Design Concept for a Nuclear Reactor-Powered Mars Rover

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Abstract. A study was recently carried out by a team from JPL and the DoE to investigate the utility of a DoE-developed 3 kWe surface fission power system for Mars missions. The team was originally tasked to perform a study to evaluate the usefulness and feasibility of incorporation of such a power system into a landed mission. In the course of the study it became clear that the application of such a power system was enabling to a wide variety of potential missions. Of these, two missions were developed, one for a stationary lander and one for a reactor-powered rover. This paper discusses the design of the rover mission, which was developed around the concept of incorporating the fission power system directly into a large rover chassis to provide high power, long range traverse capability. The rover design is based on a minimum extrapolation of technology, and adapts existing concepts developed at JPL for the 2009 Mars Science Laboratory (MSL) rover, lander and EDL systems. The small size of the reactor allowed its incorporation directly into an existing large MSL rover chassis design, allowing direct use of MSL aeroshell and pallet lander elements, beefed up to support the significantly greater mass involved in the nuclear power system and its associated shielding. This paper describes the unique design challenges encountered in the development of this mission architecture and incorporation of the fission power system in the rover, and presents a detailed description of the final design of this innovative concept for providing long range, long duration mobility on Mars.

INTRODUCTION

The planning of Mars surface missions has progressed in recent years in the direction of increasing complexity and science return within the capabilities of existing or planned technologies. This has meant, until recently, a focus primarily on solar energy, which places inherent limitations on both mission power and longevity. The longevity issue can be addressed in a very efficient manner by the use of Radioisotope Power Systems (RPS), as are currently being considered for the Mars Science Laboratory (MSL) mission in 2009. RPSs have demonstrated their capability in the Martian environment with the Viking 1 and 2 missions, which lasted six and four years, respectively, on the surface of Mars. The Viking generators provided about 70 We to each lander, and new designs currently under development will provide RPSs with a power level of about 120 We per unit.

Beyond power levels of about 1 kWe, however, the application of RPSs begins to be prohibitively massive and expensive, especially for a landed system. At levels beyond about 3 kWe, the use of a fission power system for surface applications becomes an attractive alternative. A design concept for just such a surface fission power system has been developed recently by the DOE (Lipinski, 2002) in the form of the HOMER 15 kWt heat-pipe reactor coupled with a 3 kWe Stirling converter. This surface fission power system combines low mass and a simple design supportive of near-term technical feasibility in a package that lends itself well to application in current-technology Mars lander design. A team from JPL, working together with the DOE was tasked with exploring mission options that could make use of this power system to enable innovative Mars science in missions that could be launched within the next decade. Early in the study the team decided that two concepts should be developed, one for a stationary landed mission and one to explore incorporation of the power system in a long-range rover. Stationary landers equipped with high-output, long-lived fission power systems have the potential to deliver unprecedented science return from a wide variety of different missions. The addition of mobility to a landed mission further increases the utility of the nuclear power source by providing the opportunity to perform science data collection at diverse sites, allowing a single landed mission to provide regional science data. In addition, rover-mounted power systems enable their application to multiple-landing missions, where the mobility of the power system allows it to locate and power science instrument payloads that may be landed in the vicinity of the original rover landing site.

SCIENCE

The long-range, long duration capabilities of the rover provide opportunities for a variety of science missions The current study evaluated a number of concepts for specific science objectives that would maximize the benefits provided by the rover platform and operations scenario. Study constraints limited the amount of time that could be spent on refining or optimizing the rover payload, but as a baseline the following suite of science objectives was developed:

- High resolution stereo imaging to take advantage of very high data rate to return large number of images and full motion video from diverse geographic locations
- A meteorological instrument package to characterize climate and weather variations between diverse sites
- A sampling arm with macro imager and laser raman spectrometer to evaluate regolith composition over a wide region
- An arm-mounted astrobiology package to evaluate sampled material for indicators of past or present life

Additional science alternatives considered by the study team that could be incorporated in a rover mission include:

- Towed ground penetrating radar for detailed subsurface mapping
- High powered laser-induced breakdown spectroscopy (LIBS). At the power levels available, LIBS instruments could be used to obtain remote elemental analysis of material up to 450m distant from the rover.

As mentioned, the range of potential science applications available for this rover design is broad. This study was constrained to focus primarily on design feasibility for this first look, but additional evaluation of science missions for the rover is suggested as an advisable future task

MISSION DESIGN

The selected landing site for the mission is the in the Elysium Plantetia region at 7.2° N, 217° W.

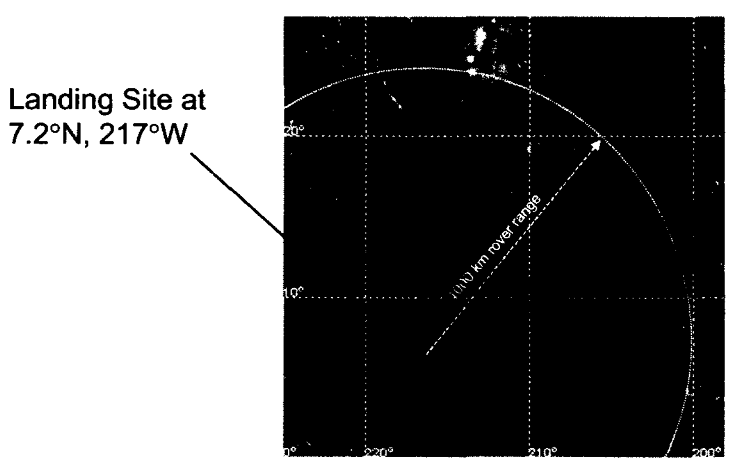


Figure 1. Landing Site.

The area provides a smooth landing site in rover range of a number of diverse geologically interesting target areas.

The study team targeted the Mars Atomic Rover for Geographic Exploration (MARGE) Mission for a late October 2011 launch resulting in an August 2012 arrival. The 2011 launch date was chosen as the first opportunity following launch of the MSL mission in 2009. The spacecraft will launch aboard a Delta IV heavy launch vehicle.

The natural transfer geometry to Mars in 2011 favors landings at low or southern latitudes. Thus the Elysium area can be reached using the most favorable transfers of this opportunity. A 20-day launch period has been found which minimizes launch energy given a constraint of a 30° declination of the launch asymptote. The resulting launch, transfer, and arrival parameters are given in the following table:

TABLE 1. Mission Transfer Parameters.

Parameter	Opening Day	Closing Day
Launch date	2011-10-30	2011-11-19
Arrival date	2012-08-28	2012-11-06
Launch energy, C_3 (km^2/s^2)	9.66	9.64
Delta 4050H capability (kg)	7860	7860

This mission uses a direct Type II transfer from Earth to Mars, leading into a direct entry into the Martian atmosphere. An MSL-derived aeroshell and heatshield was baselined to protect the lander during entry until the spacecraft has decelerated enough for a Viking-style parachute (qualified to a Mach 3 envelope) to open and slow the velocity further. Within a few kilometers of the surface, the on-board radar altimeter begins operating and at the appropriate altitude signals parachute release and initiates powered descent to a soft landing in the Elysium Planetia area at 7.2° N, 217° W. Surface operations including communications, deployment and power system startup will be battery powered until the nuclear reactor achieves full-power operations. Mobility and science operations will commence within a week or two of landing and continue for a nominal mission of 5 yr (2.6 Mars years).

ROVER DESIGN

The MARGE rover configuration was derived from an early concept model used to explore MSL rover development options (Figure 2). The MSL model represented an approximately 800 kg rover, solar powered with folding arrays. The rover length was about 2.5m. This configuration seemed ideally suited to accept the volume of the HOMER reactor, which needed only slight modifications to allow it to be placed in a horizontal orientation within the conceptual rover body. In addition it was decided that the power system should be modified to employ dual redundant stirling generators for this mission to ensure reliability over the five-year duration.

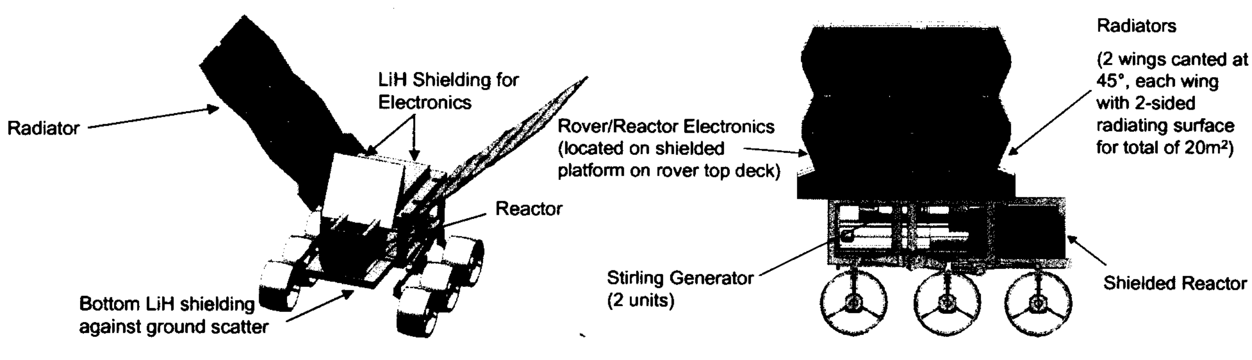


FIGURE 2. Rover Configuration.

The fission power system is incorporated inside the body of the rover, as are the batteries comprising the non-nuclear power subsystem. All electronics for the rover and instruments are located on a shielded deck on the top of the rover at the end opposite the reactor. Power system radiators form two deployable wings extending at a 45°

angle up from the deck. Each wing has a two-sided radiating surface for a total of about 20 m^2 of radiator area. Not shown in the figure are the 3m X-band high gain antenna, which will depoy above the deck, and the robot arm.

Mass Summary

The Delta IV launch vehicle provides a worst-case launch mass capability of 7860 kg for the C_3 needed for this mission. The rover mass, including the fission power system, electronics, and science payloads totals to 3284 kg, as summarized in Table 3.3 below. Using an MSL-derived pallet lander (which itself is estimated to weigh 1000 kg) brings the total landed mass to approximately 4284 kg. The MSL-derived EDL system for this mission is estimated to weigh about 1142 kg resulting in a total entry mass of about 5426 kg. A mass of about 400 kg is estimated for a basic cruise stage, patterned on those under consideration for MSL, bringing the total launch mass to 5826 kg. It should be noted that the MSL design that we are adopting uses the lander propulsion system for cruise attitude and trajectory correction maneuvers. Propellant mass is included in the mass estimate for the EDL system.

TABLE 2. MARGE Rover Mass Summary.

Element	Mass (kg)	Element	Mass (kg)
Reactor Power System	545	Power electronics	34.8
Structure	35	Radiator	72
Telecom	74.2	Shielding	1169
Thermal	2	Sampling arm and Instruments	42
Avionics box	17.3	Astrobiology science package	2.5
Primary battery (for EDL and deployment)	37	Rover Structure	1200
Secondary battery	53.4	**Total Rover Mass**	**3284.2**

The wet launch mass of 5826 kg leaves a mass margin of 2034 kg over the Delta 4050H worst-case capability. This gives a spacecraft mass margin of almost 35% for this mission.

The launch configuration was modeled after an early MSL concept and is designed to fit in the 5 m Delta IV shroud. Since the rover design study is based on fitting the power system in an existing rover concept, the landed mission elements should be easily accommodated in the MSL 4.57 m aeroshell. The MARGE mission baseline was to use an MSL-style landing system enhanced through the use of a Mach 3-qualified parachute system, which is estimated to be able to deliver a total landed mass of about 3616 kg to the surface of Mars. The total estimated landed mass of the rover mission is about 668 kg over this capability, which may push this mission to adopt a mid-L/D aeroshell for the entry system. Work performed by JSC and LaRC indicates that the application of a mid-L/D aeroshell with a Mach 3 parachute envelope may enable a total landed mass of about 4308 kg, which should be adequate for this mission.

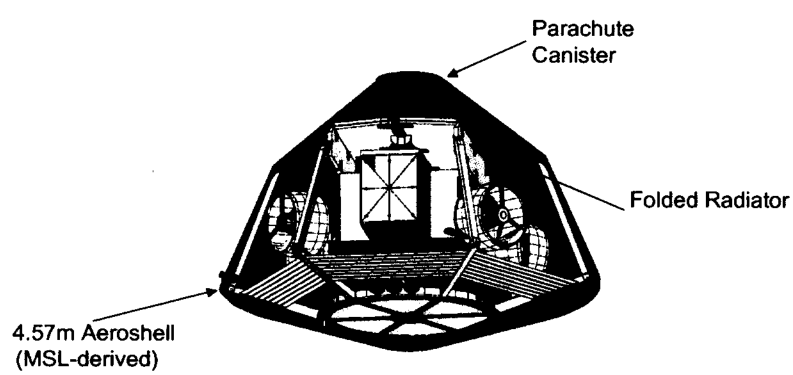


FIGURE 3. Rover in Aeroshell.

Subsystems Design

The design of subsystems for the MARGE rover maximizes the adoption of proven elements from heritage missions, or those presently in development. New technology development was kept to a minimum for implementation of any of the lander subsystems incorporated in the design.

Telecommunications

The rover has the capability to receive commands from and transmit telemetry to Earth either directly-to-Earth (DTE) at X-band, or through a Mars communications satellite (nominally the ASI Marconi satellite) at UHF. The Earth will normally be in view at least one half of each sol. Figure 4 depicts possible links.

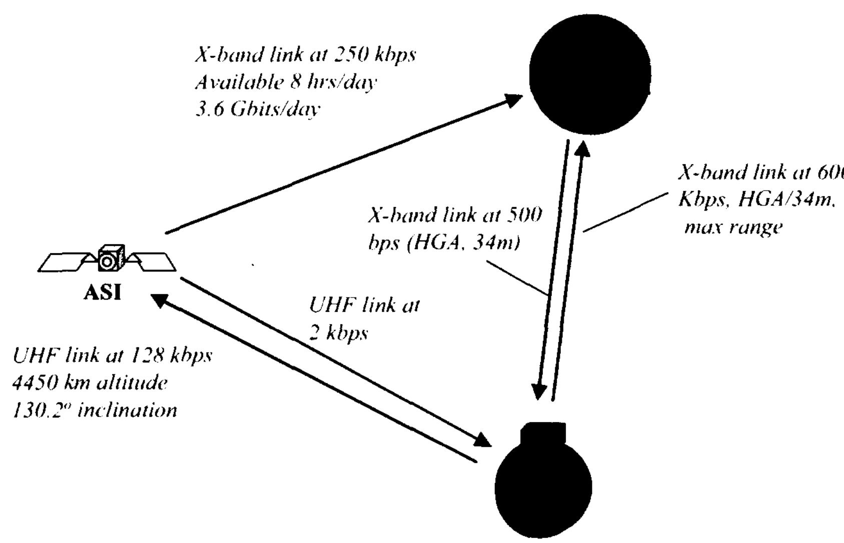


FIGURE 4. Telecommunications Links.

Telemetry return shall nominally be done at X-band directly back to Earth through the rover-mounted 3m high gain antenna. This includes the science and engineering data. The rover telecom system will support a telemetry rate of 600 kbps at the maximum Earth range of 2.65AU. The nominal data volume per sol is 2 Gb of science data and 5 Mb of engineering data.

Avionics

The MARGE electronics design is adapted from that developed for the Mars Exploration Rover (MER) and Mars Reconnaissance Orbiter (MRO) spacecraft. Rover electronics will be incorporated in a warm electronics box mounted on the shielded area of the rover's top deck. The electronics used in this design are rated to withstand a total ionizing dose of 300 krad with a radiation design margin (RDM) of 2. The electronics platform and reactor shielding design provides a maximum dose of approximately 200 krad over the five-year mission.

Power

In addition to the fission power system the rover incorporates batteries for portions of the mission when the reactor is not available. A primary battery is included to provide energy for the entry, descent and landing (EDL) phase of the mission, and to power the rover during a three-day initial deployment through initial reactor startup. This energy will be supplied by an 8400 Whr Lithium Thionyl Chloride primary battery based on an existing design developed by JPL for the US Air Force. A secondary battery will provide the energy in the event of a reactor anomaly during the rover mission. This battery is sized to provide energy for a two-day recovery period to support telecom and other engineering systems (but no science), as well as one additional reactor startup cycle. The total energy storage requirement was estimated at 2085 Whr. This requirement will be met by three 25-Ahr Li-ion batteries based on the design originally developed for the Mars '01 Lander Mission.

Surface Fission Power System

The surface fission power system (Figure 5) uses a heatpipe-cooled, UN-fueled, stainless steel-clad, pin-type reactor incorporating a dual unit redundant Stirling power conversion system (Lipinski, 2002). Heat is rejected to the cold Martian surroundings via a set of capillary pumped loops embedded in two deployable radiator wings providing about 20 m^2 of total radiating surface area. The system produces 3 kWe and its mass (excluding shielding and radiators) is presently estimated to be 545 kg. A Stirling conversion system was chosen because its high efficiency reduces the amount of fuel burnup, radiation levels, and heat that the radiator must reject. A heatpipe-cooled reactor was chosen because it provides parallel heat-removal paths for the reactor without an external pump and has the potential for reduction in development and testing costs due to its modularity (Poston, 2001). Heatpipes also have been proven to be able to handle multiple freeze-thaw cycles.

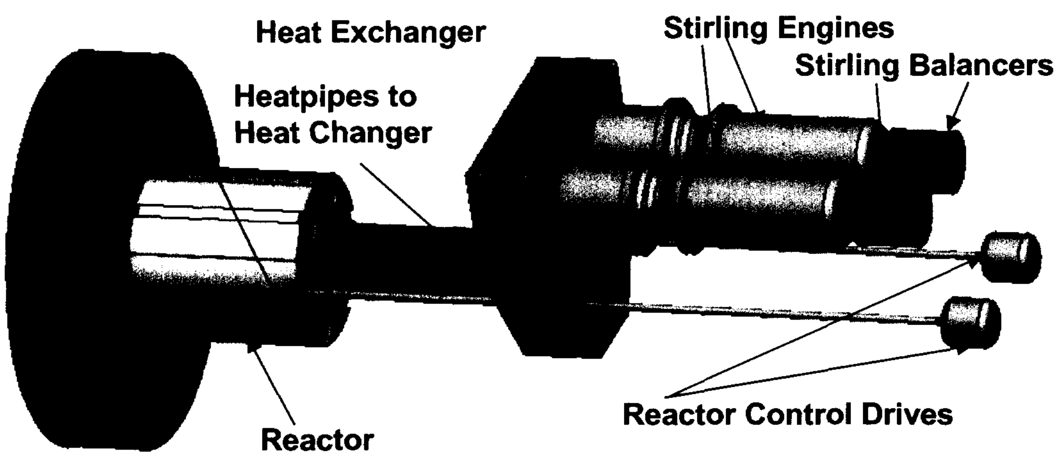
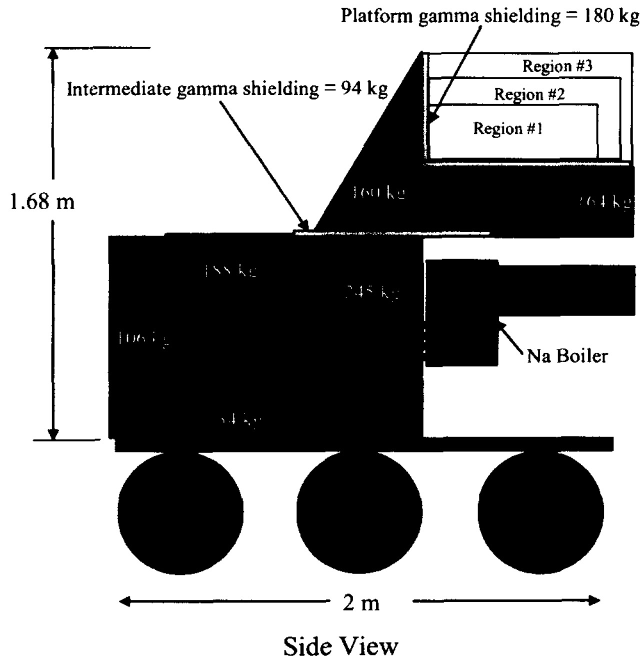


FIGURE 5. Rover Surface Fission Power System (with radial and front axial shield removed).

Shield Design

By far the dominant factor influencing the design of this mission is the shielding necessary to provide a safe haven for the rover and instrument electronics. A baseline requirement was that total mission dose to electronics should be kept below 200 krad to allow the use of currently available technology. It became clear that shielding the full area of the rover deck to acceptable levels would be a prohibitively massive proposition, and scattering from the Martian surface precluded the adoption of a simple shadow shield, such as might be effectively applied in a space environment. The solution in this case resulted in a combination of shielding consisting of two major parts: a preferential 4π shield around the reactor and additional shielding on the rover deck, resulting in a relatively well protected electronics platform as illustrated in Figure 6.

The platform shielding consists of a large slab under the electronics area to protect against scattered neutron flux, and a wedge-shaped shadow shield which serves to cut the radiation directly from the reactor. The 4π shield contains most of the mass and does most of the shielding, largely by preventing neutrons from scattering off of the surface and rover components.



Neutron Shield (kg)	
Left reactor	106
Right reactor	245
Radial reactor	188
Lower reactor	34
Dorsal platform	160
Lower platform	164
Total neutron	**895**

Gamma Shield (kg)	
Intermediate	94
Platform	180
Total gamma	**274**

Figure 6. Rover Shielding Design.

The combination of shielding used in the design totals to a mass of 1169 kg, split among the shield components as shown in Figure 6. The shielding design results in three regions of differing total dose over the area of the electronics platform. The resultant total mission doses for these three regions are shown in Table 3.

TABLE 3. Radiation Dose Results (5 years at 15 kWt).

Location	Neutron (krad)	Gamma (krad)	Total (krad)*
Platform Region 1	147	392	225
Platform Region 2	301	837	468
Platform Region 3	472	1730	818

*note that total for platform locations includes assumed 5x reduction in gamma dose provided by electronics boxes

The shielding design yields dose levels for Region 1 that approximately meet the minimum electronics requirements. Regions 2 and 3 would be reserved for those electronic components that have a higher radiation tolerance rating.

CONCLUSIONS

This design study for a Mars rover incorporating a fission power system has resulted in an innovative packaging and shielding design that fits within the constraints of current hypothetical rover configurations. As with any mission using fission power, the shielding of sensitive rover and instrument electronics drives the mission design. This becomes especially important in the confined space that a rover represents. In space, or in stationary landed systems it is possible to take advantage of distance to mitigate the amount of shielding required, but the rover system, at least in its conventional form, leaves little room for separation. This has led to a design that is compact, but massive as a result of the necessary volume of shielding required. However, the design has resulted in an estimated mass that is not above the capability of projected means of delivery to the surface, and is well below the lift capability of the baseline launch vehicle.

As a preliminary and necessarily abbreviated investigation of the viability of a fission-powered rover on Mars, the MARGE study has allowed the JPL/DoE team to explore a number of unique design challenges and no "showstoppers" were revealed that would preclude the development of such a potentially valuable long range vehicle. Many questions remain to be answered, however, and several specific recommendations for further work are listed below:

- Further detailed analysis of rover design is needed. The total mass of payload that must be carried by the rover dwarfs any previous rover design goals. It is very important if feasibility is to be confirmed that a design for a 3000 kg rover be developed. It may turn out to be very much like the concept modeled in this study, but it may be very different. One can conceive that a tread-type mobility system may be more appropriate to this level of mass. At any rate, rover design is an area that demands close attention.

- Shielding optimization should be performed in concert with rover design. The shielding design developed in this study is innovative and solves the problem of providing a shielded electronics area in a very efficient way. However, there may well be ways to trim shield mass in some areas. This will be made even more efficient when actual detailed rover design can be taken into account.

- Use of Brayton cycle power conversion could increase adaptability of power system design and commonality with in-space systems under development. It is recommended that this option be evaluated for application to the rover power system.

- Finally, the practicality of advanced EDL systems should be evaluated in light of the probable high landed masses that will be required even for an optimized rover design. The use of a mid-L/D aeroshell allows a higher landed mass, but it also offers a larger volume within the aeroshell that might have benefits for further optimizing rover design.

This study has served to give an introduction to the design challenges facing the deployment of mobile nuclear systems in a surface environment. The results indicate promise and a tremendous potential for application to a wide variety of science missions. Further study should be aimed at refining the work begun here to verify design assumptions and expand the envelope of potential applications enabled by this unique concept for Mars exploration.

ACKNOWLEDGMENTS

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