

Small-RPS Enabled Mars Rover Concept

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Abstract. Both the MER and the Mars Pathfinder rovers operated on Mars in an energy-limited mode, since the solar panels generated power during daylight hours only. At other times the rovers relied on power stored in batteries. In comparison, Radioisotope Power Systems (RPS) offer a power-enabled paradigm, where power can be generated for long mission durations (measured in years), independently from the Sun, and on a continuous basis. A study was performed at JPL to assess the feasibility of a small-RPS enabled MER-class rover concept and any associated advantages of its mission on Mars. The rover concept relied on design heritage from MER with two significant changes. First, the solar panels were replaced with two single GPHS module based small-RPSs. Second, the Mossbauer spectroscope was substituted with a laser Raman spectroscope, in order to move towards MEPAG defined astrobiology driven science goals. The highest power requirements were contributed to mobility and telecommunication type operating modes, hence influencing power system sizing. The resulting hybrid power system included two small-RPSs and two batteries. Each small-RPS was assumed to generate 50We of power or 620Wh/sol of energy (BOL), comparable to that of MER. The two 8Ah batteries were considered available during peak power usage. Mission architecture, power trades, science instruments, data, communication, thermal and radiation environments, mobility, mass issues were also addressed. The study demonstrated that a new set of RPS-enabled rover missions could be envisioned for Mars exploration within the next decade, targeting astrobiology oriented science objectives, while powered by 2 to 4 GPHS modules.

INTRODUCTION

Following the great success of the Mars Exploration Rovers (MER), Spirit and Opportunity (NASA, 2004), NASA continues working on future mission concepts in support of the Mars Exploration Program. Next decade potential missions could include rovers to achieve surface mobility, deep drills for subsurface access, in addition to landers and sample return. This section focuses on surface mobility, and describes a point design that demonstrates the feasibility of a MER-class Mars rover powered by small Radioisotope Power Systems (RPS). Although the power level for this point design is sized to match MER-class rover mission requirements, additional rover designs are identified and scaled to various power levels.

SCIENCE & MISSION GOALS

The nation's vision for space exploration (Bush, 2004) recognized Mars and the Moon as prime destinations for both robotic and human exploration. In addition, NASA's Mars Exploration Program interfaces with the Mars Exploration Program Analysis Group (MEPAG, 2004) to identify high priority science and technology issues relevant to the program. The four highest priority objectives identified by MEPAG are: (1) the search for life; understanding the (2) climate and (3) Martian geology; and (4) preparing for human exploration. Consequently, the conceptual mission design described in this study builds on heritage from the MER missions, while specifically addresses astrobiology-driven science goals. This systematic approach places the present rover mission in line with other planned Mars exploration missions, while helping to establish an exploration path that leads towards the ultimate goal of human presence on Mars.

Both MER and Mars Pathfinder (NASA, 2004) operated on Mars in an energy-limited mode, since their solar panels generated power during daylight hours only. At other times the rovers relied on power stored in secondary batteries. Radioisotope Power Systems (RPSs) offer a power-enabled paradigm, where power is generated for long mission durations (measured in years), independently from the Sun, and on a continuous basis. To take advantage of these benefits, the goal of this mission study concept is to assess the feasibility of a small RPS-enabled generic MER-class rover, and to assess the relative advantages of such a mission.

MISSION ARCHITECTURE OVERVIEW

In order to conduct high priority science in line with MEPAG goals the science community needs a mobile platform to perform astrobiology, geology and climate experiments at locations not accessible to solar powered rovers. This rover concept extends the capability and longevity of the power source, using small-RPSs, to further increase the science return. For the present astrobiology-oriented mission concept the Mars Exploration Rovers present a suitable starting point, while providing design heritage (Diehl et al., 2004). Consequently, a significant portion of this mission is based on the original MER mission architecture and hardware configuration.

The launch and arrival characteristics are determined for two launch periods, one that would allow access to maximum northern latitudes and one to maximum southern latitudes. The latitudes bridged by the two trajectories would range from 70°S to 70°N. A Type II trajectory would be used for either latitude regime. The permissible range of latitudes is limited by the launch configuration and not by the power system – RPS enabled rovers would be operational at any given Martian location.

To land between 70°S and 40°N the launch window is assumed between October 27 and November 16, 2009. This corresponds to a cruise phase of 334 to 354 days and an arrival date of October 16, 2010. The heliocentric longitude of the Sun (Ls) at arrival is 165°. The C3 for this launch period is 20km²/s². The corresponding injected mass is 3100kg on an Atlas 521 launch vehicle (LV) or 2897kg on a Delta 4450-14 LV.

To reach the maximum northern latitude of 70°N (and ranging down to 50°S), the launch window would be set between October 6 and 26, 2009. The corresponding cruise phase is ~300 days with an arrival date between July 23 and August 22, 2010. The longitude of the Sun at arrival ranges from 120° to 133°. The C3 is 15km²/s², which allows for injecting a mass of 2923kg on the Delta 4240-14 LV or 2806kg on an Atlas 511 LV.

Entry, descent and landing (EDL) is assumed using either MER type airbags or Viking/Phoenix-type powered descent. Using an airbag configuration (see Figure 1), the rover could be accommodated on a 2.57m Viking-type aeroshell, with a total launch mass of ~1070kg. The Viking-type powered landing configuration with a larger 3.65m Viking-type aeroshell would have a launch mass of ~1620kg. For both cases the launch mass is less than half of the available LV capacity. Therefore, further optimization could be made by choosing a smaller LV, for example Atlas IIB (SEC) (1995kg) or Delta IV 4040-12 (1565kg) for C=20km²/s². (NASA-KSC, 2004)

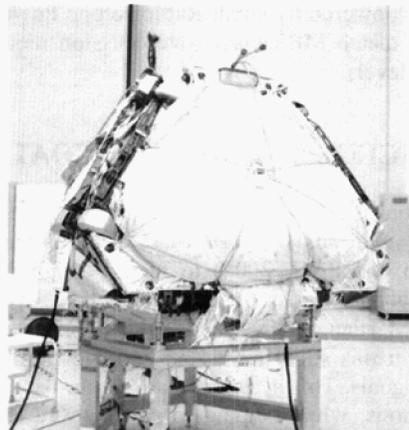


Figure 1. MER type airbag without the aeroshell

Figure 2 shows a Viking-type aeroshell and lander with the rover. The choice of airbag landing versus powered landing results in different landing accuracies and acceleration load environments. The ellipse for airbag landing with no entry guidance (attitude hold only) and optical navigation would be ~96km, similar to the MER landing ellipse. For powered descent the landing ellipse could be as small as ~10km, but at a significantly increased propellant penalty. Airbag landing results in ~40g or higher acceleration loads, while a powered landing requires only ~20g. Both configurations would employ a single parachute.

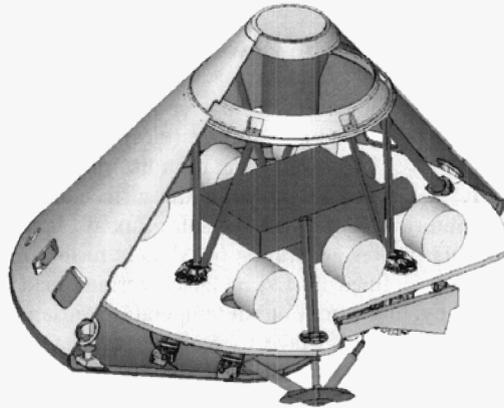


Figure 2. Viking type aeroshell, lander and rover

It is assumed that during landing, the rover decouples from the lander, performs initial health checks and environment assessment, egresses from the lander and initiates the surface operation phase. Active measurements would be planned for a 3-year mission duration, resulting in a total mission time of ~1400 days. Note that a radioisotope power system would provide continuous power through an extended mission phase. The actual mission duration is theoretically limited only by the failure of a key sub-system; most likely an actuator or other moving component, and is accelerated by uncontrolled thermal cycling. Component failures could be reduced by tight thermal control. When a mission extends over several years, additional development work is required to improve the reliability of the moving parts, including motors, actuators, wheels and robotic arm joints. The present rover configuration is shown in Figure 3. The top and mast of the rover are identical to those used on MER, and are not included in the figures to allow for better illustration of the internal components. The two small-RPSs would be placed at the end of the rover. Modular design of the RPSs would allow for much flexibility in placing them at the most suitable locations. In turn, the configuration (e.g., side-by-side, back-to-back) would impact the thermal and the radiation environments inside and around the rover. During the surface operation phase of the mission, the rover would perform scientific measurements and relays the data back to Earth. These issues are further discussed at latter sections of this paper.

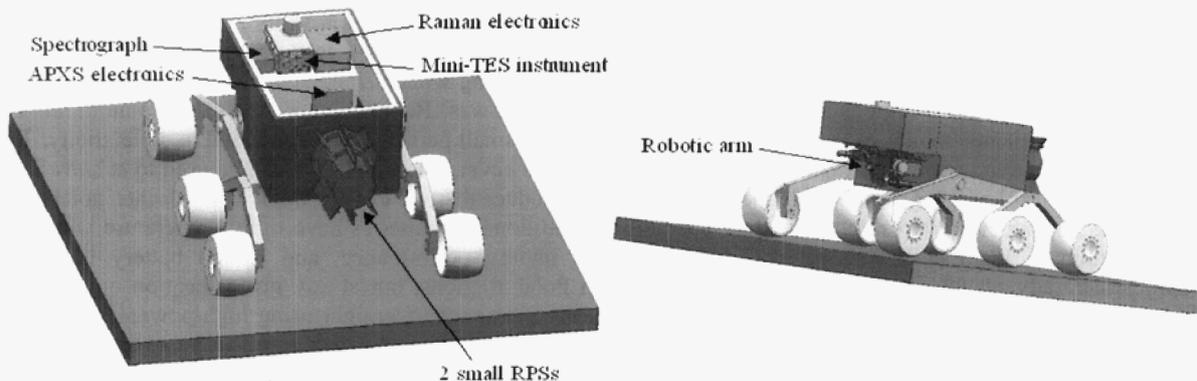


Figure 3. Rover configuration (top removed to show internal systems)

GENERAL ISSUES RELATED TO POWER

This section introduces the various issues associated with power system selection for Mars missions with a focus on small-RPS systems. It also provides a characterization of a small-RPS, and discusses alternate power systems. The actual power system sizing and power requirements for the present Mars rover will be discussed under the rover payload and system section.

Overview of the Power Source Trades

The Mars Exploration Rovers employed solar panels for power generation. The unfolded 1.3m^2 GaInP/SaAs/Ge triple-junction solar panels were capable of generating $\sim 140\text{We}$ (electrical)(BOL) peak power for up to 4 hours per sol, depending upon the season. Although solar power generation has many advantages out to 3.5 to 4.5 AU from the Sun, this section discusses the advantages of RPS power on the surface of Mars. Solar insolation varies inversely with the square of distance from the Sun (i.e., R^{-2}). Thus, the solar flux at Mars ($\sim 1.5\text{AU}$) is only about 43% of that at Earth (Balint, 2003). In addition, solar power generation on Mars is further impacted by atmospheric conditions, sand storms, operating latitude, seasons (defined by L_s), eclipses, terrain shadowing, and solar panel degradation (due to dust accumulation and thermal cycling from diurnal temperature variations) (Dawson et al., 2003). This can reduce the received solar flux on the Martian surface to 6.5% of that at Earth. Continuous year around solar availability is limited to the equatorial region and middle latitudes (from 60°N to 60°S). At higher latitudes, above 60°N and below 60°S , continuous power generation with solar panels is not feasible due to seasonal variations, resulting in low solar insolation during polar winters (see Figure 4).

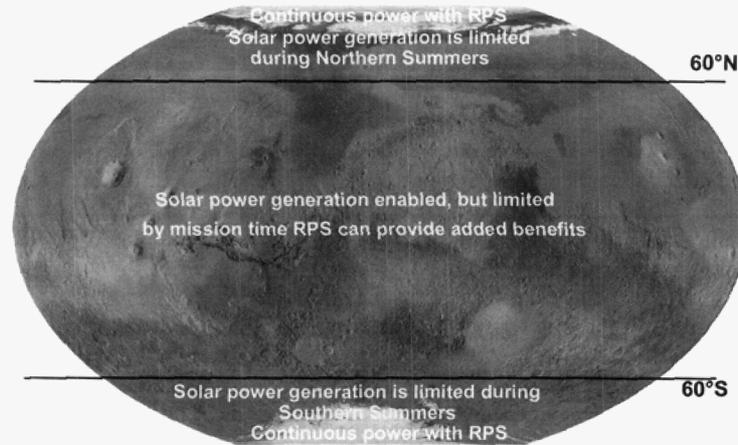


Figure 4. Power source selection for landing locations

RPS presents distinct advantages over solar panels. RPS-based power generation is independent of solar insolation and atmospheric effects. It also enables a significantly longer lifetime (measured in years), which translates into a longer mobility range that potentially allows for greater scientific returns and data accumulation. RPSs are ideal for rovers operating at high latitude regions, especially at the poles during winters. They enable operations in partially or permanently shadowed regions such as valleys, canyons and caves. Radioactive decay of the plutonium fuel generates a significant amount of thermal power, of which only a small percentage is converted into electricity. The rest is excess heat and nominally rejected to the environment. However, this waste heat can be used to achieve tight temperature control of subsystems inside the rover. This could reduce thermal cycling of the components, potentially decreasing component failures and extending operability. Additionally, batteries have tight temperature windows, and maintaining them at a constant 0°C helps preserve battery performance, and extend battery life. This characteristic advantage of RPSs is beneficial not only in Polar Regions, but at any given location on Mars. In comparison, solar powered systems rely on batteries to heat components overnight using high-powered resistance heating. It impacts the lifetime of the batteries, use up valuable resources and may result in an oversized power system, driven by system survivability requirements. Power system sizing is further discussed later in this paper.

General Characteristics of a Small-RPS

The power source for this rover study consists of two individual small-RPSs, each configured with a single GPHS module. There are 4 plutonium dioxide fuel pellets in each module. The total fuel and GPHS module masses are 0.5kg and 1.445kg, respectively. The thermal power output for each module is ~250Wt (thermal) at BOL. This heat output decreases exponentially, (approximated at a rate of ~0.79% per year) due to radioactive decay of the plutonium fuel. (Surampudi, 2001)

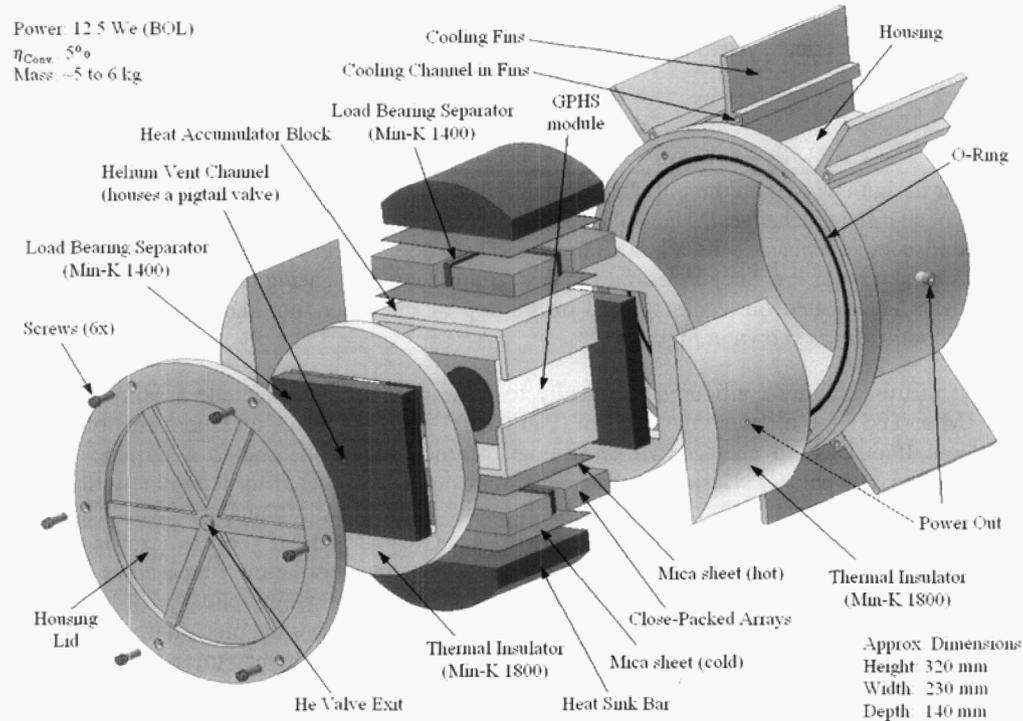


Figure 5. Conceptual small RPS using a single GPHS module

The heat generated through the decay process is converted into electric power using thermoelectric (TE) conversion. The selection of materials used for TE conversion varies, depending on the operating environment. For use in the Martian atmosphere, PbTe TAGS couples are proposed. There is a ~0.8% loss associated with TEs per year, resulting in a total power system degradation of ~1.6% per year.

Based on these assumptions, 2 small (single GPHS module based) RPSs can generate ~25We of power (or ~620Wh energy per sol) at BOL and ~23.44We (or ~580Wh/sol) at EOL. The calculated EOL values correspond to a 1 year cruise phase and 3 years of surface operation. In addition, the design also accounts for an appropriate heat rejection system for the 475Wt waste heat. The total mass of the two small-RPSs is assumed at ~12 kg, with approximate bounding dimensions of 320 mm by 230 mm by 140 mm. This is significantly smaller than a solar array system with similar power output (e.g., a 1.3 m² solar panel generates ~600Wh/sol at EOL and weights ~16.5 kg.) A conceptual drawing of a single GPHS module based RPS is presented in Figure 5 (Abelson et al., 2004), and is based on the works of Wiley & Carpenter (Wiley & Carpenter, 2004).

Alternate RPS Power Systems

For an alternate concept, segmented PbTe TAGS / BiTe couples could be used in a close-packed array (CPA) configuration, replacing the PbTe TAGS thermoelectric converters. CPA provides better structural support during acceleration loading (e.g., landing or roving) than the larger uncouples. This configuration could potentially increase the TE conversion efficiency from the conservatively assumed 5% to ~9-9.7% in the future (Wiley &

Carpenter, 2004). Beside static conversion technologies, dynamic power conversion could also be considered. A Stirling system would require less plutonium, while achieving higher power conversion efficiencies. This technology, however, has not been tested in a space environment; thus its acceleration load tolerance and lifetime must be demonstrated before use in future space missions.

PAYLOAD AND SYSTEMS DESCRIPTION OF THE MARS ROVER

This section describes the science instruments for the Mars rover and the supporting key systems such as the data and telecom systems, the thermal system and the power system. A summary of the mass breakdown is also provided.

Science Instruments

The present rover design is based on the initial MER configuration (NASA, 2004) to provide design heritage, but it incorporates two significant changes. The solar panels are replaced with two enabling small-RPSs, and the Mossbauer spectroscope is replaced with a laser Raman spectroscope to meet the astrobiology-driven science goals. The instruments on the rover are categorized into two groups: remote sensing and contact instruments. Remote sensing instruments are located on a mast placed on the top of the rover (not shown). Contact instruments are positioned on a robotic arm as shown in Figure 6.

Remote sensing instruments are configured identically to those on MER, and include a Mini-Thermal Emission Spectrometer (Mini-TES) and a Panoramic Camera (Pan Cam). Mini-TES takes measurements of emitted thermal infrared radiation. It is used to characterize mineralogy of rocks and soil, and to determine thermo-physical properties of selected soil patches. Beside surface measurements, it is directed to determine temperature profile, dust/water-ice opacity, and water vapor abundance in the lower atmospheric boundary layer. The collected data helps to understand the climate and geology of Mars (MEPAG Goals 2 and 3). The Pan Cam is used to generate 360° panoramas and multi-spectral images of the surface. This high-resolution stereoscopic imaging camera complements the rover's navigation cameras and aids in characterizing the geomorphology of the surface through the generation of terrain maps, slope maps and ranging. The Pan Cam works in conjunction with the Mini-TES to describe the Martian environment, thus providing a foundation for subsequent human missions (MEPAG Goals 3 & 4).

Contact measurements are performed with instruments positioned on the robotic arm. These instruments include a contact microscopic imager, an Alpha Particle X-ray Spectrometer (APXS), and a Mars Microbeam Raman Spectrometer (MMRS). These instruments are supported by a Rock Abrasion Tool (RAT). The microscopic imager is the combination of a microscope and a camera, and is designed to measure fine scale morphology, texture and reflectance of natural surfaces. This contributes to the petrologic and geologic interpretation of rocks and soil in support of MEPAG Goal 3. Small-scale imaging may help identify tiny veins of minerals, which potentially contain microfossils (MEPAG Goal 1). It also provides context imaging for collaborating measurements with other contact and remote sensing data. The MMRS performs mineral characterization and assists in the detection of water, organic and inorganic forms of carbon (MEPAG Goal 1). It identifies many major, minor and trace minerals and their relative proportions (i.e., Mg/Fe ratio), and carbon ratios. Sharp Raman spectral features and statistical point counting help identify minerals in complex mixtures and morphologies (MEPAG Goal 3). The APXS instrument uses alpha particles and X-rays to accurately determine the elemental chemistry of rocks and soils in order to complement and constrain the mineralogical analyses of other instruments. APXS can quantify the abundances of all rock forming elements, except hydrogen. It performs elemental analyses of Martian surface materials by direct contact with rocks or soil, and helps to understand weathering processes and water activity on Mars (MEPAG Goals 3 & 4). In order to expose the interior of rocks, a grinding wheel (RAT) is used to remove dust and upper surface layers. Rock abrasion is used as a precursor step before measurements are performed with the instruments listed above. It can also be used to measure rock hardness during RAT penetration. The performances of the above instruments are considered identical to those on MER (with the exception of the MMRS), presenting significant design heritage. (NASA, 2004) (Diehl et al., 2004)

While the remote and contact sensors are located external to the rover, the delicate instrument electronics are placed inside the rover's warm electronics box (WEB) for protection against the harsh Martian environment.

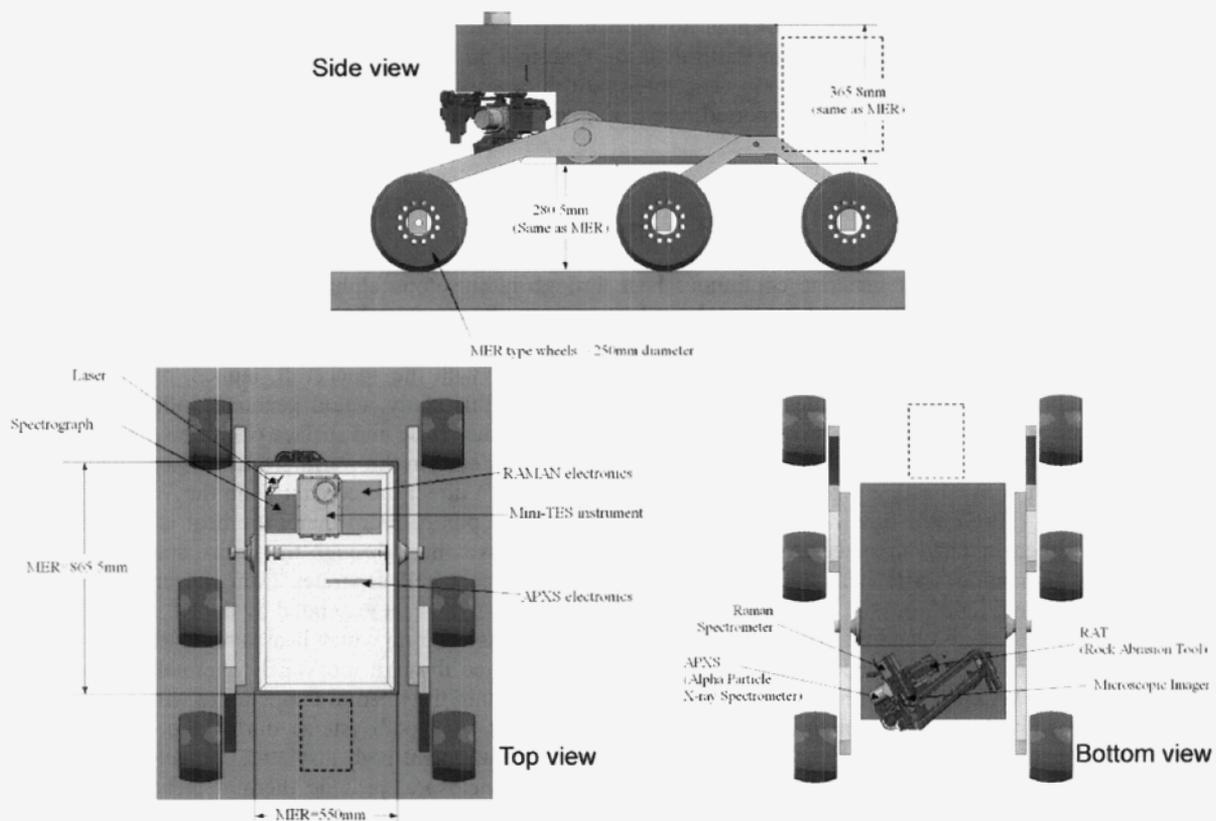


Figure 6. Rover instrumentation

Data and Communications Systems

All science instruments described above generate valuable scientific data that needs to be stored and returned to Earth. Engineering data is also collected and returned. A bounding estimate is given here for the present rover configuration. The rover is calculated to collect, on average, between 50 to 100Mbits of data per sol (Spirit and Opportunity each generated and collected up to 50Mbits of data per sol). The actual data accumulation rate is driven by the science needs. For example, taking high-resolution stereoscopic Pan Cam images or using the microscopic imager results in raw data up 12.5Mbits per image. All collected data is stored on a 256MB flash memory card. If required, this storage capacity can be increased without significant impact on the rover design.

The telecom design for the rover is similar to that used on MER. Communication between the rover and Earth relies on the Mars Telecom Orbiter planned to arrive at Mars in 2010, which for the purposes of this study would be just before the arrival of our concept rover. The MTO will orbit Mars at an altitude of 4450km with a 13.5° inclination. The rover would also utilize the Mars Global Surveyor, and/or the Mars Odyssey, and potentially any other orbiting assets available at the time of the mission.

The rover design uses X-band and UHF electronics. Antennas include a 0.28m X-band high gain antenna (HGA), an X-band low gain antenna (LGA), and a UHF monopole antenna. This configuration is identical to the MER design, except MER's CE 505 UHF transceiver is replaced with the new ElectraLite transceiver.

This configuration would be capable of transmitting up to MTO in the X-band at a rate of 1.024Mbps. The UHF downlink from MTO to the rover is available at a rate of 8kbps. From MTO the rover data is sent to the Deep Space Network (DSN) in X-band at 400kbps or Ka-band at 500kbps. Direct to Earth (DTE) communication from the rover is available from the rover's X-band HGA to the 34m DSN antenna at a rate of 1kbps. The uplink from DSN (34m) to the rover's X-band HGA can reach a maximum data rate of 2kbps.

It is concluded that with the availability of high uplink data rate to the Mars Telecom Orbiter (MTO), significantly more data can be collected and relayed to Earth than the specified 50 to 100Mbits per sol, allowing for increased operational flexibility throughout a mission. The multiple orbital assets around Mars and the capability of DTE communication would provide a well-supported mission environment for the rover to transfer all collected science and engineering data to Earth.

Thermal System

Radioisotope Power Systems generate continuous heat through radioisotope alpha decay of Pu^{238} , which has an 87.75-year atomic half-life. The generated heat degrades exponentially at a very low rate ($\sim 0.79\%$ per year), making Pu^{238} an ideal choice for powering long duration missions (Surampudi, 2001). However, the waste heat must be removed throughout all mission phases, including RPS integration with the spacecraft, launch, cruise, EDL and surface operation. Two GPHS modules of the type considered in this study would generate $\sim 500\text{Wt}$ of thermal power. For the present design, fluid thermal loops are used for both the cruise and surface operation phases. During cruise phase, heat is generated by electrical systems (CPU, avionics, etc.) in the warm electronics box that must be removed to prevent overheating (see Figure 7). Thermal valves (TV) direct the coolant from the WEB to the heat rejection system (HRS) at a flow rate of 0.5l/min , driven by a 5W pump. From there, the heat is rejected to the aeroshell and then radiated to space. An additional loop also removes heat through the cruise stage to radiators, rejecting the remaining waste heat into space. Before EDL, the aeroshell separates from the cruise stage and disconnects the fluid loop from the aeroshell. For the short EDL phase, the heat generated by the RPS is absorbed by the aeroshell. A successful landing initiates the surface operation phase, during which heat is removed by the rover's HRS, consisting of two fluid loops connected to radiators and routed through the WEB. Thermal control valves inside the rover's WEB, along with aerogel thermal insulation, maintain the internal temperature within a set range. This thermal control helps minimizing thermal cycling of critical rover subsystems during the diurnal period, thereby increasing the mission lifetime. A primary loop services equipment both inside and outside of the rover's thermal enclosure. Fluid lines, installed external to the thermal enclosure, provide thermal management to the mobility electronics (ME). The backup loop services only the equipment inside the WEB and has no lines external to the thermal enclosure. Heat exchangers outside the rover can be sized to remove waste heat during daytime, when the WEB does not require heating. This thermal design is similar to that suggested for MSL. Other heat rejection systems can also be considered, for example removing excess heat from the RPSs with heatpipes. (Diehl et al., 2004)

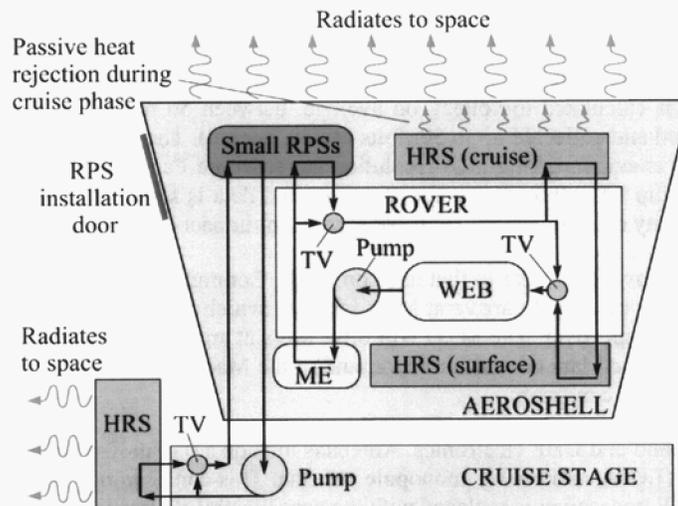


Figure 7. Thermal design concept for an RPS-enabled rover

Power System Sizing

This section describes power-sizing considerations, including power allocation to science instruments and assumed activity modes. Being a MER derivative, the power requirements for this rover are similar to that of MER, where the solar panels generate 900Wh/sol energy at BOL, and 600Wh/sol at EOL. For successful substitution of the power source, RPSs on the rover should provide as much energy as similarly sized solar panels. Thus, the RPS enabled rover requires a minimum of two GPHS modules, supplying a total of ~620Wh/sol, based on continuous power generation of ~25We at BOL. Figure 8 shows the position of the two RPSs at the back of the rover.

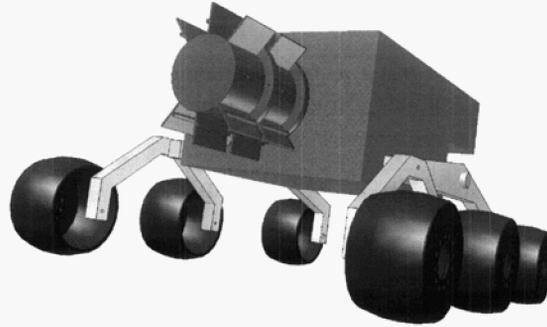


Figure 8. View of the rover wheels and the RPSs

On solar powered rovers, high load activities are performed around Martian noon to maximize the use of the peak solar flux. Since the peak power from the two RPSs would be lower than that of the solar variant, a hybrid power system is considered. This system would combine two small-RPSs and two 8Ah 28V Li Ion batteries to obtain MER type capability. The total energy stored in the fully charged secondary batteries is ~448Wh.

The power system is sized by assessing the power requirements for typical activity days, based on instrumentation, operating procedures and assumed measurement sequences. The power requirements for the rover's instruments are given in Table 1. Additional systems that require power include command and data handling, power distribution, attitude determination and control (for mobility), and telecommunications.

Five distinct activity modes are identified for the power analysis, with each representing a single activity day. The panorama mode defines the use of the panoramic camera (~11Wh). The Mini-TES mode represents the use of the Mini-Thermal Emission Spectrometer (~40Wh). Three drive modes are considered. During simple drive (low impact) the terrain is characterized by low hazard levels and low rock abundance (~85Wh). During complex drive the terrain has large rocks, deep sand or steeper hills drawing higher power than simple drive (~125Wh). Approach drive precedes the use of contact instruments and is characterized by slow motion over short (<10m) distances while drawing ~100Wh of energy. Contact measurement activities with the microscope or Raman use ~40Wh. When using the RAT, the energy requirement for this mode of operation increases to ~55Wh. The last activity is defined as a charge day, which usually follows a high-energy activity day to recharge the depleted secondary batteries.

TABLE 1. Rover instrument power requirements

Instrument	Power
<i>Remote sensing instruments</i>	
PANCAM on mast	4.3 W
Mini-TES	5.6 W
<i>Contact instruments</i>	
Microscopic Imager	2.1 W
Raman Spectrometer	18 W
APXS	0.7 W
<i>Support Instrument</i>	
Rock Abrasion Tool (RAT)	11 W
<i>Support Equipment</i>	
Hazcam/Navcam (Context)	5 W
Mast actuator	0.1 W

In addition to the energy requirements for any of these activity days, a housekeeping overhead and two 80Wh telecom loads are also added. Detailed analysis of the activities indicated that the highest power usage occurs during complex drive days, and the highest operating modes are mobility and telecom. For these operations, batteries complement RPS power. Assuming 1 hour of intense drive and two one hour telecom windows, the battery charge ends in a power negative mode, which means that the charge level at the end of sol is below that at start. This can be resolved by following on with a charge day. Continuous driving represents the bounding case for traversing, when the system uses all of the RPS generated power and simultaneously draws power from the batteries. Driving can be made more efficient by either increasing the battery size (impacting rover mass and size) or by changing from continuous drive to stop-and-go operation, where after a short drive the rover would stop, charge back the batteries and then go again.

In summary, the power analysis indicates that two GPHS modules would provide enough power and energy to enable a MER-class rover design, with a similar instrument complement and power profile.

Rover Mass Summary

The rover mass is calculated at 181kg, but the launch mass differs depending on the landing approach. For an airbag landing, the launch mass is 1070kg and the final landed mass (rover, landing platform and airbags) is 410kg. Using a powered lander the launch mass is 1620kg, and the landed mass is 700kg. The higher landed mass is attributed to the powered descent stage. A breakdown of the rover's mass allocation is shown in Table 2, detailing both the instrument mass and the support system mass allocation. The rover carries 9.5kg of science instrument payload. The support system includes components for telecommunication, attitude control system, thermal management, power, mechanical and avionics systems. Telecom covers electronics and antennas. The thermal system accounts for the heat rejection system (radiations), thermal valves, pipes and pumps. The power system includes the small RPSs (12kg), batteries (7.5kg) and power electronics. Avionics accounts for electronics and interface boards to the various systems and sub-systems. The largest mass is assigned to the mechanical components, including the rover's body (with thermal insulation), the drive mechanisms, drive train, and wheels. The dimensions, instrumentation and total mass of this rover concept are comparable to that of MER.

Table 2. Rover mass allocation

Instrument	Mass
<i>Remote sensing instruments</i>	
PANCAM on mast	0.7 kg
Mini-TES	2.7 kg
<i>Contact instruments</i>	
Microscopic Imager	0.3 kg
Raman Spectrometer	2.5 kg
APXS	0.5 kg
<i>Support Instruments</i>	
Rock Abrasion Tool (RAT)	0.9 kg
Calibration Target; Magnets etc.	1.9 kg
Total Instrument Mass	9.5 kg
<i>Rover Support Systems</i>	
Telecom	16.6 kg
ACS	2.6 kg
Thermal	2.7 kg
Power	23.0 kg
Mechanical	97.0 kg
Avionics	30.0 kg
Total Rover System with Instruments	181.4 kg

ISSUES RELATED TO ROVER OPERATIONS AND TO THE ENVIRONMENT

Mobility Related Issues

Two important mobility requirements are addressed in this section, namely traversing and hazard/obstacle avoidance. It has been shown in previous and current landed missions (NASA, 2004) that the Martian terrain varies significantly with location. Experience from the Mars Pathfinder mission showed that landing site determination is important relative to the size of the rover. The highest resolution Mars orbital cameras provide only 1.5m/pixel resolution. The Sojourner Rover, with a length of 0.6m, had to land in an area where rock size, distribution and abundance would not significantly affect its operation (Golombek, 2002). Figure 9 shows Sojourner in-situ, illustrating the relationship between rover size and environment (NASA, 2004). Similarly, boulder fields at Olympus Mons Caldera include terrains with 12m diameter rocks. Such fields with over 20% rock abundance might be difficult or even impossible to traverse using any of the planned rovers. Other areas such as the Gusev Crater and the Meridiani Planum presented a suitable environment in comparison to the size of MER.

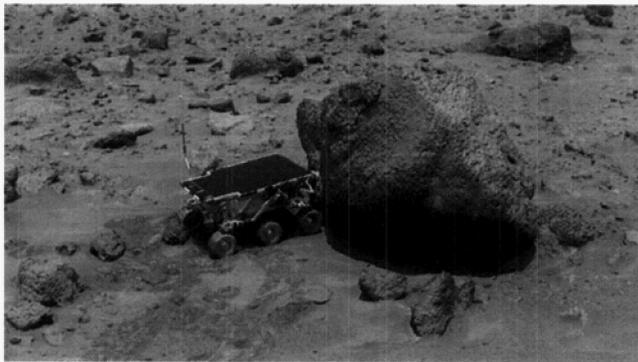


Figure 9. Sojourner and the rock named Yogi

The present design uses MER heritage for mobility. The diameter of each of the 6 wheels is 25cm (see Figure 8), identical to those on MER. Larger wheels can assist with negotiating tougher terrains, but require more torque and, consequently, larger wheel actuators. In fact, the cascade effect from an enlarged wheel size can result in a significantly greater total mass.

The terrain also influences rover traversability and associated power requirements. Driving on rocky, sandy or hilly topography requires more power than driving on flat hard surfaces. To account for these diverse conditions, the traversing analysis for this rover concept divided driving into a number of operating modes, such as complex or normal driving. These modes are further explained above under the power sizing section. MER-class rovers are capable of traversing at speeds about 35 to 72m/hour depending on the terrain. Assuming 2 drive-days per week, 1 hour drive per day and 3 years of operation on the surface, the small RPS enabled rover could traverse distances up to 20-25km over its nominal lifetime. In comparison, a solar powered rover could only cover about 1 to 2km due to its limited lifetime. It can be concluded that small RPS enabled rovers could cover an order of magnitude more terrain than solar powered rovers, due primarily to the significantly longer mission time. This would allow more opportunity for traversing, exploration, and data collection than a solar powered equivalent.

Radiation Environment

Electronic components are affected by radiation and can tolerate ionizing radiation doses only up to a certain limit. Space based instruments counteract the damaging effects by using radiation hardened components. Today's state-of-the-art radiation hardened electronics can tolerate doses up to 300-500kRad and there are discussions about increasing this tolerance in the near future to as high as 1MRad. For RPS enabled missions, ionizing radiation is attributed to natural (cosmic) radiation sources and to radiation from radioisotope decay of the Pu^{238} fuel. Decay radiation primarily consists of alpha particles, which are essentially helium nuclei. These high mass particles can be blocked easily even with a sheet of paper. However, a small amount of secondary radiation is also present in the

form of gamma and neutron flux. Neutron shielding is not effective with the available rover wall thicknesses. Hence it is necessary to address the impact of the above-mentioned ionizing radiation environment on the mission hardware.

The two small-RPSs used in the present design would be installed at the back of the rover. Two configurations are considered – side-by-side and back-to-back (see Figure 10). The radiation environment was scaled from preliminary data for a single GPHS module (Jun, 2003), and presented in Figure 10 for both studied configurations. The calculated total ionizing dose (TID) radiation levels are based on a generic mission with a conservative 1-year cruise phase and 3 years of surface operation. It is found that the radiation dose for the back-to-back configuration would be marginally higher. For this case, natural radiation accounts for $\sim 1.43\text{kRad}$ during cruise, and $\sim 0.52\text{kRad}$ on the surface, whereas with the radiation from the RPSs added, the maximum would be $\sim 16\text{kRad}$. Due to distance and radiation shielding by the structure, the internal radiation dose within the rover would be $\sim 2\text{kRad}$. The results are similar for a side-by-side configuration, where the maximum radiation dose would be $\sim 14.5\text{kRad}$.

As a result, it is concluded that radiation would not present any difficulties for MER-type instruments designed to tolerate at least 150kRad (i.e., 300kRad with a Radiation Design Factor of 2).

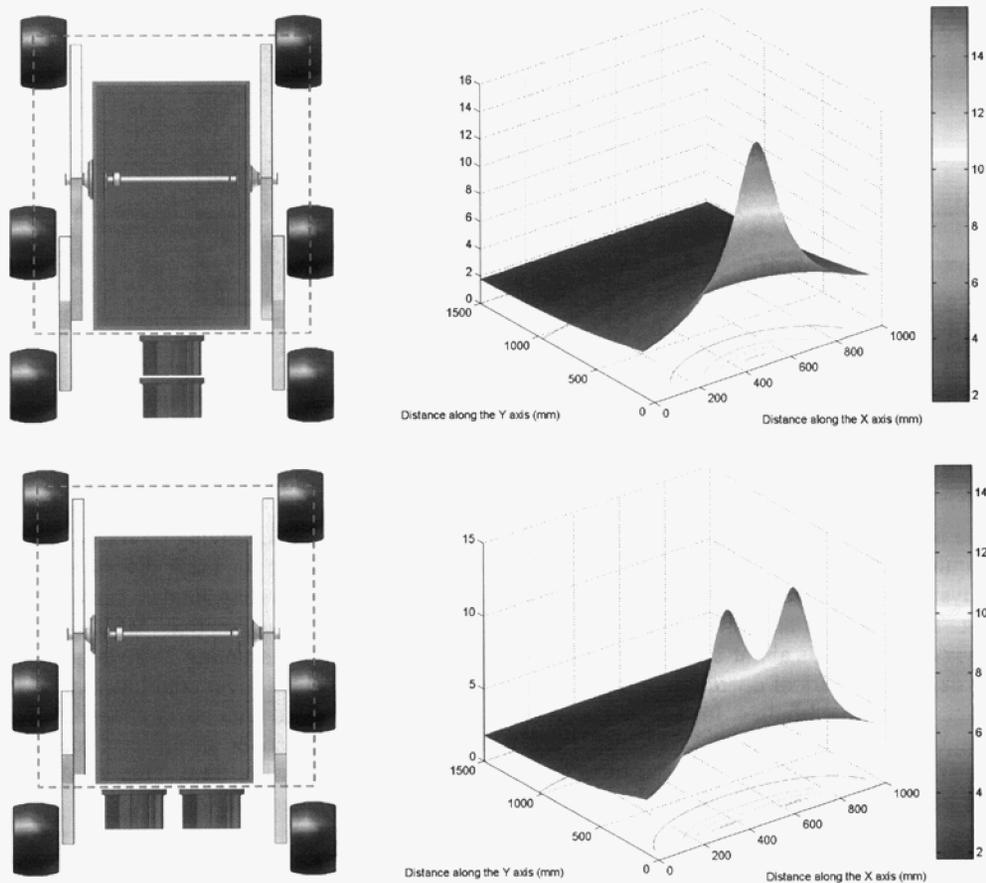


Figure 10. Radiation environment for two RPS configurations: (a) end-to-end configuration and (b) side-by-side configuration, dotted line represents area in radiation plots

ADDITIONAL RPS-ENABLED ROVER MISSIONS

This section described a Mars surface rover mission concept using 2 GPHS modules, providing 25We of power to a 180kg MER-class rover. Further studies were also performed to scale the rover up to about 230kg, requiring 50We of power (or 1250Wh/sol energy), supplied by 4 GPHS modules. The largest, but only slightly larger rover accommodated additional astrobology driven instruments, such as a Gas Chromatograph / Mass Spectrometer (GCMS) with an oven, X-ray Diffractometer / X-ray Fluorescence Spectrometer (XRD/XRF), a Mossbauer Spectrometer and a high-resolution contextual microscope. Scaling further up, a pre-decisional early variant of the MSL rover was envisioned with two multi-mission RTGs (MMRTGs), generating a total of 220We power (or 5500Wh/sol energy). However, the size of this rover and its power source is not within the scope of the present small-RPS study. Scaling down, a Mars Pathfinder-class rover required around 150Wh/sol, which corresponds to a half-fuelled GPHS module. Micro-rovers are found to be too small to accommodate a GPHS module. Radioisotope Heater Unit based power sources coupled with a battery and a capacitor could provide enough energy in a trickle charge / burst operating mode to enable a certain amount of functionality. However, the small size in relation to the surrounding terrain and the power needs to perform power intensive functions, such as traversing or telecommunication, may limit the applicability of such mobility devices (see Figure 11).

In summary, these studies demonstrated the viability of a class of small rovers enabled by 2 to 4 stacked single-GPHS module based RPSs, with special focus on a power range between 25 and 50We.

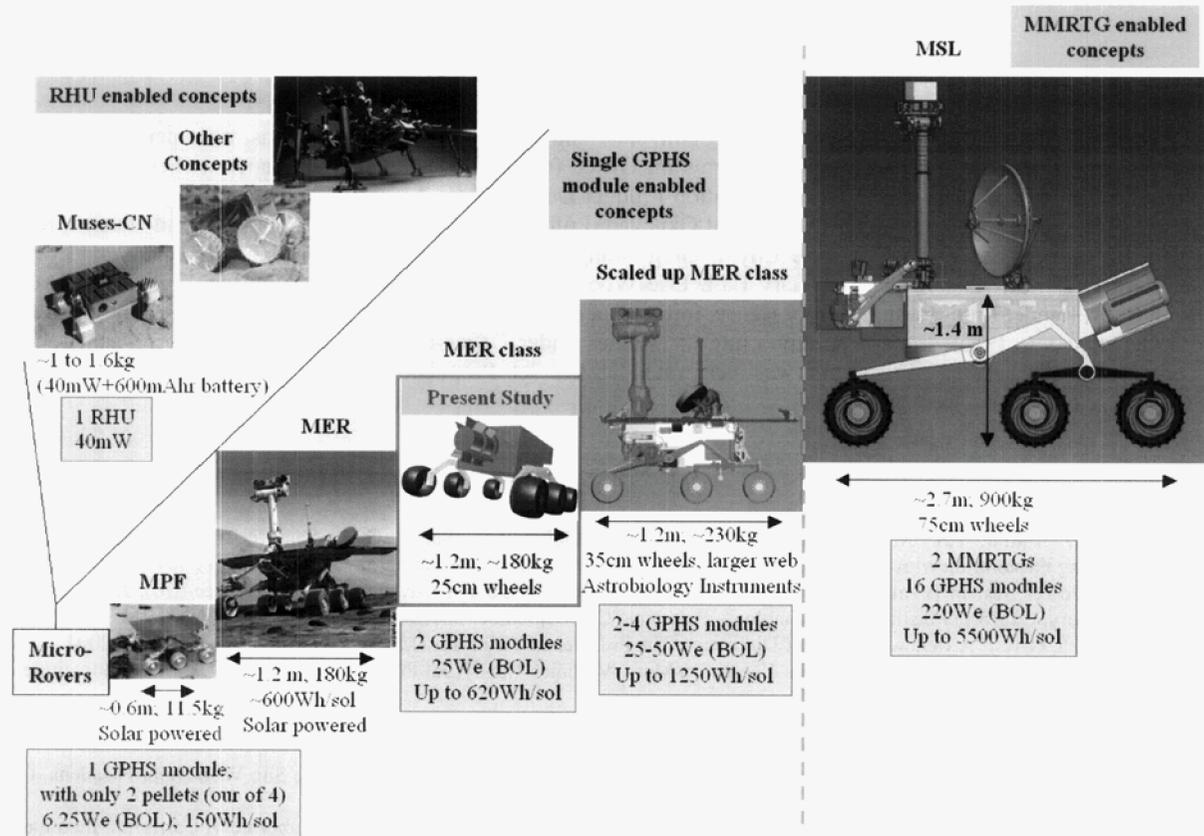


Figure 11. Additional rover concepts

CONCLUSIONS

The study described here assessed the feasibility of a MER-class rover using two small-RPSs. Each of the power systems utilizes a single GPHS module, generating ~12.5We of power. Since RPSs operate continuously, the 25We power from the two GPHS modules could produce up to 620Wh energy per sol, which with the proper battery system would enable MER-class rover operations. Assuming 3 years of surface operation and a 1-year cruise phase, the power would drop to 23.44We (corresponding to 580Wh/sol), due to degradation of the fuel and the thermoelectric converter. This energy/sol is comparable to that of MER. However, the RPS-enabled rover would have a lifetime much greater than the nominal 90 days of the MER mission. The rover's power system is sized to handle peak power demands and to maintain a positive energy balance, based on typical daily surface activities. The highest power usage is contributed to mobility and telecom for this configuration. To perform these activities, a hybrid power system was adopted using the combination of RPSs and batteries. Such a system has the potential to surpass solar powered systems in mission duration, location accessibility, and mobility over lifetime. Besides rejecting the excess heat generated by radioisotope decay, a portion of it can be utilized by routing through the rover's warm electronic box, controlled by thermal valves. This provides another unique capability even where solar power is feasible, due to tighter temperature control with waste heat utilization. It is also found that radiation from the RPSs should not present problems to the rover's electronics and instruments. While this point design focuses on a rover with two small RPSs, the conclusions are applicable to other scaled up rovers as well. Therefore, it is believed that this technology has the potential to support future rover missions for Mars exploration, targeting astrobiology related science objectives and powered by 2 to 4 GPHS modules.

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