

The Mars Science Laboratory (MSL) MMRTG In-Flight: A Power Update

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Abstract. The MSL Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) was fueled on October 28, 2008 by the Department Of Energy (DOE) in preparation for a late 2009 launch. Shortly after, the MSL launch was delayed approximately 2 years until 2011. The fueled MMRTG was placed in storage to await the new date for liftoff. Occasional measurements of the MMRTG's power output were taken and compared with power predictions that pre-dated fueling. An error in the predictive models was quickly recognized and remedied. The resultant predictions, while improved, carried significant uncertainty. This uncertainty did not deter the launch of MSL, but did alter the planned mission on the surface of Mars. 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 the 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. The MSL MMRTG is 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. This paper will elaborate on power modeling for the MSL MMRTG along with a review of some of the data recorded from the MSL cruise to Mars, EDL, and the early days of the surface mission.

Keywords: MMRTG, radioisotope, thermoelectric, generator, Mars Science Laboratory, in-space power

PRE-FLIGHT POWER ESTIMATION ISSUES AND RESOLUTION

The Department Of Energy (DOE) fueled the flight unit, designated F1, on October 28, 2008. Power predictions were made using a model developed at Teledyne Energy Systems Incorporated (TESI), one of the engineering firms that developed the MMRTG. That model relied upon data from previously flown thermocouples (heritage) and testing of another MMRTG called the Engineering Unit or EU. These power predictions were then used for planning the rover's surface operations. The predictions using this tool were made before the flight unit had been fueled and so the power model was not grounded with data from the fueled flight unit.

The MSL Project ultimately recommended to NASA in early 2009 that launch be delayed until late 2011, and the MMRTG was placed in storage at the Idaho National Laboratory (INL), a DOE National Laboratory. The storage conditions were initially chosen to be "shorted with fan cooling." This meant the MMRTG power and return were shorted together to minimize the hot-junction temperature of the thermoelectrics. In addition, fan-blown air cooled the unit further. Both steps were taken to preserve life and reduce degradation of the thermoelectrics while the unit sat fueled and operating in storage for ~2 years. Power measurements from F1 were collected quarterly; that is, the short was removed, a measurement taken, and the short then reapplied. By late-summer of 2009, the power estimate for the beginning of the MSL surface mission was ~110W. Power predictions for the MMRTG were published. Utilization of the rover's scientific instruments, driving time, drilling time, data communications, and many, many other activities were shaped by the predicted, available power for a mission to be launched in late-2009.

Data from the F1 MMRTG was being acquired at a data point per quarter during much of 2009, and the data were combined with the TESI power prediction model. By late 2009, it became clear that the model was over-predicting what F1 was actually producing and power predictions were revised downward. The paucity of data collected from F1 and the modeling issues led to a trade over the value of shorting the unit, and while deemed valuable, the need for more visibility into the MMRTG's performance was deemed more important. Ultimately, the short was removed about 18 months before launch and replaced with ground support equipment that took nearly continuous measurements. The rationale for the change is beyond the scope of the paper except to say the change enabled collection of a large data set useful in verifying the unit's health and revising the MMRTG's performance models.

The Project began to replan the rover's mission with less power and energy. In addition, a small team was formed to explore the modeling error and correct it. This was a two-part problem:

1. MMRTG power modeling was overly optimistic.
2. The physics of the MMRTG thermocouples was not understood well enough and hence there was an underlying dispersion about the generator's degradation trend.

Both parts of the problem were investigated. The first issue's resolution was aided by having three, independently-developed modeling engines for comparison. That is, two additional engines were employed along with the one noted earlier. The three engines were developed at Teledyne Energy Systems (maker of the engine noted earlier), the Jet Propulsion Laboratory (the JPL model was called DEGRA), and the Orbital Sciences Corporation/Analytix. All of the modeling engines pre-dated the MSL Mission and so were excellent verification tools; that is, they did not share a common design and hence common coding missteps. Differences between the predictions made by the three engines running models using the same physical properties and environmental conditions showed almost identical results.

With the engines validated, the models of the MMRTG's thermocouples were reviewed. The model used by TESI was the most current using both heritage data and the largest set of EU and Flight Unit (FLT) data. The JPL and OSC models used heritage information and a limited set of EU data. Differences between the three models were quickly found and a reference set of physical data were selected for all three models to use; the physical parameters of the thermocouple legs vary with time and temperature and so thermal conditions and responses had to be matched for the three models. In addition, a subset of results from power tests conducted on the EU was selected as a baseline and all three models were updated accordingly; the method for combining the heritage model with EU test results is described in a paper listed in REFERENCES at the end of this paper. This made the models as similar as was possible. Power predictions were rerun and all three models were found to show similar results.

The last step in resolving part 1 of the problem was to fold the actual measurements from F1 into the models. This was performed. And again, predictions from the three tools were nearly identical.

Part two of the problem meant evaluating the physics of degradation of the thermocouples in F1. Some data was found from tests conducted decades ago for the Viking mission's SNAP-19 generators. Unfortunately, the data were sparse and not applicable on a one-to-one basis as the thermocouples in a SNAP-19 were not identical to the thermocouples in an MMRTG. The applicable degradation data from the SNAP-19 design was combined with the data on the MMRTG thermocouples in all three models. Subsequent predictions between the three updated models were again similar but the uncertainty on the predictions was more than had been delivered to the MSL Project before this exhaustive analysis. That is, after this thorough evaluation of the three modeling engines, the three models, and the Martian surface thermal environment, the team recommended the Project carry more uncertainty on new power estimates. So not only were power estimates lower, the predictions carried uncertainty of +/- 10% on power estimates for the end of the MSL Mars mission.

A final set of power predictions were prepared in June, 2011, and the three predictions for the mission on Mars were plotted together and uncertainty assigned; see Figure 1. The MSL Project was briefed on the latest predictions, and the inherent uncertainties in the predictions. This closed the two parts of the problem noted above and the team was disbanded. MSL now chose to replan the surface mission using the revised predictions plus uncertainty. The lower power predictions meant the battery would be charged more slowly and hence some science activities would take longer to achieve and some eliminated. The re-planned mission would still meet the mission's requirements.

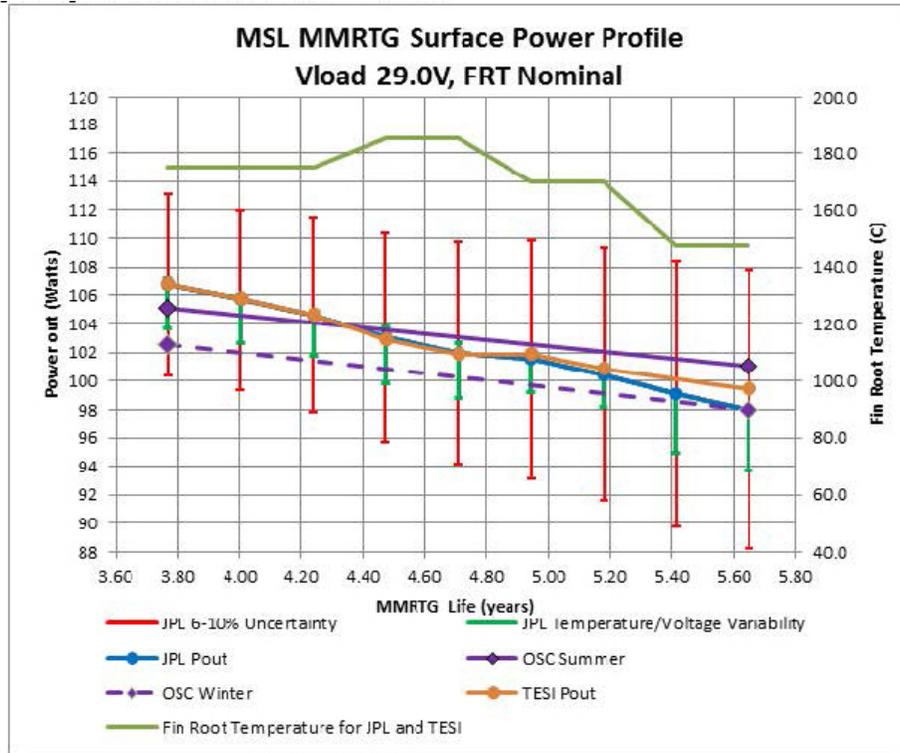


Figure 1. MMRTG/F1 power prediction throughout the MSL surface mission including uncertainty, 6% at beginning of surface mission growing to 10% at end of mission. OSC/Analytix and TESI data are also shown for comparison.

FINAL PRE-FLIGHT POWER ESTIMATIONS FOR CRUISE AND SURFACE OPERATIONS

The final run of the JPL DEGRA (power prediction tool) for the MMRTG spanned the planned mission timeline. The source heat (Q_{source}), fin root temperature (T_{fin_root}), bus voltage (Voltage) were estimated for each mission phase and a predicted output power (Pout) from the MMRTG was calculated. Table 1 summarizes the pre-flight power estimates for cruise and surface operations.

TABLE 1. Summary of the MSL MMRTG Pre-flight Power Estimations for Cruise and Surface Operations. MSL arrived at Mars on August 6, 2012 UTC, in the spring of the Martian, northern hemisphere (median temperature case, 29 V).

Phase Description	Date	Q_{source} (W)	T_{fin_root} (°C)	Voltage (V)	Pout (W)
Post Fueling	01/11/2011	1968.0	132	28.0	110.7
S/C Integration	11/18/2011	1967.7	85	28.0	104.7
Launch	11/26/2011	1967.5	180	28.0	109.1
Cruise to Mars - early	12/28/2011	1963.8	75	30.7	99.0
Cruise to Mars - late	06/12/2012	1956.8	75	32.8	95.1
Surface Ops Spring	08/06/2012	1953.2	175	29.0	106.3
Surface Ops Summer	04/21/2013	1942.3	185	29.0	102.5
Surface Ops Autumn	10/10/2013	1935.1	170	29.0	101.1
Surface Ops Winter	03/30/2014	1927.9	147.5	29.0	98.7

PRE-FLIGHT POWER DATA

Electrical integration of the MSL MMRTG to the MSL spacecraft was completed on November 18, 2011. Electrical integration activities were performed at the Atlas Vertical Integration Facility (VIF) in Launch Complex 41 at Cape Canaveral Air Force Station (CCAFS). During the electrical integration process, the MSL MMRTG output was gradually increased until its voltage matched that of the MSL spacecraft power bus voltage. Throughout this process, key MSL MMRTG parameters (voltage, current, temperature) were monitored continuously. Figure 2 shows the MSL MMRTG performance during electrical integration with the MSL spacecraft. Figure 3 shows the MSL MMRTG performance during launch.

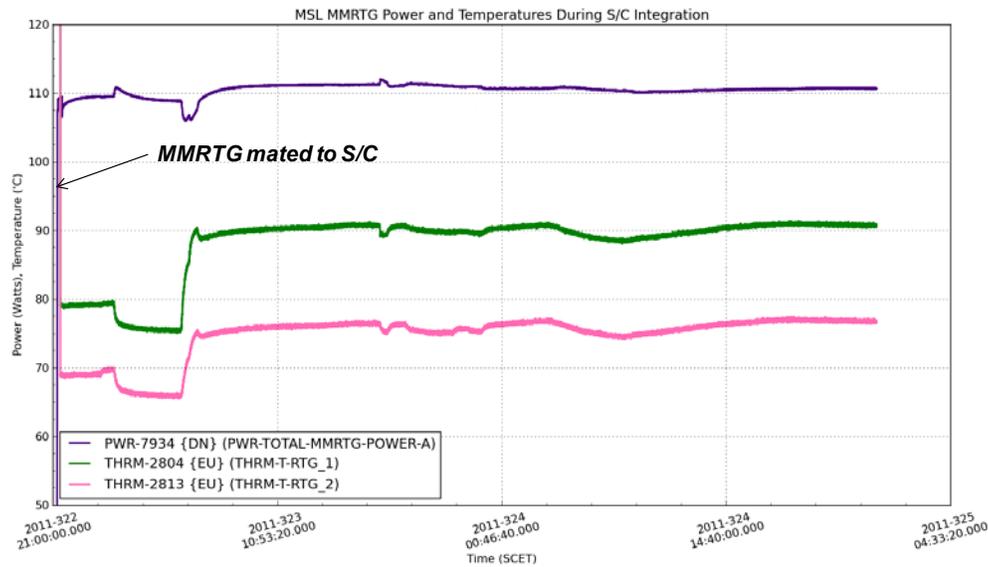


FIGURE 2. MSL MMRTG Power and Temperatures during Spacecraft Integration.

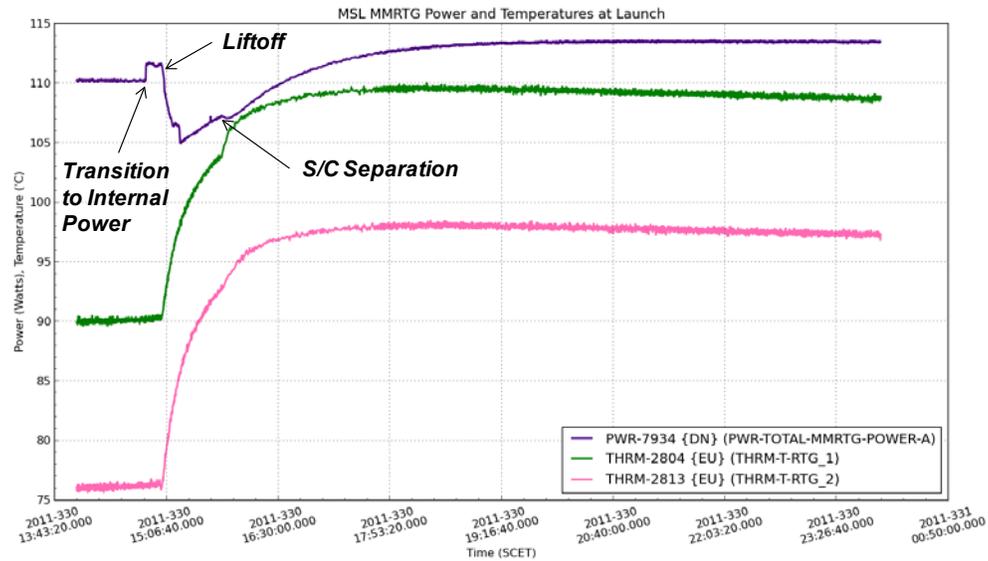


FIGURE 3. MSL MMRTG Power and Temperatures during Launch.

As discussed in previous sections, MSL MMRTG pre-flight power predictions were generated by JPL assuming the latest mission profile, as well as different temperature cases and operating voltages. Table 1 presents a summary of

pre-flight power predictions as of January 11, 2011, for the MSL MMRTG integration phase and during launch operations. Power predictions shown in Table 2 are considered representative of an average case and are compared to actuals measured. When normalized to the 28 V operating voltage used to generate these power predicts, the actuals were found to fall well within 5% of the predicted values.

TABLE 2. Summary of MSL MMRTG Pre-flight Power Predictions and a Comparison with Actuals (median temperature case, 29 V).

Phase Description	Date	Q _{source} (W)	T _{fin_root} (°C)	Voltage (V)	Pout (W)
Post Fueling (Predicted)	01/11/2011	1968	132	28	110.7
S/C Integration (Predicted)	11/18/2011	1967.7	85	28	104.7
Launch (Predicted)	11/26/2011	1967.5	180	28	109.1
Post Fueling (Actual)	01/11/2011	1968	90	31.4	111.2
S/C Integration (Actual)	11/18/2011	1967.7	76	32.9	111.1
Launch (Actual)	11/26/2011	1967.5	96	32.9	113.9

CRUISE AND APPROACH PHASE PERFORMANCE

The spacecraft entered the Cruise phase of the MSL mission after successful separation from the launch vehicle. The Cruise phase lasted about 8.5 months from November 26, 2011 until August 6, 2012. The Cruise phase consisted of:

- *Monitoring of spacecraft health and telemetry*
- *Three Trajectory Correction Maneuvers (TCMs)*
TCMs utilized the spacecraft's thrusters in order to target the desired atmospheric entry point at Mars.
- *Attitude adjustments (ACS Turns)*
Spacecraft attitude was adjusted regularly as the orientation of the Sun and Earth changed in relation to the spacecraft during the 8.5 month journey to Mars. Spacecraft attitude was chosen to ensure adequate solar power from the solar array, adequate communication margin with tracking stations, and appropriate solar insolation to stay within thermal limits.
- *Instrument and Avionics Checkouts*
Several rounds of device checkouts occurred in preparation for EDL and the Surface Phase.
- *Hardware Maintenance*
This included battery state-of-charge maintenance, exercising backup thermal hardware, and computer memory and file system maintenance.

The Approach phase of the mission began at approximately Entry-30 days, or E-30 days, and continued until the flight software began executing the EDL timeline events. Approach operations consisted of:

- *24/7 monitoring of spacecraft health*
- *Hardware Maintenance*
- *Additional TCMs*

For the Cruise and Approach phases, the MSL spacecraft power system was configured as a single power bus for the Cruise, Descent, and Rover stages. Power was sourced from both the Cruise solar array and the MMRTG. The Rover batteries also provided power during transient loads, though no large battery discharge events were planned.

The cruise phase solar array used triple junction gallium-arsenide cells. The array was 12.8 m² and used 252 parallel strings to produce 1200 W at a 30 degree sun angle at 1.61 AU (the distance at MSL entry into the Martian

atmosphere). The array supported the spacecraft loads during the Cruise and Approach phases. The solar array was jettisoned from the entry vehicle prior to entry into the Martian atmosphere.

During cruise, the MMRTG worked in conjunction with a solar array to provide the power for the avionics on the spacecraft, see Figure 4. For modeling and analysis, a power output of 105W was assumed for the MMRTG.

The rover has a pair of Li-Ion, secondary batteries rated at 43Ah nameplate for a total of 86Ah of energy storage. The two batteries are packaged in a single housing called the Rover Battery Assembly Unit (RBAU). During Cruise and Approach, these batteries handled transient loads helping to maintain a stable power bus voltage.

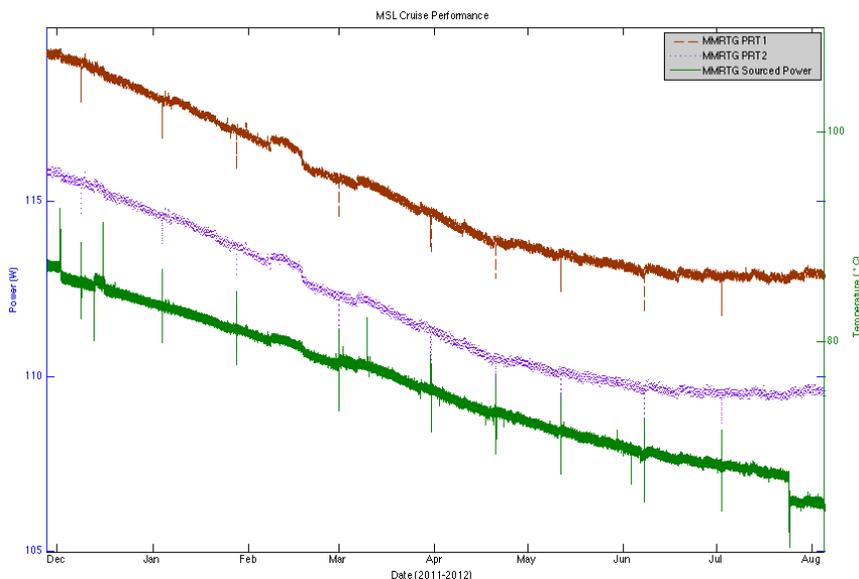


Figure 4. MMRTG Performance for Cruise/Approach - This plot shows the MMRTG performance for the entire Cruise phase. Transient spikes are maintenance and battery conditioning activities. Clearly, cooling of the MMRTG occurred as the spacecraft traveled away from the sun. Consequently, power output dropped. This was as predicted, see Table 1. PRT 1 and 2 are located near the hot shoe of one of the thermocouples and near the outboard end of the MMRTG respectively.

EDL PERFORMANCE

After an 8.5-month cruise, the MSL spacecraft started preparations for the Entry, Descent, and Landing (EDL) phase of the mission. Landing of the Curiosity rover on the surface of Mars was planned for August 6, 2012 UTC. Just prior to EDL, the power output of the MSL MMRTG was approximately 106.5 W with the rover power bus voltage at around 32.7 V. As EDL progressed, several spacecraft re-configuration events took place, which included changes to the on-board heat rejection subsystem (HRS) and deadfacing of the main power bus across spacecraft stages. In addition, the spacecraft's trajectory through the atmosphere of Mars presented a changing thermal environment.

Figure 5 shows the MSL MMRTG performance during the EDL phase of the mission. Also, for clarity, Figure 6 shows a more detailed view of the power bus and rover battery voltages during EDL. As seen in Figure 5, the MMRTG power output (~106.5 W) was observed to start a slowly decreasing trend shortly after the HRS vent action at time 2012-219, 04:57 (or 4:57 UTC on day 219 of year 2012). The MSL MMRTG temperatures were observed to start increasing shortly after HRS vent, which was expected due to the removal of the cooling loop around the MMRTG. Also as shown in Figure 5, MMRTG power output trending appeared to closely track the MMRTG temperature trending. MMRTG power output decreased at a steady rate until activation of the MSL power thermal batteries (PWTB) at time 2012-219, 05:00. The transient observed in MMRTG power at time 2012-219, 05:00 was due to an increase in Rover power bus voltage from 32.8 V to 34 V as a result of PWTB activation. This increase in power bus voltage is clearly observed in Figure 6.

The power bus voltage dropped to ~31 V (see Figure 6) following power bus deadfacing across S/C stages a few seconds after PWTB activation. This voltage change also shifted the MMRTG power operating curve to a new level, but downward trending remained at a steady rate except for a few minor transients. MMRTG power output declined until heat shield separation (HSS) at time 2012-219, 05:15. At HSS, the MMRTG power output started to recover and the rate of increase in MMRTG temperatures was also observed to slow down. The MMRTG power output completed a slow recovery until it reached a new steady state at roughly 115 W about 5 hours after HRS vent took place. This steady state value of 115 W compares to a predicted 106.3W in Table 1.

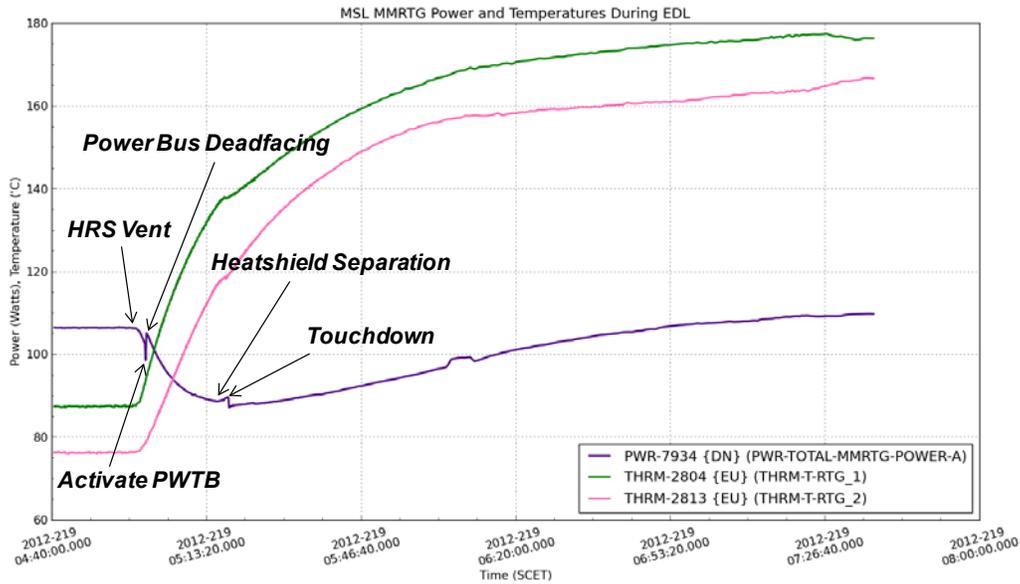


FIGURE 5. MSL MMRTG Power and Temperatures during EDL.

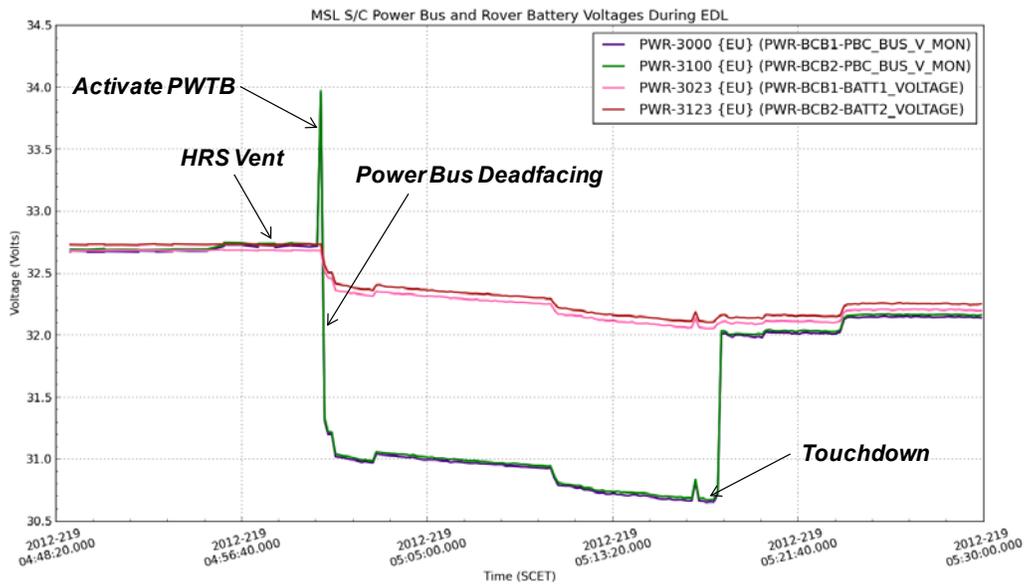


FIGURE 6. Detailed View of the S/C Power Bus and Rover Battery Voltages during EDL.

ESTIMATED PERFORMANCE FOR NOMINAL MISSION FOLLOWING LANDING AT GALE CRATER

The JPL DEGRA model was again used to predict output power of the MMRTG for the remainder of the surface mission, which is one full Martian year in duration, using the actual performance data from the Cruise Phase and first 60 sols (a sol is a Martian day) of Mars Surface Phase operations.

The following figure shows the prediction of MMRTG output power along with uncertainties for the period from sol 0 until the end of the prime mission at sol 687 including the actual for the first 60 sols, Figure 7. The use of data from the MMRTG collected over the first 60 sols of the mission has allowed uncertainty in the prediction to be reduce significantly.

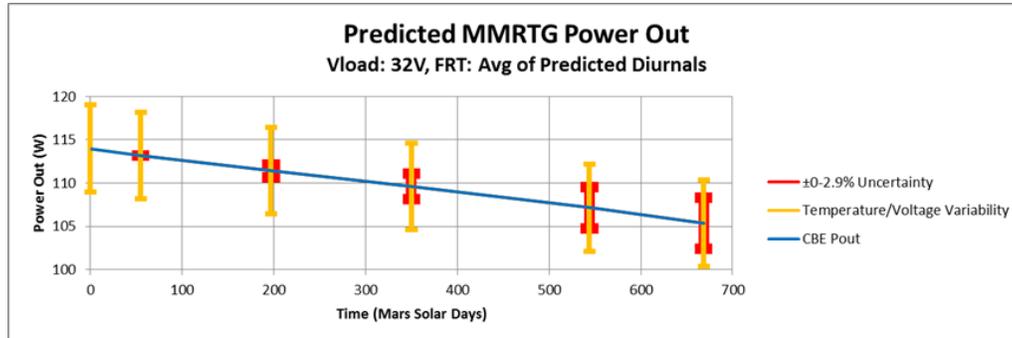


FIGURE 7. MSL MMRTG Output Power for Remaining Surface Mission.

CONCLUSION

The MSL Rover with its MMRTG was safely and successfully landed on Mars on August 6, 2012 UTC, where it has begun science operations for its primary mission. The MMRTG is providing 114W on average power which is well above that predicted before launch and before landing. The MMRTG remains healthy.

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