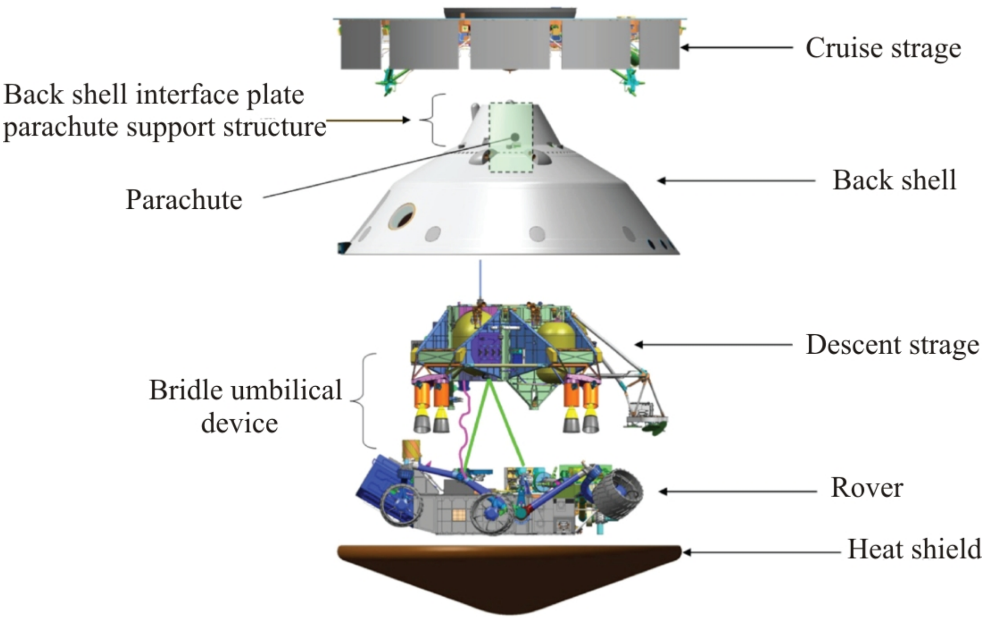

Fig. 4. Mars Science Laboratory Spacecraft. The Mars Science Laboratory spacecraft in an expanded view showing the how the key elements of the spacecraft are stacked together.

The rise in fin root temperature caused this collapse in the ΔT from the hot junction to the cold junction led to a power drop from the MMRTG. Power output declined until heat shield separation (HSS), and then the breeze of the atmosphere had an effect. At heat shield separation, the MMRTG power output started to recover. The rate of increase in MMRTG temperatures was observed to slow down. The power output completed a slow recovery until it reached a new steady state at roughly 114 W about 5 hours after the cooling fluid was vented. This actual, steady state value of 114 W compares to a predicted 106.3 W.

Primary mission power output

The monthly, average power output and the monthly temperatures are plotted in Fig. 5. The monthly average power output has steadily declined reflecting an average degradation rate of ~4.8% per year since landing. That includes fuel decay and reduced Carnot efficiency. The figure also shows that average temperatures have stayed within a 7°C band showing the generator temperature is falling with time, another indication of the fuel decaying with time. Fig.6. plots average monthly power output measurements between maximum and minimum power average curves. Power varies between minimum and maximum on a daily and monthly basis for several reasons. The causes of the greatest changes in power output on a daily basis are rover power bus-load voltage changes, temperature swings in the atmosphere, and the daily rising and setting of the Sun heating the MMRTG.

However, Fig. 5. suggests average temperatures are not moving sufficiently to be the dominant cause of change in power output. Power bus voltage changes are a dominant source of change in power output; these load changes occur daily as the rover wakes in the morning and draws on the battery throughout the day and is then put into sleep mode where the MMRTG recharges the battery for the next day’s operations.

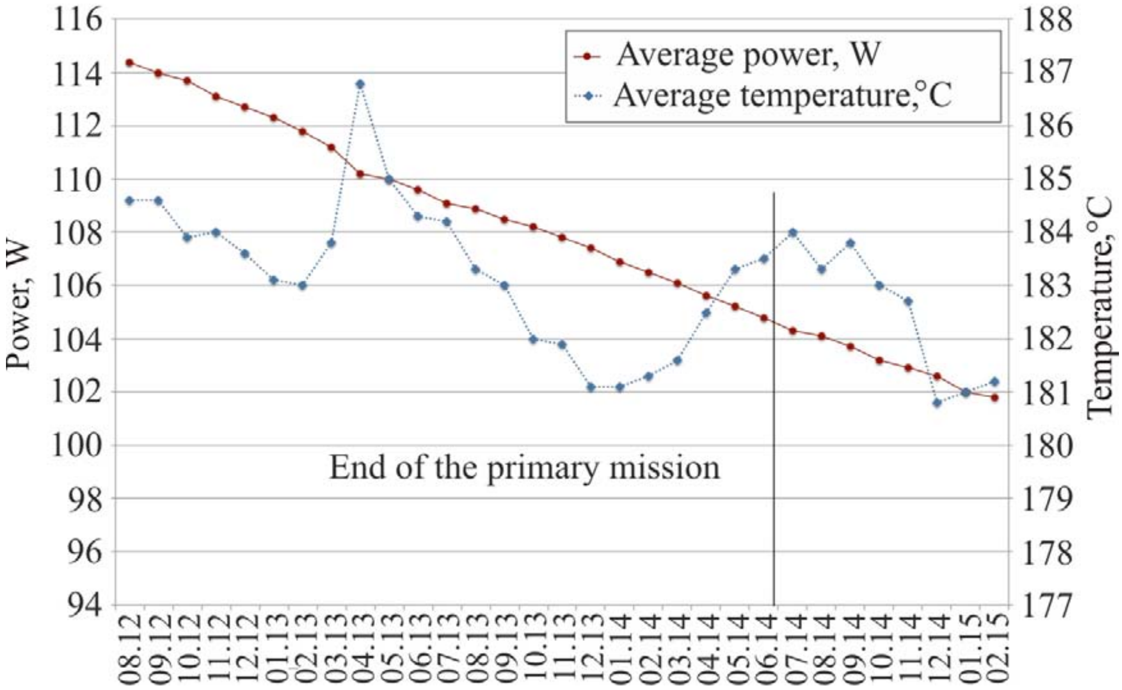

Fig. 5. MMRTG power and temperature. Monthly average power output (left axis) and monthly average temperatures (right axis) for a temperature sensor that is used in estimating the fin root temperature of the MMRTG on the Curiosity rover are plotted. Dates are read as Month-20xx.

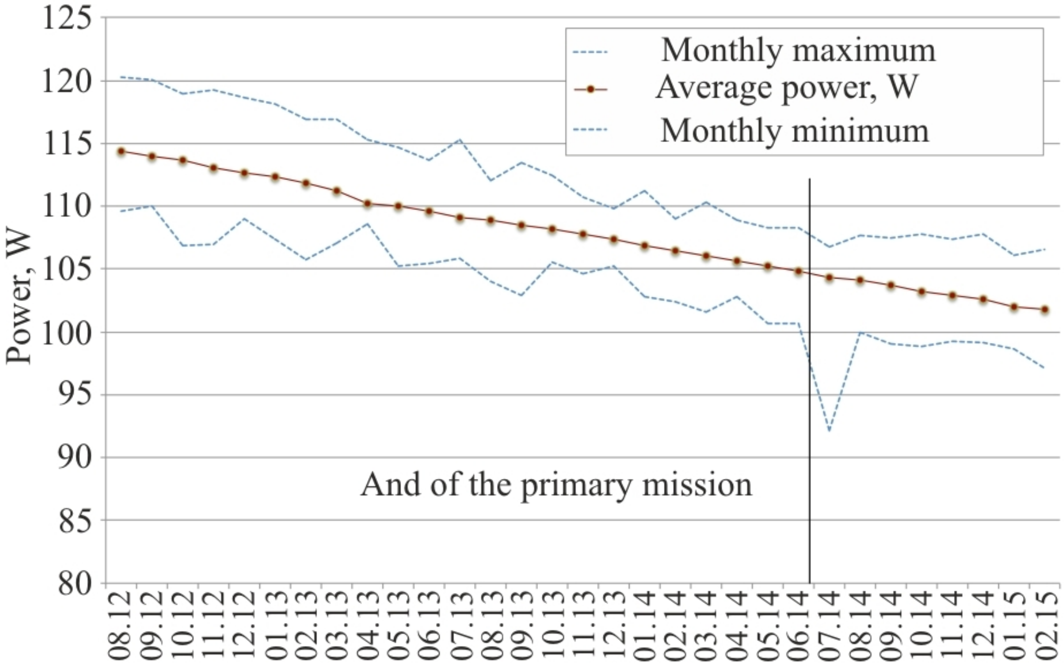

Fig. 6. MMRTG power output. Monthly averages for minimum, maximum, and average power output from the MMRTG powering the Curiosity rover. Dates are read as Month-20xx.

Winds on mars and their effects on multi-mission radioisotope thermoelectric generator temperatures

Atmospheric temperature changes are not the dominant cause of power output changes in the MMRTG on the Curiosity rover, but they can be significant. Atmospheric temperatures can drive power output to be especially volatile when daily cooling near sunset is followed by visiting “dustless” dust devils as on sol 37 [6, 7] or katabatic winds [8, 9]. In addition, thermal tides are planetary-scale gravity waves with periods that are harmonics of the solar day and are caused by the interaction of the atmosphere on the illuminated side of the planet with the solar radiation [9] and amplified by the Gale Crater topography [7].

The Rover Environmental Monitoring Station (REMS) on the MSL mission has sensors recording air and ground temperature, local atmospheric pressure, relative humidity, wind speed, as well as ultraviolet radiation in different bands (between 280 and 400 nm). Since sol 9, after landing, the REMS has collected data from all sensors simultaneously on an almost daily basis [9]. Fig. 7. is a plot of data from one of the MMRTG’s temperature sensors that closely follows the effects of the typical effect of katabatic winds seen by the REMS instrument shortly after sunset.

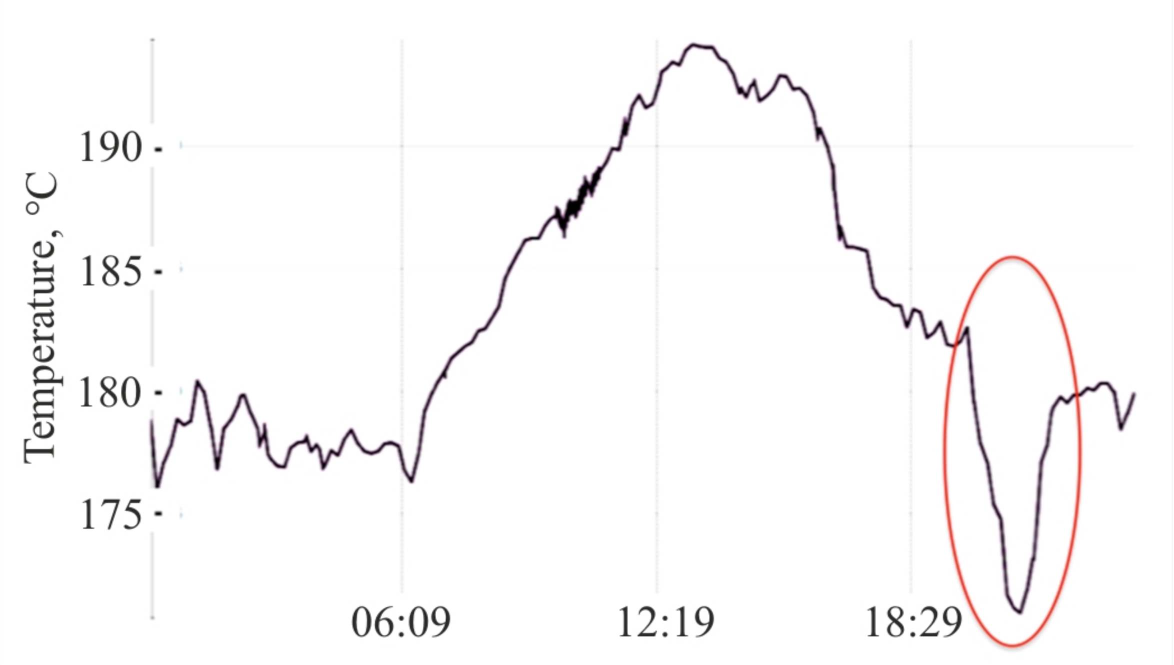

Fig. 7. Diurnal temperature swings. MMRTG fin root temperatures throughout a single sol, sol 87, are plotted; the hottest part of the sol is near noon. The circled segment of curve marks when katabatic winds blow over the MMRTG and rapidly lower the average fin root temperature. The winds then subside, and the fin root temperature rises quickly back to a nominal value. Times on the x-axis are Mars Local Times.

Heat plume over multi-mission radioisotope thermoelectric generator

The MMRTG is mounted between two nearly vertical heat exchangers, see Fig. 1., and those act as mounting points for a windscreen.

The opposite end of the MMRTG is on the rover-mounting interface. The sides of the MMRTG facing the sky and the ground are not enclosed.

The MMRTG rejects approximately 1900 W of heat continuously. Some of that heat is picked up by the rover to keep the electronics within their allowable flight temperatures. The remainder ends up in the Martian atmosphere or surface in one way or another. Before launch a thermal geyser or plume was postulated [10], the Martian atmosphere would be heated by the MMRTG's waste heat and rise over the rover, creating a buoyant plume. Fig. 7. indicates that for much of sol 87 there was little to no breeze; this pattern has been seen on most sols.

The plume may be acting as a "dust shield" for the MMRTG and aft portions of the rover by preventing dust borne by the Martian atmosphere from falling or drifting down onto the MMRTG. A series of "selfies" taken by the rover's arm-mounted camera show how soil and dust have accumulated as a function of time on the forward end of the rover. Some of that material was deposited on the rover as a result of performing sample handling, which increased after the first year on Mars; sample handling takes place on the forward end of the rover using the arm mounted there, and inevitably some material from multiple samples has been spilled onto the rover while trying to drop samples into small ports that lead to some of the instruments. However, that does not account for all of the material as some is clearly falling from the atmosphere. Fig. 8. shows accumulated dust as a function of time on the aft end of the rover well away from the sample handling equipment. In addition, the MMRTG appears to be nearly completely free of dust after approximately 2.5 years of operations on Mars. Something is shielding the MMRTG and nearby equipment from dust, likely the plume of waste heat from the generator.

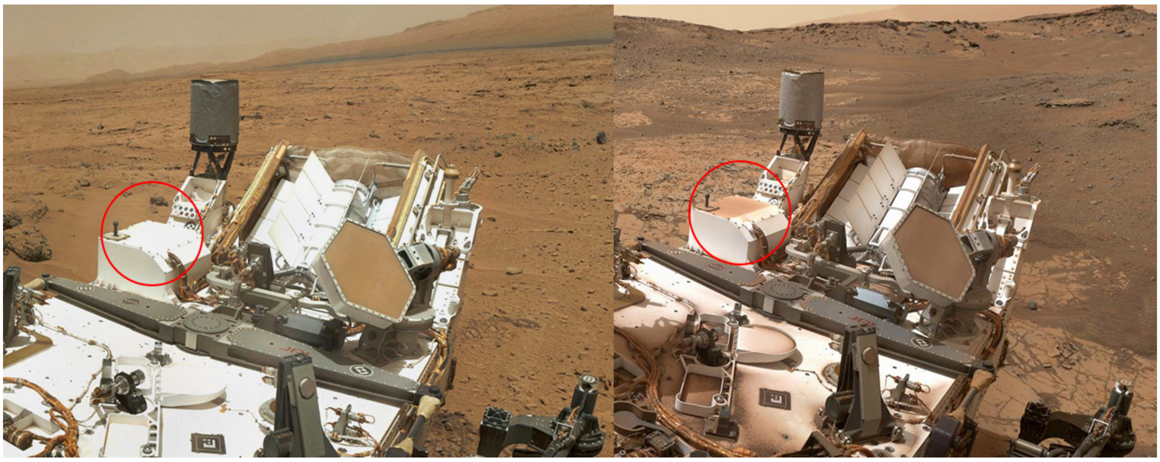

Fig. 8. Comparison of accumulated dust. Dust accumulated on the aft-end of the rover that was not deposited by the sample handling equipment. The image on the left is from October 2012, and the image on the right is from February 2015. The circled horizontal area on the right clearly shows dust accumulation over the previous years in comparison with the circled area on the left.

Extended mission (EM1 overview)

The MSL Project began planning for an extended mission in 2013 anticipating that if the rover was healthy in late 2014, NASA would likely fund an extended mission. Part of the planning included modeling available energy for science. Fig. 9. plots the estimate used for planning purposes.

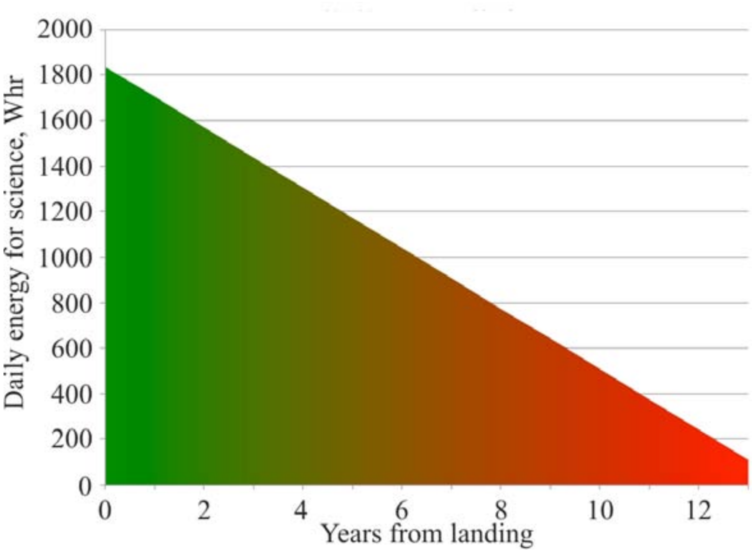

Fig. 9. Long-range energy estimate. The MSL mission uses the MMRTG to charge batteries and then draws on the batteries to conduct operations that consume high current. This plot shows how much energy should be available from the batteries as a function of time for science after accounting for the minimum energy needs of the engineering subsystems of the rover. The green section of the plot indicates there should be adequate energy to conduct all envisioned science experiments. The transition to red indicates the science experiments will likely be more limited in that timeframe.

Bumps along the way: loss of multi-mission radioisotope thermoelectric generator power circuit isolation

The Curiosity rover uses a “floated” power bus. That is, the power bus is isolated from the rover chassis by two 5 kΩ resistors. Fig. 10. is a cartoon depicting the arrangement. The MMRTG power leads are connected to two secondary batteries and separated from the rover chassis by two 5 kΩ resistors. The output from the MMRTG and batteries is used to power rover loads or is shunted to resistors. In the lower right hand corner of Fig. 10. is a depiction of known shorts in the pyrotechnic system that have tied the rover power bus return to the rover chassis; the number of shorts is unknown, but their total resistance is estimated as 6 kΩ; these shorts developed before touchdown on Mars.

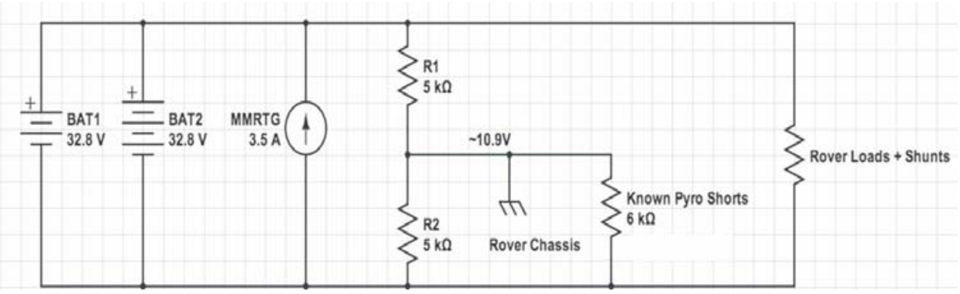

Fig. 10. Curiosity Power Bus. The diagram depicts the floating power bus used on the Curiosity rover. (Abbreviations used in the diagram are battery 1 (BAT1), battery 2 (BAT2), Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), resistance 1 (R1), and resistance 2 (R2).)

By floating the rover power bus, the spacecraft gains a single-level of fault tolerance for the power bus. If a rover load has a short in its power supply and that short connects the power bus to the chassis, rover operations would not be affected in the long run; science operations might stop temporarily as the engineers review the rover telemetry, but the hardware would continue to function normally in the presence of such a short.

On November 17, 2013, the rover's fault protection halted science operations [11] and sent an alert to the operations team in Pasadena, California. The alert came with telemetry that indicated what triggered the fault protection response to halt science operations. The power bus isolation from the chassis had changed in a significant manner; it had intermittently come and gone over several sols. NASA issued a press release on November 20, 2013 describing the situation [11]. In addition, a tiger team reviewed all of the spacecraft data and developed a fault tree. The tiger team meticulously evaluated each fault in the tree until the most likely fault was identified. The most likely fault was that the MMRTG had an internal short between its power circuit and the MMRTG housing. This behavior was seen during ground test of the engineering unit (EU) MMRTG. In addition, this behavior has been seen in other RTGs including the RTGs powering the Cassini spacecraft and Voyager spacecraft.

No adverse effect was identified as resulting from these shorts except to note that if they were to become permanent, they might degrade or eliminate the single-fault tolerance designed into the spacecraft as noted earlier. In earlier engineering unit tests and in-flight events on other missions, the shorts proved to be minor nuisances and temporary. Indeed, within a week of having detected the fault on the Curiosity rover, the fault cleared and the power bus isolation returned to its nominal value. A similar short did not return until approximately a year later.

This time, science operations were not halted. The data were reviewed and a plan put in place to attempt to clear the fault deliberately if the need arose. This time the fault did not clear in a short period, and the rover team was set to drill a nearby rock. The drill power circuit was designed to include a "battle short," a short that could be switched on and off by ground command and that shorted the power bus return to the rover chassis, thereby bypassing the isolation resistors. The battle short was built into the rover to counteract a specific power fault in the drill, but now, with the Multi-Mission Radioisotope Thermoelectric Generator suffering isolation faults, mission planners decided that activating the battle short while the MMRTG had an isolation short might send enough current through the isolation short to melt it or clear it.

Fault diagnoses during ground test of the MMRTG isolation losses and review of the isolation losses on other deep space missions indicated that the shorts were quite small dimensionally and/or were likely composed of non-metallic materials that would melt away under sufficient current. When this second MMRTG fault persisted, the rover operations team chose to attempt to "blow" the short. They activated the battle short, and within 1.5 seconds the MMRTG isolation short had cleared.

Rover drilling operations resumed almost immediately, and the short has not returned since. Similar circuits are now being designed into ground support equipment used to operate MMRTGs under life test so more detailed information can be gleaned about their shorts if they arise [12].

Conclusion

The MMRTG on the Curiosity rover continues to perform well and exceed predictions for both power and heat output. The internal shorts it infrequently experiences appear to be nuisances rather than high-risk events. The extended mission for the Curiosity rover was approved in September 2014, and the rover is now several months into that extended mission.

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