

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Program Overview¹²

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Abstract—Future NASA missions require safe, reliable, long-lived power systems for surface exploration of planetary bodies such as Mars as well as exploration of the solar system in the vacuum of space beyond Earth orbit. To address this need, the Department of Energy and NASA have initiated the development radioisotope power systems, including the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). In June of 2003, the Department of Energy (DOE) awarded the MMRTG system design, development, test and integration contract to a team led by the Boeing Company's Rocketdyne Propulsion and Power Division. Boeing and Teledyne Energy Systems collaborated on an MMRTG design concept based on heritage, SNAP 19, thermoelectric converter design utilized by Teledyne for previous space exploration missions. Boeing subsequently awarded a major subcontract to Teledyne Energy Systems to design and produce the thermoelectric converter system for the MMRTG.

The MMRTG is designed to operate on planetary bodies as well as in the vacuum of space. At beginning of mission, the MMRTG is designed to generate a minimum of 110 watts of power at 28 volts DC, and to have a design life of at least 14 years. The power level was selected to afford the capabilities of meeting the potential needs of a wider variety of planetary lander and deep space missions. Potential mission concepts that could benefit from use of the MMRTG include a Titan Biological Explorer – with both a balloon mission and a rover mission, the Mars Science Laboratory (MSL), with a follow-on Astrobiology Field Laboratory mission and finally a Neptune / Triton Orbiter mission.

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1. PROGRAM OVERVIEW

The MMRTG program consists of six phases, an initial program engineering unit phase followed by five optional phases for qualification and flight unit production

Phase I Engineering model Electrically-heated Thermoelectric Generator (ETG)

In the initial phase of the contract the preliminary design, development, fabrication and testing of an engineering unit will be accomplished. This phase began with a series of trade studies designed to provide data to select the optimum design point to satisfy the system level requirements. A preliminary requirements review (PRR) was completed in the fall of 2003. Following the trade studies and design point selection, there will be a preliminary design review (PDR) in early 2004 to provide the necessary technical confidence in the design and to proceed with fabrication of the engineering unit hardware. The engineering ETG will be assembled late in the summer of 2004, with testing planned for the last quarter of 2004. Electrical resistance heaters will be used to simulate heat generation of plutonium fuel. Boeing will complete testing of the engineering ETG early in 2005, which is when the Phase I period is completed.

Phase II Qualification model ETG

Final design will be completed under a Phase II option to fabricate and test a flight-like qualification unit. This effort will begin in early 2004 and be supported by the bulk of the technical analysis performed for the engineering ETG. All flight hardware processes, which were not developed previously, will be completed and all qualification hardware will be processed to flight fidelity standards. The

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qualification unit will be assembled and checked-out at Teledyne and then shipped to Boeing for final assembly acceptance and qualification testing. Boeing will test the qualification unit as an ETG (using a simulated, non-nuclear, heat source), and then deliver it to Argonne National Laboratory – West where it will be fueled and tested to qualification-level environments. These qualification RTG tests, which include electrical checkout, vibration, thermal vacuum, magnetics and mass properties, are scheduled for completion in mid-2006.

Phases III through VI

Flight model ETG's plus a flight spare ETG

Optional follow-on phases allow for the fabrication of flight MMRTGs, with 2 units produced in Phase III, 3 units in Phase IV, 2 units produced in Phase V and 1 spare unit produced in Phase VI. The spare unit would most likely be produced in conjunction with Phase III, along with the first flight units. (see Figure 1 for Program Schedule)

In addition to producing development, qualification and flight hardware, Boeing has a lead integration role for the processing, testing, shipment, and storage of RTG's and spacecraft integration. This activity is discussed in section 3 of this paper. Boeing also has a lead role in safety analysis for the MMRTG and safety analysis support for the applicable government agencies responsible for given space missions, transportation of RTG's and launch site safety review teams. This activity is discussed in section 4 of this paper.

Program Schedule – All Phases

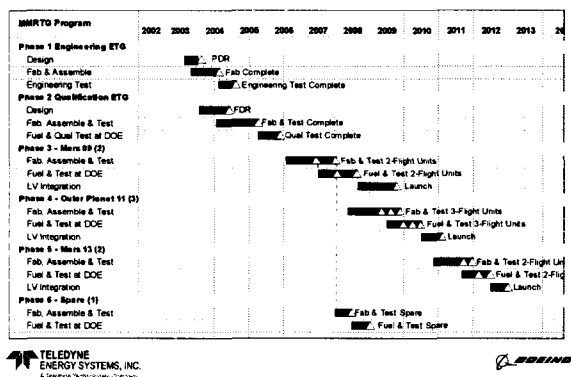


Figure 1– MMRTG Program Schedule

2. DESIGN SUMMARY

Top level requirements for the MMRTG design have been established. The heat source for the MMRTG design will consist of eight (8) enhanced General Purpose Heat Source (GPHS) modules. These modules are similar to those used in the GPHS – RTG that powered the Galileo, Ulysses, and Cassini spacecraft. Teledyne Energy Systems has lead responsibility for design and fabrication of the

thermoelectric converters. The MMRTG uses PbTe / TAGS (Tellurium-Antimony-Germanium-Silver) thermoelectrics (TES), similar to those used in the SNAP-19 generators that powered the Viking and Pioneer missions. Pioneer 10 has operated for over 30 years and is 7 billion miles from Earth.

The Viking RTGs are the only RTGs to operate on the Mars surface. The Boeing/Teledyne MMRTG design has been heavily influenced by the SNAP-19 design and shares many common elements. SNAP-19 design features were used in Teledyne's later terrestrial products and are in production today. On-going TE couple life tests at Teledyne have accumulated 3 million couple hours since 1990 with no failures.

MMRTG design requirements have been developed through coordination with key DOE and NASA personnel. These requirements have been established to meet multi-mission applications and provide RTG interchangeability mission-to-mission without modification. Establishment of the requirements has been accomplished utilizing a systems assessment approach. Figure 2 outlines the systems level approach used. Inputs were obtained through the DOE program office, from currently identified potential missions, from organizations representatives of future missions and from a review of previous mission requirements. Trade studies were performed on key parameters and the most optimal set of requirements was selected which would maximize the benefits to planetary landers and deep space exploration missions. Boeing, with input from the Jet Propulsions Laboratory (JPL/NASA), DOE, the launch vehicle contractor, and Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFS), will prepare MMRTG specifications and interface control drawings to capture these requirements.

System Assessments Support Requirements Development

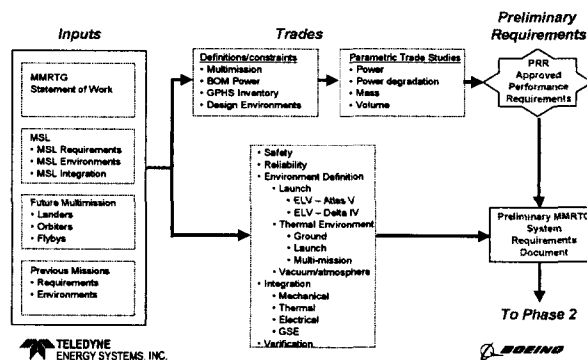


Figure 2– MMRTG System Requirements Development

3. INTERFACE AND INTEGRATION ACTIVITIES

Power system integration includes interface with government laboratories, spacecraft integration and liaison,

and launch support. Boeing has successfully integrated space power systems on 197 unclassified commercial, military, and civilian spacecraft, and would lead these integration efforts. Teledyne has ongoing programs with the DOE fueling facility and would have lead responsibility for interfacing with DOE during fueling operations.

Boeing would lead the integration activities between the Boeing / Teledyne team, DOE headquarters, NASA headquarters and program offices including the Jet Propulsion Lab (JPL), and between all DOE supporting sites including Oak Ridge National Lab (ORNL), Los Alamos National Lab (LANL) and Argonne National Lab – West (ANL). Boeing would coordinate all activities in support of MMRTG process, transportation, storage, handling and loading of the RTGs onto the spacecraft at KSC. Additionally, Boeing would coordinate all activities with MMRTG customers, when identified, for interface, environments, handling / installations and mission processing support.

Boeing is expert at complex integration tasks with Space Shuttle and Space Station being two recent examples. The MMRTG represents a complex integration task as it joins many advanced fields, complex technologies, unique materials, skills, and personnel from both government and industry working together across the entire United States.

Being multi-mission, the design has to encompass usage on crafts as varied as ground based rovers or landers, deep space probes, orbiters, and fly-by spacecraft. Missions that are to be accommodated in the design include the 2009 Mars Science Laboratory (MSL) Rover, Titan Explorer Biological Explorer missions, Astrobiological Field Laboratory (AFL), Neptune / Triton Orbiter and New Frontiers missions. Each of these missions has different needs that must be analyzed to assure the MMRTG would meet all requirements. Different missions mean different launch vehicles with different thermal and vibration environments. The MMRTG is being designed to meet the requirements of the vehicles in both the Delta and Atlas Rocket families.

Related past missions, such as ALSEP (SNAP-27), NIMBUS III (SNAP-19B3), Pioneer 10 & 11, Viking Lander, Voyager, Galileo, Ulysses, and Cassini, have been researched to understand and use the lessons learned from those successful programs.

4. SAFETY ANALYSIS

Approval to launch a nuclear power source into space depends on the successful completion of two separate safety and environmental review processes. The National Environmental Policy Act (NEPA) and the launch approval process defined in Presidential Directive PD/NSC-25 govern these processes. For the MMRTG program, NASA is the user agency and would request launch approval and submit

the Environmental Impact Statement (EIS) for the missions proposed. The DOE would provide nuclear risk safety analysis for input to the EIS and the Presidential approval process.

Should the MMRTG be selected as the power source for a mission, Boeing has prepared a comprehensive safety plan in support of the DOE for completing these approval processes. Activities would involve supporting the DOE role of providing NASA data for the EIS and supporting NASA as directed by DOE during the public review process. Boeing would perform a separate nuclear risk assessment for the DOE and document the results in safety analysis reports. Boeing would also provide support for all Interagency Nuclear Safety Review Panel (INSRP) reviews and other public review forums as directed by DOE.

Key Elements of the Boeing/Teledyne Safety Plan include:

- Development of an integrated nuclear risk assessment computer code to be supplied to the DOE
- Performance of comparative risk assessments to support design
- Performance of risk assessments in support of the NEPA process for proposed missions
- Preparation of a Preliminary Safety Analysis Report (PSAR) during Phase II
- Preparation of safety test plans
- Preparation of Draft Final Safety Analysis Reports and Final Safety Analysis Reports for missions planned in Phases III through V of the program
- Participation in INSRP reviews of the safety analysis reports

To accomplish these tasks, a senior team of nuclear safety specialists from Boeing and Teledyne is being assembled and would be augmented by additional experts in the field. These experts would include former NASA and military personnel with extensive experience in nuclear space launch activities.

5. POTENTIAL PLANETARY LANDING AND DEEP SPACE MISSION APPLICATIONS

TITAN BIOLOGICAL EXPLORER

The deep atmosphere of Titan is ideal for airborne robot, or aerobot exploration. [1, 2] Exploration of the atmosphere to 300km altitude is important to investigate in situ the photochemical reactions that yield products important to the understanding of prebiotic synthesis on Titan. Exploration of the surface would build on the discoveries of the Huygens probe and could include aerobot descents to multiple sites. The ability of the aerobot to easily traverse liquid as well as solid surfaces is an important feature for mobile in situ exploration.

A Titan Prebiotic Explorer could be implemented with

different kinds of aerobot designs depending on which facet of the Titan environment was considered to be most important.

For a surface-oriented mission, a balloon using argon as a reversible fluid (i.e., that could be released from pressurized storage to increase balloon pressure or pumped back in the storage container to reduce balloon pressure) is the preferred approach and would permit visits to hundreds of sites well distributed over the surface of the satellite. This vehicle could make numerous visits to the surface for durations of hours to days, before rising to altitude and drifting to another location. Unlike Venus, temperature variations in the Titan atmosphere are not large and thermal control considerations do not limit the duration of surface stay time. We refer to this proposed mission concept as the Titan Aerobot - Multisite (TAM) mission. (See Figure 1.)

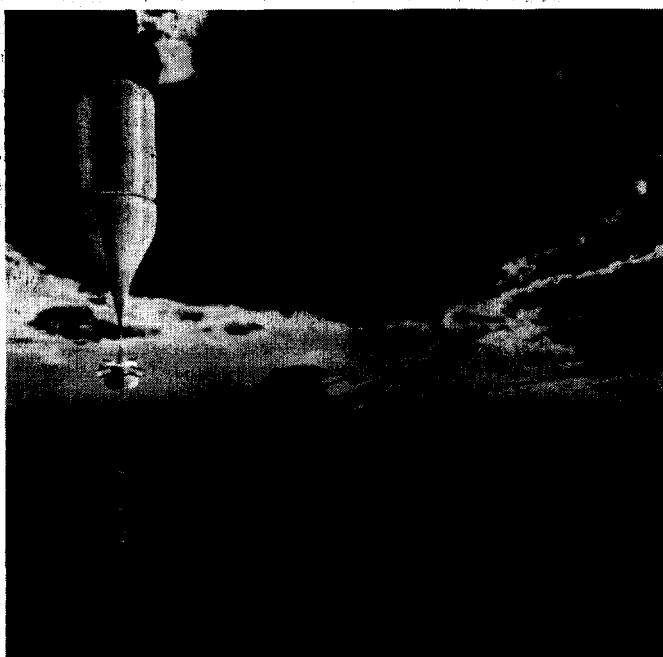


Figure 1 – Titan Aerobot

For a focus on the atmosphere, a higher altitude capability is needed and this would utilize a superpressure balloon. The vehicle would descend to the lower atmosphere of Titan for inflation and then float at an altitude of 115 to 125 km to implement its atmospheric mission. The vehicle would then vent gas and descend to near the surface and skim the terrain using a guide rope. It would conduct observations at one surface site for a distance of several tens of kilometers. This mission concept is referred to as the Titan Aerobot - Singlesite (TAS) Mission

A third variation is the hybrid combination of balloon (Aerobot) and rover technologies, and exploits Titan for its optimal hybrid vehicle environment. The first part of the mission (days, weeks, or months) is a balloon that provides aerial mapping, imaging, sampling, and real-time site selection capabilities. At some point in the flight, real-time selection of a landing site is made and the system descends to the surface. The second part of the mission is a rover that provides ground-based localized and specific target site inspection. Refer to the attached diagram for clarification of the mission sequence. These two parts are described in more detail below. (See figure 2.)

Part I: Balloon Mission

Initially, the system would inflate on entry, deploying three thick-walled balloons approximately 2 meters in diameter. These "balloons" not only serve as the lifting body, but are also used as both a landing mechanism (airbags) and as wheels in the final rover configuration. This system would maintain a nominal altitude of 7 km. By venting helium, descents are made (to approximately 200-300 meters) to retrieve surface samples from tethered coring modules.

The sample is removed and the coring shell is left behind (serving as ballast). The Aeroover then re-ascends to 7 km for repeated near-surface excursions. The balloon eventually, and permanently, descends to the surface and lands on what now become wheels/airbags. The descent is initiated by a gradual venting of helium; this is commanded by the system based on criteria such as minimum/maximum balloon mission length and the priority of landing at particular surface features. Other potential off-nominal causes include balloon lifetime limitations (i.e. faster than expected helium leakage).

Part II: Rover Mission

Once landed, the Aeroover platform provides highly localized sampling and terrain characterization. The residual helium (used for a soft landing) is replaced with ambient air through carbon absorption. Nominally, based on the landing criteria, the system has selected a specific site of interest to visit (i.e. a shoreline and lake/ocean). Using inflatable-wheel rover technology, speeds of up to 10 km/hr and high-density obstacles of up to 0.5 meters are overcome in reaching the target point. Also, non-corrosive liquid obstacles/targets (i.e. lakes or oceans) are traversed by the Aeroover as it floats/glides on the surface. Once the system reaches its target location, or other sites of interest, it can perform detailed, localized inspections of multiple sites using the same science instruments/cameras as was used for aerial sampling. The rover mission would complete the life of the Aeroover and would potentially last from days to weeks.

Titan Aerover Mission Sequence

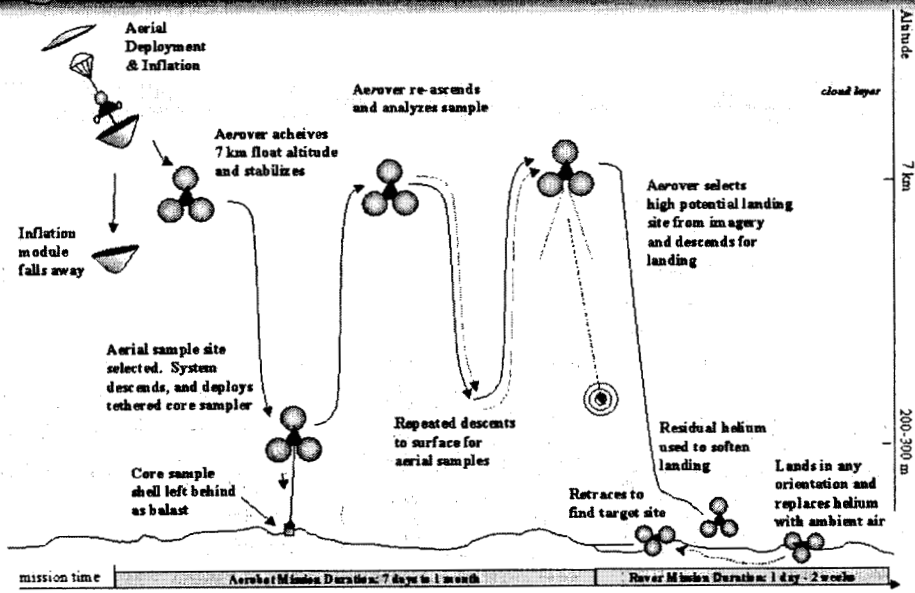
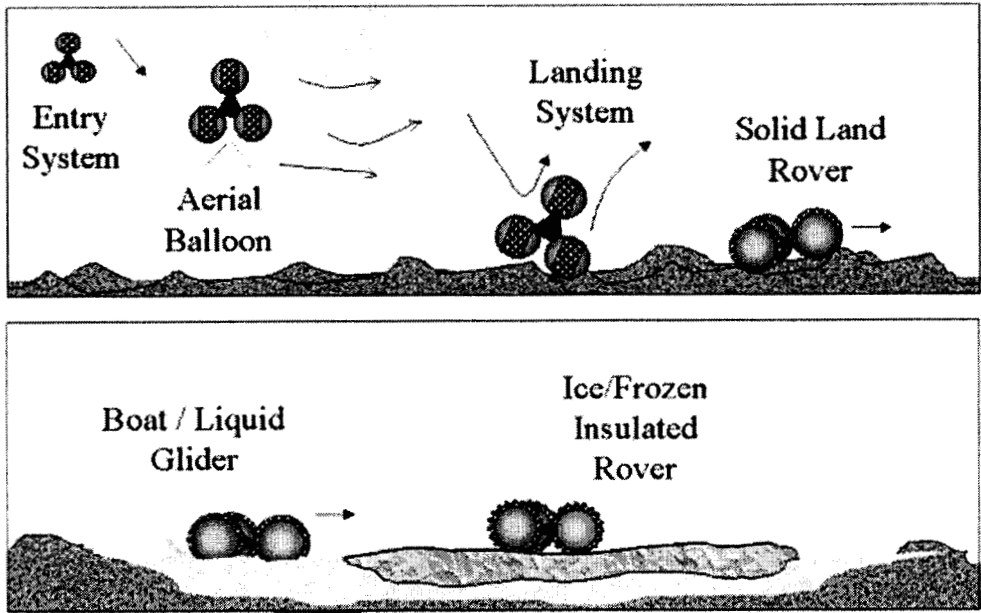


Figure 2 - Titan Aerover Mission Sequence

Aerover Multi-Roles: Aerial, Solid Frozen Land, Liquid



All three variations of the Titan mission concept under study would rely on MMRTGs to provide power. They would also plan to take advantage of the waste heat of the MMRTGs to maintain thermal balance and keep the spacecraft electronics and mechanisms within an operable range. This is a critical capability, since the average temperature of Titan is only 140 K.

MARS SCIENCE LABORATORY (MSL)

NASA proposes to develop and to launch a roving, long-range, long-duration science laboratory that would provide a major leap in surface measurements and pave the way for a future sample return mission. [3] NASA is studying options to launch this mobile science laboratory mission as early as 2009. This mission would also demonstrate the technology

for "smart landers" with accurate landing and hazard avoidance capability in order to reach what may be very promising but difficult-to-reach scientific sites. Together with long range roving capability, new remote sensing and analytical suites of instruments, and long lifetime provided by MMRTG technology being considered for the mission, it would serve as a bridge to the exploration pathways for Mars for the next decade. See figure 3 for an illustration of a potential MSL mission concept. The MMRTG's can be seen at the top of the rover, one on either side.

ASTROBIOLOGY FIELD LABORATORY

A potential follow-on to the Mars Science Laboratory (MSL) mission is the Astrobiology Field Laboratory (AFL).

The system concept is designed to achieve a linear surface traverse of 25 km (40 km odometry capability). This capability is needed to reach and explore specific sites of high scientific interest. AFL is also designed to achieve sub-surface drilling depths of 2.5 m. This drilling depth enables access to unoxidized material. It is then capable of processing rock, regolith, ice and water extracted by the drill.

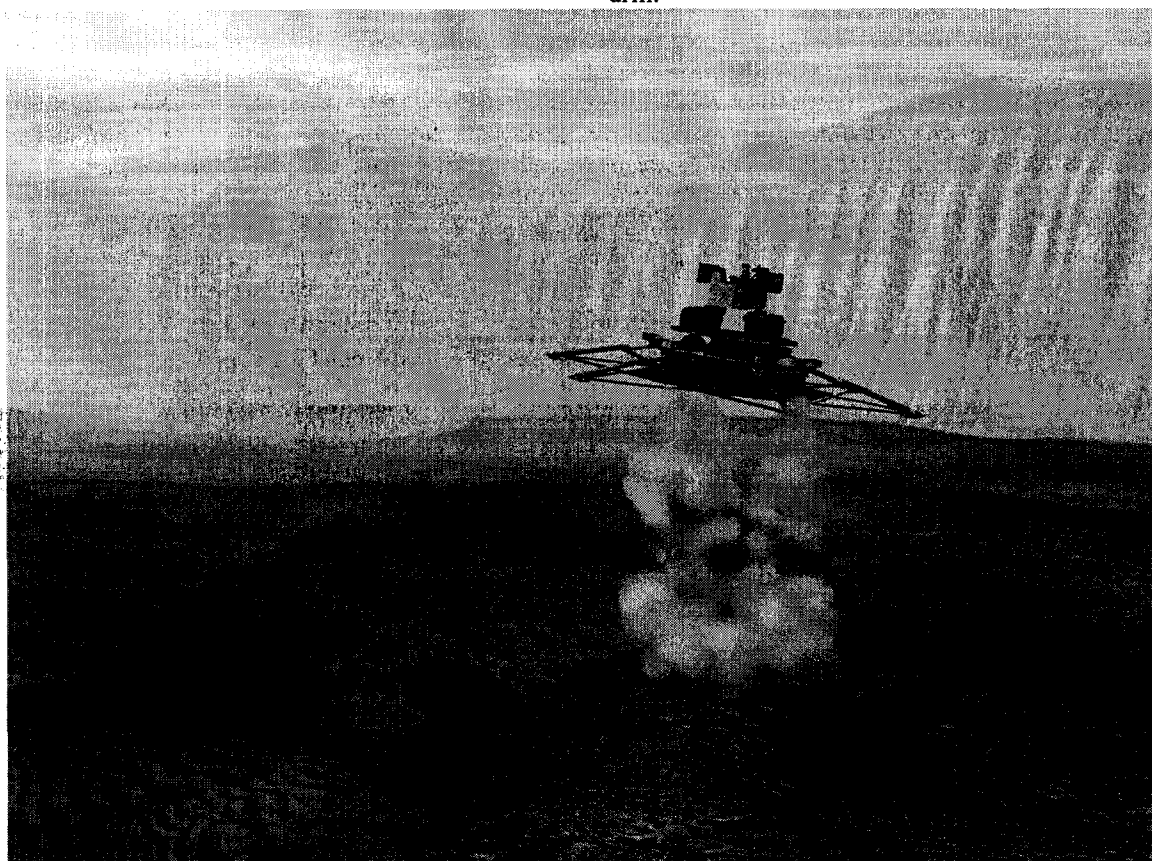


Figure 3 – Artist's conception of the Mars Science Laboratory with a robust landing system

The primary power source for the mission under study is based on use of the MMRTG and would require two units with a power generating capability of 110 W each, or 220 W total. This mission as conceived could be launched as early as 2013, depending on the results of the MSL mission. Figure 4 illustrates the location of the MMRTGs at the back of the AFL rover. See Figure 5 for an idea of how the AFL rover would look on the surface of Mars.

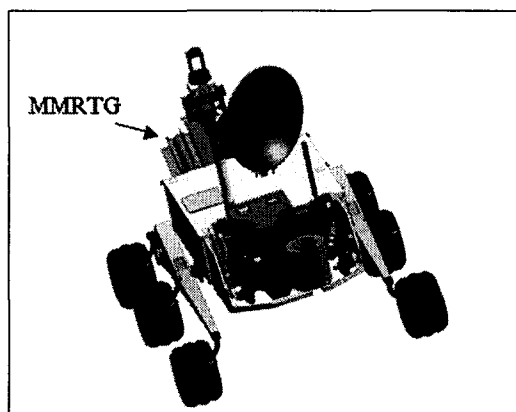


Figure 4 – Schematic of the AFL rover showing the location of the MMRTG

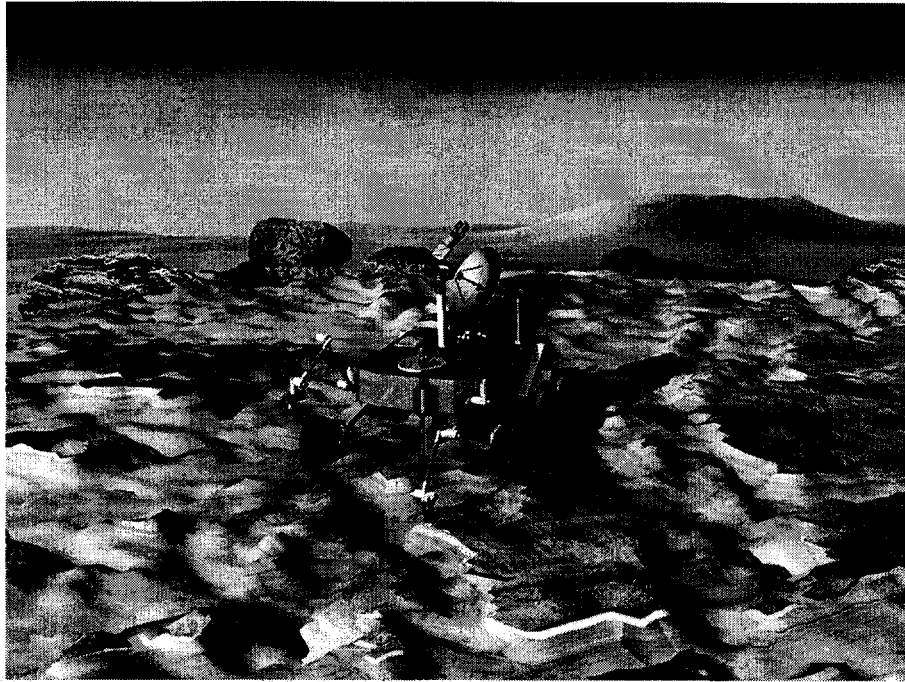


Figure 5: Artist's conception of the AFL Rover on the surface of Mars

NEPTUNE/TRITON ORBITER

The Neptune Orbiter with Probes mission concept consists of a propulsive stage that provides the delta-V necessary to get to Neptune, an orbiter/carrier spacecraft housing 9 orbital instruments, and 3 probes that would be released into the Neptune atmosphere. [4] The probes would reach a depth corresponding to at least 100 bar, which at Neptune is at a depth of about 218 km. (See Figure 6.) The probes would carry the same instruments as that proposed for a Jupiter multi-probe mission, and would collect data to study the internal structure of the Neptune atmosphere, its winds, and abundance of various constituents. The orbital instruments would provide global maps of the magnetosphere, composition, structure, and dynamics of the atmosphere at Neptune and Triton during a 2-year mission around Neptune. They would also provide information on the rings and possibly other satellites if possible at the end of the primary mission. The mission under study is envisioned to be launched in 2014, with a 12-13 year cruise. After release at an appropriate time, each of the probes would have a 3-hour descent into the Neptune atmosphere. Each probe would be released at different times at different latitudes. Their data would then be played back in a 1-2 day time period afterwards. The orbiter would have a 12-day orbit duration, and would collect roughly 3.6 Mb of data at each orbit, which would require 25 hours to transmit the data back to Earth.

The main challenges for this mission concept are the long mission duration (specifically the 12 to 13 year cruise), the development of high specific power solar arrays for electric

propulsions (EP) systems, use of advanced Solar Electric Propulsion (SEP) engines and feed systems, availability of an advanced radioisotope power source (ARPS, i.e. MMRTG) or other power system capable of providing power at 30 AU, Ka-band or optical telecom to Earth, and use of Aerocapture/Aerobraking. As the mission is currently conceived, two MMRTGs would be required to provide sufficient power for the Orbiter during its mission. Thermal controls would be required to allow for transfer of the MMRTG waste heat to radiators outside the aeroshell until the Orbiter has completed Aerocapture at Neptune. While Nuclear Electric Propulsion (NEP) has been considered as an alternative mission design, it is not clear at this time that the additional flexibility provided would justify an NEP approach, given the projected cost of an NEP system.

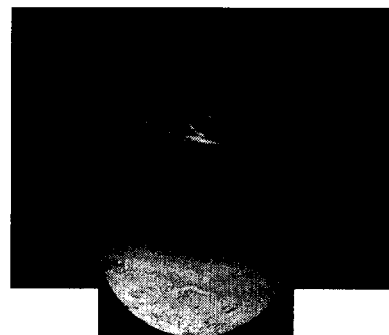


Figure 6 – Neptune and its major Satellite, Triton

6. CONCLUSIONS

A multi-mission radioisotope thermoelectric generator (MMRTG) would provide a power system to support a variety of surface missions and spacecraft destined to explore the solar system in the vacuum of space beyond Earth orbit. NASA and the Department of Energy (DOE) are working together on radioisotope power systems that could be developed in time to support potential NASA visionary exploration missions to the planet Mars, the Titan moon of Jupiter and other new frontier initiatives.

7. ACKNOWLEDGEMENTS

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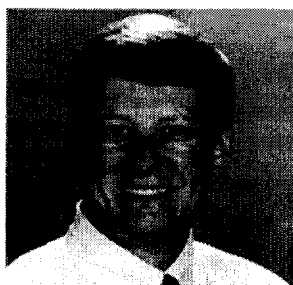
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- JPL - Aaron Bachelder and Jack Jones – Titan Aerobot concepts
- JPL – Roger Diehl and Knut Oxnevad – Mars Astrobiology concept study
- JPL – Mars Science Laboratory Project
- JPL – Advanced Mission Study Office
- Teledyne Energy Systems Inc, Hunt Valley, Maryland

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9. BIOGRAPHIES

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fabrication, assembly and integration testing would be performed. Fred has extensive background in space system payload integration with a previous position as Director of Cargo Element Integration for International Space Station (ISS) for Boeing Canoga Park. Fred also worked in a variety of engineering and management positions on the ISS program and the Space Shuttle Main Engine (SSME) program. Fred holds a BS in Engineering from Western Michigan University and an MBA from Pepperdine University.

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